INTERNATIONAL DEVELOPMENT IN FOCUS

Beyond Crop per Drop

Assessing Agricultural Water Productivity and Efficiency in a Maturing Water Economy

Susanne M. Scheierling and David O. Tréguer

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Executive Summary

WHY FOCUS ON WATER PRODUCTIVITY AND EFFICIENCY IN IRRIGATED AGRICULTURE?

Water scarcity is seen as a major risk in many parts of the world, and water crises are consistently cited as among the top global risks. Irrigated agriculture is by far the largest water use worldwide, accounting for an estimated 70 percent of total freshwater withdrawals. In many drier countries, agricultural water use accounts for more than 90 percent of total withdrawals. As water becomes increasingly scarce, the management of agricultural irrigation moves to the center of water management concerns. Without advances in management and more integrated policy making in both developed and developing countries, water scarcity and related water problems will significantly worsen over the next several decades. Yet the question of how best to adapt agricultural water management is complicated, not least because irrigated agriculture is at the center of two large and conflicting trends.

On the one hand, irrigated agriculture is rapidly expanding with the growing demand for agricultural products. The amount of irrigated area almost doubled worldwide over the past half century, and concomitant water use also increased. Global demand for agricultural products is projected to grow by about 70 percent by 2050—as a result of population growth, rising meat and dairy consumption, and expanding biofuel use—requiring a continued increase in water use. The effects of climate change, including the increased variability of water supplies, have further contributed to the expansion of irrigated agriculture.

On the other hand, additional demands for irrigation water are increasingly difficult to accommodate in many parts of the world. Agricultural withdrawals already account for unsustainable shares of total renewable water resources in many of the drier countries. And the growing demand for water from other sectors is further intensifying the competition for water resources. Because water use in irrigated agriculture is seen as having relatively low net returns compared with other water uses, other sectors increasingly look to agriculture as a potential source of water.

Probably the most common and widely promoted approach for adapting agricultural water management to the increasing scarcity of water is to focus on improving agricultural water productivity and efficiency—and thus to achieve more crop per drop. Given the large amounts of water involved, and the widely-held belief that water use in agriculture is relatively inefficient and unproductive, even small increases in water efficiency and productivity are believed to have large implications for local and global water budgets. Such improvements would allow either higher agricultural production with the same amount of water, or the same amount of agricultural production with less water. In the latter case, the water savings could be reallocated to other higher-value uses, or freed up to ensure some level of environmental flows. The implicit assumption is that such improvements in water productivity and efficiency would help address the trade-off between increased agricultural production and agricultural water conservation and reallocation.

Many international organizations and national agencies concerned with water management are promoting an increase in agricultural water productivity and efficiency as an important policy goal. In line with this thinking, significant public and private investments for improving water productivity and efficiency in irrigated agriculture are being made in both developed and developing countries.

Yet some serious problems are associated with this approach. They include conceptual issues, the methods used for measuring agricultural water productivity and efficiency, and the application of these concepts and methods in different contexts—all of which influence the choice of interventions and the evaluation of their implementation.

This report aims to shed further light on these issues: first, by clarifying some of the underlying concepts in the discussion of agricultural water productivity and efficiency; second, by reviewing and analyzing the available methods for assessing water productivity and efficiency; and, third, by discussing their application and relevance in different contexts. As the background for this analysis, the report highlights the central role of water use in irrigated agriculture and its link with increasing water scarcity.

This is discussed in the context of the transition from an expansionary water economy to a mature water economy. The report further develops this framework to reflect water management issues in irrigated agriculture (table ES.1). The expansionary phase is characterized by readily available water supplies to meet the growing demand for irrigation water as agricultural production increases. In the mature phase, the intensifying competition for water tends to be perceived as an increasing scarcity of water. In the transition from the expansionary phase to the mature phase, the interdependencies among water users increase, and the hydrologic setting and the rising externalities need to be taken into account. The policy objective of increasing agricultural production needs to be balanced with the new objective of water conservation. The interventions, which in the expansionary phase were focused on engineering and technological interventions to expand agricultural water supplies, need to increasingly incorporate demand-side interventions and options for reallocations, and to further develop context-specific policy and institutional arrangements as the water economy matures.

The methods for evaluating the choice and implementation of interventions need to adjust accordingly: While benefit-cost analysis is the main assessment method in the expansionary phase, the methods in the mature phase need to

TABLE ES.1 Irrigated Agriculture in the Expansionary and Mature Phases of a Water Economy

	EXPANSIONARY PHASE	MATURE PHASE
Demand and supply of agricultural water	Low demand, but growing	High demand and growing
	Minimal competition for water	Intense and increasing competition for water
	Readily available supplies (with incremental cost of new supplies relatively low, and constant over time)	Increasing water scarcity (with rapidly escalating incremental cost of new supplies, at some point exceeding the economic value foregone in some of the existing uses)
Hydrologic setting	Water users relatively independent and with few conflicts	Increasing interdependence between up- and downstream users, especially when return flows are important
	Minimal externalities	Significant externalities, with severity depending on the hydrological and institutional contexts
Policy objectives	Increasing agricultural production (and agricultural net income)	Addressing trade-offs between agricultural production growth and water conservation (or reallocation)
Interventions	Emphasis on expanding agricultural water supplies with investments in (relatively low-cost) infrastructure projects	Emphasis on demand-side interventions, and on facilitating reallocations and aligning private investments
	Focus on engineering and technological interventions off-farm	Increasing importance of context-specific policy and institutional interventions
Methods for evaluating the choice and implementation of interventions	Benefit-cost analysis of individual projects (without particular attention to water issues)	More comprehensive methods incorporating the hydrologic and institutional contexts, and the trade-offs
	Focus on the internal rate of return	Focus on the value of water, and environmental flows

incorporate water issues in more detail, reflect more comprehensively the hydrologic and institutional contexts, and focus on the value of water to assess reallocations.

The report applies the framework of the changing water economy to make the case that, with increasing water scarcity, the ongoing efforts for improving agricultural water productivity and efficiency need to move beyond crop per drop approaches, because they are in many circumstances an insufficient and sometimes counterproductive attempt to adapt agricultural water management to a maturing water economy.

BACKGROUND FACTS ON WATER USE IN IRRIGATED AGRICULTURE

The unique characteristics of water that distinguish it from most other resources and commodities need to be kept in mind in any discussion of the role of water use in irrigated agriculture. These include water's mobility and variable supply, and that it is rarely completely "consumed" in the course of its use. In irrigated agriculture, it is not unusual for half of the water withdrawn for irrigation to be returned to the hydrologic system as return flows—upon which downstream users may increasingly rely as water becomes scarcer.

These characteristics add to the complexity surrounding the use of water and the improvement of its use, and require several distinct measures of water quantity. Water withdrawn from a source, water applied to the place of use (such as a farm), and water consumed (also called evapotranspiration in irrigated agriculture) are key measures. Return flows are the difference between water withdrawn and water consumed.

The report illustrates the central role of water use in irrigated agriculture by presenting global trends in agricultural and total water use, both in terms of water withdrawn and consumed, and as share of total water use. Using country-level data from Food and Agriculture Organization of the United Nations (FAO) databases, we find a close link between agricultural withdrawals and total withdrawals, and between agricultural withdrawals and the area equipped for irrigation.

We further illustrate the link between irrigated agriculture and water scarcity with data at the global level. We show that agricultural water use is a key contributor to water scarcity—and thus to the transition from an expansionary to a mature phase of the water economy—in an increasing number of countries. So far, a country's level of water scarcity seems to have had little effect on the trends in its agricultural withdrawals and area equipped for irrigation.

CONCEPTUAL ISSUES: EFFICIENCY AND PRODUCTIVITY IN AGRICULTURAL WATER USE

The report then discusses conceptual issues related to efficiency and productivity in agricultural water use. A range of disciplines is involved in the topic, including hydrology and hydrogeology, civil and irrigation engineering, agronomy and crop physiology, and economics, with each discipline applying its own concepts and terms but with little interdisciplinary exchange.

We argue that a key distinction needs to be made between the concepts and terms from the fields of engineering and agronomy that dominate the irrigation literature, and the concepts and terms from the field of economics. The former tends to be based on single-factor approaches and focus on farm-level effects, while the latter applies multifactor approaches and can also consider basin-wide effects.

These conceptual differences are in part the reason for various methods developed and applied in the literature of the different fields concerned with assessing agricultural water productivity and efficiency. Furthermore, different interventions for improving agricultural water productivity and efficiency are emphasized depending on the assessment method employed.

The irrigation literature is dominated by *single-factor productivity measures,* such as crop per drop ratios. The economics literature on agricultural productivity and efficiency mainly employs two other groups of methods, *total factor productivity indices* and *frontier methods*. In addition to these three groups of methods, there is a fourth group called *deductive methods* that constitutes an important part of the agricultural and irrigation water economics literature. While total factor productivity indices and frontier methods are *inductive methods*—employing inductive logic, usually as formal statistical or econometric procedures, to infer generalizations from individual observations—*deductive method*s involve logical processes to reason from general premises to particular conclusions. They employ constructed models comprising a set of behavioral postulates (i.e., profit maximization) and empirical assumptions, and include residual imputation methods, mathematical programming, hydro-economic models, and computable general equilibrium models.

METHODS FOR ASSESSING AGRICULTURAL WATER PRODUCTIVITY AND EFFICIENCY

The report analyses the four main methods that have been, or could be, used to study agricultural water productivity and efficiency. We review the various approaches and applications of the four methods, and present key findings. We also use selected key features to compare across the four methods and provide insights into their respective strengths and weaknesses (table ES.2).

TABLE ES.2 Characteristics of the Methods by Key Features

	SINGLE-FACTOR PRODUCTIVITY MEASURES	TOTAL FACTOR PRODUCTIVITY INDICES	FRONTIER METHODS	DEDUCTIVE METHODS
Background of method				
Research field	Irrigation engineering, agronomy	Agricultural production economics (productivity and efficiency analysis)	Agricultural production economics (productivity and efficiency analysis)	Agricultural and irrigation/ water economics
Analytic approach	Calculation of ratios (in physical or "economic" terms)	Econometric analysis	Econometric or optimiza-tion analysis	Usually optimization
Focus of analysis	Often "gap analysis" of ratios	Focus on technological change	Usually assessment of technical efficiency of decision-making units	Policy analysis ("what if")
Incorporation of water				
Measure of water use	Water withdrawn, water applied, water consumed	Usually proxy variables (e.g., irrigated land)	Often proxy variables (e.g., number of irrigation events), also water applied	Water withdrawn, water applied, water consumed
Consideration of scales				
Spatial scale	Field; with aggregation in "economic terms" also farm and basin	National level (more recently also subnational)	Decision-making unit, mostly farm (also regional)	Field, farm, region, basin, economy-wide
Temporal scale	Usually cropping season	Annual	Cropping season; multiyear (with panel data)	Various scales, including projections
Assessment of agricultural water productivity and efficiency				
Data sources	Measured and modeled data	Measured/aggregate data	Primary data, with variability among farms	Range of data sources, mostly secondary data
Underlying production function	No	Yes (based on indices)	Yes (function may be estimated)	Yes (often implicit)
Efficiency and productivity concepts	Productivity concept originated to go beyond classical irrigation efficiency	Productivity and efficiency concepts from economic theory	Productivity and efficiency from economic theory; focus on multifac-tor technical efficiency	Not explicitly concerned with productivity, but measures can be estimated; technical efficiency not explicitly addressed
Inputs	Focus on water input (neglecting other inputs)	Inclusion of all (market-ed) inputs	Inclusion of all inputs relevant for decision-making units	Inclusion of all inputs
Outputs	Focus on output of one crop ("economic" measures may include other output)	Inclusion of all (market-ed) outputs	Single output is most common, but multiple outputs can be included; output often measured in terms of revenue	Inclusion of multiple outputs (at farm/basin levels)
Prices and costs	Output prices used for aggregation in "economic" measures (costs of inputs could be incorporated)	Prices and costs used for aggregation	Frontiers can be ex-pressed in terms of cost, profit, or revenue	Inclusion of regional/"rep-resentative" prices and costs

The strength of *single-factor productivity* studies that focus on crop per drop ratios is their special attention to the water input (or factor), and the ease with which they can incorporate different measures of water quantity. They often find large variations in agricultural water productivity, yet do not usually empirically investigate the factors that might explain such differing results. Their weakness is their disregard of other (nonwater) factors, prices, and costs, and the different sources of productivity.

Total factor productivity indices attempt to include all inputs, outputs, and prices and costs in their analysis of agricultural productivity growth—usually at the national level. Improvements are usually attributed to technological change. Yet because of data problems, with regard to both quantity and price, water aspects tend to be mostly included as dummy variables (such as irrigated vs. non-irrigated cropland), if at all. This does not generate much insight into the effect of water on agricultural productivity patterns, and water conservation aspects cannot be considered.

Frontier method studies can also incorporate multiple inputs and outputs. They are concerned with how well decision-making units (usually farms) manage their conversion of inputs to outputs. The basic measure of performance is technical efficiency (often equated with unobservable managerial ability), measured as potential input reduction or potential output expansion, relative to a reference "best practice" or efficient frontier, constructed with different techniques from observed inputs and their output realizations. So far, relatively few studies have explicitly incorporated a measure of water quantity, and in each case it has been water applied. Some of these studies posit that output could be increased if technical inefficiency related to water were decreased, for example, by training farmers. Possible effects on consumptive use and return flows are usually not discussed.

Deductive methods can address some of the shortcomings of the other methods. They can include multiple factors and outputs, and consider all measures of water quantity. The more complex approaches employ a variety of temporal and spatial scales. In particular, the hydro-economic models can incorporate basin-level issues, including the externalities among users. While deductive methods are not explicitly concerned with productivity issues, estimates of water productivity can be derived that incorporate the opportunity cost of all nonwater inputs and reflect the economic value of water. However, deductive methods are less suited to reflect "best practices" and improvements toward them, which is a strength of the frontier methods.

APPLICATIONS OF THE METHODS IN A MATURING WATER ECONOMY

The next step is a broader analysis of the methods with regard to their usefulness when applied in either the expansionary or mature phases of a water economy. We use the five characteristics introduced in table ES.1 to evaluate the extent to which each of the methods incorporates and addresses the changing conditions. The results are summarized in table ES.3. Overall, we find that the four methods with their stronger incorporation of water-related aspects have some advantages over benefit-cost analyses, the main assessment method in the expansionary

TABLE ES.3 Relevance of the Methods in a Maturing Water Economy

	SINGLE-FACTOR PRODUCTIVITY MEASURES	TOTAL FACTOR PRODUCTIVITY INDICES	FRONTIER METHODS	DEDUCTIVE METHODS
Demand and supply of agricultural water	Consideration of water scarcity; often erroneous assumption that addressing the perceived inefficient and unproductive use of water (off- and on-farm) would help overcome it	No consideration of water scarcity	No consideration of water scarcity	Inclusion of agricultural water demand and supply, with assessment of the effect of interventions on water scarcity
Hydrologic setting	Frequent focus on the field level, with insufficient recognition of users' interdependence Insufficient recognition of externalities (and contexts)	Water as one of many inputs in highly aggregated analysis of agricultural productivity, without consideration of spatial issues and externalities	Focus on farm level without capturing interdependencies between different water users	Complexities of the hydrological setting often incorporated
Policy objectives	Implicit focus usually on agricultural production (in some cases on water conservation) Often erroneous assumption that improving crop per drop ratios would address the trade-off between the objectives	Focus on (national or regional) agricultural growth	Focus tends to be on agricultural production on-farm; also consideration of water-specific and input-oriented technical efficiency (yet so far only in terms of water applied)	Mostly optimization of agricultural net income, but water conservation objectives can also be modeled
Interventions	Emphasis on engineering and technological interventions on-farm and in irrigation systems (often in existing infrastructure projects) that contribute to more crop per drop	Water is seen as an enabler of agricultural growth, yet without consideration of water-related interventions	Emphasis on engineering and technological interventions at the farm level; the impact of management-related intervention can also be captured	Incorporation of various interventions (engineering and technological, but also policy and institutional) and institutional contexts for assessments of trade-offs (including intra- and intersectoral)
Methods for evaluating the choice and implementation of interventions	Focus on comparison of crop per drop ratios over space and time With explicit inclusion of only one input, analysis of ratios usually does not allow specific ex ante recommendations on interventions; analysis of changes in ratios ex post does indicate causes	Assessments over time allow ex post evaluations of the contribution of (country-level) interventions related to irrigation water on agricultural growth	Typically ex post assessment; assessments over time could evaluate progress in the move toward the production frontier Could be used for ex ante assessments on scope of interventions, including improving farmers' managerial skills	Useful for ex ante analysis of policy options and their impact on farmers' income and water resources; used less for ex post analysis With ability to estimate the value of water, preferred choice for assessments of reallocations between farms, regions, and sectors (including the environment)

phase of the water economy; yet care must be taken when using some of them for assessing adaptation interventions in a maturing water economy.

Single-factor productivity measures have been developed and promoted with a concern about the increasing scarcity of water. Comparisons of single-factor productivity measures can be useful in the context of field experiments when the other relevant factors besides water are relatively well controlled (i.e., "all else is kept equal"). In such situations, the ratios can provide guidance for "closing gaps," for example, with improvements in irrigation scheduling. However, when ratios are compared across widely varying locations and across time, the critical factors causing the differences cannot be identified—and recommendations with regard to the choice of interventions cannot be made—without more in-depth analysis. Also, the ratios cannot sufficiently reflect the interdependencies among users.

Despite these shortcomings, a common recommendation in single-factor productivity studies—and in much of the public debate—is to invest in engineering and technological interventions on-farm and in irrigation systems. The resulting improvements in crop per drop ratios do not necessarily imply that trade-offs between agricultural production growth and water conservation have been addressed. It is not even clear to which objective they may have contributed, or if changes related to the water input were the reason for the improvement. Depending on the formulation of the ratios and the context, they may have actually made water scarcity even worse—for example, when return flows matter, and farmers are allowed to fully consume their water rights.

Total factor productivity studies are oriented toward agricultural production growth. They do not consider water scarcity situations. Even if a measure of water use could be properly incorporated in the analysis, it would be difficult to derive insights on water-related interventions that should be undertaken to, for example, improve resource allocation or help conserve water. Total factor productivity indices can be considered assessment methods from (and for) the expansionary phase of the water economy.

Frontier method studies have mostly been output oriented, and thus interested in how agricultural production could be raised with a given set of inputs. A few input-oriented studies use the notion of water-specific technical efficiency to investigate potential water conservation. However, because they focus on the farm level, they take a perspective that in many cases would be too narrow for deriving broader implications for improving irrigation water management to cope with water scarcity. This is because they have so far only considered water applied, and implicitly assumed that any reduction in this measure would constitute water saving—which may not be the case in areas where return flows are an important water source for downstream users.

Frontier method studies tend to emphasize technical efficiency and the potential to move farms toward the production frontier by improving farmers' managerial skills. Training programs on the use of irrigation technologies and the management of irrigation water are a common recommendation.

Frontier studies have so far not attempted to take into account interdependencies among water uses. This is not an issue in hydrologic settings where return flows are not important. In such situations, frontier studies can provide insights into the design of farm-based interventions and their later evaluation. Using data from detailed farmer surveys, frontier methods could create a baseline during project preparation on the more and less efficient farmers and the underlying probable causes of inefficiency. This would help guide project design on how to help reduce technical inefficiency by focusing on information, knowledge, and management issues—which are often neglected areas and could contribute to inclusion and poverty reduction objectives. If follow-up surveys are carried out, including at project completion, a frontier study could help provide insight into key developments during implementation.

In comparison with the other three main methods, *deductive methods* are probably the most suitable tool for assessing the choice and implementation of adaptation interventions in a changing water economy. A key factor is their flexibility for adjustment to reflect different contexts, not only to the hydrologic setting but also to the policy and institutional contexts.

The hydrologic context, including complex physical processes such as those between surface and groundwater, is often explicitly considered in hydroeconomic models.

Regarding the policy context, deductive methods can be formulated to explore each of the three objectives: addressing approaches for increasing irrigated agricultural production, identifying opportunities for water conservation, and providing insights into the role of irrigated agriculture in income support and economic development. They have been used to tackle the complexity of the varying objectives of water-related interventions at different spatial and temporal scales, including the trade-offs.

Regarding the institutional context, deductive methods are also uniquely suited to account for it in their assessments. Institutional arrangements are concerned with the rights of users and their exposure to the rights of others, and how these rights structure the incentives and disincentives between and among users in their decisions regarding water use. As water scarcity increases, the laws, rules, and entities affecting water allocation become more formal and—while technological advances tend to reduce transaction costs—more elaborate systems of water rights and their administration emerge. While the institutional context is a critical factor in determining appropriate adaptation interventions, at the same time, interventions need to increasingly focus on further developing and adjusting the institutional arrangements in order to reduce conflicts associated with increasing water competition and to facilitate more sustainable agricultural water management. Deductive methods, especially the programming models, can incorporate various institutional "rules," and also assess what effects the adoption of different rules would have on farmers' likely behavior and on the water-related effects.

Deductive methods are flexible to incorporate different interventions. They can assess engineering and technological interventions, and are probably most advanced for assessing policy and institutional interventions that become increasingly necessary in a maturing water economy. Furthermore, with their focus on the economic value of water, they can contribute to a more efficient allocation of water resources in times of scarcity. They are usually applied *ex ante* to assess the choice of interventions but, after implementation, the predicted and actual effects can be compared and analyzed.

SOME IMPLICATIONS FOR GOING FORWARD

As water scarcity intensifies and a growing number of countries move from an expansionary to a mature phase of the water economy, the need for adaptation investments in agricultural water management from both private and public sectors will increase. Currently, much of the public debate advocates for efforts to improve agricultural water productivity and efficiency and achieve more crop per drop. Our analysis of the underlying conceptual issues of such single-factor productivity measures, as well as their applications and suitability in a maturing water economy, has shown important limitations of the measures.

There is now also an expanding body of empirical evidence of the effects of the engineering and technological interventions that are usually promoted—and subsidized with technical and financial assistance—under this approach, in particular the conversion to more capital-intensive irrigation technologies. In the past, the water-related effects of such interventions were not well explored beyond the farm or irrigation system level, in part because of the lack of data on the key water measures—including water withdrawn, applied, and consumed—and how they may change as a result of particular interventions. For the United States, for example, a growing number of studies—mostly based on deductive methods—show that while such investments may reduce on-farm applications, they do not necessarily contribute to water conservation. Their results indicate mixed if not counterproductive effects on the water scarcity situation. A main reason is the various adjustments that farmers can make—for example, expanding the irrigated area.

As the water economies mature, there is a need to design interventions with the local hydrologic, policy, and institutional contexts in mind. In addition, context-specific policy and institutional interventions become increasingly important. This implies that more and better ex ante assessments should be carried out to estimate the economic and financial costs and benefits as well as the water-related effects of different options. More emphasis should also be given to ex post assessments to evaluate the implementation processes and results in line with the underlying objectives. These assessments would help inform decision makers in both the public and private sectors.

The analysis in this report suggests that, in water-scarce regions, the debate needs to urgently move beyond crop per drop issues. Our analysis of available measurement methods demonstrates that better and more comprehensive approaches are available to take into account the requirements of a maturing water economy, in particular among the deductive methods. These methods are well suited to and often effectively integrate context-specific issues. The water-focused multifactor productivity measures incorporating the opportunity costs of nonwater inputs that are implicit in most deductive methods could be more widely reported and discussed. While the application of multifactor methods may require more resources, time, and skills than the currently dominating single-factor productivity measures, a wider use of such methods can in many instances be justified given the magnitude of the ongoing public investments in interventions that address water scarcity—and the need to choose and implement them wisely.

Abbreviations

FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
IWMI	International Water Management Institute
OECD	Organisation for Economic Co-operation and Development

1 Why Focus on Water Management in Irrigated Agriculture?

Water scarcity is increasingly acknowledged as a major risk in many parts of the world, with water crises consistently featured among the top-ranked global risks (World Economic Forum 2017). Projections indicate that without advances in water management and more integrated policy making in both developed and developing countries, water scarcity and related water problems will significantly worsen over the next several decades (Jiménez Cisneros et al. 2014; WWAP 2012).

Water use in irrigated agriculture is among the main factors that contribute to this situation. Irrigated agriculture is by far the largest use of water worldwide, estimated to account for about 70 percent of total freshwater withdrawals (Molden 2007). In many drier countries, it is not unusual for agricultural water use to account for more than 90 percent of total withdrawals (FAO 2016a). With increasing water scarcity, agricultural water management is therefore moving to the center of water management concerns.

Yet the question of how best to adapt water management in irrigated agriculture is complicated, not least because irrigated agriculture is at the center of two large and conflicting trends. On the one hand, irrigated agriculture is rapidly expanding with the growing demand for agricultural products. Over the past half century, irrigated area almost doubled and concomitant water use also expanded (FAO 2016b). Global demand for agricultural products is projected to grow by about 70 percent by 2050 (World Resources Institute 2014). This increase in agricultural demand— resulting from population growth, rising meat and dairy consumption, and expanding biofuel use—is expected to require a continued increase in agricultural water use (Alexandratos and Bruinsma 2012). Efforts to adapt to climate change and the increasing variability of water supplies further contribute to the expansion of water use in irrigated agriculture (Elliott et al. 2014; World Bank 2012).

On the other hand, additional demands for irrigation water are increasingly difficult to accommodate in many parts of the world. Agricultural withdrawals are already accounting for unsustainable shares of total renewable water resources in many of the drier countries (FAO 2016a). And the growing demand for water from other sectors is further intensifying the competition for water resources. Because water use in irrigated agriculture is seen as having relatively low net returns compared with other uses, other sectors increasingly look to agriculture as a potential source of water.

Probably the most common approach for addressing these challenges—and adapting agricultural water management to increasing water scarcity—is to focus efforts on improving *agricultural water productivity and efficiency* and thus achieve more crop per drop. Given the large amounts of water involved, and the widely-held belief that water use in agriculture is relatively inefficient and unproductive, even small increases in water efficiency and productivity are believed to have large implications for local and global water budgets. Such improvements would allow either higher agricultural production with the same amount of water, or the same amount of agricultural production with less water. In the latter case, the water savings could be reallocated to other higher-value uses, or freed up to ensure some level of environmental flows. The implicit assumption is that such improvements in water productivity and efficiency would help address the trade-off between increased agricultural production and agricultural water conservation and reallocation.

Many international organizations concerned with water management are also promoting an increase in agricultural water productivity and efficiency as an important policy goal. Among them are the Global Water Partnership (2000), the World Water Council (2000), the International Water Management Institute (Molden 2007), the World Water Assessment Program (WWAP 2009, 2012), the United Nations Environment Program (Keys, Barron, and Lannerstad 2012), the Asian Development Bank (2013), the World Bank (2013), and the Food and Agriculture Organization of the United Nations (FAO 2012, 2017). In line with this thinking, significant public and private investments are being made to increase water productivity and efficiency in agriculture in both developed and developing countries.

Yet some serious problems are associated with this common approach (Scheierling, Tréguer, and Booker 2016; Scheierling and Tréguer 2016a). They are related to conceptual issues, the methods for measuring agricultural water productivity and efficiency, and their application in different contexts—which then influence the choice of interventions and the evaluation of their implementation.

In much of the public debate, the terms agricultural water productivity and efficiency are used quite vaguely. David Seckler, as newly appointed head of the International Irrigation Management Institute,[1] was probably the first to advocate for a focus on water productivity in agriculture to better address increasing water scarcity (Seckler 1996). Since then, a large body of research, especially in the irrigation literature, has dealt with assessing and improving water productivity in agriculture (Giordano et al. 2017). If a definition of the term is given or implied, it is usually along the lines of more crop per drop, emphasizing water as if it were the only input that mattered.[2] Often it is not specified which "crops" and which "drops" to consider, and how to measure them. The policy objectives to which such efforts about crops and drops could or should contribute—such as growth in agricultural production and increases in farmers' net revenues, or water conservation and reallocation—are also usually not spelled out. If an objective is stated, improvements in crop per drop measures are mostly intended to help address water scarcity (FAO 2017; GFFA 2017). The situation is similar with the term water efficiency. Water efficiency is often used interchangeably with water use efficiency and irrigation efficiency. Yet these terms may have quite different underlying concepts and meanings, and what is measured may differ. The usual understanding is that an increase in water efficiency would imply a reduction in waste by bringing the amount of water used closer to the amount of water required for a particular purpose. Water conservation tends to be the envisioned policy objective.

Partly because of this lack of clarity related to the conceptual frameworks and related assessment methods as well as their proper application, the choice and impact of interventions for enhancing agricultural water productivity and efficiency are also seldom systematically discussed. Investments in improved irrigation infrastructure, in particular more capital-intensive on-farm irrigation technologies, are a popular and widely adopted intervention. These investments are assumed to increase irrigation efficiency and lead to higher water productivity in terms of more crop per drop. Yet without more detailed analysis, the actual effects of such interventions on agricultural water use and water scarcity often remain uncertain and, in some cases, may even lead to unintended or counterproductive outcomes.

This report aims to shed further light on these issues with a focus on the conceptual issues, the assessment methods, and their application and relevance in different contexts.

IRRIGATED AGRICULTURE IN A MATURING WATER ECONOMY: A FRAMEWORK

An underlying framework of the analysis is the view of the water economy transitioning from an expansionary to a mature water economy. This characterization was first introduced by Randall (1981) to describe the Australian water economy under increasing scarcity, and to call for policy reforms to adapt to the new context. It was later taken up by Young and Haveman (1985) as a framework for analyzing changing water issues in the western United States and the related adaptation needs in public policy and institutional arrangements. Since then, the framework has also been applied to other countries with increasing water scarcity, such as Chile (Rosegrant et al. 2000). It has also been used more generally—for example, to review the evolution of economic water policy models and their increasing sophistication—to reflect the situation of a maturing water economy (Booker et al. 2012).

In this report, the framework is further developed to reflect water management issues in irrigated agriculture. Table 1.1 provides an overview of both the expansionary and mature phases of a water economy based on five characteristics. These characteristics play a role throughout the report, including in the discussion of the advantages and disadvantages of the different concepts and methods, and their application in different contexts.

Demand and Supply of Agricultural Water. The expansionary phase is characterized by readily available water supplies to meet the growing demand for irrigation water to increase agricultural production. The demand can be easily accommodated with investments in relatively low-cost infrastructure projects. The incremental economic cost of these new water supplies is relatively low.

The situation becomes more challenging in the mature phase. Water competition intensifies, which tends to be perceived as increasing scarcity of water. The demand for water to expand irrigated agriculture continues to increase; but at the same time, other sectors are looking for reallocations of

TABLE 1.1 Irrigated Agriculture in the Expansionary and Mature Phases of a Water Economy

	EXPANSIONARY PHASE	MATURE PHASE
Demand and supply of agricultural water	Low demand, but growing	High demand and growing
	Minimal competition for water	Intense and increasing competition for water
	Readily available supplies (with incremental cost of new supplies relatively low, and constant over time)	Increasing water scarcity (with rapidly escalating incremental cost of new supplies, at some point exceeding the economic value foregone in some of the existing uses)
Hydrologic setting	Water users relatively independent and with few conflicts	Increasing interdependence between up- and downstream users, especially when return flows are important
	Minimal externalities	Significant externalities, with severity depending on the hydrological and institutional contexts
Policy objectives	Increasing agricultural production (and agricultural net income)	Addressing trade-offs between agricultural production growth and water conservation (or reallocation)
Interventions	Emphasis on expanding agricultural water supplies with investments in (relatively low-cost) infrastructure projects	Emphasis on demand-side interventions, and on facilitating reallocations and aligning private investments
	Focus on engineering and technological interventions off-farm	Increasing importance of context-specific policy and institutional interventions
Methods for evaluating the choice and implementation of interventions	Benefit-cost analysis of individual projects (without particular attention to water issues)	More comprehensive methods incorporating the hydrologic and institutional contexts, and the trade-offs
	Focus on the internal rate of return	Focus on the value of water, and environmental flows

agricultural water. This is because irrigated agriculture typically uses the largest share of water, and its long-run marginal value of water tends to be lower than in the competing uses. When these other demands are rapidly increasing, the foregone net benefits from reducing agricultural water use may be less than the costs of a new supply. Such water reallocation to the higher value uses, possibly combined with water conservation measures in agriculture, may lead to substantial economic savings compared with investments in new water supply projects.

Hydrologic Setting. Not much attention needs to be paid to the hydrologic setting in the expansionary phase. The competition for water is minimal, and the interdependencies among water users and related externalities tend to be negligible. However, in the mature phase the interdependence between upstream and downstream users can become pervasive, especially when return flows are important. These externalities need to be taken into account when applying methods and evaluating interventions.

Policy Objectives. A significant shift can also be observed with regard to the policy objectives in the two phases (Scheierling and Tréguer 2016a). The key objective of the expansionary phase is increasing agricultural production, and concomitantly, agricultural net income. In the mature phase, a balance needs to be achieved with the new objective of agricultural water conservation. This may be in response to pressures for reallocating water to other uses (including environmental requirements) or for coping with water scarcity.

Interventions. The types of interventions need to change in a maturing water economy, moving from supply-side interventions focused on engineering and technological measures to demand-side interventions that increasingly incorporate policy and institutional adaptation measures.

Methods. There are also implications for the role of economics in water policy and the methods that need to be applied (Booker et al. 2012). In the expansionary phase, a main activity is the benefit-cost analysis of proposed and often subsidized infrastructure projects for developing new supplies. The focus of the analysis is usually on the internal rate of return, ensuring that scarce capital is used most beneficially, without particular consideration of the water resource.

In the mature phase, when the interdependencies among water users are increasingly pervasive, benefit-cost analysis becomes more challenging. Economic assessments increasingly rely on more comprehensive methods that are able to account for different hydrological and institutional contexts and to assess various trade-offs, including those between different objectives and interventions. Assessments are also more oriented toward estimating the economic value of water in different uses, times, and places, to help guide a more efficient allocation across multiple uses.

The report applies the framework of the changing water economy to make the case that the ongoing efforts to improve agricultural water productivity and efficiency and achieve more crop per drop are, in many circumstances, an insufficient and sometimes counterproductive attempt to adapt to a maturing water economy. In light of the five characteristics of table 1.1, the shortcomings include (a) the erroneous belief that overcoming the perceived inefficient and unproductive use of agricultural water would automatically address scarcity issues; (b) a frequent focus on the field or farm level that prevents a sufficient recognition of users' interdependence; (c) the implicit assumption that the trade-off between the objectives of agricultural production and water conservation would be addressed by improving agricultural water productivity and efficiency; (d) the continued emphasis on engineering and technological interventions without much consideration of policy and institutional interventions; and (e) methodologically, a focus on crop per drop ratios that tend to disregard the influence of other factors besides water, and cannot take into account institutional arrangements that, for example, may influence farmers' behavior.

SCOPE OF THE REPORT AND ROADMAP

In order to contribute to a reorientation of the public debate on agricultural water productivity and efficiency, the report aims to clarify some of the underlying concepts, review and analyze the available methods for assessing water productivity and efficiency, and discuss their application and relevance in different contexts.

Clarifying Conceptual Issues. Given that the limitations of the common approach are partly the result of conceptual issues, such as the definitions of efficiency and productivity, the first aim is to clarify the underlying concepts. A complicating factor is that a range of disciplines is involved in the topic, including hydrology and hydrogeology, civil and irrigation engineering, agronomy and crop physiology, and economics, with each discipline applying its own concepts and terms and often little exchange among the disciplines. We argue that a key distinction needs to be made between the concepts and terms from the fields of engineering and agronomy that dominate the irrigation literature, and the concepts and terms from economics. The former tend to be based on single-factor approaches and focus on farm-level effects, while the latter apply multifactor approaches and can also consider basin-wide effects.

These conceptual differences partially explain the different methods developed and applied in the various parts of the literature concerned with assessing agricultural water productivity and efficiency. Furthermore, different interventions for improving agricultural water productivity and efficiency are emphasized depending on the assessment method employed.

Reviewing the Assessment Methods. A second aim of the report is to provide an in-depth review and analysis of the available assessment methods. Our review of the literature shows four groups of methods. The irrigation literature is dominated by single-factor productivity measures, such as crop per drop ratios. The economics literature on agricultural productivity and efficiency mainly employs total factor productivity indices and frontier methods. The former method attempts to include "all" factors of production, and is used for national or subnational level economic productivity analyses; the latter method can account for multiple inputs and outputs, and focuses on measuring farms' technical efficiency relative to a "best practice" or efficient frontier.

In addition to these three groups of methods, there is a fourth group called deductive methods that constitutes an important part of the agricultural and irrigation water economics literature. While total factor productivity indices and frontier methods belong to the inductive methods—employing inductive logic, usually as formal statistical or econometric procedures, to infer generalizations from individual observations—deductive methods involve logical processes to reason from general premises to particular conclusions. They employ constructed models comprising a set of behavioral postulates (i.e., profit maximization) and empirical assumptions, and include residual imputation methods, mathematical programming, hydro-economic models, and computable general equilibrium models. Deductive methods also include multiple inputs and outputs and can be formulated for different scales (usually based on "representative farm models"), and used for policy analysis and project planning.

Analyzing the Relevance of the Methods in a Maturing Water Economy. A third aim of the report is to provide a broader analysis of the methods with regard to their usefulness when applied in the expansionary or mature phase of a water economy. In particular, the five characteristics in table 1.1 are used to evaluate the extent to which each of the methods incorporates and addresses the changing conditions. A key finding is that deductive methods provide the flexibility to overcome many of the limitations of the other methods, and are able to accommodate the various requirements posed by a maturing water economy.

The report builds on and expands some of our earlier work on agricultural water productivity and efficiency (Giordano et al. 2017; Scheierling et al. 2014; Scheierling, Tréguer, and Booker 2016; Scheierling and Tréguer 2016a, 2016b), and situates it into the broader framework of the maturing water economy. The emphasis of the report is on water quantity measures. Water quality aspects and other agricultural activities besides irrigated agriculture are not included. To our knowledge, this is the first effort to undertake such a broad assessment in order to reorient the public debate on assessing agricultural water productivity and efficiency in a situation of increasing water scarcity. The focus of the report is on illuminating the assessment methods, and less on providing policy directions. Future work may further develop the latter area.

To set the stage for this analysis, chapter 2 presents background facts on water use in agriculture. The preliminaries include a discussion of the special characteristics of water. A key feature is that water is rarely completely consumed in the course of its use. As water scarcity becomes more severe, downstream users increasingly depend on the return flows of water, and are affected by any changes that result from water-related interventions by upstream users. Thus water-related changes observed at the farm level may not provide insight into changes at the basin level. Only carefully defined and applied measures of water use can help to improve the understanding.

This discussion is followed by a global view on irrigated agriculture and water resources. Based on the key measures of water use, global trends in agricultural water use are displayed. Using country-level data from Food and Agriculture Organization of the United Nations (FAO) databases, we find a close link between agricultural withdrawals and total withdrawals, and between agricultural withdrawals and the area equipped for irrigation. We also show that agricultural water use is a key contributor to water scarcity—and thus to the transition from an expansionary to a mature phase of the water economy—in an increasing number of countries. Yet trends in agricultural withdrawals and the area equipped for irrigation seem to not yet be driven by a country's water scarcity level.

Chapter 3 discusses conceptual issues related to efficiency and productivity in agricultural water use. We argue that a key distinction needs to be made between the concepts and terms from the fields of engineering and agronomy that dominate the irrigation literature, and the concepts and terms from economics. The former tend to be based on single-factor approaches and focus on farm-level effects, while he latter apply multifactor approaches and can consider basin-wide effects. Partly as a result of these conceptual differences, different methods have been developed and applied for measuring agricultural water productivity and efficiency. And, further, different interventions for improving agricultural water productivity and efficiency are emphasized depending on the measurement method.

Chapter 4 presents the four main groups of methods that have been, or could be, used to study agricultural water productivity. Given the extensive literature on each of the methods, our presentation does not attempt to be exhaustive. We review the various approaches and applications and present key findings. We also use selected key features to compare the four methods more systematically, and to provide insights on their respective strengths and weaknesses.

Finally, chapter 5 moves into a broader analysis of each of the methods with regard to their usefulness when applied to assessing the choice and implementation of interventions for adapting agricultural water management in a maturing water economy. We find that deductive methods are probably the most suitable tool given their flexibility to reflect different hydrologic settings as well as policy and institutional contexts. The chapter concludes with some implications for going forward.

NOTES

1. Since 2000 it is officially recognized as the International Water Management Institute (IWMI).
2. For example, an address of the United Nations Secretary General to a summit of the "Group of 77" developing countries stated: "…we need a Blue Revolution in agriculture that focuses on increasing productivity per unit of water, or 'more crop per drop'" (Annan 2002).

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2 Background Facts on Water Use in Irrigated Agriculture

Any discussion of water use in irrigated agriculture needs to consider the unique characteristics of water that distinguish it from most other resources and commodities. As further elaborated in the next section, these characteristics add to the complexity of assessing the use of water—particularly in times of increasing water scarcity—and require several distinct measures of water quantity. The following sections discuss the central role of water use in irrigated agriculture, and illustrate the close link between agricultural water use and water scarcity.

PRELIMINARIES: SPECIAL CHARACTERISTICS AND MEASURES OF WATER

Water has special characteristics that distinguish it from most other resources and commodities (Young 1986, 2005; Young and Haveman 1985). This poses significant challenges, both for defining and applying measures related to its use as an input to agricultural production and for assessing and improving agricultural water management. Some of the key characteristics of water on the supply and demand side are discussed below, followed by their implications for water measurement.

Special Characteristics of Water

Supply Characteristics. A key physical characteristic of water on the supply side is its *mobility*. Typically found in liquid form, water tends to flow, evaporate, and seep as it moves through the hydrologic cycle. This makes it a high-exclusion-cost resource, as the exclusive property rights, which are the basis of a market or exchange economy, are relatively difficult and expensive to establish and enforce.

Although generally renewable, raw water supplies tend to be *variable and unpredictable* with regard to time, space, and quality. Local water availability usually changes systematically throughout the seasons of the year and over longer cyclical swings. Climate change now affects both short- and longer-term supply trends as well as the extremes of the probability distributions, such as floods and droughts.

Demand Characteristics. As with the supply side, *variability* also affects water demand. The needs of irrigated agriculture change in response to rainfall and temperature patterns over the seasons of a year and over longer cycles.

Another demand characteristic is the *diversity of uses*. Most water use is by producers, who use it as an intermediate good; for other users, water is a final consumption good. Each use may change the place, form, time dimension, and quantity of water.

Furthermore, water exhibits a relatively *low economic value* at the margin, in particular in the majority of its uses in irrigated agriculture. The costs for transportation, lifting, and storage are usually high in comparison.

Other Water-Specific Considerations. Because of variations in water supply and local demand, water-related *problems are typically site-specific*. Thus, interventions often need to be adapted to the local context to ensure that they achieve desired outcomes.

Also, water causes unique *interdependencies* among water users that become more pervasive and complex as water scarcity intensifies. This is because water is rarely completely "consumed" in the course of human production and consumption activities. It is not unusual for half of the water withdrawn for irrigation to be returned to the hydrologic system in the form of surface runoff or subsurface drainage. An even larger proportion is typically returned from municipal and industrial withdrawals. Other users, particularly those downstream, are greatly affected by the quantity, quality, and timing of releases or return flows from upstream irrigators. The presence of these externalities implies that the full costs of an economic activity are not recognized in individual decisions. As a result, decisions that are rational from the individual perspective result in outcomes that are not optimal from the perspective of water users as a group, or of society as a whole. Public policy and interventions become necessary to align private and social objectives.

A complicating factor is the large number of water users and individual decision makers. While each individual act of water use may have a negligible impact, the *cumulative impact of many small decisions* can be of major importance—especially when markets or other mechanisms that ration resources are absent. Effective public regulation of many small, scattered, decision makers is difficult and expensive.

Part of the reason is that the *transaction costs*—the resources for obtaining information and reaching and enforcing agreements, contracts, and public laws—tend to be relatively high compared with the economic value of water. This is especially the case for irrigated agriculture. However, increased water scarcity, in combination with technological advances that reduce transaction costs, encourages the establishment of more elaborate management systems.

Measures of Water

The special characteristics of water require different measures of water use. In particular, to take into account that water is rarely fully consumed in any of its uses, it is useful to distinguish between three different measures of water use: water withdrawal, water application, and water consumption. Table 2.1 provides definitions for the three measures.

TABLE 2.1 Measures of Water Use

TERMS AND DEFINITIONS
- **Water withdrawal** (or diversion): Amount of water removed from a surface or groundwater source
- **Water application** (or delivery): Amount of water delivered to the place of use, for example, the farm
Conveyance loss: Difference between water withdrawal and application
- **Water consumption** (or consumptive use, depletion, evapotranspiration): Amount of water that is actually consumed by the use
Return flows: Difference between water withdrawal and consumption

Source: Based on Young 2005.

It is especially critical to distinguish among the different measures in irrigated agriculture (Scheierling, Young, and Cardon 2004). *Water withdrawal*—the amount of water removed from a water source—exceeds *water application* on the farm because of the amount of water lost in transit from the point of withdrawal to the point of use. The difference is the *conveyance loss*. The main reasons for this loss are leakages, such as from unlined earthen canals.

Water consumption in irrigated agriculture is also called evapotranspiration. It refers to the amount of water transferred to the atmosphere through evaporation from plant and soil surfaces and transpiration by plants, and includes water incorporated into plant products or otherwise removed from the immediate water environment.

The difference between water application and consumption is mainly the result of on-farm transit and field losses from the imprecision of water application practices. In the case of flood irrigation, for example, excess water is applied at the beginning to ensure that sufficient water reaches plants at the end of the field. Also, irrigators may not know the precise amount of water needed and apply more than strictly necessary. In some areas, water in excess of consumptive use may also be applied to carry salts below the crop root zone. Consumptive use typically amounts to 40 percent–60 percent of water application.

The difference between water withdrawal and consumption—the sum of conveyance losses and on-farm losses—is called *return flows*. In many river basins, these return flows constitute an important part of the downstream water supply.

Data on the irrigation sector in the United States (Solley et al. 1998, cited in Young 2005) illustrate the importance of distinguishing among the three measures of water use, and the magnitude of the return flows. Water applications amounted to about 80 percent of water withdrawals, and reported water consumption was about 60 percent of water applied. Overall, the net amount consumed was less than half the amount originally withdrawn. Therefore, the return flows—and their variation—have significant economic (and environmental) implications.

In discussing water use in agriculture in the following section, it is essential to consider the water quantity being measured, and to interpret the findings accordingly.

CENTRAL ROLE OF WATER USE IN IRRIGATED AGRICULTURE

This section shows the central role of water use in irrigated agriculture, starting with a display of global trends in agricultural water use and total water use—in terms of both water withdrawals and water consumption. This is followed by our analysis of data from the Food and Agriculture Organization (FAO 2016a, 2016b) of country-level agricultural water use.

Global Trends in Agricultural and Total Water Use

Based on estimates from Shiklomanov and Rodda (2003) and reported data from the FAO (2016a), figure 2.1 shows the developments in agricultural and total water use at the global level since 1900. The illustration includes two measures of water use: water withdrawals and water consumption.

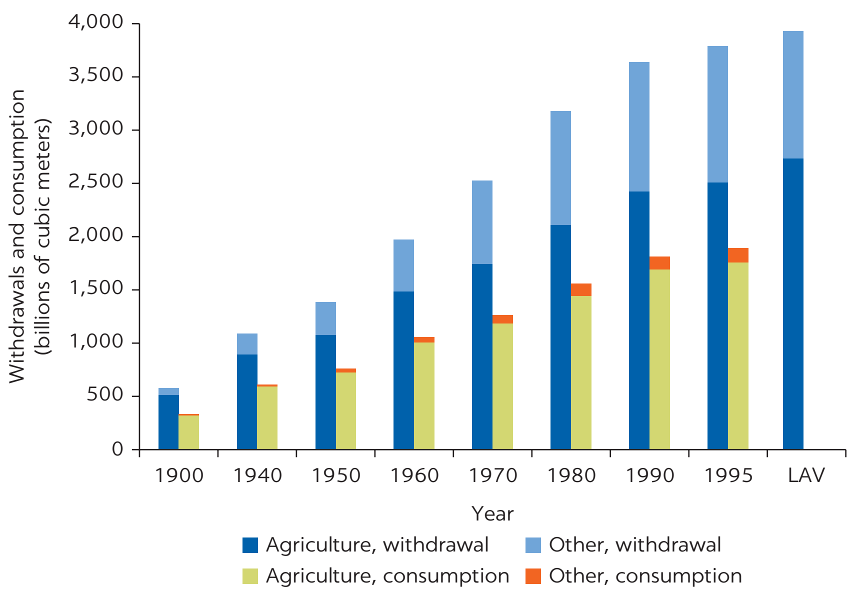
The agricultural sector has historically accounted for the largest share, by far, of total water withdrawals.[1] From 1900 to 1995 the agricultural share decreased from 89 percent of total water withdrawals to 66 percent, but more recently it increased again to 70 percent (FAO 2016a).

Almost all of total water consumption has also been in agriculture. The share slightly decreased from 97 percent in 1900 to 93 percent in 1995. However, over the same period, agricultural consumption as a share of agricultural water withdrawals increased from 63 percent to 70 percent.

Overall, both total and agricultural water withdrawals have increased dramatically since 1900, but their rates of growth have declined since about 1980. In most Organisation for Economic Co-operation and Development (OECD) countries, total and agricultural water withdrawals have tended to remain stable or decrease (OECD 2015), which has contributed to this outcome.

FIGURE 2.1

Global Trends in Agricultural and Total Water Withdrawals and Consumption



Source: Scheierling and Tréguer 2016a, based on FAO 2016a; Shiklomanov and Rodda 2003.
Note: LAV = latest available value.

Country-Level Agricultural Water Use

The analysis of country-level agricultural water use starts with a discussion of the 10 countries with the largest agricultural withdrawals. This is followed by illustrations of the close relationship between agricultural withdrawals and total withdrawals, and between agricultural withdrawals and the area equipped for irrigation.

Countries with the Largest Agricultural Withdrawals. The 10 countries with the largest annual agricultural water withdrawals, based on the latest available data from FAO (2016a), are listed in table 2.2. India is by far the leading country, followed by China, the United States, and Pakistan.

The 10 countries with the largest agricultural withdrawals are also responsible for the largest total withdrawals. Not surprisingly, they are also among the countries with the largest areas equipped for irrigation[2] (FAO 2016b).[3]

Except for the United States and China, the 10 countries' percentage of total water withdrawals allocated for agriculture is larger than the worldwide average of about 70 percent that is usually cited in the literature (Molden and Oweis 2007). A record 95 percent of total withdrawals in Vietnam are for agriculture, followed by 94 percent in Pakistan and 92 percent in the Islamic Republic of Iran.

When dividing the amount of agricultural water withdrawals by the area equipped for irrigation, half of the 10 countries are shown to withdraw an irrigation depth of 1 meter or more for their respective areas equipped for irrigation. The lowest value of 0.5 meter is shown for China. Even though China has a larger area equipped for irrigation than India (69 million hectares compared with 67 million), it withdraws only 52 percent of the water India withdraws for agricultural purposes.

Linking Agricultural Withdrawals and Total Withdrawals. Figure 2.2 shows agricultural and total water withdrawals for all countries based on the latest data available in FAO (2016a). The point in the upper right corner of the first graph represents India, the country with the largest agricultural and total withdrawals. Overall, our estimates indicate that agricultural withdrawals are highly

TABLE 2.2 Countries with the Largest Agricultural Water Withdrawals

COUNTRY	AGRICULTURAL WATER WITHDRAWALS (billion m^3)	TOTAL WATER WITHDRAWALS (billion m^3)	AGRICULTURAL WATER WITHDRAWALS AS PERCENT OF TOTAL WATER WITHDRAWAL (%)	AREA EQUIPPED FOR IRRIGATION (m ha)	AREA EQUIPPED FOR IRRIGATION AS PERCENT OF AGRICULTURAL AREA (%)	AGRICULTURAL WATER WITHDRAWALS PER AREA EQUIPPED FOR IRRIGATION (m)
India	688	761	90	67	37	1.0
China	358	554	65	69	13	0.5
United States	175	486	40	26	6	0.7
Pakistan	172	184	94	20	75	0.9
Indonesia	93	113	82	7	12	1.3
Iran, Islamic Rep.	86	93	92	10	19	0.9
Vietnam	78	82	95	5	42	1.6
Philippines	67	82	82	2	13	3.4
Egypt, Arab Rep.	67	78	86	4	100	1.5
Mexico	62	80	77	7	6	0.9

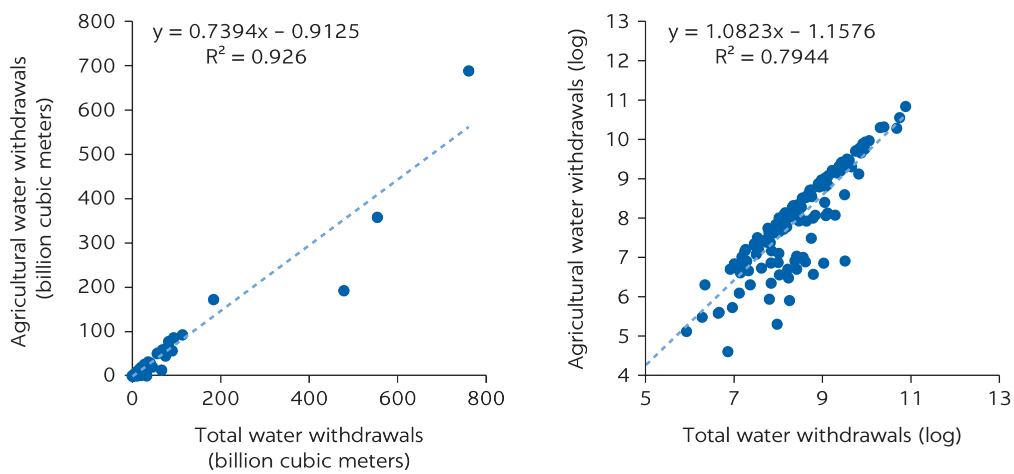
Source: Scheierling and Tréguer 2016b, based on FAO 2016a, 2016b.

correlated with total withdrawals.[4] According to the first graph in figure 2.2, on average, one cubic meter of total withdrawals is associated with about 0.74 cubic meters of agricultural withdrawals.[5] In other words, about 74 percent of the water withdrawals worldwide are for agricultural purposes. This reconfirms earlier estimates cited above.

Linking Agricultural Withdrawal and Area Equipped for Irrigation. Data on agricultural withdrawals and area equipped for irrigation for all countries are in figure 2.3. Our estimates indicate that agricultural water withdrawals are also highly correlated with the area equipped for irrigation. According to the first graph of figure 2.3, one square meter of area equipped for irrigation is, on average, associated with an agricultural water withdrawal amounting to 0.77 cubic

FIGURE 2.2

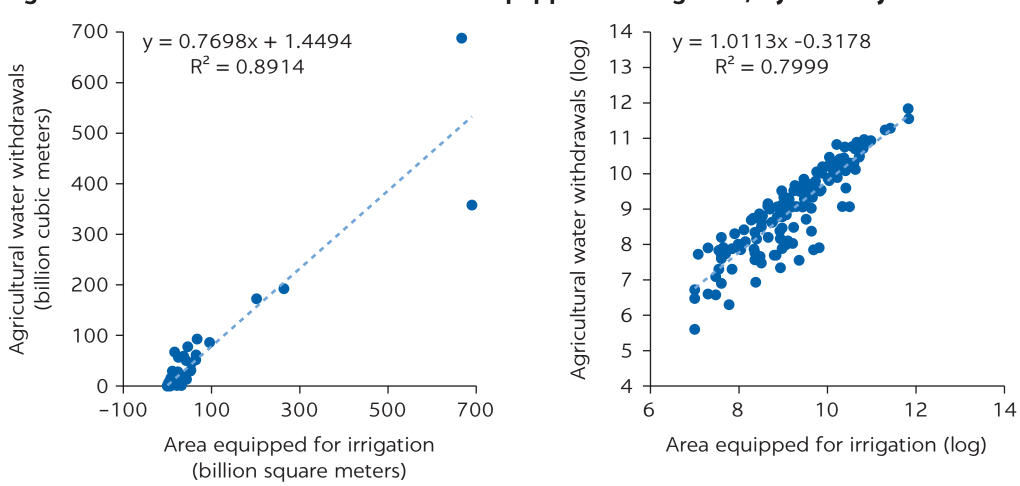
Agricultural Water Withdrawals and Total Water Withdrawals, by Country



Source: Scheierling and Tréguer 2016b, based on FAO 2016a.
Note: First graph with standard error of 0.0174, and *t*-stat of 42.46; second graph with standard error of 0.0457, and *t*-stat of 23.67.

FIGURE 2.3

Agricultural Water Withdrawals and Area Equipped for Irrigation, by Country



Source: Scheierling and Tréguer 2016b, based on FAO 2016a, 2016b.
Note: First graph with standard error of 0.0224, and *t*-stat of 34.37; second graph with standard error of 0.0423, and *t*-stat of 23.91.

meters. This implies an average irrigation depth worldwide of 0.77 meters. This is about the irrigation depth found for the United States (table 2.2).[6]

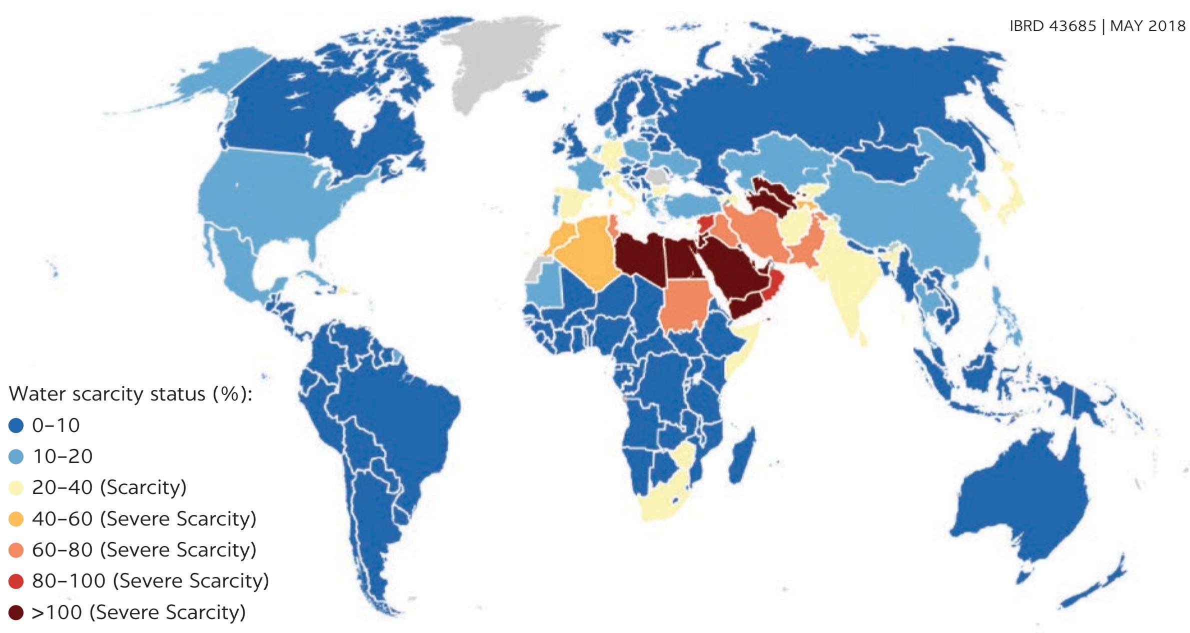
IRRIGATED AGRICULTURE AND WATER SCARCITY

A number of issues make it difficult to establish a link between irrigated agriculture and water scarcity at the global level. Among them are not only the special characteristics of water discussed in the previous section, but also the definition of water scarcity and the availability of data related to agricultural water use (Scheierling and Tréguer 2016b).[7] In this section we show a close link between irrigated agriculture and water scarcity at the global level, based on a widely used indicator for water scarcity. This is followed by illustrations of trends in area equipped for irrigation at the regional level, trends in agricultural withdrawals, and scarcity levels of selected countries. The section ends with a review of projections on future agricultural water use.

Linking Agricultural Withdrawals and Water Scarcity. Various definitions of water scarcity have been proposed in the literature and different indicators applied (UNEP 2012). One widely used indicator is based on a comparison of annual data of total water withdrawals and total renewable water resources at the national level (UNEP 2012).[8] A country is considered to experience "scarcity" in a particular year if the total water withdrawals are from 20 percent to 40 percent of the total renewable water resources, and "severe scarcity" if this value exceeds 40 percent. Map 2.1 displays this indicator based on data for 2013, or the latest year available, from FAO (2016a). Countries in the Middle East and North Africa are all shown to experience severe water scarcity. In other parts of the world, including most countries in South Asia and Central Asia, water is also considered scarce or severely scarce. Some countries' water withdrawals are

MAP 2.1

Total Water Withdrawals as a Percent of Total Renewable Water Resources



Source: Scheierling and Tréguer 2016b, based on FAO 2016a.

even higher than their total renewable water resources. Saudi Arabia is the most extreme case, withdrawing almost 10 times the amount of renewable resources available, and thus relying mostly on non-renewable groundwater.

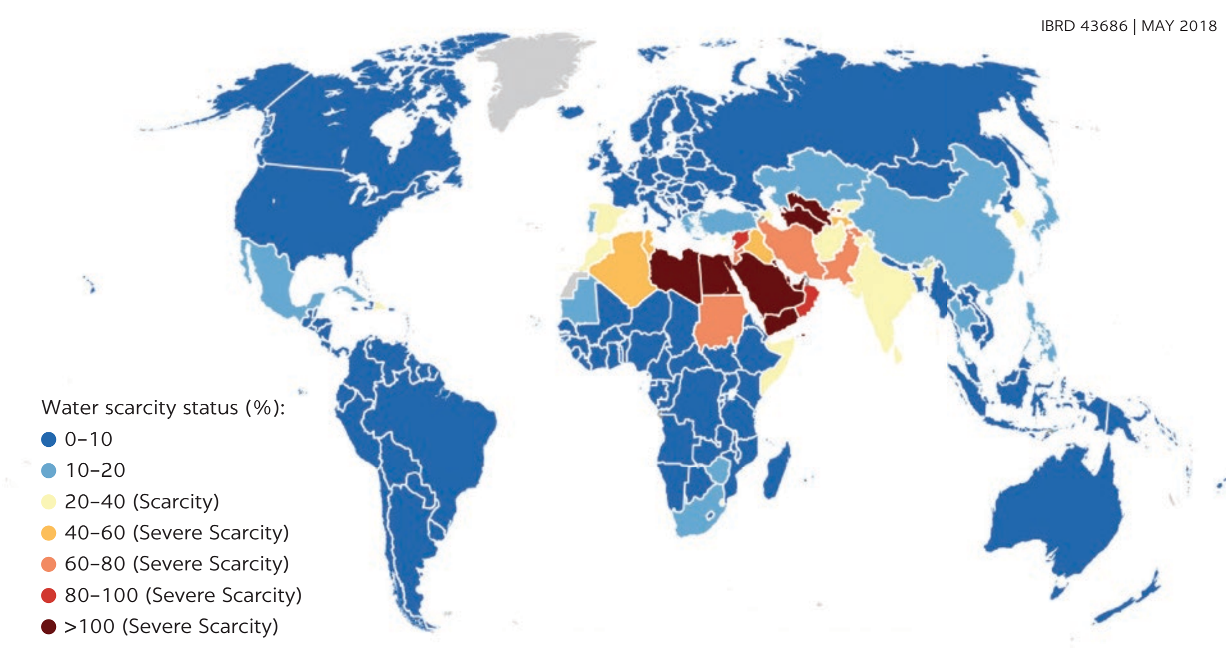
To illustrate the link between water scarcity and irrigated agriculture, we modify the indicator and, instead of total water withdrawals, compare agricultural water withdrawals to total renewable water resources. Map 2.2 shows the data for the modified indicator, again for 2013 or the latest year available.

The classification of countries with "scarcity" and "severe scarcity" is almost the same as in map 2.1, even though only agricultural withdrawals are considered. The details for the two water scarcity indicators—in terms of total withdrawals and agricultural withdrawals—are shown for each country in table A.1 in the appendix. Both the maps and the table illustrate the central role of irrigated agriculture in assessments of water scarcity at the national level. The most extreme cases are in the Middle East and North Africa in Saudi Arabia, water withdrawn for irrigated agriculture alone is more than eight times the amount of total renewable water resources; in Libya, it is about five times; in the Republic of Yemen one and a half times; and in the Arab Republic of Egypt slightly more than the amount of total renewable water resources.

Some caveats apply to both indicators. On the one hand, they may underestimate water scarcity. Because they refer to the national level and apply annual data, they do not indicate water scarcity situations that may occur at the regional or local levels—especially in large countries, such as the United States or China. They do not reflect the large intra-annual variations in water supply and demand (referred to in the section on the special water characteristics) that may lead to large variations in water scarcity within a year. They also do not consider water quality issues or water requirements for the environment, such as minimum flows in rivers. On the other hand, they may overestimate water scarcity, because

MAP 2.2

Agricultural Water Withdrawals as a Percent of Total Renewable Water Resources



Source: Scheierling and Tréguer 2016b, based on FAO 2016a.

withdrawal data include the reuse of return flows that can be substantial in many cases—such as along the Nile in Egypt, where return flows may be reused several times.

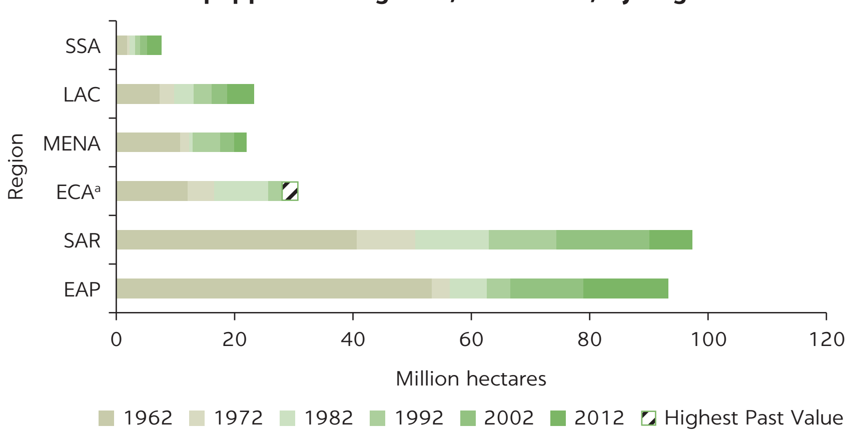
Trends in Area Equipped for Irrigation at the Regional Level. The available data on agricultural withdrawals do not allow for an analysis of how trends in agricultural water withdrawals have affected water scarcity over time at the global level. However, a look at historical data on area equipped for irrigation can provide some insights (FAO 2016b). Worldwide, the area equipped for irrigation almost doubled from 164 million hectares to 324 million hectares (ha) over a 50-year period. This represents an increase from 12 percent of the cultivated area in 1962 to 21 percent in 2012. Figure 2.4 shows the trends by geographical region (excluding high-income countries) from 1962 to 2012. Figure A.1 in the appendix also shows trends in cultivated area, and the percentage of the cultivated area that is equipped for irrigation, by geographical region and globally.

Among the regions, the largest expansion in the area equipped for irrigation since 1962 occurred in South Asia—followed by East Asia and the Pacific, the two regions that already had the largest irrigated areas in 1962. The only decline in the area equipped for irrigation has occurred in the Europe and Central Asia region since around the mid–1990s, mainly due to reductions in the countries of the former Soviet Union. As of 2012, South Asia was the region with the largest area equipped for irrigation (about 97 million hectares), and with the highest share of its cultivated area equipped for irrigation (46 percent). Sub-Saharan Africa has the lowest share with 4 percent, but it experienced the largest relative increase (by more than 400 percent) in area equipped for irrigation between 1962 and 2012.

At the country level, some of the largest expansions in percentage terms occurred in countries of the Middle East and North Africa. The highest percentage increase occurred in Saudi Arabia, with more than 430 percent (from 0.3 million ha to 1.6 million ha), followed by Libya with 300 percent (from 0.1 million

FIGURE 2.4

Trends in Area Equipped for Irrigation, 1962–2012, by Region



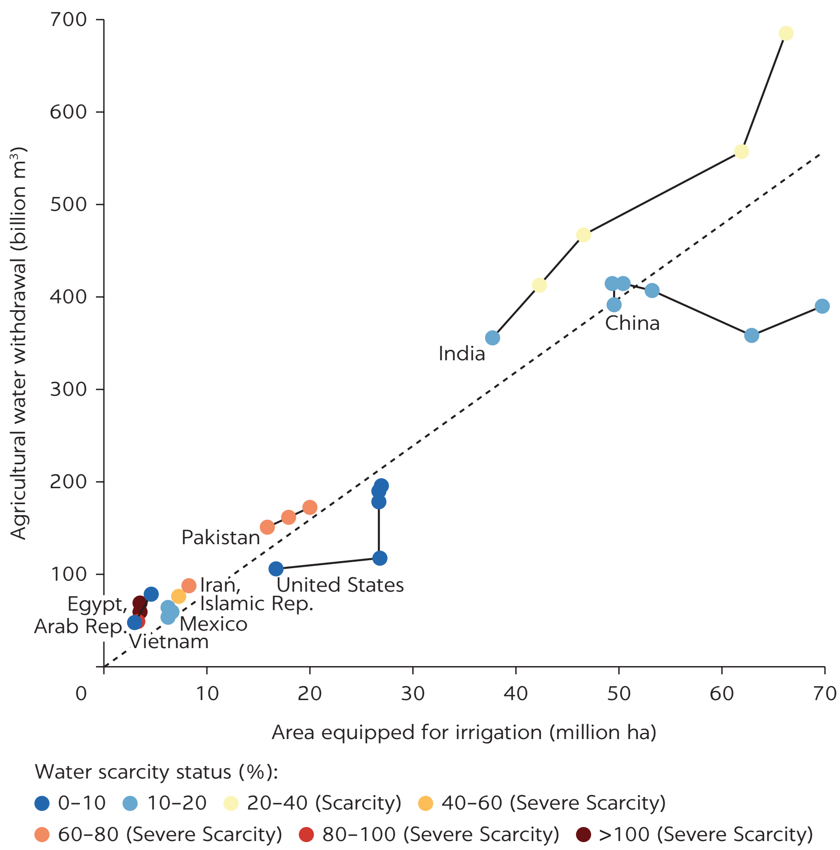
Source: Scheierling and Tréguer 2016a, based on FAO 2016b.
Note: SSA = Sub-Saharan Africa, LAC = Latin America and the Caribbean, MENA = Middle East and North Africa, ECA = Europe and Central Asia, SAR = South Asia Region, EAP = East Asia and Pacific.
a. Includes data for USSR/Russian Federation.

ha to 0.5 million ha) and the Republic of Yemen with 150 percent (from 0.2 million ha to 0.7 million ha). As mentioned in connection with map 2.2, the same three countries are now also experiencing the most severe levels of water scarcity. Large area increases, in both percentage and absolute terms, also occurred in India (from 26 million ha to 67 million ha), a country now considered water scarce, and in China (from 45 million ha to 68 million ha).

Trends in Agricultural Withdrawals, Area Equipped for Irrigation, and Scarcity Levels. Data from FAO (2016a, 2016b) allow a partial analysis, for a few countries, of the changes over time in agricultural withdrawals and area equipped for irrigation, and the related water scarcity status. Figure 2.5 exhibits the trends in these variables for some of the countries with the largest agricultural withdrawals[9] and figure 2.6 for a number of countries with smaller agricultural withdrawals. Each point in figures 2.5 and 2.6 represents a year for which data are available, with the color indicating the country's scarcity level.[10] The slope of a ray from the origin through a point represents the irrigation depth for that observation. The dotted lines in figures 2.5 and 2.6 indicate the average irrigation depth of about 0.8 meters worldwide (as in figure 2.3).

FIGURE 2.5

Trends in Agricultural Withdrawals and Area Equipped for Irrigation for Countries with the Largest Agricultural Withdrawals

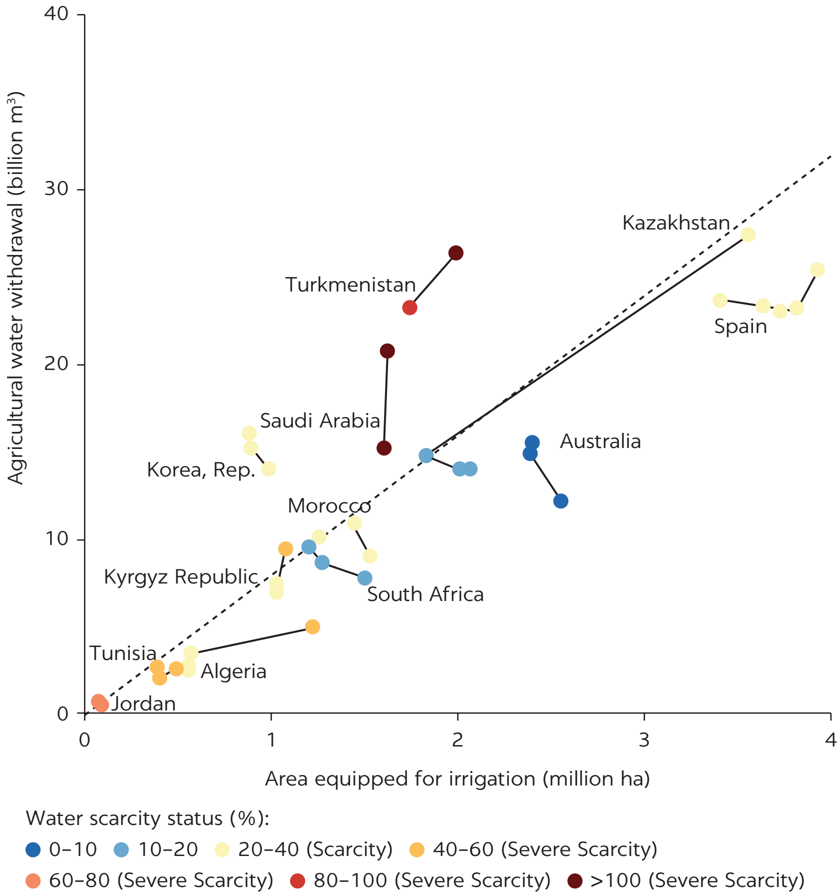


Source: Based on FAO 2016a, 2016b.

Note: India (1977, 1982, 1987, 2002, 2012); China (1982, 1987, 1992, 1997, 2007, 2017); United States (1977, 1982, 1992, 2002, 2007, 2012); Pakistan (1992, 2002, 2012); The Islamic Republic of Iran (1997, 2007); Vietnam (1992, 2007); The Arab Republic of Egypt (1997, 2002, 2012); Mexico (1997, 2002, 2007, 2012).

FIGURE 2.6

Trends in Agricultural Withdrawals and Area Equipped for Irrigation for Other Countries



Source: Based on FAO 2016a, 2016b.
Note: Turkmenistan (1997, 2007); Spain (1992, 1997, 2002, 2007, 2012); Saudi Arabia (1992, 2007); Kazakhstan (1997, 2002, 2007, 2012); The Republic of Korea (1992, 1997, 2002); Australia (1997, 2002, 2007); Morocco (1992, 2002, 2012); South Africa (1992, 1997, 2002); The Kyrgyz Republic (1997, 2007, 2012); Algeria (1992, 2002, 2012); Tunisia (1992, 2002, 2012); Jordan (1992, 2007).

Figures 2.5 and 2.6 suggest that countries are on diverging, and in some instances counterintuitive, paths. India and China are striking examples: the two countries with the largest agricultural withdrawals and area equipped for irrigation. While both countries substantially expanded the area equipped for irrigation over the past three or four decades, agricultural withdrawals increased concomitantly in India, but remained the same in China (and were slightly lower in 2017 than in 1982). The average irrigation depth in India was higher in 2012 than it was in 1977, while in China it significantly decreased.

Table 2.3 groups the countries according to the direction of their respective developments in agricultural withdrawals and area equipped for irrigation.

Most countries have continued to increase agricultural withdrawals and the area equipped for irrigation—including countries that already suffer from severe scarcity, such as Egypt, Turkmenistan, and Saudi Arabia. Based on the latest available data, they now withdraw more water for agriculture than their available renewable water resources (table A.1 in the appendix). The most extreme trends are found in Saudi Arabia, where the area equipped for irrigation expanded only slightly between 1992 and 2007, but agricultural withdrawals

TABLE 2.3 Trends in Agricultural Withdrawals and Area Equipped for Irrigation for Selected Countries

AGRICULTURAL WITHDRAWALS	AREA EQUIPPED FOR IRRIGATION	
	INCREASING	DECREASING
Increasing		
- Countries with largest withdrawals	India; Pakistan; Iran, Islamic Rep.; Mexico; Vietnam; Egypt, Arab Rep.	
- Other countries	Spain, Turkmenistan, Saudi Arabia, Algeria, Tunisia	Korea, Dem. People's Rep.
Decreasing		
- Countries with largest withdrawals	China	United States
- Other countries	Australia, Morocco, South Africa, Jordan	Kazakhstan, Kyrgyz Republic

Source: Based on FAO 2016a.

grew by about 40 percent. These examples suggest that even severe water scarcity does not necessarily lead countries to limit agricultural water withdrawals.

A few countries show a decrease in both agricultural withdrawals and the area equipped for irrigation. Among the countries with the largest agricultural withdrawals, the United States is the only one with relatively small decreases. Among the other countries, Kazakhstan and the Kyrgyz Republic show larger reductions in these variables; both countries experienced significant declines in the irrigation sector in the years following the breakup of the Soviet Union.

A number of countries showed decreasing trends in water withdrawals while the area equipped for irrigation continued to increase. Besides China, these include Australia, Morocco, South Africa, and Jordan. One factor that may have facilitated this development was the transition to more capital-intensive irrigation technologies. Some data on trends in the use of on-farm irrigation systems are available from FAO (2016a). A distinction is made between three main irrigation systems: surface irrigation,[11] sprinkler irrigation,[12] and localized irrigation.[13] Figures A.2 and A.3 in the appendix show the trends in the use of the different irrigation technologies as a share of the area equipped for irrigation, for the countries with the largest withdrawals and the other countries, respectively. All of the five countries show a move away from gravity irrigation toward more capital-intensive irrigation technologies, such as sprinklers and drip irrigation. Jordan and South Africa are furthest along in this conversion, with only about 18 percent of the area equipped for irrigation remaining under gravity irrigation in Jordan by 2007, and 23 percent in South Africa by 2012.

It would be of interest to analyze trends in crop per drop, yet country-level data on irrigated crops are not available. If "area equipped for irrigation" is used as a proxy for crop production output from the irrigated area and thus as a measure for "crops," and agricultural withdrawals as a measure for "drops," the slope of a ray from the origin through a particular point representing the irrigation depth in figures 2.5 and 2.6 could then be interpreted as the inverse of crop per drop. Trends toward more crop per drop would then be represented by a movement of the rays toward the lower left corner of the respective figure, such as in the case of South Africa from 1992 to 2002 (figure 2.6). However, it is important to keep in mind that crop per drop ratios do not necessarily provide any insight from a water scarcity viewpoint. For example, China's move from 2007 to 2017 was approximately along the same slope; yet agricultural water withdrawals increased by about 10 percent (or 34.2 billion m^3), a change that is masked by the constant crop per drop ratio.

There are some caveats—in particular with regard to water use—with respect to the trend analyses above. As in the case of the water scarcity indicators, the data refer to the national level and represent annual amounts; thus they may hide potentially large spatial and temporal variations. Also, even if a country shows a reduction in agricultural withdrawals resulting from a switch to more capital-intensive irrigation technologies—and possibly other interventions, this does not necessarily imply that the amount of water actually consumed by the crops is also reduced. It may be the case that just the withdrawals and the resulting return flows are reduced. If the area equipped for irrigation continues to increase, it is likely that water consumption increases concomitantly—and the effect on water scarcity may be negative, even though withdrawals may decline.

Projected Trends in Agricultural Water Use. Agricultural water use will continue to be a major factor shaping the water situation worldwide, particularly given the expected need for an increase in irrigated area as demand rises for agricultural products. Global projections vary depending on the models employed as well as the data, assumptions, and scenarios used. A review of recent projections on agricultural water use is found in OECD (2014), including an analysis of convergences and divergences. Among the most comprehensive studies were the projections by the FAO (Alexandratos and Bruinsma 2012). They indicate that to meet the likely demand, agricultural production in 2050 would have to be 60 percent higher than in 2005 and 2007, and irrigation water withdrawals would need to increase from 2,761 to 2,926 billion cubic meters per year. Considering the historical trends in global water use in figure 2.1 and the rapidly growing other water demands, especially from the municipal and environmental sectors, this projected increase—which is based on rather optimistic assumptions—is quite worrisome.

Projections become even direr—and more uncertain—when the effects of climate change are taken into account. Climate change will further increase the need for water-related adaptations in irrigated agriculture, and add layers of complexity for both irrigated and rainfed agriculture (Jiménez Cisneros et al. 2014; Pachauri and Reisinger 2007). Freshwater resources will be affected by the altered amounts and frequencies of precipitation—especially in semiarid and arid areas that often already experience water scarcity. With more intense precipitation and prolonged dry periods, rainfed cropland may need to be irrigated. Crop growth will more generally be affected, not only by changes in precipitation, but also by changes in temperature, soil moisture, evapotranspiration, and carbon concentration.

By the end of this century, according to projections (Elliott et al. 2014), total renewable water resources may still allow a net increase in irrigated agriculture in some regions, such as the northern and eastern United States, and in parts of South America and Southeast Asia. In other areas, such as the western United States, China, the Middle East and North Africa, and Central and South Asia, the previous expansion from rainfed to irrigated agriculture would need to be reversed.

NOTES

1. Total water withdrawals include the annual quantities of water withdrawn for agricultural, industrial, and municipal purposes. Agricultural water withdrawals include the annual quantities of water withdrawn for irrigation, livestock, and aquaculture purposes. In-stream uses, such as recreation, navigation, and hydropower are not considered (FAO 2016a).

2. Data on the area equipped for irrigation includes areas equipped for full and partial control irrigation, equipped lowland areas, pastures, and areas equipped for spate irrigation (FAO 2016b). The area equipped does not necessarily represent the area that is actually irrigated. However, the available data on the area actually irrigated are too limited to be included here.
3. The ten countries are also among the 17 most populous in the world (World Bank 2016).
4. Using a similar approach, a study by the International Monetary Fund found that population, GDP in purchasing power parity, and agricultural GDP are also highly correlated with total withdrawals (Kochhar et al. 2015).
5. Alternatively, the second graph in figure 2.2 shows that a 1 percent increase in total water withdrawals leads to a similar increase in agricultural water withdrawals (1.08 percent).
6. Alternatively, the second graph in figure 2.3 shows that a 1 percent increase in the area equipped for irrigation leads to a similar increase in agricultural water withdrawals (1.01 percent).
7. FAO (2016a) provides only withdrawal data at the country level—reported once, if at all, for a five-year interval.
8. Total renewable water resources comprise internal renewable water resources (specifically, the long-term average annual flow of rivers and recharge of aquifers generated from endogenous precipitation) and external renewable water resources (such as surface water and groundwater inflows from upstream countries).
9. The countries are the same as in table 2.2, except Indonesia and the Philippines.
10. The water scarcity level is in terms of agricultural withdrawals as a percent of total renewable water resources, as in map 2.2.
11. Surface irrigation systems are based on the principle of moving water over the land by gravity in order to moisten the soil. They can be subdivided into furrow, borderstrip, and basin irrigation (including submersion irrigation of rice). Manual irrigation using buckets or watering cans is also included.
12. A sprinkler (or overhead) irrigation system consists of a pipe network, through which water moves under pressure before being delivered to the crop via sprinkler nozzles. The system basically simulates rainfall in that water is applied through overhead spraying.
13. Localized irrigation (also called microirrigation, trickle irrigation, daily flow irrigation, drip irrigation, sip irrigation, or diurnal irrigation) is a system where the water is distributed under low pressure through a piped network, in a predetermined pattern, and applied as a small discharge to each plant or adjacent to it. There are three main categories: drip irrigation (where drip emitters are used to apply water slowly to the soil surface), spray or microsprinkler irrigation (where water is sprayed to the soil near individual plants or trees), and bubbler irrigation (where a small stream is applied to flood small basins or the soil adjacent to individual trees).

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3 Conceptual Issues: Efficiency and Productivity in Agricultural Water Use

This chapter discusses some of the key conceptual issues related to efficiency and productivity in agricultural water use. It highlights the key distinction between the definitions and use of the terms efficiency and productivity in the irrigation literature—dominated by approaches from engineering and agronomy—, and in the economics literature. The first section focuses on irrigation efficiency and water productivity as applied in the engineering and agronomy literature, and the second section on efficiency and productivity as applied in the economic literature. Chapter 4 will discuss methods and approaches that rely on the concepts and terms from engineering and agronomy, and others that rely on the concepts and terms from economics.

IRRIGATION EFFICIENCY AND WATER PRODUCTIVITY IN ENGINEERING AND AGRONOMY

Much of the public debate on the need to improve agricultural water productivity and efficiency to address water scarcity issues is based on concepts and terms from the irrigation literature (Scheierling, Tréguer, and Booker 2016). Studies in the irrigation literature originate from various disciplines—civil and irrigation engineering in particular, and agronomy and plant physiology—but are less likely to originate from economics.

Key Concepts and Terms. Water-related efficiency terms have dominated the discussion in the irrigation literature for many decades. They are closely related to the different measures of water use (table 2.1), and are formulated to take into account one of the special characteristics of water: that it is seldom completely "used up" or consumed in the course of irrigated agricultural production. Some key terms and their common definitions are presented in table 3.1.

Irrigation efficiency is a key term in irrigation engineering. In its classical definition, it refers to the ratio (in percent) of the water consumed relative to the water withdrawn or, in an alternative formulation, relative to water applied (Israelsen 1950; Jensen 2007). It aims to express the percentage of irrigation water that is efficiently used and the percentage that is "lost."

If irrigation efficiency is understood as the ratio of water consumed relative to water withdrawn, it can be subdivided into conveyance efficiency and water application efficiency. *Conveyance efficiency*—the ratio of the water delivered at the farm gate relative to the water withdrawn from a water source—represents the efficiency of water transport in canals. *Water application efficiency*—the ratio of the water stored in the root zone, and ultimately consumed, relative to the water delivered to the farm—represents the efficiency of water application on the farm. For example, if irrigation efficiency is estimated at 60 percent, the remaining 40 percent would constitute return flows (table 2.2). Alternatively, if irrigation efficiency refers to the ratio of water consumed relative to water applied, it would be the same as water application efficiency.

The efficiency ratios can have widely varying values (Brouwer et al. 1989). Water application efficiency may range from 40 percent for flood irrigation, and 60 percent for other surface irrigation systems, to about 75 percent for some types of sprinkler irrigation, and up to 90 percent and higher for drip irrigation. Conveyance efficiency mainly depends on the length of the canals, the soil type or permeability of the canal banks, and the condition of the canals. It may range from about 60 percent in long earthen canals in sandy soil up to 95 percent in lined canals (i.e., the conveyance loss would amount to between 5 percent and 40 percent).

Many variations of these terms with slightly different names and definitions can be found in the irrigation literature.[1] In the following discussion, the focus is on irrigation efficiency defined as the ratio of water consumed relative to water applied on the farm. Conveyance efficiency is referred to separately.

Water use efficiency is a term often used by agronomists and crop physiologists, and applied in different definitions—such as the ratio of plant biomass, or yield, relative to transpiration or water consumed (Hsiao, Steduto, and Fereres 2007). If applied as the ratio of yield to water consumed, it is equivalent to one of the definitions of water productivity and a version of crop per drop.

Water productivity is a more recent term, and has only become more widely used after Seckler—who at the time headed the International Water Management Institute (IWMI)[2]—pointed out that under increasing water scarcity, local improvements in irrigation efficiency—for example, by switching to more capital-intensive irrigation technologies at the farm level—may not necessarily lead to real water savings available for reallocations, or necessarily translate into basin-wide efficiency gains (Seckler 1996). He recommended a focus on water productivity in irrigated agriculture instead—but did not define the term further.

Other authors, many associated with IWMI, subsequently provided definitions, often along the lines of *crop per drop* (Molden 1997; Molden and Oweis 2007; Molden and Sakthivadivel 1999; Molden et al. 2003). These, in turn, were further refined and applied in numerous studies (Giordano et al. 2017).

Water productivity as a crop per drop ratio can be defined as a yield relative to water withdrawn, applied, or consumed. If defined as yield relative to water consumed, it could be the same as water use efficiency in one of its definitions. Water productivity is usually expressed as yield in relation to one of the measures of water use for the case of a particular crop at the field or farm level. If water productivity is estimated for more than one crop at the farm level, for example, output prices are often used for aggregation, and water productivity is expressed in so-called “economic” terms.

Focus on a Single Factor. The efficiency and productivity terms from the irrigation literature presented in table 3.1 focus on a single factor: water. That is, they do not explicitly incorporate any additional factors, such as other inputs to the production process, or environmental factors that may also affect the different ratios. Furthermore, the terms are physical expressions that do not consider prices of outputs and inputs that may influence farmers' behavior with regard to water use and many other variables. The "economic value" definition of water productivity includes output prices, yet only for aggregation purposes.

Focus on Farm-Level Effects. The terms are mainly focused on the field or farm level because of their concern for the efficiency and productivity with which a certain supply of water is used for crop production (considering the remainder as "lost"). Basin-wide issues receive insufficient recognition, including the interdependencies between up- and downstream users that are of increasing importance in a maturing water economy, and come about through the "losses" (not only in terms of quantity, but also quality and timing).

The farm-level focus is further illustrated below, involving a switch to more capital-intensive irrigation technology with higher on-farm irrigation efficiency. Such a transition is frequently promoted as an important approach for making agricultural water use more productive and efficient (as defined in table 3.1), and contributing to adaptation in the face of increasing scarcity of and competition for water. But that is not necessarily the case, especially in a hydrologic setting where return flows matter to downstream users.

In figure 3.1, on-farm irrigation efficiency improves as a result of the switch from a gravity system to a sprinkler system.[3] The role of other inputs is neglected, as is the influence of prices and costs. The farmer is assumed to have the knowledge and ability to fully achieve the increased level of irrigation efficiency made possible by the new technology. Water productivity is measured as a ratio of yield related to the water input. Depending on which measure of water use is considered for the water input—such as water withdrawn, water applied, or water consumed—the crop per drop ratios and their respective changes as a result of the efficiency improvements may differ, and may provide conflicting messages about water use and the basin-wide effects.

TABLE 3.1 Water-Related Terms of Efficiency and Productivity from Engineering and Agronomy

TERM	DEFINITION	DISCIPLINE
Classical irrigation efficiency	Ratio of the water consumed relative to the water withdrawn from a source or applied (Israelsen 1950; Jensen 2007)	Irrigation engineering
Conveyance efficiency	Ratio of the water delivered at the farm gate relative to the water withdrawn from the water source (Jensen 2007)	Civil engineering
Water application efficiency	Ratio of the water stored in the root zone (and ultimately consumed) relative to the water delivered to/applied on the farm (Jensen 2007)	Irrigation engineering
Water use efficiency	Ratio of the plant biomass or yield relative to transpiration or consumptive use (Hsiao, Steduto, and Fereres 2007; Molden 1997)	Agronomy and plant physiology
Water productivity	Ratio of physical production (in yield) or so-called "economic value" of production (usually in terms of revenue), relative to water use (in terms of water withdrawn, applied, or consumed) (Molden 1997)	Agronomy and plant physiology

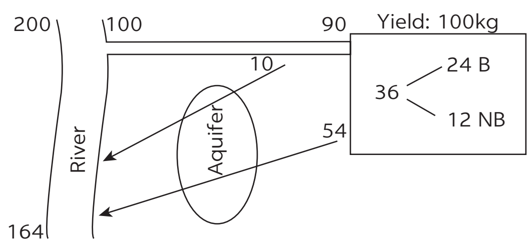
Source: Scheierling, Tréguer, and Booker 2016.

Figure 3.1 assumes that an irrigated area initially produces 100 kg of a particular crop. Water is withdrawn from a river and delivered to the area via a canal. The conveyance efficiency is about 90 percent, with 10 percent of the water withdrawn from a river lost to seepage in the canal. Conveyance losses and other water not consumed on-farm are assumed to move back to the river via a shallow aquifer as return flows. In case i, the original on-farm irrigation efficiency, defined as the ratio of water consumed relative to water applied, is 40 percent. Water consumption amounts to 36 m^3, composed of 24 m^3 of beneficial consumption (which is necessary for plant growth) and 12 m^3 of nonbeneficial consumption (which may comprise, for example, evaporation from soil surfaces). Thus, 90 m^3 of water would have to be applied to the irrigated

FIGURE 3.1

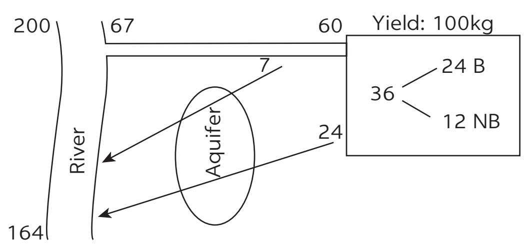
Effects of Improved On-Farm Irrigation Efficiency on Crop per Drop Ratios and River Flow

Case i: 40 percent irrigation efficiency



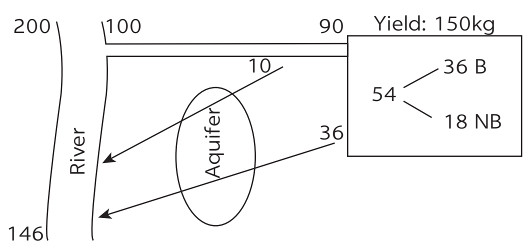
	WATER MEASURE (m^3)	CROP PER DROP (kg/m^3)
Water		
Withdrawn	100	1.0
Applied	90	1.1
Consumed	36	2.8

Case ii: 60 percent irrigation efficiency, no water spreading



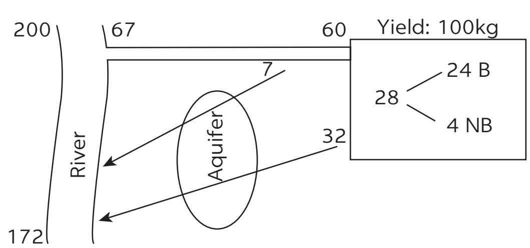
	WATER MEASURE (m^3)	CROP PER DROP (kg/m^3)
Water		
Withdrawn	67	1.5
Applied	60	1.8
Consumed	36	2.8

Case iii: 60 percent irrigation efficiency, water spreading



	WATER MEASURE (m^3)	CROP PER DROP (kg/m^3)
Water		
Withdrawn	100	1.5
Applied	90	1.7
Consumed	54	2.8

Case iv: 60 percent irrigation efficiency, no water spreading, reduction of nonbeneficial consumptive use (NB) by 66 percent



	WATER MEASURE (m^3)	CROP PER DROP (kg/m^3)
Water		
Withdrawn	67	1.5
Applied	60	1.7
Consumed	28	3.6

Source: Scheierling, Tréguer, and Booker 2016.

area, and 100 m^3 withdrawn from the river. Depending on the underlying water measure in the crop per drop ratio, the values for agricultural water productivity range from 1.0 to 2.8.

Case ii shows the effects of an improvement in on-farm irrigation efficiency from 40 percent to 60 percent. If everything else stays the same, water application could be reduced from 90 m^3 to 60 m^3, and withdrawals from 100 m^3 to 67 m^3. The respective crop per drop values increase significantly. Yet because water consumption does not change,[4] the value for agricultural water productivity in terms of water consumed would stay the same. Even though it seems that water was conserved as a result of the intervention (with significant reductions in water withdrawn and applied), there was actually no water conservation in terms of water consumed, with the river flow downstream of the irrigated area remaining at the same level as before.

Case iii presents the situation where the farmer, after switching to a higher on-farm irrigation efficiency, would continue to withdraw the original amount of water and spread it over an expanded area. Yield would increase to 150 kg, and water consumption to 54 m^3. The values for agricultural water productivity would be the same as in case (ii), yet the river flow downstream is reduced from 164 m^3 to 146 m^3.

In case iv, additional interventions beyond the increase in irrigation efficiency (such as improved agronomic practices) are made to generate higher return flows from the farm than in case ii, while not affecting yields. The beneficial consumption of 24 m^3 necessary for crop growth remains the same as in the cases i and ii, but the nonbeneficial consumption is reduced by two thirds—from 12 m^3 to 4 m^3—as a result of the additional interventions. The additional return flows amount to 8 m^3. The crop per drop values for water withdrawn and water applied are the same as in cases i and ii, but the crop per drop value for water consumed increases.

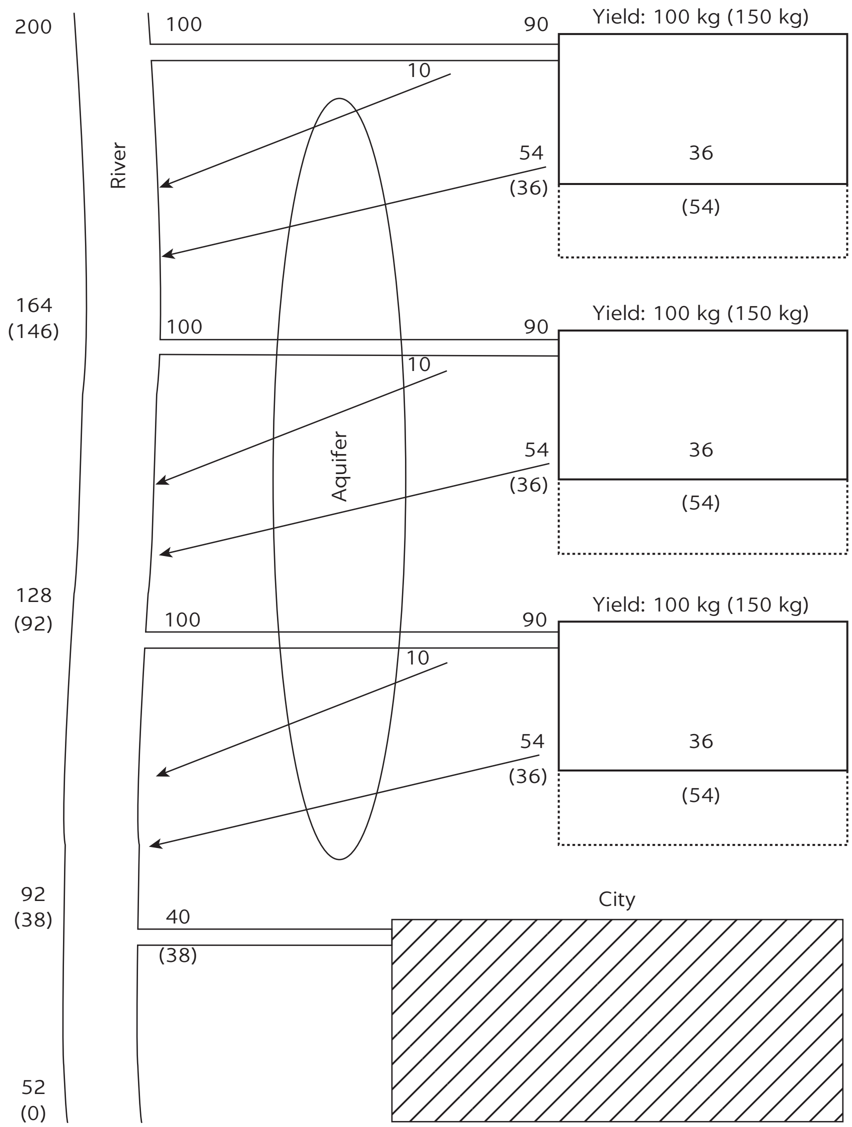
In an expansionary water economy with minimal competition for water, the changes resulting from the improved irrigation efficiency would likely matter relatively little beyond the farm level. For example, if no water production or consumption activities are taking place downstream, the decline in return flows from water spreading in case ii, or increase from the reduction in nonbeneficial consumption in case iv, would not affect the river flow much. However, the situation would drastically change in a mature water economy, where many additional users may be located downstream and depend on the water from the river—including the return flows from the upstream user. In that case, the additional return flows generated with the interventions in case iv would really represent conserved water for additional uses downstream.

Basin-Level Effects. Figure 3.2 shows a basin-level situation with the same river and several users downstream. This includes two additional irrigated areas with features similar to the original irrigated area in figure 3.1, and a city requiring 40 m^3 of water consumption.

Initially, as in case i, the three irrigated areas operate with an on-farm irrigation efficiency of 40 percent, with each producing a yield of 100 kg. Under these circumstances, the city can be supplied with the necessary water of 40 m^3, and the river flow downstream amounts to 52 m^3, which would be considered sufficient for environmental purposes. If the irrigated areas switch to an on-farm irrigation efficiency of 60 percent, as in case iii, and continue to withdraw the same water amounts (because the water rights are formulated in terms of withdrawals, for example), they can spread the water on more land and increase their combined yield from 300 kg to 450 kg (shown in parentheses in figure 3.2). However, the return flows from the irrigated areas would decrease, and the city would now have water problems. Even if the city withdrew all the water left in the river, it would only receive 38 m^3. In such a situation, negotiations between upstream and downstream users may help to resolve the problem. The city could, for example, subsidize the farmers in the irrigated areas to adopt additional agronomic measures to reduce nonbeneficial consumption by two-thirds. This would guarantee the city's water needs, but the environmental uses further downstream might still be negatively affected.

FIGURE 3.2

Basin-Wide Effects of an Increase in On-Farm Irrigation Efficiency from 40 Percent to 60 Percent



Source: Scheierling, Tréguer, and Booker 2016.
Note: The effects of water spreading are indicated in parentheses.

Accounting for the Hydrologic Setting. The cases in figures 3.1 and 3.2 are based on the assumption of a shallow aquifer that allows all conveyance and on-farm water "losses" to come back to the river as return flows, and are thus available for further use. In a mature water economy, water conservation would then need to take the basin-level view and focus on reducing consumptive use, as in case iv in figure 3.1.

However, depending on the hydrologic setting, not all return flows may become available for further use downstream. There may be hydrologic settings where flows return only partially, or not at all, to the river. They may be lost to sinks from which they can no longer be withdrawn or used because of quality issues. For example, when an irrigated area is located close to the ocean, the return flows may not be recoverable. Other hydrologic settings may also not allow the further use of return flows, such as when the underlying soils and aquifers are too saline or polluted for reuse. Another situation could be when the water source is not a river but a very deep, fossil aquifer that the return flows may never reach, or reach only after many decades.

In hydrologic settings where return flows are indeed lost—i.e., not available or recoverable for further use—water conservation could take the field- or farm-level view. Interventions could then focus on improving irrigation efficiency (conveyance and water application efficiency) and make as much use consumptively of the available withdrawal and application amounts as possible. This could involve, for example, a move from case i to case iii in figure 3.1 with water spreading, which now would keep the river flow constant at 100; or a move from case i to case iv with a reduction of nonbeneficial consumptive use—yet now combined with further water spreading—which would again keep the river flow at 100. Alternatively, if water needs to be conserved and made available for other downstream uses, withdrawal and application amounts could be reduced up to the minimum level that still guarantees the historical consumptive use, by moving from case i to case ii, which would now increase the river flow from 100 to 133. Additional interventions for reducing nonbeneficial consumptive use levels, as in case iv, would not contribute to further water conservation.

EFFICIENCY AND PRODUCTIVITY IN ECONOMICS

This section reviews the key concepts of efficiency and productivity from the economics literature. Compared with the irrigation literature, the approaches in economics allow for a broader consideration of the sources of changes in productivity. Prices and costs are incorporated, and efforts are made to consider not just one, but all inputs influencing output levels. In the case of water, the focus has been on the two key measures of water use that tend to be under the control of the farmer or irrigation agency: withdrawals from a water source and water applications at the farm level, sometimes without making a precise distinction. More recently, advances in modeling coupled with data from remote sensing have allowed progress in incorporating the third measure of water: consumptive use.

Key Concepts and Terms. In the economics literature, particularly in agricultural production economics, productivity and efficiency are defined differently than in engineering and agronomy. The *productivity* of a firm is defined as the ratio of its output to its input, and the *efficiency* is a comparison between observed and optimal values of its output and input (Fried, Knox Lovell, and Schmidt 2007).

Productivity is widely used as a performance measure where larger values of the ratio are associated with better performance. It can be simply measured as a single-factor productivity indicator, relating one output to one input. An example of such an indicator is crop per drop. The more comprehensive measure of total factor productivity is a ratio that relates the aggregate of all outputs to the aggregate of all inputs.

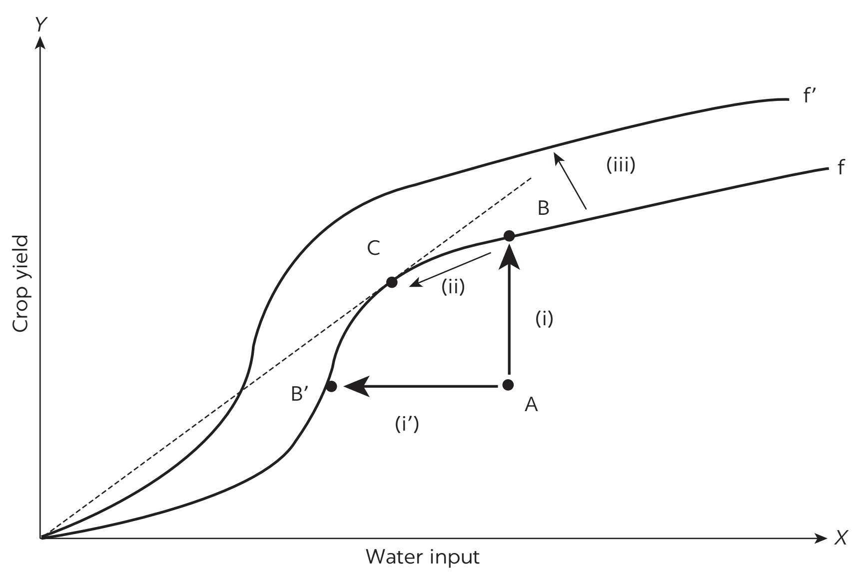
Potential productivity improvement can be assessed when firms are compared to a benchmark: with cross-sectional data, firms are compared with each other in the same period, while time-series data allow comparisons over time. In the former case, a firm can increase its productivity relative to other firms by improving its technical efficiency, allocative efficiency, or scale efficiency. In the latter case, technological change is an additional source of productivity growth; it involves an upward shift of the production function, implying that a firm can produce more output for each level of input (Latruffe 2010).

To illustrate the different sources of productivity increases, figure 3.3 shows a single input–single output case (Y= f [X]), with X representing the water input, Y crop yield, and f the production frontier. Initially the firm operates at point A.

Productivity may improve through (a) increased *technical efficiency*, i.e., the same level of output is produced with less input (a move from point A toward point B'), or more output is produced with the same level of input (a move from point A toward point B), which in both cases involves a move toward the production frontier; (b) *economies of scale*, i.e., operating at the point of (technically) optimal scale where the ray from the origin is a tangent to the production frontier (a move from point B to point C); and (c) *technological change*, which may be represented by an upward shift in the production function (a move from f to f'). If prices (and a behavioral assumption) are also included in the analysis, *allocative efficiency* as another source of productivity change can be considered.

FIGURE 3.3

Sources of Improvements in Productivity



Source: Based on Coelli et al. 2005.

In input selection, this would involve selecting that mix of inputs that provides a given quantity of output at a minimum cost.

A ray through the origin in figure 3.3 has the slope y/x and thus provides a measure of average productivity, as in the measure crop per drop. More crop per drop could be achieved by any of the moves described above. Thus, even in the single input–single output case, an increase in that ratio could be the result of different sources, and be associated with less or more water use; without further analysis, these underlying causes would not be obvious (Scheierling, Tréguer, and Booker 2016).

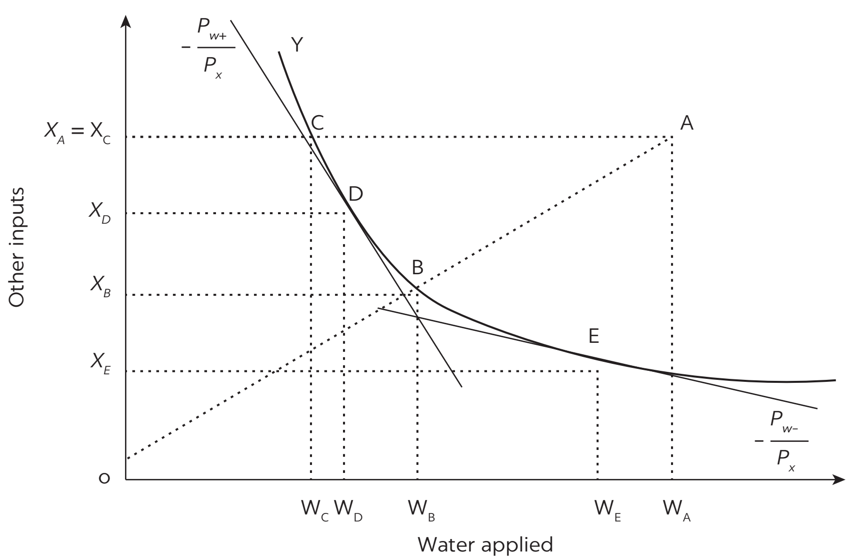
Beyond a Single-Factor Framework. Figure 3.4 illustrates a situation when more than one input is considered in the production of an output. It also allows for a discussion of the concepts of technical and allocative efficiency. It represents the situation where a farmer, originally at point A, produces a given crop in the quantity Y by applying irrigation water in the amount of W_A (with a traditional technology, say a gravity system) and all other inputs in the amount of X_A.[5]

Following Karagiannis (Karagiannis, Tzouvelekas, and Xepapadeas 2003), the *water-specific technical efficiency* is measured by the ratio of two distances, $X_A C/X_A A = W_C/W_A$. This measure determines the minimum amount of water applied (W_C), and also the maximum potential reduction in water applied ($W_A - W_C$) that would still allow the production of Y while keeping the other inputs at X_A. *Input-oriented technical efficiency* would imply a move to point B where the quantity of water applied would decrease to W_B. This potential reduction ($W_A - W_B$) is smaller than ($W_A - W_C$), with the latter considered as an upper bound.

Taking into account the prices of inputs, the farmer could strive to be *efficient from an allocative point of view*, reaching a level of water applied of W_E or W_D (with $W_E > W_D$) depending on the price of water, P_{W-} or P_{W+} (with $P_{W-} < P_{W+}$), respectively.

FIGURE 3.4

Effects of Water-Specific Technical Efficiency, Input-Oriented Technical Efficiency, and Allocative Efficiency on Water Applied and Other Input Use



More generally, points such as D and E represent an allocatively efficient use of water and other inputs contingent on the ratio of the prices of water and the other inputs. According to standard production theory, least cost production of outputs Y is achieved when the ratio of the marginal products of water and the other inputs equals their price ratio $(MP_W/MP_X) = (P_W/P_X)$ for any point (or combination of inputs) on the isoquant, with P_W and P_X giving the full opportunity costs of using water and the other inputs, respectively. The marginal product of water can then be written as $MP_W = (P_W/P_X)\ MP_X$. This implies that a measure for agricultural water productivity, when expressed not as an average product as in "crop per drop" but as a marginal product, should be expected to be high when the price of water is high, the cost of other inputs is low, and the marginal product of the other inputs is high.

Beyond Farm-Level Effects. It is important to note that the focus in figure 3.4 is on the farm level—with the consideration of water applied and a neglect of return flow issues. Yet basin-wide issues can be taken into account in the multi-factor framework. In the case of the situation in figure 3.4, the farmer in point A would produce the same quantity Y as after the move to a point on the production frontier. In all these cases, the quantity of water consumed would remain constant. Only the quantity of water applied and the resulting return flows would change, whereas the river flow would remain the same. The situation would become different in the case, for example, of technological change, when the production function would move and a higher quantity of output could be produced with the same amount of inputs. This would lead to an increase in consumptive use and a reduction in return flows.

NOTES

1. For example, water application efficiency may refer not to the farm, but the field level—and is then often termed field application efficiency (Brouwer et al. 1989).
2. It was then known as the International Irrigation Management Institute (IIMI).
3. Similar illustrations were presented in Hartmann and Seastone 1965, Huffaker and Whittlesey 1995, and Huffaker and Whittlesey, 2003 though without a focus on ratios of agricultural water productivity. The numbers used in the illustrations are not intended to represent a real-world irrigated area or river basin.
4. Water consumption is closely related to crop yield. With constant crop yield in case ii, a constant level of water consumption is assumed, regardless of the level of water application. This assumption is also made in the cases that follow.
5. Other inputs, denoted as X in figure 3.4, are assumed to be a composite of all the other inputs except water that can be modified by the farmer in the short run, typically during a cropping season. The level of capital used, including the type of irrigation technology, is assumed to be constant during this timeframe.

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4 Methods for Assessing Agricultural Water Productivity and Efficiency

In a situation with readily available water supplies and minimal competition for water, investments are mostly focused on infrastructure projects for expanding agricultural water supplies, and the main method for assessing the choice and implementation of such investments is benefit-cost analysis (table 1.1). Benefit-cost analysis was developed in the United States during the 1930s, when federal support for large-scale irrigation and other water projects increased rapidly, with the aim to ensure that the new funds were spent properly. In discussing the economics of project evaluation for water resource development, Eckstein (1958) treated benefit-cost analysis as a means of testing the quality of a project and of selecting the most desirable projects from the point of view of economic efficiency. The focus was on the internal rate of return, ensuring that scarce capital was used most efficiently—without particular consideration of the water resource.

With increasing competition for water, benefit-cost analysis becomes more challenging. Assessments need to rely on methods that can more explicitly incorporate water. The first section of this chapter analyzes the main methods, distinguishing between four groups: single-factor productivity measures, total factor productivity indices, frontier methods, and deductive methods. We review the various approaches and present key findings. Given the extensive literature on each of these methods, our presentation does not attempt to be exhaustive. The second section provides more systematic insights into the methods by comparing them by key features considered to be important for our analysis. This comparison provides the background for the next chapter with a broader assessment of the applications of the methods in a maturing water economy.

ANALYSIS OF THE METHODS

The analysis of the four main methods is based on a systematic literature review carried out in the relevant fields (Giordano et al. 2017; Scheierling, Tréguer, and Booker 2016; Scheierling and Tréguer 2016). Each of the methods and its related approaches are discussed, highlighting selected studies, and key findings presented.

Single-Factor Productivity Measures

The body of literature on single-factor productivity measures is vast and probably larger than for any other method. The studies originate mainly from civil and irrigation engineering, and agronomy and plant physiology, and are mostly found in the irrigation literature. The origin of water productivity measures can be traced to Seckler (1996). Other authors, many associated with the International Water Management Institute (IWMI), subsequently provided definitions, often along the lines of crop per drop (Molden 1997; Molden and Oweis 2007; Molden and Sakthivadivel 1999; Molden et al. 2003), which were further refined and applied in numerous studies.

Review of Approaches. Single-factor productivity measures are ratios or indices that relate output to only one input. Applied to agricultural water productivity, the ratios usually refer to agricultural output per unit volume of water (table 3.1). Probably the most common measures are ratios with the numerator in physical terms, or in terms of revenue (the physical expression of the output multiplied by the output price). Much less frequently applied are measures in terms of returns over variable cost, or in terms of net income. Accounting-based measures are a special case. These are further discussed below.

Measures in Physical Terms. In its basic form, physical agricultural water productivity relates annual output per unit land area to the annual water input per unit land area. The numerator is usually expressed as physical mass of production, such as biomass or crop yield (in kg/m^3) (Giordano et al. 2017; Molden 2007). The denominator, water input, is usually expressed as one of the three measures of water use: water withdrawn, water applied, or water consumed (table 2.1). At the field level, water applied is often used; at the farm level, water consumed can be of interest, while water withdrawn is an important water measure at the irrigation scheme level. Thus, the denominator tends to be chosen depending on the purpose of the study, the spatial and temporal scale of interest, and data availability.

Traditionally, single-factor productivity measures in terms of crop yield and water use have been applied by agronomists for field experiments at experimental stations and farmer fields. Such studies typically try to control for other relevant inputs, and are often carried out across multiple years to be able to account for climatic variations (see, for example, Oweis, Hachum, and Kijne 1999; Oweis and Hachum 2003). The only input "variable" is the irrigation water which can then be quite precisely related to the varying output of a particular crop. Such studies tend to be time- and resource-intensive, and their results cannot be easily extrapolated to other conditions.

However, many other studies compare measures in physical terms not only using field experiment data at a particular location, but also observations across widely varying locations—usually with a focus on the yield of a major crop such as wheat. Comparisons have been made for crops in a particular irrigation scheme, across basins and countries, and even on a global scale. The aim was often to identify critical factors and thus to articulate recommendations for policy reform and interventions to "close the gap" in the water productivity findings. Substantial differences in spatial and temporal water productivities have been documented, depending on the particular ratio chosen but also with the same definition of the ratio (e.g., Sakhthivadivel et al. 1999). Many authors use such findings to argue that a large scope exists to improve water productivity and thus to increase yields or save water. The identified policy implications tend to be wide-reaching, and often not supported with robust evidence from the analyses carried out. A few authors, such as Cai et al. (2010), have rightly pointed out that the ratios are affected by many factors, including natural and management conditions—and that comparisons of ratios within and across production systems and the related interpretations need to take this context into account.

Observed data have also been supplemented with estimates generated with various methods, including modeling and remote sensing. An example for a combination of measured data with an agrohydrological model to estimate physical crop water productivities is Vazifedoust et al. (2008). They applied the soil water atmosphere plant (SWAP) model calibrated with farmers' field data to an irrigation district in the Islamic Republic of Iran. Other studies combined agrohydrological modeling with remote sensing and geographical information systems (GIS) data to assess water productivity at larger scales. For example, Singh et al. (2006) used the SWAP model together with geographical and satellite data to calculate agricultural water productivity in a district in India using different definitions.

Some studies modeled crop water productivities on a global scale. Zwart et al. (2010) focused on wheat and, based on input data sets derived from remote sensing, developed a model for mapping water productivity (WATPRO) in terms of estimated yield over water consumed. In an application of the model on a global scale, they find large variations in the water productivity measures. In their opinion, the model results facilitate the planning of food production in relation to limited water resources for agriculture. An updated WATPRO model was used by Bastiaanssen and Steduto (2017) to develop global maps of water productivity for wheat, rice, and maize based on estimates of yield and water consumed. To facilitate comparisons, they adjusted for crop types, climate, and local production potential, and reasoned that the differences not explainable by physical factors may be associated with on-farm decision making.

A combination of remote sensing data, farmer surveys, and field measurements was applied in an innovative multiyear effort to examine the impact of the adoption of "resource conservation" technologies (laser leveling of fields and zero tillage) on water use at the field, farm, and irrigation system level in a rice-wheat copping system in Punjab Province (Ahmad et al. 2007a, 2007b; Ahmad, Masih, and Giordano 2014). Factors influencing the adoption were increased yields and reduced input costs. Water applications also decreased. As the authors point out, whether this translates into reductions in water consumption and real water savings at the larger scales depends on the context, including the water balance and the broader hydrologic system, and the institutional arrangements affecting farmers' adjustments. In this case, the increased profitability allowed many farmers—in particular medium- and large-scale farmers with better access to fallow land and the necessary machinery—to expand the cultivated area or increase cropping intensity. In fresh groundwater areas, farmers improved application efficiency of (regulated) canal water and, at the same time, increased (unregulated) groundwater abstraction from the region's permeable aquifer, and overall water consumption increased substantially. While all farmers benefitted, the medium- and large-scale farmers received a disproportionate share of the benefits. Overall, improvements in field-scale water productivity (in terms of yield and income per unit of water application) did not result in reduced water use (in terms of consumptive use) at the farm or larger scales—the opposite was the result. This research is among the very few that empirically shows the rebound effect.

Measures in Revenue Terms. Some studies have used revenue in the numerator (e.g., Cai et al. 2010). This involves the use of market (or other) prices to transform the physically-based measure into an economic measure which begins to capture the value to the producer or society from the specific crop production. Measures in revenue terms also allow to account for multiple outputs on a farm or in an irrigation system, and to compare irrigated production of different crops in different locations. However, similar to the measures in physical terms, they do not consider the other inputs, which in some contexts may be as important or even more important than water. While output prices are included, the related costs for producing the output are not taken into account.

Measures in Terms of Returns over Variable Cost. Single-factor productivity measures may not only attempt to capture the revenue of crop output, but also the costs for the inputs. Such measures are used less commonly in the single-factor productivity literature. Yet they can explicitly account for the widely differing input requirements (e.g., labor or fertilizer) of different crops. When only explicit payments (i.e., for purchased inputs) are included as costs, the resulting estimate is a measure in terms of returns over variable cost.

Measures in Terms of Net Income. If only variable costs are included, the inputs that—similarly to the water input in many contexts—are not regularly purchased on competitive markets but are "owned" by the firm are not taken into account. However, they are a critical part of fully accounting for opportunity costs (Young 2005). When "shadow" or implicit values of the owned inputs (e.g., land, equity capital, entrepreneurial and management skills) are incorporated in the estimation, the resulting measure is in terms of net income. The opportunity cost of an owned input is the foregone benefit in the best alternative use. If the input is to some degree marketed, the prevailing or expected market price can be considered an appropriate measure of opportunity cost. Under certain conditions, if prices for all owned inputs except water can be assigned, the resulting residual can be considered the net return to, or economic value of, water. These values, if commensurable in terms of place, form, and time, can be used for comparison among uses, including for water allocation choices. If properly calculated, measures in terms of net income are the same as those developed from crop budgets that serve as a key input into many deductive methods applied in irrigation water economics—though in that literature they are usually not discussed as a way to estimate productivity measures. Productivity measures in these terms are often recommended as more preferable than physical measures or measures based only on revenues (see, for example, Kijne, Barker, and Molden 2003). Possibly due to the relatively intensive data collection requirements, the measures have so far not been much used.

Accounting-Based Measures. Accounting-based measures are not built on water-crop production functions but rather use macro-level data at the national level for estimating water productivity. For the numerator gross domestic product (GDP) or a variant is used. The denominator is expressed in total freshwater withdrawal based on data from FAO (2016). Different accounting-based measures can be formulated. For example, the World Development Indicators (WDI) database from the World Bank reports on the indicator "water productivity" in terms of constant US$ GDP per cubic meter of total freshwater withdrawal. It measures the water intensity of economic activity and can be useful in monitoring how a given economy uses water over time. The global average of this indicator was $18/m^3 in 2014, with a very wide distribution (e.g., from $1/m^3 in Afghanistan to $1,481/m^3 in Singapore). Caution should thus be applied in conducting cross-country comparisons, as the indicator captures very different country circumstances, both for the numerator and the denominator.

An adaptation of this economy-wide indicator to agriculture would be to measure "agricultural water productivity," defined as agricultural GDP divided by agricultural withdrawals. However, this indicator would measure the economic activity of both rainfed and irrigated agriculture for the numerator—but the denominator would only relate to irrigated agriculture. For countries with a large share of rainfed agriculture, changes in the level of this indicator would to a large extent reflect factors such as variations in climate variables affecting agricultural production.

An alternative indicator could be created by restricting "agricultural water productivity" to irrigated agriculture. The indicator would thus be defined as GDP in the irrigated agriculture divided by agricultural freshwater withdrawals. For a given country, this indicator could track over time the water intensity (in terms of agricultural withdrawals) of the irrigated portion of agricultural production, and capture major shifts in the irrigation sector. However, currently there is a lack of data on the GDP originating from irrigated agriculture.

Key Findings. Single-factor productivity measures applied to agricultural water productivity are ratios or indices that relate agricultural output to only the water input. They do not attempt to incorporate other inputs or environmental factors that may play a role in the production process—but they are influenced by the intensity and timing of the use in these other factors without being able to directly account for them. They are not explicitly based on productivity concepts, and cannot reveal the different sources of productivity improvements.

However, being water-focused, single-factor productivity studies excel in taking into account the different measures of water quantity, and are flexible in considering the appropriate scale of analysis. They can also be used dynamically to assess the effects of changes, such as of farmers' on-farm activities due to a change in policy or another intervention.

More recent studies that combine water productivity ratios with other data, including from measurements, modeling, and remote sensing, can provide important insights, especially when they are carried out in combination with suitable water accounting frameworks (Chalmers, Godfrey, and Potter 2012; Escriva-Bou et al. 2016).

While some studies estimating single-factor productivity measures do not clarify which objective they target, in principle they can pursue any of the three major ones: production growth, agricultural net incomes, and water conservation. The implicit focus is often on increasing agricultural production. Yet, not least since the original impetus for promoting the concept of agricultural water productivity in the irrigation literature was the concern about increasing water scarcity and how to ensure that real water savings on a basin scale are achieved, many studies explicitly pursue the water conservation objective.

Single-factor productivity measures on their own are not suitable for deriving recommendations with regard to water management, farmers' practices, or policy changes. Many papers provide recommendations on how to improve water productivity, and in most cases suggest agronomic and engineering interventions that seem to be unrelated to the analysis carried out. If ratios are compared for a particular crop among otherwise similar farmers within an irrigation scheme, for example, important insights may be gained—at least as a basis for further analyzing the factors behind the variations; however, such results are context-specific. Variations across different locations or even regions reflect the influence of many other factors. Recent research tries to account for at least a number of physical and institutional factors (Giordano et al. 2017).

Progress could be made with refining the numerator term, in particular by moving toward incorporating revenues and the costs of all inputs except water. If properly estimated, the resulting residual would reflect the net return to water, and could be used for comparisons among users and uses. It would also serve as a building block for the deductive methods.

Total Factor Productivity Indices

Like single-factor productivity measures, total factor productivity (TFP) indices are expressed as a ratio of outputs to inputs. In contrast to single-factor productivity measures, they are concerned with the inclusion of all factors of the production process,[1] and can also account for multiple outputs. Thus, they relate a single output or an aggregate output index to an aggregate input index. The indices typically require quantity and price information for the outputs and inputs included.

Review of Approaches. Conceptually, indices measure changes in a set of related variables from a reference or "base" period, with the period for which the index is calculated referred to as current period. One way to measure productivity change then is to use a measure of output growth, net of growth in inputs (Coelli et al. 2005). For example, if output has doubled from the base to the current period, and if this output growth was achieved using only a 60 percent growth in input use, it is concluded that the firm has achieved a productivity improvement. Thus, total factor productivity indices are used for comparisons over time, but they can also be used for measuring productivity levels across firms, industries, regions, or countries (Coelli et al. 2005). Higher scores are associated with better productive performance.

Different ways of aggregation lead to different total factor productivity indices, with Laspeyres, Paasche, Fisher, and Törnqvist indices being the most commonly used (Latruffe 2010). Each index implicitly assumes a specific underlying production function. For example, the Laspeyres index implies a Leontief production function, which implies that the factors of production are used in fixed, technologically predetermined proportions without substitutability between them. The indices are constructed using price weights; in the case of a firm, the price weights account for the relative share of each output in the firm's revenue and the relative share of each input in the firm's costs. Similar to single-factor productivity measures, the commonly used indices assume implicitly that firms are efficient. Changes in total factor productivity over time are therefore attributed to technological change (and other sources of productivity improvements are not identified). An exception is the Malmquist index; it allows a decomposition of the productivity change into various components, including efficiency change and technological change (Coelli et al. 2005).

Total factor productivity indices have been employed in a large number of empirical studies, mostly at the national level but more recently also at subnational levels. The commonly used indices account for marketed outputs of goods and services but tend to disregard items, such as water, that are usually not marketed (i.e., not traded or priced, even at an opportunity cost). The neglect of nonmarketed goods and services has long been recognized as a problem (Antle and Capalbo 1988). According to Gollop and Swinand (1998), "because the consumption of water resources involves true opportunity costs no less than does the consumption of labor, capital, or material inputs, total factor productivity measures must be viewed as biased barometers of how well society is allocating its scarce resources" (p. 577). From a different perspective, Fuglie, Wang, and Ball (2012a) point out that future gains in agricultural production need to save not only land but also a wider array of natural resources, such as water, to avoid negative impacts to the environment from agricultural intensification. Data limitations regarding the water input continue to be a factor (Alston and Pardey 2014). For example, Wang et al. (2013) mentions that the contribution of water as a separate input in growth estimates for total factor productivity in China could not be accounted for because of a lack of appropriate data. Even in cases where water and pumping costs are included in estimations of total factor productivity, these inputs may be undervalued if prices paid by farmers do not reflect their social opportunity cost.

Approaches allowing the partial inclusion of water aspects, usually in the form of dummy variables or by treating rainfed and irrigated cropland as separate categories of inputs, can be found in studies on agricultural productivity patterns at the national, regional, or global levels included in two recent books by Alston, Babcock, and Pardey (2010a) and Fuglie, Wang, and Ball (2012b). For example, Fuglie (2010a) distinguished between irrigated and non-irrigated cropland in a study on agricultural growth in Indonesia. Growth in irrigated land was assumed to have a larger impact on output than increases in rainfed land. When examining the shifting patterns of agricultural productivity in the United States, Alston, Babcock, and Pardey (2010b) also distinguished between irrigated and non-irrigated cropland, and added a miscellaneous input category to account for irrigation fees. Fuglie (2010b), in a study of total factor productivity in the global agricultural economy using FAO data, divided cropland into rainfed cropland and cropland equipped for irrigation, and included irrigation fees in the cost share of agricultural land. These examples illustrate the challenges of including water aspects in studies at national or higher levels, with attempts being made to approximate irrigation water through the area of land irrigated, and price or opportunity cost of water through irrigation water fees. While these studies can account for the contribution of changes in irrigated area to agricultural growth, they do not provide any further conclusions related to the effect of water on agricultural productivity patterns.

Water aspects are incorporated in more detail in a few studies at the subnational level, such as the provincial and district levels. An example is Conradie, Piesse, and Thirtle (2009), who focused on agricultural total factor productivity in South Africa's Western Cape Province, and further disaggregated indices for its regions and districts. They found that water availability (included as a dummy variable to indicate whether a district had a major river running through it) was an important explanatory variable. In a study of agricultural growth across Indian states, Rada and Schimmelpfennig (2015) found that expansion of irrigation, especially from groundwater, increased farm-level total factor productivity. Since irrigation and pumping costs have been heavily subsidized in India, and therefore are not fully reflected in farm input costs, the measured gains in total factor productivity are likely to be at least partially due to the undervaluation of the real cost of irrigation.

Key Findings. Total factor productivity indices attempt to capture all inputs into the production process, and can also accommodate all outputs. Prices and costs are incorporated as weights for calculating the indices. Underlying the indices are different production functions. The approaches allow comparisons over time and also across different scales—yet the scales are not water-related but rather concerned with different levels of aggregation up to the national (or even global) level. Due to the assumptions underlying the indices, the changes identified are usually attributed to technological change. Yet some indices allow a further decomposition into the sources of productivity growth.

Most studies that incorporated water aspects were concerned with the analysis of agricultural growth at the national or subnational/regional level. Gaps in agricultural water data, including its social opportunity cost, at these levels have caused these studies to include water in the form of dummy variables (such as irrigated vs. rainfed cropland). While this can shed light on how the expansion of irrigation contributes to agricultural growth, it is difficult to draw further conclusions related to the effect of water on agricultural productivity patterns. Water conservation aspects are also not mentioned. However, the need to better integrate sustainable use and management of water in agricultural policy, and the related research on agricultural productivity, is increasingly recognized—if only to prevent a trade-off between productivity growth in the short term and long term that would be associated with a progressive depletion of water resource assets (OECD 2015). A reflection of this concern was the call, as part of the G20 Ministers' Action Plan 2017, to expand the analytical framework for improving agricultural water productivity and sustainability to further embed water-related aspects (G20 2017).

Frontier Methods

Like total factor productivity indices, frontier methods can account for multiple inputs and multiple outputs and are part of the agricultural productivity and efficiency literature. Frontier methods are concerned with measuring the performance of "decision-making units" in terms of how well they manage their conversion of inputs into outputs. The basic measure of performance is technical efficiency—often implicitly equated with unobservable managerial ability. Technical efficiency is measured as a potential input reduction or potential output expansion, relative to a reference "best practice" or efficient frontier, constructed from observed inputs and their output realizations.

Review of Approaches. Techniques for defining the frontier can be classified into *parametric* and *nonparametric* methods (Latruffe 2010). Parametric methods rely on specifying a production frontier and estimating its parameters. *Deterministic frontier analysis* calibrates the parameters assuming that any deviation from the frontier is due to inefficiency. *Stochastic frontier analysis* estimates the parameters econometrically, allowing for both inefficiency and statistical noise in the data; this is modeled through a composed error structure, with a one-sided component measuring inefficiency and a two-sided symmetric term capturing statistical noise. Stochastic production frontiers are limited to a single output in their formulation; yet multiple outputs can be included by aggregating the quantities of outputs using prices so that the single measure of output is the value of agricultural production.

Nonparametric methods, on the other hand, use mathematical programming techniques to construct a piecewise linear surface (or frontier) over the output-input space and then calculate the level of inefficiency as the distance to the frontier. The most popular method to do this is *data envelopment analysis*. Data envelopment analysis can deal with different quantities of multiple outputs. However, when the sample size is relatively small in relation to the number of input and output variables, similar aggregation techniques as in stochastic frontier analysis are employed to reduce the dimensionality of the problem.

Our in-depth review of the frontier studies in the agricultural production economics literature incorporating water aspects, based on Scheierling et al. (2014) and Bravo-Ureta et al. (2016), found 110 water-related studies. Except for 10 studies that used aggregate data aggregated for a region, all other studies were farm-based. Most studies used proxy variables for the quantity of water (such as the number or duration of irrigation events, or the area or percentage of the area under irrigation). Only 28 studies incorporated a measure of water use: water applied, in all cases. Some studies used additional water-related variables (such as precipitation, or a dummy variable for the irrigation system).

Of the 28 studies, 17 studies reported a water-specific performance indicator: output response to water, water-specific technical efficiency (figure 3.4), irrigation technical cost efficiency, or a shadow value of water in irrigated agriculture. Among these, 11 studies apply stochastic frontier analysis (6 input-oriented and 5 output-oriented), 6 studies apply data envelopment analysis (5 input-oriented and 1 output-oriented), and one study uses aggregate data.

The studies by McGuckin, Gollehon, and Ghosh (1992) and Karagiannis, Tzouvelekas, and Xepapadeas (2003) are of particular interest for our purposes here. Both applied stochastic frontier modeling to irrigated farms, and emphasized the importance of distinguishing between irrigation efficiency (as used in the irrigation engineering literature) and economic efficiency involving technical and allocative efficiency.[2] They note that irrigation efficiency is only one dimension of input use, a physical measure of the irrigation technology assuming a level of management, while technical and allocative efficiency are measures of management capability.[3] Both studies include irrigation water (in terms of water applied) as a continuous variable, and are concerned with farmers' irrigation water savings. However, the "water savings" discussed therein are in the form of reduced water applications and not water consumed, thus ignoring potential externalities beyond the farm level in terms of return flows.

McGuckin, Gollehon, and Ghosh (1992) used farm observations for U.S. corn producers in a homogeneous crop region of Nebraska who applied groundwater by gravity or sprinkler systems as supplemental irrigation. They estimated the production frontier as a Cobb-Douglas model of irrigation in terms of water applied—with soil conditions, rainfall, and irrigation technology included as exogenous variables that shift the frontier, and all other inputs excluded. The authors hypothesize that technical inefficiency of irrigation depends on available field information (e.g., soil moisture monitoring, commercial scheduling, or weather reports). Thus, information on field conditions from moisture sensors could be an important factor for improving technical efficiency of irrigation.

Karagiannis, Tzouvelekas, and Xepapadeas (2003) measured irrigation water efficiency on farms with out-of-season (greenhouse) vegetable cultivation in Crete, Greece. They define irrigation water efficiency not along the lines of the engineering-oriented concept of irrigation efficiency, but use the concept of water-specific technical efficiency—defined as "the ratio of the minimum feasible water use to observed water use, conditional on the production technology and observed levels of output and other inputs used" (p. 58). They note that the cost saving related to adjusting irrigation water to a technically efficient level, while holding all other inputs and output at observed levels, will vary with prices. Thus "relatively inefficient water use in a physical sense can be relatively efficient in a cost sense, and vice versa" (p. 60).[4] While the measures of output-oriented and input-oriented technical efficiency do not identify the efficient use of individual inputs, "water-specific technical efficiency" is an input-oriented single-factor measure that provides information on how much water use could be decreased without altering the output produced, the technology (including the irrigation technology) utilized, and the quantities of other inputs used (see section 3.2). Empirical results indicate that water-specific technical efficiency is on average much lower than output-oriented technical efficiency, indicating that farmers could become significantly more efficient in irrigation water use, given the present state of technology and input use. Modern greenhouse technologies, education, and extension services are the main factors positively associated with the degree of water-specific technical efficiency.

Key Findings. A central characteristic of frontier methods is the production function that is estimated as part of the modeling. Their focus is on technical efficiency. Yet, with panel data, technological progress can also be estimated and used to explain output growth. Overall, relatively few frontier studies in the agricultural production economics literature incorporate a measure of water use, and in each case it is (only) water applied. This may be related to the fact that most studies focus at the farm level, and that water application is the key water-related decision variable for farmers. But this has so far prevented water-related externalities, such as return flows, to be taken into account.

The objective of most frontier studies is to increase the level of agricultural output or income over time (depending on how the output is defined), and the recommendations are geared toward increasing the levels of output. The studies estimating water-specific technical efficiency usually find that water applications could be reduced without affecting the amount of output produced. The inefficiency is explained by a lack of ability or knowledge that can be addressed with training or information about watering needs. The possible effect on consumptive use and return flows is not discussed.

Some studies show that a switch to a more advanced technology is not an assurance that overall technical efficiency or water-specific efficiency will increase, suggesting that a shift of focus from the promotion of new technology to the mastery of existing technology may in some cases be advisable.

Deductive Methods

Deductive methods form a fourth group of methods that is frequently used in the agricultural and irrigation water economics literature. Like total factor productivity indices and frontier methods, they belong to the category of multifactor approaches. Yet while total factor productivity indices and frontier methods rely on inductive techniques, involving a process of reasoning from the particular to the general (i.e., from observations to general relationships), they use deductive techniques, involving reasoning from the general to the particular. In irrigation water economics, deductive methods start with hypothetical water users and combine quantitative data on the physical and financial conditions with behavioral assumptions on the objectives of these users (e.g., profit or utility maximization) to derive estimates of production, water use, revenue, costs, and net income (Young 2005). A direct outcome of deductive methods are estimates of the contribution of irrigation water to crop production and producer incomes. Implicit in these outcomes are various measures of water productivity.

Deductive methods include a range of approaches. The six main approaches are shown in table 4.1. A recent review of deductive methods in the irrigation water economics literature found 354 journal publications (Booker 2016). They ranged from applications using simple crop budgets, to optimization methods applied at the farm and broader scales, to systems models. Such models can extend implications of basic local or regional water productivity to account for the hydrologic setting and users' interdependencies (hydro-economic models) as well as for farm sector interactions with the broader economy (e.g., computable general equilibrium models). This breadth of applications reflects the inherent flexibility of deductive methods to incorporate factors relevant to the specific questions under consideration while explicitly representing the physical and other constraints under which farm production is undertaken. Because of their ability to model different scenarios, deductive methods are also used for policy analysis and project planning.

Derivation of Water Productivity Estimates. Deductive methods are based on drawing conclusions from the general (e.g., typical crop budgets) and applying these understandings to the particular (e.g., future farm conditions, including water availability). Implicit in the general, such as the crop budgets, are single-factor productivity measures for individual crops; and in the particular, the potential for weighted measures of crop mixes projected for representative farms or regions. Both physical measures (*yield per unit of water*) and measures incorporating output prices (*revenue per unit of water*) can be derived. To the extent that all inputs can be priced, simple multifactor productivity measures incorporating the opportunity costs of nonwater inputs (*net income per unit of water*) can also be derived. This approach relies upon the idea of basic residual

TABLE 4.1 Main Approaches of Deductive Methods

CLASSIFICATION	CHARACTERISTICS
Crop budgeting	Application of basic residual imputation to a single-product case
Linear programming and related approaches	Discrete production activities; deterministic; independent production regions. Objectives can include production, revenue, or income
General mathematical programming	Derived water demand or variable output price; nonlinear objective; explicit water transfers
Stochastic/dynamic programming	Explicit treatment of risk; discrete activities or derived demand
Hydro-economic models	Economic objectives with consistent hydrologic detail; integrated or modular
Computable general equilibrium	Representation of full economic system

Sources: Booker 2016; Young 2005.

imputation: the productivity of the water input in monetary terms, conditioned on the specified use of other inputs, is the net income to the production unit calculated as the difference between crop revenue and the opportunity costs of all nonwater inputs. A detailed discussion, including for the nonwater inputs as well as equipment, labor, land, management and entrepreneurial skill, rented capital, and equity in the farm enterprise, is in Young (2005).

Most applications of deductive methods utilize behavior responses to outcomes (in terms of net income) of choices, such as crop mixes and water use. Net incomes, given by the difference between revenues and costs, are typically assumed to be an important incentive leading to a particular outcome. Common behavioral assumptions include producers seeking to maximize income, to maximize the probability of achieving a threshold income, or to minimize to income losses under adverse conditions (e.g., drought).

Approaches relying on deductive methods range from applications of basic crop budgeting to computable general equilibrium models that seek to fully represent interactions between irrigated production and a broader economy. More typically, mathematical programming models (sometimes including hundreds or thousands of possible production activities and potentially complex representations of risk) seek to represent the range of choices facing producers, and to explore responses to those choices. Such programming models, explicitly representing production of specific crops (or linked crops in rotations) may also represent in significant detail physical features of irrigation water use. In addition to activities specifying irrigation technology, accounting for consumptive use, return flows, and groundwater interactions is straightforward and commonly integrated into model specifications. As hydrologic and institutional complexity grows, hydro-economic models focused on water use and allocation commonly abstract from production of specific crops, and represent irrigated regions through the use of derived demand functions for water. In these integrated system models, interdependencies between water-using regions are transparent, and the policy conditions under which water is allocated must be explicitly represented.

Independent of the approach, the deduced responses would allow (even retroactively) the calculation of a variety of single-factor productivity measures and water-focused multifactor productivity measures which incorporate the opportunity costs of nonwater inputs. Where the production of specific crops is represented, productivity measures can be created through trivial calculations. In many cases it is possible to calculate single- or multi-factor productivity using the studies' tables and findings. In other cases where the authors were less focused on the details of crop output than on water use and income estimates, it may be necessary to return to the original model to recover the necessary crop production figures that lead to the water productivity estimates.

In cases where derived demand for irrigation water is used as a starting point for representing irrigation outcomes (e.g., in most hydro-economic models), it would be necessary to return to the studies upon which the derived demand estimates are based to recover the production figures necessary for estimating single-factor productivity measures. Because a central feature of such model solutions is the shadow or opportunity cost of water to the represented regions (e.g., Vaux and Howitt 1984), a multifactor net income productivity measure (i.e., net income per unit of water) is always available from model solutions, and is typically reported and highlighted in the model's results. But these productivity estimates are also typically multiproduct, aggregating across production of a variety of crop types.

Review of Approaches. Deductive methods are further discussed below along the classification of table 4.1.

Crop Budgeting. A crop budget can be understood as the application of the residual imputation method for a single-output case. Residual imputation is derived from the neoclassical theory of the firm. In general terms, if the production function and the quantities of all other inputs are known, and accurate prices can be assigned to all inputs but one (in this case, water), invoking the production exhaustion theorem allows the imputation of the remainder of total value of product to that input. This allows to derive a point estimate of the producer's net income attributable to the optimally applied input water (Young 2005). This approach provides the building block for the more complex deductive approaches that incorporate changes in water supply and multiproduct cases.

The (physical) production function parameters may reflect typical regional patterns of input use for a particular crop, or other values as appropriate for the analysis. If regional input use rates are used, then these will reflect technical efficiencies in production which are often substantially less than 1. While improved management could in principle move crop yields closer to the production frontier, crop budgets cannot easily reflect either the management changes or policy interventions which could lead to increased technical efficiency. If such best practices are envisaged as being ultimately representative, then input levels consistent with technical and allocative efficiency would be used.

In order to address agricultural water productivity issues with deductive methods, the most direct application is to consider a crop budget for a particular output. If producers were to follow a particular recipe of inputs, and were able to procure inputs and sell the output at specified prices, then the budget predicts physical measure of water productivity (e.g., kg/m^3), a revenue based measure (\$/m^3), and a net income (or economic) measure (\$/m^3). The net income measure is a residual, reflecting the economic value remaining after economic costs of production are subtracted. This residual measure can be interpreted as a multifactor productivity measure, as it includes information on all inputs through its use of total costs of crop production. By incorporating all input use into the productivity measure, and including the value of the produced crop, the net income measure is able to provide an indication of the practicality of a specific cropping practice. More explicitly, the multifactor productivity measure is found as follows:

$$\text{Net income} = (PQ - \Sigma_i w_i X_i) / X,$$

where P is the unit value (\$/kg) of the crop, Q is the total production (kg), X_i is the ith input, w_i is the opportunity cost of the ith input (\$/unit), and X is the water quantity (m^3). Revenue and costs may be a combination of marketed inputs and output and those owned (e.g., labor) or directly consumed (e.g., some portion of production). If the land cost included in the crop budget is a rental price for land without irrigation water, then the estimated net income from crop production can be interpreted as a measure of the average value of water in crop production (Young 2005).

A number of practical issues arise in the application of crop budgets to productivity analysis. These include data limitations, the treatment of risk, and also conceptual issues—especially in the residual imputation of net income.

A particular issue is the valuation of non-priced inputs into crop production, including owned inputs, such as land and management. While local rental markets often provide reasonable measures for irrigated and non-irrigated land, the value of owner-provided management may be difficult to quantify. This is problematic because benefits of management are potentially large compared to net income from crop production (as suggested by the frontier literature). Because the management input is potentially transferrable to other economic activity, it should be valued at its opportunity cost in the highest valued alternative; however, in practice, this alternative is rarely observable.

One additional distinction merits special attention. Many agricultural production inputs and their associated costs are fixed in the short run. Such fixed costs should be included, in addition to variable costs of production, when the purpose of residual imputation is to provide a long run value for a net income measure of water productivity. This is especially important if methods based on residual imputation are used to consider the economic viability of introducing irrigated crop production in a currently non-irrigated area. In this case all costs of irrigation development, including irrigation system costs, should be included as opportunity costs. When all relevant costs are included, the residual net income can be attributed solely to the water input (Young 2005). This calculated economic water productivity is most commonly referred to as the "economic value of water."

Residual (or net income) measures are inherently very sensitive to parameter assumptions. Because net income is the difference between parameter estimates, and because typical values are a relatively small percentage of revenues and costs, uncertainty in the estimated value can be relatively large. This is not a limitation of the approach, but rather a reflection of the economic sensitivity of irrigated agricultural production to underlying physical and economic conditions.

Overall, few studies in the literature explicitly use residual imputation with crop budgets alone, and include yield and water use data that allows calculation of single-factor productivity. Yet in some cases, descriptions of programming models are provided at a level of detail which illustrate the underlying crop budgets. For example, Howe and Ahrens (1988) provide net income estimates for eight irrigated crops across eight subbasins of the upper Colorado River basin in the U.S. They include all variable and fixed costs and order their estimates to develop a crude supply curve for potential reallocation to other basin water uses. Because production and yield data are provided, it is possible to compare alternative productivity measures by crop and subbasin. The authors use consumptive use as their water metric. This is especially appropriate for work at the river basin level where return flows are captured by downstream users: Crop budgets typically express water use in terms of water applied at the field level. But return flows in excess of consumptive use are likely to have downstream users, and groundwater interactions through seepage and off-farm flows may affect limited groundwater availability, water logging, or water quality. In all these cases it would be desirable to also include in crop budgets the consumptive use portion in addition to the amount of water applied. Howe and Ahrens also illustrate that simple ordering of net-income–based productivity measures from crop budget residuals produces a downward sloping derived demand for the irrigation water input. In this (typical) case average water productivities will exceed the marginal value in the least productive use.

Linear Programming. It is often desirable to consider irrigated production with a variety of crops, production practices, and scales beyond the farm level. The policy purpose could be identifying combinations which are advantageous for economic development and supporting stable farm incomes (e.g., Bowen and Young 1985). A common alternative policy perspective focuses on identifying water conservation alternatives (Scheierling, Young, and Cardon 2006), or on opportunities for irrigation water reallocation for new uses (Howe and Ahrens 1988). In each case, revenues and costs in underlying crop budgets were systematically employed to compare alternative combinations of crops, practices, and scales.

Linear programming (and related optimization approaches) are widely used to choose specific crop and irrigation combinations (termed activities) under conditions of fixed resources such as land and water. Formally, linear programming models start with a set of activities describing yields, input costs, revenues, and water application or consumptive use for specific irrigation alternatives and crops. The simplest formulation, where land and water are the limiting resources, is: maximize Y, subject to $\sum_{crop=1}^{n} X_{crop} \leq area, \ \sum_{crop=1}^{n} Q_{crop} \leq Q_{total}$, where Y is net income, X_{crop} is the planted and harvested area of each crop activity, *area* is the total farm area, Q_{crop} is the total irrigation application for each crop activity, and Q_{total} is the total available irrigation application for the farm. The solutions to programming problems which maximize income will utilize technically and allocatively efficient combinations of crop activities. Thus while the budget and yield data upon which the models are based may themselves represent inefficient (though typical) producer practices, programming solutions will necessarily use these activities in efficient combinations. In most cases many possible crop activities will not be included in any model solutions. For example, when considering a single crop which could be produced with varying irrigation water application levels or irrigation technologies, only one of the activities may enter model solutions. If an activity shows increasing returns to an input relative to related activities, that activity will dominate all activities using lesser quantities of the input.

Linear programming assumes constant returns to scale with each crop budget, with solutions identifying production at whatever scale (farm, region, and basin levels) is most advantageous given the objective function and constraints.[5] They may be developed using annual, seasonal, irrigation period, or other time scales (with complexity increasing quickly as multiple interacting time scales are introduced). Generally, linear programming approaches can easily incorporate detailed agronomic and hydrologic factors, and are well suited to considering irrigator responses to changes in water availability (including rainfall and irrigation water as well as quality of the water) or policy (e.g., pricing). Linear programming studies tracking water withdrawals, soil moisture, and return flows are common in the literature.

General Mathematical Programming. General mathematical programming typically uses extensions of linear programming models to offer a variety of behavioral, institutional, and physical refinements. In most of this work the concept of net-income-based water productivity (i.e., the "economic value of water") is central.

One extension is positive mathematical programming, which helps address the common problem that outcomes of large linear programming models rarely result in solutions that closely reflect observed crop patterns or other producer behavior. The differences may result from unobserved costs and details of production and market conditions, as well as nonmodeled risk considerations. The standard modeling approach has been to impose a combination of land constraints and penalty functions which lead to rigidities in the models. To circumvent this problem, positive mathematical programming was developed which recognizes the existence of unobserved heterogeneities and incorporates these into a self-calibration procedure (Howitt 1995). This and related approaches are now commonly used in a variety of programming models which seek to describe producer behavior at farm, regional, and river basin scales.

Stochastic and Dynamic Programming. There is typically a trade-off between income and risk. A common extension of linear programming methods is to include a risk penalty in the objective function, which then typically takes the form of the difference between expected net income and a risk penalty. With risk presented as the income variance across states of nature, the objective function is quadratic in the water use decision variable, and the result is a quadratic program. Stochastic programming is an alternative approach specifically incorporating risk and showing the welfare consequences of variability.

In addition, water use decisions made at different points in time are unlikely to independently impact farm incomes. For example, early season irrigation will impact yield gains from subsequent irrigations, while in the case of groundwater pumping, each season's groundwater use is likely to affect future aquifer stocks and costs. Similarly, surface reservoir management problems are inherently dynamic. Programming formulations of problems with interdependencies over time are dynamic programs, and are an optimization approach widely applied in the economics and related water literatures. They commonly formulate decision making in stochastic and dynamic settings as discrete stochastic programs (DSP), often represented as a series of sequential decision-making steps in discrete stochastic sequential programs (DSSP). Common applications include intraseasonal irrigation decisions when irrigation supplies at different growth stages are uncertain. Numerous applications include conjunctive use of groundwater, and water quality and drainage problems.

Hydro-Economic Models. Deductive methods can be used to incorporate physical externalities, such as those illustrated in figure 3.2. Hydro-economic models are approaches that explicitly consider empirical hydrologic structures (Booker et al. 2012; Harou et al. 2009). Such integrated models are particularly useful for assessing the effects of improved irrigation efficiency through more capital-intensive on-farm irrigation technology. That water withdrawals and applications are likely to decline, while consumptive use and hence basin-wide water depletion may remain the same or even increase, was demonstrated in theory by Huffaker and Whittlesey (2003) and with integrated modeling by Scheierling, Young, and Cardon (2006) and Ward and Pulido-Velazquez (2008). More generally, hydro-economic models seek to incorporate the notion that water users are potentially linked through complex physical processes, including those between surface and ground water. An early application of such an approach was by Bredehoeft and Young (1970) who explored intertemporal allocation options for improved irrigation outcomes in a linked stream-aquifer system where farmers could draw from both ground and surface water. The explicit treatment of return flows as a physical externality was recently addressed by Taylor et al. (2014).

Computable General Equilibrium Models. While hydro-economic models may include important physical linkages, they are mostly partial equilibrium models from an economic perspective—with linkages with key related economic sectors (e.g., labor markets) likely to be absent. General equilibrium approaches are needed to include feedback from farm-level changes to the wider economy, and vice versa. Roe et al. (2005) provide a discussion of related issues, and an application of a computable general equilibrium model to irrigation water management. An application involving conjunctive ground and surface water use is in Diao et al. (2008), and more recent applications in Luckmann (2016). However, in moving toward computable general equilibrium models, many of the key physical linkages and distinctions between, for example, water applied and consumed are often lost, and some of the data limitations which challenge total factor productivity studies may reemerge.

Key Findings. The deductive methods form an extensively used and mature set of tools for assessing water use in irrigated agriculture. They are based on water-crop production functions. Their usual starting point are crop budgets which include multiple inputs and their costs or, alternatively, derived demand estimates which incorporate input costs. This is in contrast to single-factor productivity measures that do not control for nonwater input uses, and as such provide only imperfect information on the physical outcome of specific irrigated crop practices. The basic residual imputation method for estimating net income specifically deducts other input usage as a cost, leading to lower net income productivity as nonwater input use increases. Deductive methods can also be viewed as a method for developing a set of consistent weights for aggregating inputs and outputs. In this sense, net income productivity measures of water use are closely related to total factor productivity approaches.

Central to deductive methods are assumptions on the behavior of irrigators. For example, irrigators may choose to minimize risk, subject to an income threshold. Producer behavior and preferences need to be explicitly considered and represented in assessing agricultural water use, and deductive methods provide a variety of approaches to accomplish this.

Multiple sources of data can be included in deductive methods. While in practice crop budgets representing typical irrigated production practices are a common starting point, experimental results can be used, as can observations on past irrigator behavior. For example, single-factor productivity measures reported from field experiments can be utilized in subsequent residual imputation work, while producer survey data from frontier studies could, if detailed enough on specific crop production input use, be used as the source of alternative production activities in a linear program. Furthermore, deductive methods are not limited to existing practices, but can include and directly evaluate proposed alternatives.

Any and all measures of water quantity can be incorporated in deductive approaches. The more complex approaches employ a variety of temporal and spatial scales (from farm to region, to basin, and economy wide). As the spatial scale increases, the physical externalities inherent in irrigation become increasingly important. Hydro-economic models force attention on these interdependencies.

Deductive methods are well suited to address issues related to different objectives, including increasing irrigated agricultural production, identifying opportunities for water conservation, and providing insight into the role of irrigated production in supporting incomes and economic development.

In contrast to productivity measures in physical terms, deductive methods directly value the physical production in economic terms—and with residual imputation provide a net income estimate giving an economic value to that production. This is an important starting point for understanding contributions to farm net income and economic development which could arise from the particular irrigated crop production. Where water conservation is a central objective, the clear distinctions made between marginal and average productivities will provide additional policy relevant conclusions.

CHARACTERISTICS OF THE METHODS BY KEY FEATURES

The analysis of the four main methods in the preceding section revealed a large variety of approaches and techniques, and their application in many studies with various perspectives. While this makes it difficult to generalize, it is nevertheless possible to derive more general insights into the methods when comparing each of them with some key features we consider important for the analysis.

Key Features. The first feature is the *background of the method*. It gives information on the research field in which a particular method is mostly employed. It also describes the main analytic approach and focus of the method's analysis. Another feature is the *incorporation of water*. Given the special characteristics and measurement issues of water, the methods use many different ways of incorporating the water input. A desirable option is the inclusion of a measure of water quantity that is well defined. The most sophisticated way would be to consider and distinguish between all of the key measures: water withdrawn, applied, and consumed. A third feature, related to the special water characteristics, is the *consideration of the appropriate spatial and temporal scale* of analysis. For example, in some hydrologic settings a focus on the field or farm level may be too limiting, especially when return flow issues play a large role and downstream users depend on them. Similarly, if the temporal scale is limited to a whole cropping season, important intraseasonal issues such as the timing of water supplies during the growing period of a particular crop and the different yield effects may not be considered with sufficient detail. Finally, the fourth feature is the *assessment of agricultural water productivity and efficiency*. This includes the main sources of data, and whether the method has (explicitly or implicitly) an underlying water-crop production function. The feature also refers to how the terms productivity and efficiency are understood and applied, and which aspects of the efficiency and productivity concepts are emphasized. It also considers whether multiple inputs and outputs are included, and prices and costs incorporated.

Some Insights on the Methods. Table 4.2 highlights characteristics of the methods by the key features. Overall, each of the methods shows some limitations in light of these features.

The strength of *single-factor productivity* studies is their special focus on water, and the incorporation of different measures of water use—often considering more than one measure. They can also be applied to various spatial scales, ranging from the field to the basin and even global levels. Single-factor productivity measures, expressed in crop per drop ratios, tend to find large variations in agricultural water productivity, yet usually do not proceed to empirically investigate the factors that might explain the different findings. The use of such measures, where all variations in output are attributed to the water input, is problematic—especially when they form the basis of recommendations for reducing the "gaps" between ratios found in different locations. These measures

TABLE 4.2 Characteristics of the Methods by Key Features

	SINGLE-FACTOR PRODUCTIVITY MEASURES	TOTAL FACTOR PRODUCTIVITY INDICES	FRONTIER METHODS	DEDUCTIVE METHODS
Background of method				
Research field	Irrigation engineering, agronomy	Agricultural production economics (productivity and efficiency analysis)	Agricultural production economics (productivity and efficiency analysis)	Agricultural and irrigation/water economics
Analytic approach	Calculation of ratios (in physical or "economic" terms)	Econometric analysis	Econometric or optimization analysis	Usually optimization
Focus of analysis	Often "gap analysis" of ratios	Focus on technological change	Usually assessment of technical efficiency of decision-making units	Policy analysis ("what if")
Incorporation of water				
Measure of water use	Water withdrawn, water applied, water consumed	Usually proxy variables (e.g., irrigated land)	Often proxy variables (e.g., number of irrigation events), also water applied	Water withdrawn, water applied, water consumed
Consideration of scales				
Spatial scale	Field; with aggregation in "economic terms" also farm and basin	National level (more recently also subnational)	Decision-making unit, mostly farm (also regional)	Field, farm, region, basin, economy-wide
Temporal scale	Usually cropping season	Annual	Cropping season; multiyear (with panel data)	Various scales, including projections
Assessment of agricultural water productivity and efficiency				
Data sources	Measured and modeled data	Measured/aggregate data	Primary data, with variability among farms	Range of data sources, mostly secondary data
Underlying production function	No	Yes (based on indices)	Yes (function may be estimated)	Yes (often implicit)
Efficiency and productivity concepts	Productivity concept originated to go beyond classical irrigation efficiency	Productivity and efficiency concepts from economic theory	Productivity and efficiency from economic theory; focus on multiyear technical efficiency	Not explicitly concerned with productivity, but measures can be estimated; technical efficiency not explicitly addressed
Inputs	Focus on water input (neglecting other inputs)	Inclusion of all (marketed) inputs	Inclusion of all inputs relevant for decision-making units	Inclusion of all inputs
Outputs	Focus on output of one crop ("economic" measures may include other output)	Inclusion of all (marketed) outputs	Single output is most common, but multiple outputs can be included; output often measured in terms of revenue	Inclusion of multiple outputs (at farm/basin levels)
Prices and costs	Output prices used for aggregation in "economic" measures (costs of inputs could be incorporated)	Prices and costs used for aggregation	Frontiers can be expressed in terms of cost, profit, or revenue	Inclusion of regional/"representative" prices and costs

disregard the effects of linkages with other inputs (including environmental influences), do not incorporate prices or costs, and do not consider the different sources of productivity.

As multifactor approaches, total factor productivity indices and frontier models avoid some of the pitfalls of single-factor productivity measures. Yet they have their own shortcomings when it comes to incorporating water aspects and providing insights into how water could be used more productively. *Total factor* *productivity* studies, usually applied at the national level, tend to not include water as a separate input, often due to data problems. A few studies at subnational levels, such as the district level, capture water aspects as dummy variables and may show, for example, that water availability (in connection with other factors) is an important input associated with total factor productivity growth.

The *frontier method* studies tend to be based on farm-level data and focus mostly on technical efficiency. With a few exceptions, they include water aspects only in qualitative form as proxy or dummy variables. Most of the studies examine the extent of inefficiency as well as the significance and magnitude of the factors that may be causing the inefficiency. Depending on the particular case, the problem analyzed, and the approach used, frontier method studies find that water aspects (such as water availability, irrigation infrastructure, farms' location along a canal, or farmers' water management arrangements) play a role in terms of technical efficiency. Two frontier model studies, by McGuckin, Gollehon, and Ghosh (1992) and Karagiannis, Tzouvelekas, and Xepapadeas (2003), stand out: they specifically examine the efficiency of irrigation water in economic terms, and try to estimate potential water savings. However, both studies are limited in that they only consider one measure of water use at the farm level, water applied, and assume that any reduction in this measure would constitute a decrease in water "waste" and thus a water saving. This is not necessarily the case when return flows are important for downstream users—even if irrigation water efficiency is considered in economic instead of in engineering terms.

No study applying total factor productivity indices or frontier methods seems to have yet presented an approach incorporating not only multiple inputs and outputs but also basin-level issues.

Deductive methods can address some of the shortcomings of the other methods. They can include multiple factors and multiple outputs. All measures of water quantity can be considered. Deductive methods can be applied at any spatial scale and, if linked with hydrological modeling, can incorporate basin-level issues. They are also flexible with regard to temporal scales. A range of data sources can be used for deductive methods. They are based mostly on secondary data that are used to formulate "representative" irrigated production practices. Yet they can also include proposed alternatives. This allows their use for ex ante evaluations of water allocation and policy options in a comprehensive fashion. While deductive methods are not explicitly concerned with productivity measures, they can be calculated in a manner that incorporates all factors and generates estimates of the economic value of water.

Since the building blocks of deductive methods are "representative" conditions of patterns of input use for a particular crop that most likely do not represent technically efficient points on the production frontier, deductive methods cannot easily reflect management changes or policy interventions that would lead to increased technical efficiency.

NOTES

1. Because of the difficulty of capturing *all* inputs influencing output levels, total factor productivity indices are also referred to as multifactor productivity indices (Coelli et al. 2005).
2. Karagiannis, Tzouvelekas, and Xepapadeas (2003) refer to McGuckin, Gollehon, and Ghosh (1992).
3. As McGuckin, Gollehon, and Ghosh (1992) put it: "Compared to a furrow system, a sprinkler irrigation system could reduce water use and increase irrigation efficiency but at the

expense of an increase in capital. With very low cost water, the sprinkler would be allocatively inefficient. More subtly, a sprinkler could also be technically inefficient. With improved management, a sprinkler system might use as much water as the furrow system and thus be technically inefficient compared to the well-managed furrow system" (pp. 306–307).

4. A similar point was made by Barker, Dawe, and Inocencio (2003) in their critique of single-factor productivity measures.
5. Implicitly the model represents a single production unit, or multiple units in which inputs can be fully traded at the assumed input price levels. Unless otherwise constrained, all inputs can be freely used within the production unit represented by the model. In this, particularly regarding water inputs, programming models may be susceptible to overestimating resource mobility at larger scales.

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5 Applications of the Methods in a Maturing Water Economy

Following the comparison of the four main methods along selected key features in the previous section, this chapter moves to a broader analysis of each of the methods with regard to their usefulness when applied in the expansionary or mature phases of the water economy. The first section discusses the relevance of the methods in the different contexts. The second section concludes with some implications for going forward.

RELEVANCE OF THE METHODS IN DIFFERENT CONTEXTS

Based on the framework of the expansionary and mature phases of a water economy outlined in chapter 1, the broader analysis of the methods focuses on their ability to incorporate and address the particular contexts. This is a key determinant for their usefulness in guiding the choice of adaptation interventions and evaluating the effects of their implementation—with regard to both the water resources and their contributions to different activities.

We use the five characteristics introduced in table 1.1 to evaluate the extent to which each of the methods incorporates and addresses the changing conditions. The results are summarized in table 5.1. Overall, we find that the four methods with their stronger incorporation of water-related aspects have some advantages over benefit-cost analyses, the main assessment method in the expansionary phase of the water economy; yet care must be taken when using some of them for assessing adaptation interventions in a maturing water economy.

Single-factor productivity measures have been developed and promoted with a concern about the increasing scarcity of water. However, since they expressed as ratios of crop per drop and usually focus on the field level, they cannot sufficiently reflect the interdependencies among users. The maximization of agricultural water productivity seems to be the implicit overarching objective, and calls are made for efforts to "close the gap" of farmers or whole regions that are below levels achieved elsewhere. However, increases in the ratios by themselves do not indicate whether a contribution has been made to the objective of increasing agricultural production or to the objective of conserving water.

TABLE 5.1 Relevance of the Methods in a Maturing Water Economy

	SINGLE-FACTOR PRODUCTIVITY MEASURES	TOTAL FACTOR PRODUCTIVITY INDICES	FRONTIER METHODS	DEDUCTIVE METHODS
Demand and supply of agricultural water	Consideration of water scarcity; often erroneous assumption that addressing the perceived inefficient and unproductive use of water (off- and on-farm) would help overcome it	No consideration of water scarcity	No consideration of water scarcity	Inclusion of agricultural water demand and supply, with assessment of the effect of interventions on water scarcity
Hydrologic setting	Frequent focus on the field level, with insufficient recognition of users' interdependence Insufficient recognition of externalities (and contexts)	Water as one of many inputs in highly aggregated analysis of agricultural productivity, without consideration of spatial issues and externalities	Focus on farm level without capturing interdependencies between different water users	Complexities of the hydrological setting often incorporated
Policy objectives	Implicit focus usually on agricultural production (in some cases on water conservation) Often erroneous assumption that improving crop per drop ratios would address the trade-off between the objectives	Focus on (national or regional) agricultural growth	Focus tends to be on agricultural production on-farm; also consideration of water-specific and input-oriented technical efficiency (yet so far only in terms of water applied)	Mostly optimization of agricultural net income, but water conservation objectives can also be modeled
Interventions	Emphasis on engineering and technological interventions on-farm and in irrigation systems (often in existing infrastructure projects) that contribute to more crop per drop	Water is seen as an enabler of agricultural growth, yet without consideration of water-related interventions	Emphasis on engineering and technological interventions at the farm level; the impact of management-related intervention can also be captured	Incorporation of various interventions (engineering and technological, but also policy and institutional) and institutional contexts for assessments of trade-offs (including intra- and intersectoral)
Methods for evaluating the choice and implementation of interventions	Focus on comparison of crop per drop ratios over space and time With explicit inclusion of only one input, analysis of ratios usually does not allow specific ex ante recommendations on interventions; analysis of changes in ratios ex post does indicate causes	Assessments over time allow ex post evaluations of the contribution of (country-level) interventions related to irrigation water on agricultural growth	Typically ex post assessment; assessments over time could evaluate progress in the move toward the production frontier Could be used for ex ante assessments on scope of interventions, including improving farmers' managerial skills	Useful for ex ante analysis of policy options and their impact on farmers' income and water resources; used less for ex post analysis With ability to estimate the value of water, preferred choice for assessments of reallocations between farms, regions, and sectors (including the environment)

Comparisons of single-factor productivity measures can be useful in the context of field experiments when the other relevant factors besides water are relatively well controlled (i.e., "all else is kept equal"). In such situations, the ratios can provide guidance for "closing gaps," for example, with improvements in irrigation scheduling. When a water-related adaptation intervention is implemented, they are also very suitable for monitoring and evaluating the change.

However, when ratios are compared across widely varying locations and across time, the critical factors causing the differences cannot be identified—and recommendations with regard to the choice of interventions cannot be made—without more in-depth (and probably some type of multifactor) analysis. Despite these shortcomings, a common recommendation in the irrigation literature—and in much of the public debate—is to invest in on-farm engineering and technological interventions and in irrigation systems. This is in line with the underlying concepts and terms originating from the fields of engineering and agronomy. For example, studies that estimate crop per drop ratios for particular crops in terms of yield to water consumed—often employing agro-hydrological models in combination with remote sensing—tend to recommend better soil, water, and crop management to increase the ratios.

Another drawback is that the resulting improvements in crop per drop ratios do not imply that trade-offs between agricultural production growth and water conservation are addressed. It is not even clear to which objective they may have contributed, or if changes related to the water input were the reason for the improvement. Depending on the formulation of the ratios and the context (for example, when return flows matter and farmers are allowed to fully consume their water rights), they may have made water scarcity even worse.

Total factor productivity studies are oriented toward agricultural growth. They do not consider any water scarcity situations, partly because water prices are usually not available (or used). Even if data would allow that a measure of water use is incorporated, it would be difficult to derive insights on water-related interventions that should be undertaken to, for example, improve resource allocation or help conserve water. They can be considered assessment methods from (and for) the expansionary phase of the water economy.

Frontier method studies have mostly been output-oriented, and thus interested in how agricultural production could be raised with a given set of inputs. A few input-oriented studies use the notion of water-specific technical efficiency to investigate potential water conservation. However, due to their focus on the farm level, they take a perspective that in many cases would be too narrow for deriving broader implications for improving irrigation water management to cope with water scarcity. This is because they have only considered water applied—if a measure of water use was included at all—and implicitly assumed that any reduction in this measure would constitute water saving, which may not be the case in areas where return flows are an important water source for downstream users. Furthermore, given the current institutional arrangements in many locations, farmers may have little incentive to release this water for other uses.

Frontier method studies, in line with their estimation approaches, tend to emphasize technical efficiency and the potential of moving farms toward the production frontier by improving farmers' managerial skills. Common recommendations are training programs on the use of irrigation technologies and the management of irrigation water. Frontier studies have so far not attempted to take into account interdependencies among water uses. Yet this would not matter in hydrologic settings where return flows are not important. In such situations, frontier studies could provide insights in the design of farm-based interventions and later their evaluation. Using data from detailed farmer surveys, frontier methods could create a baseline during project preparation on the more and less efficient farmers and the underlying causes. This would help guide project design on how to help reduce technical inefficiency by focusing on information, knowledge, and management issues—which are often neglected areas and could contribute to inclusion and poverty reduction objectives. If follow-up surveys are carried out, including at project completion, a frontier study could help provide insight into key developments during implementation. For example, it could show the various on-farm effects of technology adoption decisions or the improved provision of extension services (and also a combination of the two). Unlike deductive methods which are usually built on "representative" farms' conditions, frontier methods would be able to capture the heterogeneity between farms and allow to explicitly address distributional issues.

In comparison to the other three main methods, *deductive methods* in their varied approaches are probably the most suitable tool for assessing the choice and implementation of adaptation interventions in a changing water economy. A key factor is their flexibility for adjustment to reflect different hydrologic, policy, and institutional contexts.

The hydrologic context, including complex physical processes such as those between surface and groundwater, is often explicitly considered in hydro-economic models.

Regarding the policy context, deductive methods can be formulated to explore each of the three objectives: addressing approaches for increasing irrigated agricultural production; identifying opportunities for water conservation; and providing insights into the role of irrigated agriculture in income support and economic development. They have been used to tackle the complexity of the varying objectives of water-related interventions at different spatial and temporal scales, including the trade-offs.

Deductive methods are also uniquely suited to account for the institutional context in their assessments. Institutional arrangements are concerned with the rights of users and their exposure to the rights of others; and how these rights structure the incentives and disincentives between and among users in their decisions regarding water use (Young 2005; Young and Haveman 1985). As water scarcity increases, the laws, rules, and entities affecting water allocation are becoming more formal and—while technological advances tend to reduce transaction costs—more elaborate systems of water rights and their administration evolve.[1] While the institutional context is a critical factor in determining appropriate adaptation interventions, at the same time, interventions need to increasingly focus on further developing and adjusting the institutional arrangements in order to reduce conflicts associated with increasing water competition and facilitate more sustainable agricultural water management. Deductive methods, especially the programming models, can incorporate various institutional "rules," and also assess what effects the adoption of different rules would have on farmers' likely behavior and the water-related effects.

Deductive methods are flexible to incorporate different interventions. They can assess engineering and technological interventions, and are probably most advanced for assessing policy and institutional interventions that become increasingly necessary in a maturing water economy. Furthermore, with their focus on the economic value of water, they can contribute to a more efficient allocation of water resources in times of scarcity. They are usually applied ex ante to assess the choice of interventions but, after implementation, the predicted and actual effects can be compared and analyzed.

SOME IMPLICATIONS FOR GOING FORWARD

As water scarcity intensifies, and a growing number of countries move from an expansionary to a mature phase of the water economy, the need for adaptation investments in agricultural water management from both private and public sectors will increase. Currently, much of the public debate advocates for efforts to improve agricultural water productivity and efficiency and achieve more crop per drop. Our analysis of the underlying conceptual issues of such single-factor productivity measures, as well as their applications and suitability in a maturing water economy, has shown important limitations.

There is now also an expanding body of empirical evidence of the effects of the engineering and technological interventions that are usually promoted—and subsidized with technical and financial assistance—under this approach, in particular the conversion to more capital-intensive irrigation technologies. In the past, the water-related effects of such interventions were not well explored beyond the farm or irrigation system level, in part because of the lack of data on the key water measures—including water withdrawn, applied, and consumed—and how they may change as a result of particular interventions. For the United States, for example, a growing number of studies—mostly based on deductive methods—now show that while such investments may reduce on-farm applications, they do not necessarily contribute to water conservation. Their results indicate mixed, if not counterproductive, effects on the water scarcity situation (OECD 2015; Scheierling and Tréguer 2016). The main reasons are the various adjustments that farmers can make—for example, expanding the irrigated area (as illustrated in figure 3.2).

As water economies mature, there is a need to design interventions with the local hydrologic, policy, and institutional contexts in mind. In addition, context-specific policy and institutional interventions become increasingly important. This implies that more and better ex ante assessments should be carried out to estimate the economic and financial costs and benefits as well as the water-related effects of different options. More emphasis should also be given to ex post assessments, to evaluate the implementation processes and results in line with the underlying objectives. These assessments would help inform decision makers in both the public and private sectors.

The analysis of this report suggests that, in water-scarce regions, the debate needs to urgently move beyond crop per drop issues. Our analysis of available measurement methods demonstrates that better and more comprehensive approaches are available to take into account the requirements of a maturing water economy, in particular among the deductive methods. These methods are well-suited to and often effectively integrate context-specific issues. The water-focused multifactor productivity measures incorporating the opportunity costs of nonwater inputs that are implicit in most deductive methods could be more widely reported and discussed. While the application of multifactor methods may require more resources, time, and skills than the currently dominating single-factor productivity measures, a wider use of such methods can in many instances be justified given the magnitude of the ongoing public investments in interventions for helping to address water scarcity—and the need to choose and implement them wisely.

NOTE

1. An important aspect already alluded to in figure 3.1 is the specification of the water rights. Regarding surface water, for example, water rights in much of the western United States designate a specific volume (in terms of surface water withdrawals) for use in a specific place and for a specific purpose, with a fixed priority vis-à-vis other water rights holders.

In some states, such as Colorado, there is also a prohibition to extend irrigated land beyond the original land to which a water right applies, and an emphasis on the historical consumptive use—to ensure that downstream users are not negatively affected by reductions in return flows (Scheierling, Young, and Cardon 2006). Much of the irrigated area in Colorado feeds shallow alluvial, as assumed in figure 3.1. Thus, a farmer could not move from case (i) to case (ii) due to the limit on the irrigated area and the limit on the reduction of return flows; otherwise downstream users could intervene. Regarding groundwater, many western states issue permits but California does not (Escriva-Bou et al. 2016). In the latter situation, interventions aimed at agricultural (surface) water conservation are likely to lead to increased groundwater use.

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Appendix
Table and Figures

TABLE A.1 **Water Withdrawals as Percent of Total Renewable Resources, by Country**

COUNTRY	TOTAL WITHDRAWAL AS PERCENT OF TOTAL RENEWABLE WATER RESOURCES	AGRICULTURAL WITHDRAWAL AS PERCENT OF TOTAL RENEWABLE WATER RESOURCES
Afghanistan	31.04	30.61
Albania	0.04	0.02
Algeria	72.19	42.76
Angola	0	0
Antigua and Barbuda	0.22	0.03
Argentina	0.04	0.03
Armenia	0.38	0.15
Australia	0.04	0.03
Austria	0.04	0
Azerbaijan	34.52	29.12
Bahrain	308.10	137.24
Bangladesh	0.03	0.03
Barbados	101.25	68.50
Belarus	0.03	0.01
Belgium	0.33	0
Belize	0	0
Benin	0	0
Bhutan	0	0
Bolivia	0	0
Botswana	0.02	0.01
Brazil	0.01	0.01
Brunei Darussalam	0.01	0
Bulgaria	0.29	0.04
Burkina Faso	0.06	0.03
Burundi	0.02	0.02
Cabo Verde	0.07	0.07
Cambodia	0	0
Cameroon	0	0
Canada	0.01	0
Central African Republic	0	0
Chad	0.02	0.01
Chile	0.04	0.03
China	0.21	0.14
Colombia	0	0
Comoros	0.01	0
Congo, Dem. Rep.	0	0
Congo, Rep.	0	0
Costa Rica	0.02	0.01
Côte d'Ivoire	0.02	0.01
Croatia	0.01	0
Cuba	0.18	0.12
Cyprus	32.73	21.49
Czech Republic	0.13	0
Denmark	0.11	0.03
Djibouti	0.06	0.01
Dominica	0.1	0.01
Dominican Republic	30.45	24.32
Ecuador	0.02	0.02
Egypt, Arab Rep.	133.79	114.92
El Salvador	0.08	0.05
Equatorial Guinea	0	0
Eritrea	0.08	0.08
Estonia	0.13	0
Ethiopia	0.09	0.08
Fiji	0	0
Finland	0.06	0

(continued)

TABLE A.1, *continued*

COUNTRY	TOTAL WITHDRAWAL AS PERCENT OF TOTAL RENEWABLE WATER RESOURCES	AGRICULTURAL WITHDRAWAL AS PERCENT OF TOTAL RENEWABLE WATER RESOURCES
France	0.14	0.01
Gabon	0	0
Gambia, The	0.01	0
Georgia	0.03	0.02
Germany	0.21	0
Ghana	0.02	0.01
Greece	0.14	0.12
Grenada	0.07	0.01
Guatemala	0.03	0.01
Guinea	0	0
Guinea-Bissau	0.01	0
Guyana	0.01	0.01
Haiti	0.1	0.09
Honduras	0.02	0.01
Hungary	0.05	0
India	39.82	36
Indonesia	0.06	0.05
Iran, Islamic Rep.	68.10	62.77
Iraq	73.45	57.87
Ireland	0.02	0
Israel	109.78	63.43
Italy	0.24	0.1
Jamaica	0.08	0.04
Japan	0.19	0.13
Jordan	100.42	65.23
Kazakhstan	0.2	0.13
Kenya	0.1	0.06
Korea, Rep.	41.89	22.9
Kuwait	4,566.00	2,459.50
Kyrgyz Republic	33.9	31.53
Lao PDR	0.01	0.01
Latvia	0.01	0
Lebanon	0.29	0.17
Lesotho	0.01	0
Liberia	0	0
Libya	832.86	692.86
Lithuania	0.03	0
Luxembourg	0.01	0
Macedonia, FYR	0.09	0.02
Madagascar	0.04	0.04
Malawi	0.08	0.07
Malaysia	0.02	0
Mali	0.04	0.04
Malta	89.70	57.43
Mauritania	0.12	0.11
Mauritius	0.26	0.18
Mexico	0.17	0.13
Moldova	0.09	0
Mongolia	0.02	0.01
Morocco	35.97	31.57
Mozambique	0.01	0
Myanmar	0.03	0.03
Namibia	0.01	0.01
Nepal	0.05	0.04
Netherlands	0.12	0
New Zealand	0.02	0.01
Nicaragua	0.01	0.01
Niger	0.03	0.02
Nigeria	0.04	0.02
Norway	0.01	0
Oman	94.36	83.43
Pakistan	74.35	69.85
Panama	0.01	0
Papua New Guinea	0	0
Paraguay	0.01	0
Peru	0.01	0.01
Philippines	0.17	0.14
Poland	0.19	0.02
Puerto Rico	0.58	0.01
Qatar	765.52	451.72
Romania	0.03	0.01
Russian Federation	0.01	0
Rwanda	0.01	0.01
Saudi Arabia	986.25	867.92
Senegal	0.06	0.05
Serbia	0.03	0
Sierra Leone	0	0
Singapore	0.32	0.01
Slovak Republic	0.01	0
Slovenia	0.04	0
Somalia	22.44	22.32
South Africa	0.3	0.19
South Sudan	0.01	0
Spain	33.5	22.84
Sri Lanka	24.53	21.42
St. Kitts and Nevis	0.65	0.01
St. Lucia	0.14	0.1
Sudan	71.24	68.54

(continued)

TABLE A.1, *continued*

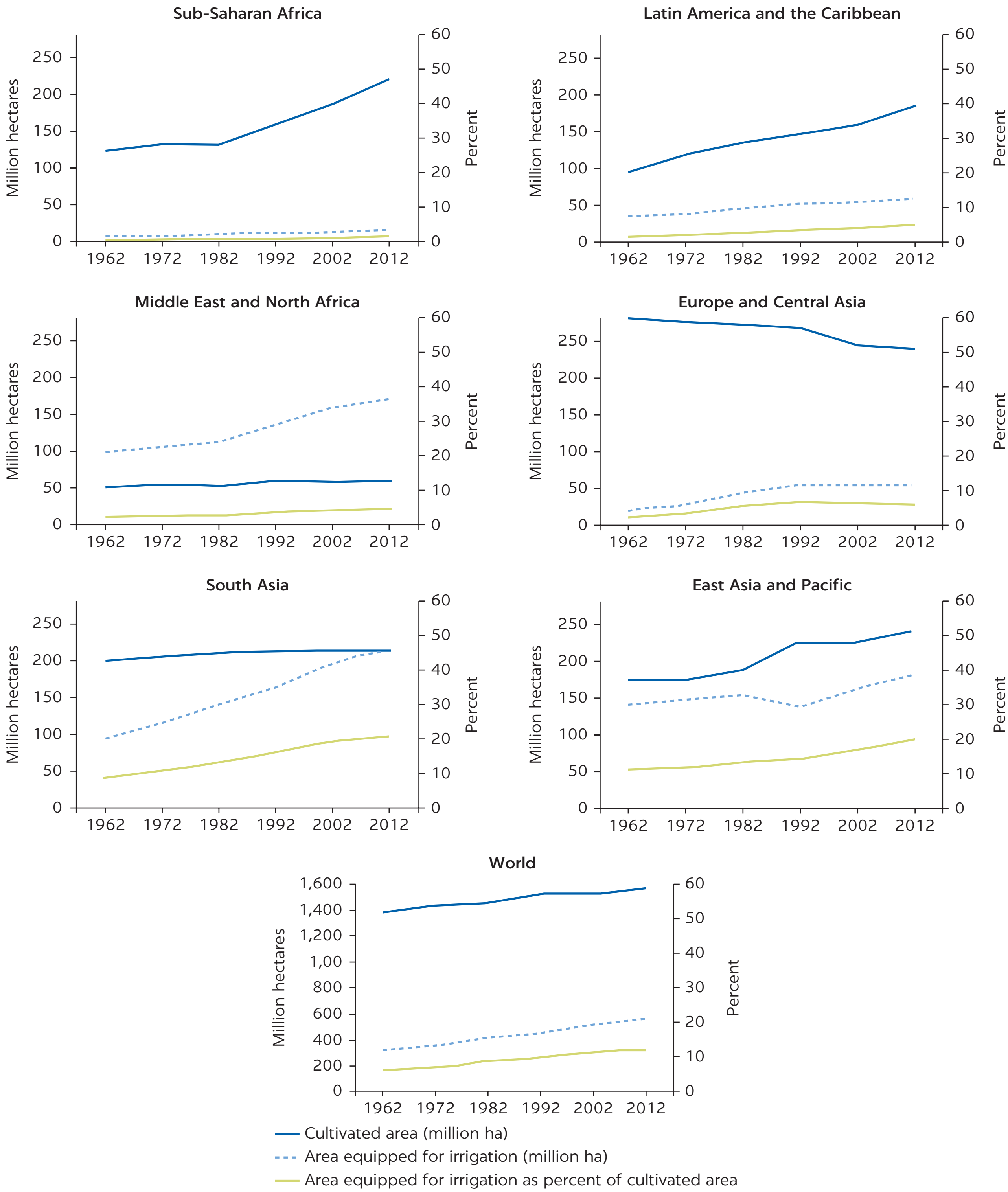
COUNTRY	TOTAL WITHDRAWAL AS PERCENT OF TOTAL RENEWABLE WATER RESOURCES	AGRICULTURAL WITHDRAWAL AS PERCENT OF TOTAL RENEWABLE WATER RESOURCES
Suriname	0.01	0
Swaziland	23.1	22.31
Sweden	0.02	0
Switzerland	0.04	0
Syrian Arab Republic	99.76	87.32
Tajikistan	52.44	47.65
Tanzania	0.05	0.05
Thailand	0.13	0.12
Timor-Leste	0.14	0.13
Togo	0.01	0.01
Trinidad and Tobago	0.1	0
Tunisia	71.61	57.29
Turkey	0.2	0.16
Turkmenistan	112.84	106.42
Uganda	0.01	0
Ukraine	0.08	0.03
United Arab Emirates	2,665.33	2,208.00
United Kingdom	0.06	0.01
United States	0.16	0.06
Uruguay	0.02	0.02
Uzbekistan	114.59	103.13
Venezuela, RB	0.02	0.01
Vietnam	0.09	0.09
West Bank and Gaza	49.94	22.58
Yemen, Rep.	169.76	154.05
Zambia	0.02	0.01
Zimbabwe	0.18	0.15

Source: Based on FAO 2016.

Water scarcity status (%):
● 0–10 ● 10–20 ● 20–40 (Scarcity) ● 40–60 (Severe Scarcity)
● 60–80 (Severe Scarcity) ● 80–100 (Severe Scarcity) ● >100 (Severe Scarcity)

FIGURE A.1

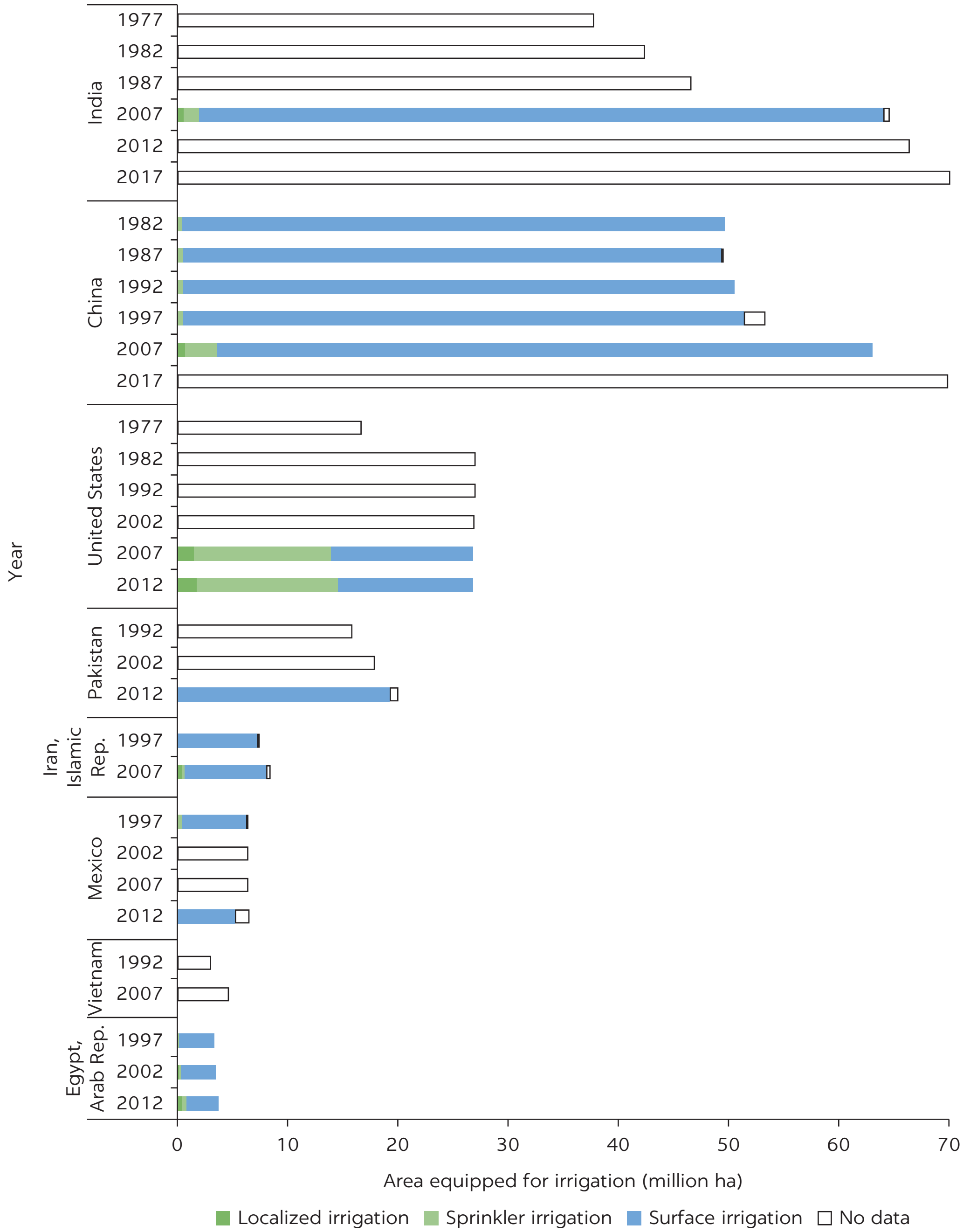
Area Cultivated and Area Equipped for Irrigation, by Region



Source: Based on FAO 2016.

FIGURE A.2

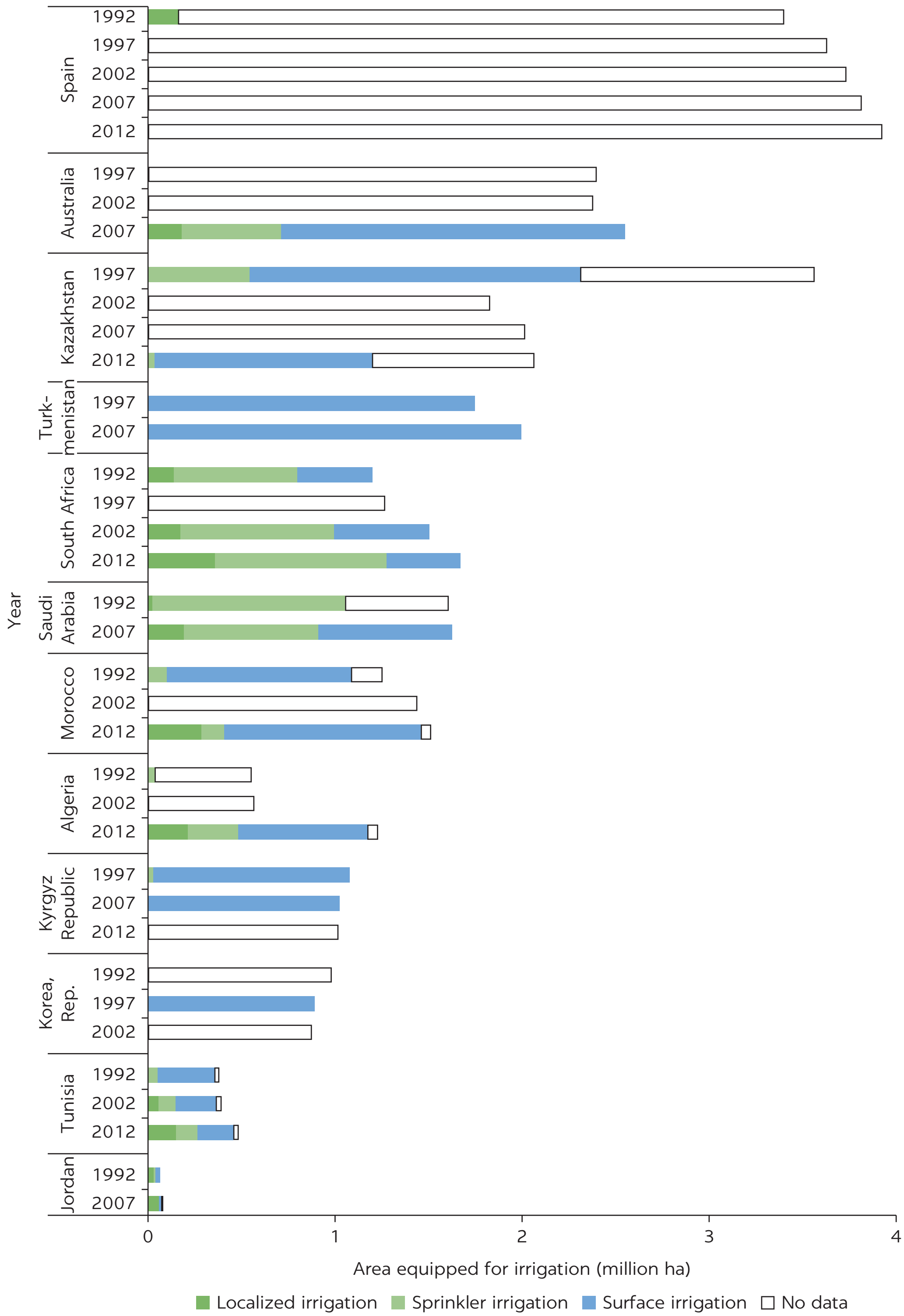
Trends in Area Equipped for Irrigation and Irrigation Systems for Countries with the Largest Agricultural Withdrawals



Source: Based on FAO 2016.

FIGURE A.3

Trends in Area Equipped for Irrigation and Irrigation Systems for Other Countries



Source: Based on FAO 2016.

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green press INITIATIVE

With growing water scarcity in many parts of the world and projections that indicate the need to increase agricultural production and, concurrently, agricultural water use, the calls to improve agricultural water productivity and efficiency—and thus achieve more crop per drop—are growing. Many international organizations that focus on water management are also promoting these efforts, and significant public and private investments are being made in both developed and developing countries. Yet some serious problems are associated with this approach. They include conceptual issues, the methods used for measuring agricultural water productivity and efficiency, and the application of these concepts and methods in different contexts—all of which influence the choice of interventions and the evaluation of their implementation.

The report aims to shed further light on these issues: first, by clarifying some of the underlying concepts in the discussion of agricultural water productivity and efficiency; second, by reviewing and analyzing the available methods for assessing water productivity and efficiency, including single-factor productivity measures, total factor productivity indices, frontier methods, and deductive methods; and, third, by discussing their application and relevance in different contexts. As a background for this analysis, the report highlights the central role of water use in irrigated agriculture and its link with increasing water scarcity.

An underlying framework of the analysis is the view of the water economy transitioning from an expansionary to a mature phase. The report further develops this framework to reflect water management issues in irrigated agriculture. The framework is then applied to make the case that, with increasing water scarcity, the ongoing efforts for improving agricultural water productivity and efficiency need to move beyond crop-per-drop approaches, because they are in many circumstances an insufficient and sometimes counterproductive attempt to adapt agricultural water management to a maturing water economy.

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