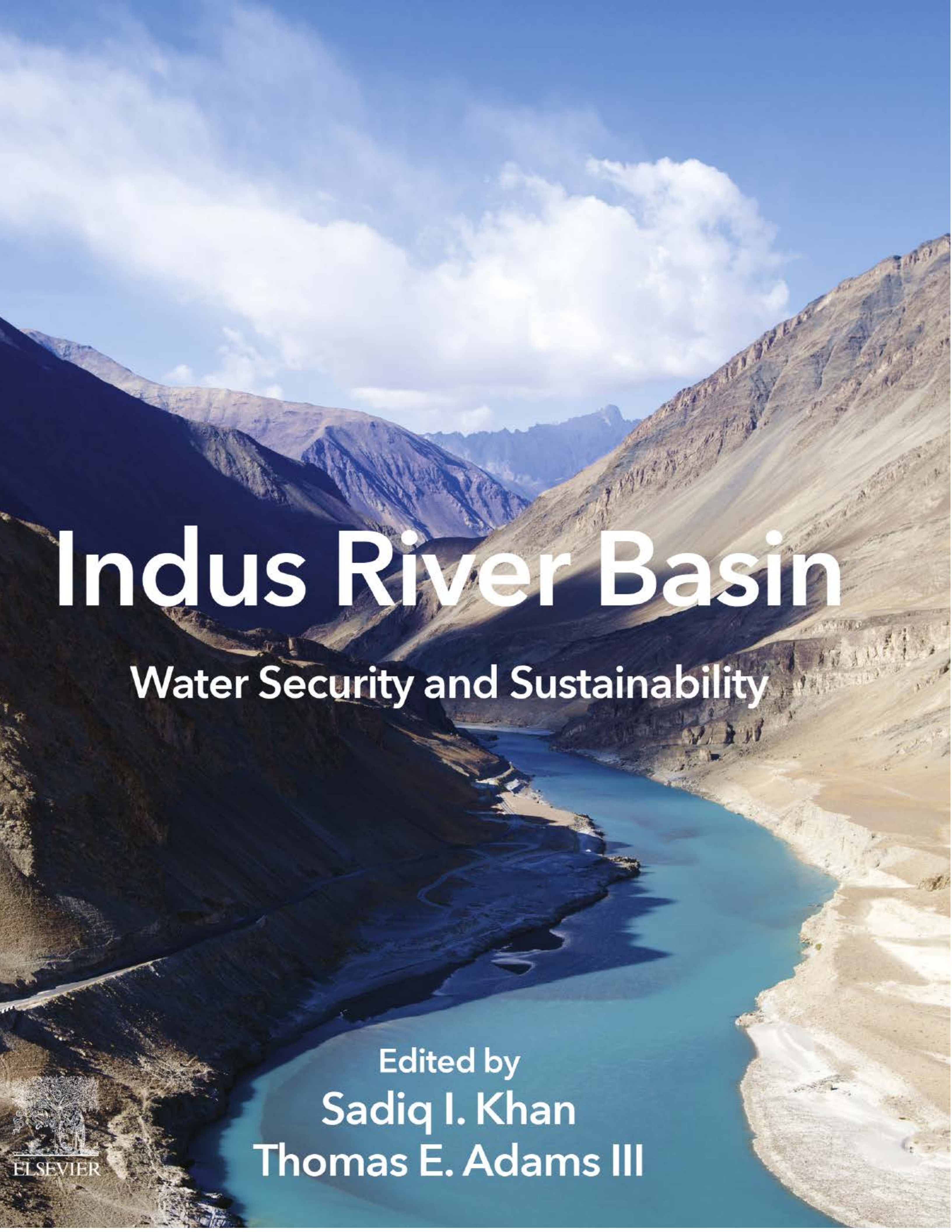

Indus River Basin

Water Security and Sustainability

Edited by
Sadiq I. Khan
Thomas E. Adams III

ELSEVIER

Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

© 2019 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices
Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-0-12-812782-7

For information on all Elsevier publications visit our website at https://www.elsevier.com/books-and-journals

ELSEVIER
Book Aid International
Working together to grow libraries in developing countries
www.elsevier.com • www.bookaid.org

Publisher: Candice Janco
Acquisition Editor: Louisa Hutchins
Editorial Project Manager: Emily Thomson
Production Project Manager: Prem Kumar Kaliamoorthi
Cover Designer: Greg Harris

Typeset by SPi Global, India

Contents

PART I

INDUS RIVER BASIN—PAST, PRESENT AND FUTURE

Introduction of Indus River Basin: Water Security and Sustainability

SADIQ I. KHAN, THOMAS E. ADAMS III

1. Water Resources Modeling and Prospective Evaluation in the Indus River Under Present and Prospective Climate Change

DANIELE BOCCHIOLA, ANDREA SONCINI

2. Challenges in Forecasting Water Resources of the Indus River Basin: Lessons From the Analysis and Modeling of Atmospheric and Hydrological Processes

MICHEL D.S. MESQUITA, YVAN J. ORSOLINI, INDRANI PAL, VIDYUNMALA VELDORE, LU LI, KRISHNAN RAGHAVAN, ASHWINI M. PANANDIKER, VIVEKANAND HONNUNGAR, DAVID GOCHIS, JOHN F. BURKHART

3. Past and Future Glacier Changes in the Indus River Basin

TOBIAS BOLCH

PART II

CLIMATE-ECO-HYDROLOGY OF INDUS RIVER BASIN

4. Probabilistic Precipitation Analysis in the Central Indus River Basin

PAOLO REGGIANI, OLEKSIY BOYKO, TOM H. RIENTJES, ASIF KHAN

5. Glaciers in the Indus Basin

SAMJWAL RATNA BAJRACHARYA, SUDAN BIKASH MAHARJAN, FINU SHRESTHA

6. A Review on the Projected Changes in Climate Over the Indus Basin

ARUN BHAKTA SHRESTHA, NISHA WAGLE, RUPAK RAJBHANDARI

7. A Hydrological Perspective on Interpretation of Available Climate Projections for the Upper Indus Basin

NATHAN FORSYTHE, DAVID R. ARCHER, DAVID PRITCHARD, HAYLEY FOWLER

PART III

WATER AND FOOD SECURITY OF INDUS RIVER BASIN

8. Transboundary Indus River Basin: Potential Threats to Its Integrity

MUHAMMAD JEHANZEB MASUD CHEEMA, MUHAMMAD UZAIR QAMAR

9. Indo-Ganges River Basin Land Use/Land Cover (LULC) and Irrigated Area Mapping

MURALI KRISHNA GUMMA, PRASAD S. THENKABAIL, PARDHASARADHI TELUGUNTLA, ANTHONY M. WHITBREAD

10. Increasing Water Productivity in the Agricultural Sector

ASAD SARWAR QURESHI

11. Hydrological Cycle Over the Indus Basin at Monsoon Margins: Present and Future

SHABEH UL HASSON, JÜRGEN BÖHNER

PART IV

WATER EXTREMES IN INDUS RIVER BASIN

12. Water Resources Forecasting Within the Indus River Basin: A Call for Comprehensive Modeling

THOMAS E. ADAMS III

13. Review of Hydrometeorological Monitoring and Forecasting System for Floods in the Indus Basin in Pakistan

MANDIRA SINGH SHRESTHA, MUHAMMAD RIAZ KHAN, NISHA WAGLE, ZAHEER AHMAD BABAR, VIJAY RATAN KHADGI, SHAHZAD SULTAN

14. Flood Monitoring System Using Distributed Hydrologic Modeling for Indus River Basin

SADIQ I. KHAN, ZACHARY FLAMIG, YANG HONG

15. Annual Flood Monitoring Using Synchronized Floodwater Index in 2010 Indus River Flood

YOUNG-JOO KWAK, JONGGEOL PARK

PART V

WATER MANAGEMENT IN INDUS RIVER BASIN

16. Water Management in the Indus Basin in Pakistan: Challenges and Opportunities

MUHAMMAD BASHARAT

17. Integrated Irrigation and Agriculture Planning in Punjab: Toward a Multiscale, Multisector Framework

AYESHA SHAHID, AFREEN SIDDIQI, JAMES L. WESCOAT JR.

18. Developing Groundwater Hotspots: An Emerging Challenge for Integrated Water Resources Management in the Indus Basin

MUHAMMAD BASHARAT

19. Quantitative Estimation of Resource Linkages in Water Infrastructure Planning

AKHTAR ALI, MUHAMMAD AKRAM

CHAPTER

10

Increasing Water Productivity in the Agricultural Sector

Asad Sarwar Qureshi
International Center for Biosaline Agriculture (ICBA), Dubai, United Arab Emirates

10.1 INTRODUCTION

The world population is expected to increase to more than 9 billion by 2050 (FAO, 2011). Demand for food and fiber will also increase as incomes and standards of nutrition rise and as people consume more land- and water-intensive diets (i.e., consumption of more meat and dairy products). Current estimates suggest that by 2050 annual cereal production will rise to about three billion tonnes and meat production to more than 200 million tonnes (FAO, 2006). To produce this amount of food, irrigated land must increase by 35%, and 20% more water must be diverted to agriculture. However, due to increasing inter-sectoral competition for water and decreasing investment in irrigation development, expansion of irrigated lands will be no more than 5%, and water diversions for irrigation are projected to decrease by 8% because of climate change and other management issues. Thus in the future irrigation's contribution to food security will have to come from improving existing systems and increasing the productivity of available water resources. Under the "business as usual" scenario (i.e., continuing with the current agricultural practices and water productivity levels), 4500 km ^{3} yr^{-1} more water will be needed to feed the world's population by 2050 (Falkenmark et al., 2009). This is roughly twice the amount of water presently used in irrigation (Kijne et al., 2009).

Alarmingly, most of this population increase is expected in developing countries where access to water for agriculture and domestic purposes is already under stress and where 1.2 billion people lack access to safe drinking water. Physical water scarcity is already affecting food production in the arid parts of the world, for example, in North Africa and the Middle East. Although there are varying opinions on the degree and severity of water scarcity in Asia and Africa, there is broad agreement that increasing water scarcity will turn water into a key limiting factor in food production and the livelihoods of people who are impoverished

https://doi.org/10.1016/B978-0-12-812782-7.00011-4

throughout rural Asia and most of Africa, with particularly severe water scarcity in the breadbaskets of Northwest India and Northern China.

Water distribution across regions is also not equitable. Asia is particularly hard hit, with just 36% of the world's water resources supporting 60% of the world's population (Qureshi and Shoaib, 2015). Africa has a better balance, 11% of the world's available fresh water with 13% of the world's population. The population of the Arab world is 3% of the world's population, but it receives only 1% of the world's renewable water resources. For Arab countries in the Gulf, per capita water availability is very low; that is, except for Egypt, which has 1120 m^3, the per capita water availability ranges between 107 m^3 in Kuwait and 148 m^3 in Saudi Arabia. Due to population growth, it is expected that per capita water availability will reduce to half by 2025. Increasing demand and decreasing quality have put enormous pressure on the agricultural sector to reduce its use of water. Currently, more than 90% of the available water in Asia and 88% in the Arab world is used for agriculture (Qureshi et al., 2016). Despite this high-water allocation for agriculture, more than 50% of their food requirements are imported, and this gap is likely to double in the next two decades.

The water demand is driven by four major factors: population growth; increased living standards; water allocation between agriculture, industry, and domestic sectors; and efficiency of water use and distribution systems. The issue of water demand must be addressed because, if per capita water allocations are not modified, economies will be destabilized and food security will be threatened. Land expansion is no more a viable option to increase agricultural production due to increasing land degradation and urbanization problems (Cai et al., 2011). As opportunities for development of new water resources are limited and costs are rising, increasing the productivity of existing water resources becomes a more attractive alternative. Increasing the *productivity* of existing water resources is central to produce more food, to fight poverty, to reduce competition for water, and to ensure that there is enough water for nature.

It must be realized that it is not just the volume of water delivered but also the way it is delivered that controls the effective use of resources. Increasing water productivity means using less water for crops while maintaining or even increasing total crop productivity (unrelated to the economic value of water) by enhancing the efficient use of water through improved management and advanced irrigation technologies. Several strategies can be considered as a part of these activities, such as redesigning total irrigation systems for higher efficiency, reusing marginal waters, reducing evaporation losses, practicing deficit irrigations, and minimizing water losses to unrecoverable sinks. Replacing high-water-consuming crops with lower-water-consuming crops can also increase the economic productivity of water if the high-value crop has a shorter growing season and the land is cropped only once a year. Increasing on-farm irrigation efficiencies may not save water; however, improved irrigation systems make farm operations more efficient and competitive.

Management of the demand for water requires increased water productivity in agriculture, rational water allocations for different sectors, and reduced water loss at all levels. Improvements in water productivity can generate higher agricultural outputs, increase farm incomes, and reduce poverty. Averting a water crisis is a massive undertaking that will require a combination of conservation, improved efficiency, and increased cooperation among competing interests. This chapter discusses concepts of water productivity at different scales and targets different strategies, with the aim of enabling policies and institutions to successfully adopt different interventions that can help increase water productivity at different scales.

10.2 CONCEPTS OF WATER PRODUCTIVITY

The term water productivity is defined as the amount of beneficial output per unit of water depleted. In a broader sense, it is related to "crop production per unit of water used" (Molden et al., 2010; Kijne et al., 2009). Improving agricultural water productivity is related not only to increased production of rain-fed and irrigated crops but also to maximized production of fish, trees, and livestock. The used water includes "green" water (effective rainfall) for rain-fed areas and both "green" and "blue" water (diverted water from surface and groundwater systems) for irrigated areas.

$$\text{Water Productivity (WP)} = \frac{\text{Crop produced}}{\text{Water consumed}}$$

In defining water productivity, we need to express explicitly which *production* (biomass or yield) and which *water consumption* (transpiration or evapotranspiration) is being considered (Perry et al., 2009). Water productivity can be expressed in physical or economic terms. Physical water productivity is the quantity of the product divided by the quantity of the input and can be expressed in terms of mass (kg), or even in monitory terms ($) to compare different crops (Molden et al., 2007). The physical production may include crop yield, biomass, fish, and livestock production, which are expressed in unit of kilogram; it can also be stated in economic values ($) like market value of grain and/or biomass or nutritional values (kilocalories). Water input can be gross inflow, net inflow, available water, irrigation, and actual evapotranspiration.

The physical production of a crop per unit of consumed water is denoted by different indicators. The water productivity is expressed as the biomass or yield (kg) per cubic meter (m^3) of evapotranspiration (ET) or crop transpiration (T). Evapotranspiration is the sum of evaporation (E) and transpiration (T) of soil water through plant systems and into the atmosphere. Transpiration is the flow of water vapor from stomates of leaves that causes liquid water to move from soil to roots, through stems, and on to leaves. Water vapor exits through the same stomates that carbon dioxide enters. The water vapor lost by transpiration in exchange for carbon dioxide is the primary process for plant growth and development. Other nutrients are delivered to crops from the soil by the water used in transpiration. Evaporation is the direct conversion of water into water vapor when wet leaves or soil are exposed to drier air and radiant heat.

Generally, a linear relationship is observed between crop biomass and transpiration for a given situation; however; the slope of this relationship may vary for diverse conditions (Howell, 1990). Since crop transpiration is usually considered a direct measure of the physiological performance of a crop, water productivity is expressed as crop yield/biomass per unit of transpiration ($WP_T = Y/T$). The inevitable loss of water due to soil evaporation negatively affects the water productivity from WP_T to WP_{ET}, which is expressed in terms of yield/biomass per unit of ET. WP_{ET} represents the total amount of water used in crop production.

WP_T is used for farm-level analysis whereas for the scales above farm level, WP_{ET} is widely used. Relatively lower WP_{ET} values stress the need to reduce soil evaporation through different management measures. When water is a limiting resource, actual yield per unit of applied water (i.e., irrigation and precipitation) ($WP_{AW} = Y_{act}/AW_{I+P}$) also becomes important

(Molden, 2007). Economic productivity ($\$/m^3$) uses valuation techniques to derive the value of water, income obtained from water use and benefits derived from water or increased welfare. The introduction of water productivity measures makes it possible to undertake a holistic and integrated performance assessment by.

- including all types of water uses in a system;
- including a wide variety of outputs;
- integrating measures of technical and allocative efficiency;
- incorporating multiple use and sequential reuse as the water cascades through the basin;
- including multiple sources of water; and
- integrating nonwater factors that affect productivity.

Water productivity can be measured at different scales to meet the needs of different stakeholders in the system, from farmers to policymakers. Farmers are interested in increasing WP at field scale to reduce water charges and generate more income. For irrigation managers, increasing WP at the system scale is important, whereas for policymakers, maximizing outputs from efficient use of all available water is the key issue. As pursuit of "maximum outputs from the system" is often the research focus, balancing the benefits of all stakeholders is always important to ensure sustainable development. This is achieved by defining the inputs of water and outputs in units appropriate to the users' indicator needs.

The output derived from water use can be defined in the following ways:

- Physical output, which can be total biomass or harvestable product
- Economic output (the cash value of output) either gross benefit or net benefit
- Water input, which can be specified as volume (m^3) or as the value of water expressed as the highest opportunity cost in alternative uses of the water

Different indicators used to assess water productivity for a cropping system at different scales are briefly discussed next (Cook et al., 2009):

- *Plant scale*: At this scale crop physiologists need to assess how efficient a crop or cultivar of a crop is in converting water into biomass or crop yield. The output can be quantified either as total biomass or as crop yield (harvestable produce), whereas the relevant water input is the water used in transpiration.
- *Field scale*: This scale is central in assessing how efficiently a cropping system converts water into beneficial output. At this scale the output can be quantified as total biomass or crop yield (kg) and the water inputs as the amount of water that was used in transpiration (m^3).
- *Farm scale*: This scale is of interest to farmers, agronomists, and water specialists in assessing the opportunities of saving water lost through non-beneficial use. At this scale the output can be quantified as total biomass, crop yield (kg), or crop value ($), while the water input is the amount of water depleted from the system through (1) evaporation, (2) flows to sinks that are not recoverable, (3) pollution to levels that render it unfit for use, and (4) incorporation into the product.
- *Irrigation system scale*: At this scale it is important to evaluate how productively the water available to the irrigation system is being used. The irrigation manager considers both the amount of water depleted and the amount recaptured for reuse downstream. At this scale the output can be quantified in physical and economic terms, and the water can be accounted for in either volume or value terms.

- *Basin scale*: This scale is important for assessing options for increasing productivity of the renewable water that enters the basin, mainly as rainfall. The output includes all the benefits derived by, for example, biomass or harvestable produce, landscape, and could even include the value of near-shore marine life. The water input becomes the net inflow, which is difficult to value in monetary terms and therefore generally is assessed as volume. This approach is particularly useful in assessing the opportunities for investing in water infrastructure.

10.3 AGRICULTURAL WATER PRODUCTIVITY ACROSS THE GLOBE

The major objective of improving agricultural water productivity is to increase crop production in irrigated and rain-fed areas and the associated economic, social, environmental, and ecological benefits per unit of water used (Molden et al., 2007). This also includes enhancing benefits from livestock, agroforestry, and aquaculture sectors with minimum water use (Rockström and Barron, 2007; Cai et al., 2011). The concepts of water use efficiency and water productivity are often used in the same context of increasing crop production by using least water resources, although they vary in definitions. Water use efficiency considers water input, whereas water productivity is usually calculated based on the amount of water consumed.

There is significant variation in water productivity across different cropping systems, under both irrigated and rain-fed conditions. The lower water productivities are usually found in sub-Saharan Africa and regions in South Asia due to poor access to irrigation water and items such as seeds, fertilizer, and pesticides. Therefore increasing productivity of water in these regions would result in greater food security and improved livelihood for the millions of rural people living in poverty in these areas (Rockström et al., 2010). It has been estimated that 80% of the required additional food can be obtained by increasing the productivity of low-yield farming systems (Molden, 2007; Cai et al., 2011). The estimated water productivity values of wheat crops for different countries are given in Table 10.1.

The differences in WP values can be linked to yield gaps in different countries. In addition to irrigation water availability, crop yields are also dependent on non-water factors such as rate of fertilizer use, seed quality, disease, and pest management (FAO, 2009; Kingwell et al., 2016). For example, wheat yields are ranging between 1.0 and 7.0 $t ha^{-1}$ at different locations in Iran. Hussain et al. (2003) reported a yield of 4.5 and 4.1 $t ha^{-1}$ for wheat production in India (Bhakra region) and Pakistan (Punjab region), respectively. The crop yields obtained in sub-Saharan Africa are about half of the yields achieved in parts of South Asia (Kadigi et al., 2012). The yield gaps (difference between the average national yield and the average potential yields) are the highest in developing countries and most notably in sub-Saharan Africa (World Bank, 2007). The potential yield of a crop is the yield that is attained without any water, nutrients, and biotic stress during crop growth (van Ittersum et al., 2013). However, actual obtained yields are usually lower than the potential yields, resulting in yield gaps. In addition to low use of fertilizer and poor extension services, yield gaps can also be caused by volatile weather conditions resulting in frequent crop failure such as in Russia and other Central Asian countries (Schierhorn et al., 2014) (Fig. 10.1).

TABLE 10.1 Estimated Water Productivity Values of Wheat Crop for Selected Countries

Countries	Water Productivity (kg/m^3)	Reference
Syria	0.48–1.10	Oweis et al. (2000)
Iran	0.86–2.50	Abbasi and Mehrpour (2004)
India	1.28–1.82	Zhang et al. (2003)
China	1.23–1.49	Hussain et al. (2003)
Morocco	0.32–1.06	Mrabet (2002)
Pakistan	1.08–1.62	Hussain et al. (2003)
Turkey	1.33–1.45	Sezen and Yazar (1996)
Uzbekistan	0.44–1.02	Kamilov et al. (2003)

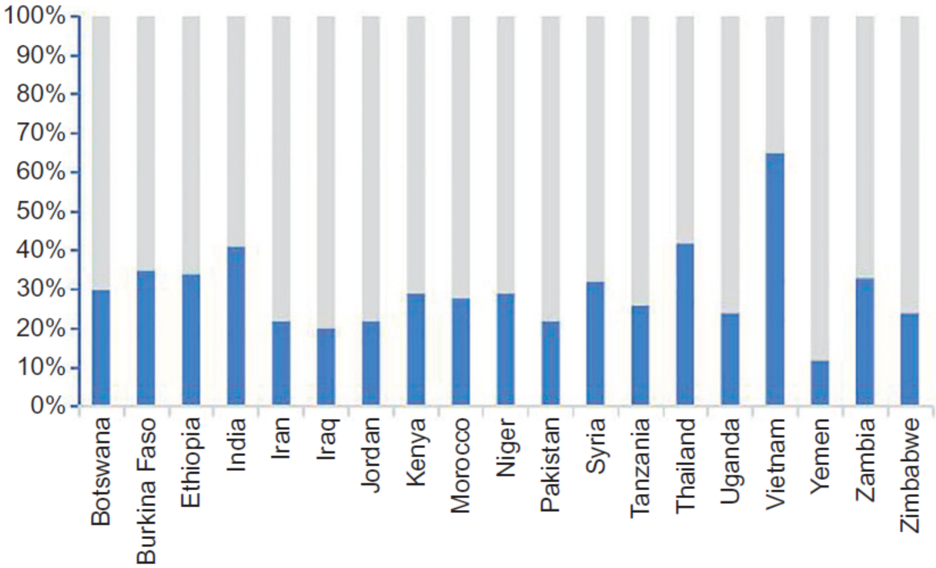

FIG. 10.1 Yield gaps for major grains in different countries (*blue* columns denote actual obtained yields as a percentage of potential yields). *(Modified from Rockström, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., Qiang, Z., 2010. Managing water in rainfed agriculture: the need for a paradigm shift. Agric. Water Manag. 97, 543–550. doi:10.1016/j.agwat.2009.09.009; Qureshi, A.S., 2014. Reducing carbon emissions through improved irrigation management: a case study from Pakistan. Irrig. Drain. 63, 132–138.)*

10.4 OPPORTUNITIES FOR INCREASING WATER PRODUCTIVITY IN AGRICULTURE SECTOR

Increasing demand and decreasing water quality and quantity have put enormous pressure on the agriculture sector to increase productivity of the available water resources in order to save water for industrial, environmental, and domestic needs. Improvements in water productivity can be achieved by choosing and adapting water-efficient crops, reducing unproductive water losses, and maintaining ideal agronomic conditions for crop production (Kijne et al., 2003; Rockström and Barron, 2007). The adoption of improved agronomic practices can reduce unproductive water losses thereby increasing water use efficiency and crop production. However, it is important to realize that higher crop water productivities also require management of other soil and plant stresses, such as nutrient deficiencies and management of weeds and crop diseases (Bouman, 2007). Other interventions can also contribute significantly in increasing crop water productivity, such as supplemental and deficit irrigation, precision agriculture, soil fertility management, soil moisture conservation, and the use of drought- and disease-resistant crop varieties (Oweis and Hachum, 2009; de Vries et al., 2010; Mzezewa et al., 2011).

In water-scarce basins it is inevitable that water use in one sector or at one scale will have a direct impact on water quality and quantity in other sectors of the same basin. Effective management of basin water for production requires a better understanding of a complex set of water-related interactions that occur across spatial and temporal scales, and within various locations in the same basin. Effective integrated management of basin water resources is complicated by the fact that the use of water and land at one location affects how water is used at other locations, often in complex ways. Misunderstanding can lead to policies that adversely affect one set of users while trying to improve conditions for other users. There are at least two dimensions to this—one is the consequence of upstream use on downstream availability, and the other is how actions taken at one scale affect users at another scale. For example, the degree to which field-scale interventions improve water productivity at the basin scale or the degree to which policies affecting basin allocation affect farm and community practices are often not clear.

The key levels usually considered for water resources in agriculture are for an individual plant, a field, an irrigation scheme, or a river basin. As we move from one scale to another scale, key processes change. For example, for a rain-fed agricultural field, infiltration, transpiration, and evaporation are important parameters. However, for at basin scale, stream flow and water allocation among multiple users and environmental flows get priority. Therefore there is a strong need to develop common water accounting procedures for analyzing the use, depletion, and productivity of water at the plant, field, irrigation system, and basin scale (Falkenmark et al., 1989). These procedures are necessary to evaluate the impact of alternative water management interventions on water productivity at different scales.

At each scale different actions are needed to enhance water productivity. The range of options to increase water productivity at different scales is discussed next. However, successful implementation of these options requires more in-depth analysis and evaluation of the cost of various interventions for increasing productivity. Implementing these options may be constrained by the lack of incentives of local farmers and irrigation system managers. Devolution of responsibility to local user groups may be effective in increasing irrigation efficiency and water productivity in some situations.

10.4.1 Plant-Scale Interventions

In water-scarce environments about half of yield improvements are attained due to improvements in the crop genotypes and the other half due to better agronomic and water management practices (Morison et al., 2008). Plant breeding and genetic improvement of plants have delivered substantial productivity gains over recent decades. Genetic modifications have helped in increasing susceptibility of crops to pests and diseases, producing more grains, reducing the growing period, and increasing the capacity of plants to tolerate more heat and water stress. Crops that withstand disease and pest attacks increase water productivity by reducing crop failure and unproductive water consumption. Similarly, drought tolerance (that is, capacity of a plant to survive severe water stress and continue to maturity) also increases production from low and unreliable rainfall.

Genetically improved crop varieties with more efficient photosynthetic processes may produce more biomass for the same amount of transpiration (Perry et al., 2009). Significant progress has been made for the genetic enhancement of dryland crops with a view toward increasing crop productivity (Gowda et al., 2009). More drought-tolerant varieties of pearl millet, sorghum, cowpeas, and barley are now available for dry areas of Asia and Africa. The successful plantation of these varieties in sub-Saharan Africa is relatively lower than in Asia due to the unavailability of nonwater inputs such as good nitrogen and disease-free seed and lack of pest management. Moreover, in this region many "orphan crops" (e.g., cassava, millet, yams, and teff) are grown. The productivities of these crops are low due to the lack of physiologically advanced varieties that can withstand water and heat and that are salt-resistant (Mueller et al., 2012).

Water productivity improvements can also be achieved by using crop varieties that are most adaptable to local conditions and by growing the crops in seasons and/or areas that have low atmospheric evaporative demands. The adoption of improved, early maturing, and high-yielding crop varieties during the past 25 years has increased the average yields of many cereal crops and reduced the growth period. The improvements in plant breeding have shorten the growth cycle of many crops, which helps in reducing soil evaporation. The introduction of high-yielding and short-duration rice varieties has increased average yields from 2 to 3 tha^{-1} to 5–6 tha^{-1} and reduced the crop duration time from 140 days to 110 days (Hobbs and Gupta, 2003). The availability of hybrid varieties can produce 15% to 20% more rice than inbred high-yielding varieties with comparable maturity periods. Better nutrient management offers another opportunity to increase rice yields with the same amount of water consumption.

10.4.2 Field-Scale Interventions

Water productivity at the field scale can be increased by (1) reducing evaporation, especially during early growth stages of a crop, (2) reducing seepage and percolation losses during irrigation events, (3) choosing suitable soils for different crops, especially for rice, and (4) minimizing non-beneficial use of water by weeds and trees. At the field scale interventions should aim at increasing water productivity by reducing non-beneficial evaporation and/or increasing productive transpiration (Sadler et al., 2007). Practicing night-time irrigation, better weed control, and mulching of fields in high-temperature areas and seasons are also good options for controlling excessive evaporation. Options for capturing more water from the soil include the use of varieties with deeper rooting systems and practices that control the moisture of soil. Applying irrigation according to a crop's actual water requirements can help reduce unproductive soil evaporation. Since crops at different growth stages react differently to water stress, ensuring full water deliveries at crops' critical growth stages can have a large impact on crop yields (Perry et al., 2009).

Commonly used flooding and basin irrigation methods are less expensive and easy to operate but are considered less efficient because much of the applied water is wasted through evaporation, runoff, and percolation below the root zone. Improvements in water productivity at the field scale can be attained by adopting improved irrigation methods and deficit irrigation concepts. Water conservation measures such as precision land leveling, zero tillage, and bed planting can reduce water use considerably at the field scale. Bed planting uses 40% less water than the basin irrigation method does (Qureshi, 2014). These technologies have the capacity to improve water productivity at the field level if farmers do not at the same time expand their cultivated area or increase their cropping intensity (Ahmad et al., 2007). However, these methods require precise grading of the topography, high instant flow rates, and relatively high levels of automation and management. Zero tillage technology is now widely practiced in many countries, including the United States, Brazil, Argentina, Pakistan, India, and Zimbabwe.

The bed planting in rice-wheat cropping systems used in India, Pakistan, and Uzbekistan have shown significant savings in water (Hobbs and Gupta, 2003; Mollah et al., 2009). Improved irrigation management for rice crops can yield maximum water savings, as nearly 55% of all the rice and wheat produced in the world comes from irrigated areas (Qureshi et al., 2004). Different irrigation regimens have been developed to reduce rice crops' consumption of water. These regimens include a shallow water layer with wetting and drying (SWD), alternate wetting and drying (AWD), and semi-dry cultivation (SDC). In China these irrigation regimens have shown water savings of 318%, 7% to 25%, and 20% to 50% under SWD, AWAD, and SDC, respectively (Tuong et al., 2009).

The alternate wetting and drying (AWD) method for rice has become popular in many countries, including the Philippines, Bangladesh, and Vietnam. With the AWD regimen farmers allow ponded water to disappear from the field and infiltrate for several days until the perched field's water table reaches a depth of 15–20cm. In Bangladesh, for example, where 90% of the irrigation water is used for rice production, changing from flooding to the AWD irrigation method reduces the water demand by 20% to 30%, amounting to $73 million worth of irrigation costs (Mollah et al., 2009).

The available evidence indicates that higher water productivity can be obtained using the AWD method for rice (Bouman, 2007; Tuong et al., 2009). This technique may also boost concentrations of essential nutrients, particularly zinc, in harvested rice (Price et al., 2013). Fereres and Soriano (2006) estimated that annual water diversions can be reduced by as much as 40% from full ET under a deficit irrigation technique (deliberately under-irrigating in less sensitive crop growth periods and ensuring full deliveries at critical growth periods), depending on the crop. However, the impact of all these techniques on different agro-ecological conditions needs to be carefully evaluated, as reduced irrigation applications may increase the threat of soil salinization.

In irrigated areas the efficiency of the irrigation can be increased up to 95% by using pressurized systems, that is, drip and sprinkler systems, because they reduce seepage losses in the conveyance and distribution systems. At present 15% of the total irrigated area in the world (44 million ha) is equipped with pressurized systems (35 million ha with sprinklers and

9 million ha with drip systems), and most of these are concentrated in Europe and America (Kulkarni, 2011). These irrigation methods provide unique agronomic as well as water and energy conservation benefits. Farmers prefer these systems to achieve higher water use efficiencies and to expand their irrigated area with the same diverted volume of water. The major disadvantages of these systems, especially for smallholder farmers, are their capital and operational costs. Manufacturing these systems locally along with making improvements to reduce labor via automation may help reduce costs and achieve higher irrigation efficiencies.

Different irrigation technologies involve different trade-offs between crop yield, water use, and capital cost of equipment and structures. Modern irrigation methods such as drip or trickle irrigation, surge irrigation, and sprinkler systems are more expensive but usually offer greater potential to minimize runoff, drainage, and soil evaporation. Therefore choice of appropriate irrigation method based on soil type, crops grown, crop water demand, and cost are of paramount importance for managing water for irrigation.

10.4.3 Irrigation System-Scale Interventions

At the irrigation system level water efficiency depends on the management of water runoff and control of seepage and percolation losses in both the water delivery system and on-farm independent, interactive systems. System water losses (the amount of water that leaves the system without contributing productively) caused by interacting problems may be quite serious in certain situations. To increase water productivity at the irrigation system level, we need to improve water allocation and distribution so that all using the system get their fair share. In situations where allocation and distribution are not equitable, farmers getting less than their share are underproductive, and those who get extra water usually tend to waste it through over-irrigation and/or bad management.

A typical example of such a system is the Indus Basin Irrigation System (IBIS) in Pakistan, which irrigates about 16 million ha of land (Qureshi, 2014). This is a fixed rotational distribution system, where each farmer can take an entire flow of the outlet once every seven days and for a period proportional to the size of his land holding. The supplied amount of water is usually not sufficient to irrigate the entire farm in one irrigation turn, and the farmers must decide whether to under-irrigate all land or leave a fraction unirrigated (Qureshi, 2014). The fixed rotational system favors head-end farmers and discriminates against tail-ender farmers. The tail-end farmers get 20% less water than middle farmers, who in turn get 20% less water than head-end farmers. Similar trends are seen in the crop water productivity of head-end, middle, and tail-end farmers (Latif and Tariq, 2009). Equitable water distribution among all farmers therefore remains a challenge in traditional irrigation systems.

For improving water productivity at the irrigation system-scale, managers must provide irrigation water in an equitable, predictable, and timely manner to all water users. However, this task is done less and less satisfactorily due to monopoly, discretion, and negligence in the water sector. This results in inequitable distribution of water, poor technical performance, and a pervasive environment of mistrust and conflict between water managers and water users. The managers should explore hydrometeorological networks, databases, and information systems that can support reservoir and canal operations, provide information on the initiation of floods and droughts, and help farmers with suitable irrigation schedules for different crops (Pereira et al., 2002). The managers should also use tools to develop water allocation and delivery operation rules to ensure equitable and timely delivery of irrigation water to all farmers regardless of their location and land holding (Rossi et al., 2002). Developing small farm reservoirs to harvest rainwater and spate irrigation could be a useful strategy for increasing water supplies (Oweis and Hachum, 2009).

The distribution of irrigation water can be improved from simple syphon tubes for field water use to sophisticated canal automation and telemetry (Kulkarni, 2011). The water administration system used by water-user associations in South Africa to manage their water accounts and supply to clients has reduced water loss up to 20% through improved water releases in canals (ICID, 2008). An upgrade of the traditional irrigation system used in the Mula region in the southeastern part of Spain has led to a fivefold reduction in annual water loss. This has resulted in less exploitation of groundwater with significant savings in pumping energy and an increase in crop productivity and the quality of fruits (Kulkarni, 2011). Automatic hydrodynamic gates on irrigation canals are already in place in France, Morocco, Iran, and Pakistan. In Iran water is delivered to farmers based on actual crop water requirements. The downstream control water canals in the northern province of Pakistan are providing water on a crop-demand basis, thereby reducing releases from reservoirs.

Reuse of drainage water and wastewater offers an attractive way to increase water use efficiency and productivity of an irrigation system. The conjunctive use of groundwater with surface water in the rice-wheat irrigation systems in Pakistan and India is of special significance. Seepage and percolation from rice fields and irrigation networks become a recharge to shallow unconfined aquifers. The water stored in the aquifer can be used again to supplement canal irrigation supplies at the time of need. However, this practice will increase production costs, as energy for pumping groundwater is becoming expensive.

The possibility of recycling does not negate the need to conserve water on-farm. Water recycling and the conjunctive use of groundwater and surface water are happening as a desperate response from farmers where surface water supplies are limited. Therefore the cost-effectiveness of recycling and conjunctive use of ground water and surface water need to be carefully compared with other conservation measures, such as canal lining to reduce seepage and percolation losses in irrigation systems. The recycled waters are mostly of inferior quality; therefore their effects on soil, crops, and the environment need to be carefully evaluated.

To reduce non-beneficial evaporation in an irrigation system, fallow lands and free surface areas should be reduced. Development and adoption of new irrigation schedules for preparing land using early season rainfalls could make it possible to conserve water in reservoirs, allowing more area to be irrigated in the dry season. The adoption of the above-mentioned interventions usually requires more resources, such as labor, capital, and management skills. Therefore an economic analysis of the adoption of alternative interventions for raising water productivity is very essential to increase the effectiveness of these strategies.

10.4.4 Basin-Scale Interventions

Water productivity improvement at the basin level relates to interventions at the level of field, farm, and irrigation systems. From the basin perspective water that would otherwise be lost to sink, percolate to saline groundwater, or flow to the sea can be of value. Therefore such losses need to be controlled in order to increase water productivity at the basin scale.

The reuse of drainage and wastewater is of immense importance for increasing water productivity at the basin level. However, making it feasible to use this water for agricultural use requires maintaining the quality of the drainage and wastewater.

Basin-level water productivity can also be increased by shifting from low-value crops to higher value crops. For example, in the face of declining returns for rice and wheat, diversification to higher valued crops has been encouraged in many countries. However, often it is done without an assured water supply and support for research, extension, and marketing services needed for success. This is perhaps the major reason for farmers' lack of interest in diversified cropping. To promote successful diversification, an assured water supply together with proper market access and extension services need to be ensured. Otherwise, farmers will continue growing traditional crops without caring about the value of water.

For better management of basin water resources, an effective institutional and managerial system is inevitable. A study of 15 irrigation systems in South and Southeast Asia has shown that without addressing institutional and managerial capacity, it is not possible to increase the performance of a basin (Murray-Rust and Snellen, 1993). Basin-level management should have the capacity to effectively operate and maintain different sub-basins, including water allocation and distribution, and to coordinate the entire system through effective feedback and communication. Management should also take important actions like constructing new storages to preserve extra amounts of water.

To understand interactions of different users in a basin and their shared consequences, simulation models may be the most appropriate tools to use. Models can help determine the current situation and processes and, through scenario calculations, can predict what might happen in the future at different scales with the adoption of alternative water-management strategies.

For basin-scale analysis it is not sufficient to have models that look only at the impact on one sector or one class of users because the potential benefits identified by using such models may be outweighed by their greater cost to other users or sectors. For example, if based on field-scale model simulations, we choose to change cropping patterns to improve water productivity and farm profitability in one part of the basin, its effects on other users in other parts of the basin must also be studied using a different model that can simulate a larger domain.

Currently, a wealth of simulation models for different scales and different purposes are available and can be used for up-scaling purposes. For successful application of integrated modeling at field, farm, irrigation systems, and basin scales, four sequential steps are involved:

(1) Data collection and establishment of a structured database
(2) Data analysis using range of appropriate tools
(3) Model development/or application to understand current conditions
(4) Scenario development and assessment leading to conclusions and recommendations

Different water users in a basin are affected not only by the flow of water as inputs and outputs of the different sub-systems but also by the spatial and temporal relationships among the users. Spatial relationships are important in terms of both water quantity and water quality. Irrigation activities at the upstream affect the downstream in two ways: water deliveries may be increased due to augmentation of return flow, but the quality of these return flows may create an adverse effect on downstream users. This is particularly true in basins where extensive irrigated agriculture is practiced at the upstream part of the basin. As a result, salinity inevitably increases at the downstream part of the basin and directly effects the production potential of downstream areas. The situation becomes even worse when there are water quality requirements for the downstream users to fulfill environmental and ecosystem demands.

From the temporal perspective we may find that short-term "losses" may turn out to be useful water gains in the long term. Groundwater is important in this regard. Aquifers act as reservoirs to capture seepages from canals, percolation from rivers and irrigated areas, and recharges from rainfall. Although these supplies are not immediately available, they can be tapped at later stages when no other water resources are available, such as periods of low rainfall or incidences of drought. It is generally argued that improvement in productivity primarily depends on better matching irrigation supplies with crop demands. Therefore a more flexible irrigation scheduling system capable of distributing water on demand is necessary for the optimization of crop production.

10.5 CONCLUSIONS

Global water resources are under stress due to quality degradation and overuse, whereas the growing population's demand for food is increasing. Therefore increasing the productivity of existing lands with the same amount of available water is critical to produce more food, to fight poverty, to reduce competition for water, and to ensure that there is enough water for the environment. Water productivity can be improved by (1) improving the management capacity of farmers through the adoption of innovative irrigation technologies and water delivery systems and (2) optimizing water applications using scientific irrigation schedules for different crops to avoid non-beneficial water losses.

Using water conservation techniques, introducing water-efficient cropping systems, and using deep-rooted crops to maximize the utilization of stored soil water and nutrients are verified ways to increase water productivity. The management of irrigation water is linked to the maintenance of soil water through improved timing of irrigation to minimize negative effects of water deficits on yields and quality. Therefore changes to the physical and managerial aspects of water delivery and to the design of farm irrigation systems will be required to enable farmers to irrigate their fields with the right amount of water at the right time.

The efficiency of water use can be improved several ways. These include building small pits or basins (mini reservoirs) to store water accessed during high flow seasons and then using it during low flow periods. Reducing non-beneficial losses through night-time irrigation can reduce loss due to evaporation. Better weed control and mulching of fields in high-temperature areas and seasons can also control field losses and improve water productivity.

Despite their high installation and maintenance costs, pressurized irrigation systems (such as drip and sprinkler systems) offer greater potential for minimizing runoff, drainage, and soil evaporation. The disadvantage of these methods is that they require intensive supervision; therefore management tools such as decision support systems are needed to provide accurate predictions of crop water requirements, application efficiencies, and timing of chemical applications to control pest outbreaks. System-level management is needed to reduce conveyance losses, field runoff, and leaching and for equitable water distribution to all water users. Poorly managed advanced irrigation systems can be as inefficient and unproductive as poorly managed traditional systems. Therefore the choice of an appropriate irrigation method, based on soil type, crops grown, crop water demand, and cost, is of paramount importance for improving the productivity of water.

To increase basin-level water productivity, water losses to sinks and saline groundwater should be controlled, and a paradigm shift is needed to move from low-value crops to higher value crops. For example, to address the issue of water-deprived basins, many countries have encouraged replacing rice with higher valued crops. However, this requires an assured water supply and support for research, extension, and marketing services. Otherwise, farmers will continue to practice their traditional cropping patterns without caring about the value of water.

References

Abbasi, N., Mehrpour, M., 2004. Effect of Water Deficit Stress on Physiological Properties of Promising Lines of Wheat. Research Report No. 33, Agricultural Engineering Research Institute, Iran.

Ahmad, M.D., Turral, H., Masih, I., Giordano, M., Masood, Z., 2007. Water saving technologies: myths and realities revealed in Pakistan's rice-wheat systems. International Water Management Institute, Colombo, Sri Lanka. (IWMI Research Report 108): 44 pp.

Bouman, B., 2007. A conceptual framework for the improvement of crop water productivity at different spatial scales. Agric. Syst. 93, 43–60.

Cai, X., Molden, D., Mainuddin, M., Sharma, B., Ahmad, M., Karimi, P., 2011. Producing more food with less water in a changing world: assessment of water productivity in 10 major river basins. Water Int. 36, 42–62. https://dx.doi.org/10.1080/02508060.2011.542403.

Cook, S.E., Fisher, M.J., Andersson, M.S., Rubiano, J., Giordano, M., 2009. Water, food and livelihoods in river basins. Water Int. 34, 13–29.

de Vries, M.E., Rodenburg, J., Bado, B.V., Sow, A., Leffenaar, P., Giller, K.E., 2010. Rice production with less irrigation water is possible in a Sahelian environment. Field Crops Res. 116, 154–164. https://dx.doi.org/10.1016/j.fcr.2009.12.006.

Falkenmark, M., Lundquist, J., Widstrand, C., 1989. Macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development. Nat. Resour. Forum 13, 258–267.

Falkenmark, M., Karlberg, L., Rockström, J., 2009. Present and future water requirements for feeding humanity. Food Security 1, 59–69.

FAO, 2006. World Agriculture: Towards 2030/2050. Interim Report. Prospects for Food, Nutrition, Agriculture and Major Commodity Groups. FAO, Rome. Available at http://www.fao.org/fileadmin/user_upload/esag/docs/Interim_report_AT2050web.pdf.

FAO, 2009. FAO Water Unit | Water News: water scarcity. http://www.fao.org/ (Accessed 12 March 2009).

FAO, 2011. The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) – Managing Systems at Risk. Food and Agriculture Organization of the United Nations/Earthscan, Rome/London.

Fereres, E., Soriano, A., 2006. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58 (2), 147–159. https://dx.doi.org/10.1093/jxb/erl165.

Gowda, C.L.L., Serraj, R., Srinivasan, G., Chauham, Y.S., 2009. Opportunities for improving crop water productivity through genetic enhancement of dryland crops. In: Wani, S.P., et al. (Eds), Rainfed Agriculture: unlocking the potential. CABI International, Wallingford, UK, pp. 133–163.

Hobbs, P.R., Gupta, R.K., 2003. Resource-conserving technologies for wheat in the rice-wheat system. In: Improving Productivity and Sustainability of Rice-Wheat Systems: Issues and Impact. Am. Soc. Agron. Spec. Publ. 65, 149–171.

Howell, T.A., 1990. Relationships between crop production and transpiration, evapotranspiration, and irrigation. Irrigation of agricultural crops. Agron. Monogr No. 30.

Hussain, I., Sakthivadivel, R., Amarasinghe, U., 2003. Land and water productivity of wheat in the Western Indo-Gangetic plains of India and Pakistan: a comparative analysis. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement. In: Comprehensive Assessment of Water Management in Agriculture Series, vol. 1. CAB International, Wallingford, UK, pp. 251–271. In Association with International Water Management Institute (IWMI), Colombo.

ICID, 2008. Water Saving in Agriculture. International Commission on Irrigation and Drainage, New Delhi. Publication No. 95.

Kadigi, R.M.J., Tesfay, G., Bizoza, A., Zinabo, G., 2012. Irrigation water Use Efficiency in Sub-Saharan Africa. Briefing Paper No. 4, Agriculture Policy Series, The Global Development Network (GDN), Oxford.

Kamilov, B., Ibragimov, N., Esanbekov, Y., Evett, S., Heng, L., 2003. Irrigation scheduling study of drip irrigated cotton by use of soil moisture neutron probe. In: Proceedings of the UNCGRI/IAEA National Workshop in Optimization of Water and Fertilizer use for Major Crops of Cotton Rotation, Tashkent, Uzbekistan, 24–25 December, 2002.

Kijne, J.W., Barker, R., Molden, D. (Eds.), 2003. Water Productivity in Agriculture: Limits and Opportunities for Improvement. In: Comprehensive Assessment of Water Management in Agriculture Series, vol. 1. CABI International/In Association with International Water Management Institute (IWMI), UK/Colombo.

Kijne, J., Barron, J., Hoff, H., Rockström, j., Karlberg, L., Gowing, J., Wani, S.P., Wichelns, D., 2009. Opportunities to Increase Water Productivity in Agriculture with Special Reference to Africa and Asia. Project Report, Stockholm Environment Institute, Sweden. 39 pp.

Kingwell, R., Carter, C., Elliott, M.P., White, P., 2016. Russia's Wheat Industry: Implications for Australia. Aegic.

Kulkarni, S., 2011. Innovative technologies for water saving in irrigated agriculture. Int. J. Water Resour. Arid Environ. 1 (3), 226–231.

Latif, M., Tariq, J.A., 2009. Performance assessment of irrigation management transfer from government to farmer-managed irrigation system: a case study. Irrig. Drain. 58, 275–286.

Molden, D. (Ed.), 2007. Water for Food, Water for Life: Comprehensive Assessment of Water Management in Agriculture. Earthscan/In Association with International Water Management Institute (IWMI), London/Colombo.

Molden, D., Oweis, T.Y., Steduto, P., Kijne, J.W., Hanjra, M.A., Bindraban, P.S., 2007. Pathways for increasing agricultural water productivity. In: Molden, D. (Ed.), Water for Food, Water for Life: Comprehensive Assessment of Water Management in Agriculture. Earthscan/in Association with International Water Management Institute (IWMI), London/Colombo, pp. 279–310.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: between optimism and caution. Agric. Water Manag. 97, 528–535. https://dx.doi.org/10.1016/j.agwat.2009.03.023.

Mollah, M.I.U., Bhuyia, M.S.U., Kabir, M.H., 2009. Bed planting – a new crop establishment method for wheat in Rice-wheat cropping system. J. Agric. Rural Dev. 7 (1&2), 23–31.

Morison, J.I.L., Baker, N.R., Mullineaux, P.M., Davies, W.J., 2008. Improving water use in crop production. Phil. Trans. Roy. Soc. B 363, 639–658.

Mrabet, R., 2002. Wheat yield and water use efficiency under contrasting residue and tillage management systems in a semi-arid area of Morocco. Exp. Agric. 38, 237–248.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490 (7419), 254–257.

Murray-Rust, M., Snellen, W.B., 1993. Irrigation-water management for sustainable development in Iran. In: Irrigation/Water Management for Sustainable Agricultural Development. Report of the Expert Consultation of the Asian Network on Irrigation/Water Management, 25–27 August 1992, Bangkok, Thailand, pp. 216–221 RAPA Publication 1994/24.

Mzezewa, J., Gwata, E.T., van Rensburg, L.D., 2011. Yield and seasonal water productivity of sunflower as affected by tillage and cropping systems under dryland conditions in the Limpopo Province of South Africa. Agric. Water Manag. 98, 1641–1648.

Oweis, T., Hachum, A., 2009. Water harvesting for improved rainfed agriculture in the dry environments. In: Wani S.P., Rockström, J., Oweis, T. (Eds.), Rainfed Agriculture: Unlocking the Potential. In: Comprehensive Assessment of Water Management in Agriculture Series, vol. 7. CAB International/In Association with International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)/International Water Management Institute (IWMI), Wallingford, UK/Patancheru, Andhra Pradesh, India/Colombo, pp. 164–181.

Oweis, S., Zhang, H., Pala, M., 2000. Water use efficiency of rainfed and irrigated bread wheat in a Mediterranean environment. Agron. J. 92, 231–238.

Pereira, L.S., Oweis, T., Zairi, A., 2002. Irrigation management under water scarcity. Agric. Water Manag. 57, 175–206.

Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities. Agric. Water Manag. 98, 1641–1648. https://dx.doi.org/10.1016/j.agwat.2009.05.005.

Price, A.H., Norton, G.J., Salt, D.E., Oliver Ebenhoeh, O., Meharg, A.A., Meharg, C., Islam, M.R., Sarma, R.N., Dasgupta, T., Ismail, A.M., McNally, K.L., Zhang, H., Dodd, I.C., Davies, W.J., 2013. Alternate wetting and drying irrigation for rice in Bangladesh: is it sustainable and has plant breeding something to offer? Food Energy Security 2, 120–129.

Qureshi, A.S., 2014. Reducing carbon emissions through improved irrigation management: a case study from Pakistan. Irrig. Drain. 63, 132–138.

Qureshi, A.S., Shoaib, I., 2015. Evaluating benefits and risks of using treated municipal wastewater for a agricultural production under desert conditions. In: Paper presented in the DT12 Conference, held in Cairo, November 16–19, 2015.

Qureshi, A.S., Masih, I., Turral, H., 2004. Furrow-Bed technologies: Option for improving water use efficiency in the rice-wheat cropping systems. In: Paper Presented in the workshop on Water and Wastewater Development for Development Countries (WAMDEC), July 28–30, Zimbabwe.

Qureshi, A.S., Iftikhar, M.I., Shoaib, I., Khan, Q.M., 2016. Evaluating heavy metal accumulation and potential health risks in vegetables irrigated with treated wastewater. Chemosphere 163, 54–61. https://dx.doi.org/10.1016/j.chemosphere.2016.07.073.

Rockström, J., Barron, J., 2007. Water productivity in rainfed systems: overview of challenges and analysis of opportunities in water scarcity prone savannahs. Irrig. Sci. 25, 299–311.

Rockström, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., Qiang, Z., 2010. Managing water in rainfed agriculture: the need for a paradigm shift. Agric. Water Manag. 97, 543–550. https://dx.doi.org/10.1016/j.agwat.2009.09.009.

Rossi, G., Cancellieri, A., Preira, S.L., Oweis, T., Shatanawi, M., Zairi, A. (Eds.), 2002. Tools for Drought Mitigation in Mediterranean Regions. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Sadler, E.J., Camp, C.R., Evans, R.G., 2007. In: Lascano, R.J., Sojka, R.E. (Eds.), New and future technology in irrigation of agricultural crops. American Society of Agronomy, Madison, WI, pp. 609–626. Agronomy Monograph 30 (2).

Schierhorn, F., Faramarzi, M., Prishchepov, A., Koch, V., Müller, D.F., 2014. Quantifying yield gaps in wheat production in Russia. Environ. Res. Lett. 9, 84–97.

Sezen, S.M., Yazar, A., 1996. Determination of water-yield relationship of wheat under Cukurova conditions. J. Agric. Forest. 20, 41–48 (in Turkish, with English abstract).

Tuong, T.P., Bouman, B.A., Lampayan, R., 2009. A Simple Tool to Effectively Implement Water Saving Alternate Wetting and Drying Irrigation for Rice. ICID Newsletter, Issue 2009/4.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. Field Crops Res. 143, 4–17.

World Bank, 2007. Agriculture for Development. World Development Report 2008. World Bank, Washington, DC.

Zhang, X., Pei, D., Hu, C., 2003. Conserving groundwater for the North China Plain. Irrig. Sci. 21, 159–166.