IWMI Research Report

169

Beyond "More Crop per Drop": Evolving Thinking on Agricultural Water Productivity

Meredith Giordano, Hugh Turral, Susanne M. Scheierling, David O. Tréguer and Peter G. McCornick

International Water Management Institute

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IWMI's mission is to *provide evidence-based solutions to sustainably manage water and land resources for food security, people's livelihoods and the environment.* IWMI works in partnership with governments, civil society and the private sector to develop scalable agricultural water management solutions that have a tangible impact on poverty reduction, food security and ecosystem health.

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"Everything has been said before, but since no one listens, one must always start again."

André Gide
(quoted in Seckler 1999)

International Water Management Institute (IWMI)
P O Box 2075, Colombo, Sri Lanka

The authors: Meredith Giordano is Principal Researcher at the International Water Management Institute (IWMI) in Washington, DC, USA; Hugh Turral was formerly Theme Leader - Basin Water Management at IWMI in Colombo, Sri Lanka; Susanne M. Scheierling is Senior Irrigation Water Economist at The World Bank, Washington, DC, USA; David O. Tréguer is Agricultural Economist at The World Bank, Washington, DC, USA; and Peter G. McCornick is Executive Director of the Robert B. Daugherty Water for Food Global Institute at the University of Nebraska, Lincoln, Nebraska, USA. Peter was formerly Deputy Director General – Research (DDG) at IWMI in Colombo, Sri Lanka.

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Summary

Twenty years ago, the International Water Management Institute (IWMI), then known as the International Irrigation Management Institute (IIMI), published its first Research Report entitled *The new era of water resources management: From "dry" to "wet" water savings*. The report stressed the increasingly difficult problems facing water management, including growing demands for, and competition over, scarce water resources, and the physical, economic and environmental constraints to developing additional supplies. While a large body of research already existed on opportunities to improve irrigation efficiency and water-use efficiency, David Seckler, the newly appointed Director General of IIMI at that time and author of the research report, argued that the classical notions of 'efficiency' may be inappropriate for water management and planning at the basin level, as they do not take into account the potential reuse of water within larger hydrologic systems. To incorporate these reuse effects, Seckler proposed the concept of agricultural water productivity as an alternative metric to guide future basin management strategies aimed at achieving *real* efficiency gains and *real* water savings.

Since the publication of that first Research Report, improving agricultural water productivity has been a core component of IWMI's research agenda and a number of initiatives led by the Institute. This Research Report chronicles the evolution of thinking on water productivity in the research agenda of IWMI and in the broader irrigation literature over the past 20 years. It describes the origins of the concept and the methodological developments, its operationalization through applied research, and some lessons learned over the two decades of research. This report further highlights how a focus on agricultural water productivity has brought greater attention to critical water scarcity issues, and the role of agricultural water management in supporting broader development objectives such as increasing agricultural production, reducing agricultural water use, raising farm-level incomes, and alleviating poverty and inequity. Yet, reliance on a single-factor productivity metric, such as agricultural water productivity defined as "crop per drop," in multi-factor and multi-output production processes can mask the complexity of agricultural systems as well as the trade-offs required to achieve desired outcomes. The findings from this retrospective underscore the limitations of single-factor productivity metrics while also highlighting opportunities to support more comprehensive approaches to address water scarcity concerns and, ultimately, achieve the broader development objectives.

A reflection on the lessons learned is especially relevant given the adoption of the United Nations (UN) 2030 Agenda for Sustainable Development in 2015 and their supporting Sustainable Development Goals (SDGs). In particular, Goal 6.4 aims to "by 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity." This is the first time that the efficiency with which water is used has a place on the mainstream development agenda. The insights and opportunities presented in this report are intended to inform the development and application of appropriate indicators and measures to meaningfully track progress towards this stated goal, and support the UN's broader objective of achieving sustainable development for people, planet and prosperity.

Beyond "More Crop per Drop": Evolving Thinking on Agricultural Water Productivity

Meredith Giordano, Hugh Turral, Susanne M. Scheierling, David O. Tréguer and Peter G. McCornick

1. Introduction

Improving agricultural water productivity has been a core component of the International Water Management Institute's (IWMI's) research agenda since the mid-1990s.[1] In 1996, David Seckler, the newly appointed Director General of IIMI at that time, published the first IWMI Research Report, *The new era of water resources management: From "dry" to "wet" water savings* (Seckler 1996). The report outlined several key ideas that fundamentally changed IWMI's research paradigm from one that focused on 'irrigation efficiency' and 'performance of irrigation systems' to one centered on 'water productivity' and 'river basin management' (Rijsberman 2006). Since that time, IWMI has contributed significantly to developing the concept of water productivity, particularly as it relates to surface water and groundwater,[2] and supporting its application across a range of geographic and agroecological settings.

Water productivity has been central to many IWMI research projects and to a number of major programs led by the Institute, including the Consultative Group on International Agricultural Research (CGIAR) System-Wide Initiative on Water Management (SWIM); Comprehensive Assessment of Water Management in Agriculture (CA); CGIAR Challenge Program on Water and Food (CPWF); and the CGIAR Research Program on Water, Land and Ecosystems (WLE). While IWMI's view and approach to the concept of water productivity has evolved through the research and experiences of these programs, the concept has remained a core component in each of them (Box 1).

These four programs have contributed a significant body of work on water productivity—conceptually and operationally—addressing different geographies, scales and contexts. Snapshots of this large body of work have been provided by a number of earlier reviews. A book related to the CA program on the limits and opportunities for improving water productivity in agriculture was an effort to collate the latest knowledge on concepts, methodologies, and case studies globally (Kijne et al. 2003b). This was followed by a book reviewing IWMI's research from 1996 to 2006 with a focus on the 'more crop per drop' paradigm (Giordano et al. 2006). A synthesis of the CPWF described how the program's research prompted a fundamental shift in thinking from water productivity as a "principle objective" to water productivity as an "entry point" to understand limitations to water access and availability (Vidal et al. 2014). Furthermore, Clement (2013) and Lautze et al. (2014) offered important insights on the concept of water productivity and the extent to which the concept is a true paradigm or, rather, an element of (or indicator within) the larger food-water-ecosystem discourse.

Building on the earlier reviews, this report synthesizes 20 years of research on water productivity and lessons learned across the four major IWMI-led programs. It expands on a background paper (IWMI 2015a) commissioned by The World Bank as part of a study carried out by the Water and Agriculture Global Practices

[1] IWMI was formally established as the International Irrigation Management Institute (IIMI) by an Act of the Parliament of Sri Lanka in 1985, and was officially recognized as the International Water Management Institute (IWMI) in 2000.

[2] In this report, 'water productivity' refers to agricultural water productivity, unless otherwise stated.

Box 1. Major IWMI-led programs focused on water productivity.

CGIAR System-Wide Initiative on Water Management (SWIM) (1995-1999): SWIM supported much of the early work on water productivity. Launched in 1995 by the Technical Advisory Committee of the CGIAR, SWIM was a collaborative research program focusing on broad issues of water management and agricultural production within a basin context. Key research themes included water accounting, salinity management, water-land relations, water productivity, multiple uses, water harvesting and basin-scale modeling. Many of the fundamental water productivity concepts, tools and indicators emerged from this body of work. Visit: http://www.iwmi.cgiar.org/publications/other-publication-types/swim-papers

Comprehensive Assessment of Water Management in Agriculture (CA) (2001-2006): Commencement of the CA program in 2001 fostered a broader, multi-disciplinary body of conceptual and applied research on water—globally, regionally and in selected river basins in Asia and Africa. The program, involving hundreds of CGIAR researchers and partners, aimed to improve water investment and management decisions to meet poverty, hunger, and environmental sustainability objectives by understanding the (i) options to enhance agricultural water productivity; (ii) benefits, costs and impacts from past developments in irrigated agriculture; and (iii) water requirements to meet future food security and environmental sustainability goals. Visit: http://www.iwmi.cgiar.org/assessment/Publications/books.htm

CGIAR Challenge Program on Water and Food (CPWF) (2004-2013): Informed by SWIM and early CA research, IWMI called for a major new research-for-development program to catalyze water productivity improvements that are effective and efficient as well as pro-poor, gender-equitable, and environmentally sustainable. This call led to the launch of the CPWF. The program was a major multi-partner program with the aim of raising water productivity and improving food security while helping to alleviate poverty, improve health, and attain environmental security. Over the course of a decade, the program funded over a hundred projects, concentrated primarily in 10 major river basins in Asia, Africa and South America. Visit: https://waterandfood.org

CGIAR Research Program on Water, Land and Ecosystems (WLE) (2012-present): In 2011, the CPWF was reoriented to become part of the new CGIAR Research Program on Water, Land and Ecosystems (WLE). It comprises 11 CGIAR centers and the Food and Agriculture Organization of the United Nations (FAO) as core partners. Through collaboration with research, policy and implementing organizations in Asia, Africa and South America, WLE aims to increase water and land productivity in a sustainable manner in order to secure the provision of ecosystem services, improve food security, reduce poverty, and promote gender and social equity. Visit: https://wle.cgiar.org

on *Improving agricultural water productivity and beyond: what are the options?* (Scheierling et al. 2014). This report aims to provide key highlights from two decades of IWMI research and the broader irrigation literature on agricultural water productivity, with an emphasis on the evolution and application of the concept, highlighting its contributions and limitations while identifying opportunities for further refinements in the way it is understood and applied. Chapter 2 describes the origins of the concept of agricultural water productivity and its methodological developments. Chapter 3 illustrates the different ways the concept has been operationalized in applied research, offers a description of the pathways—with their associated interventions—for improving water productivity, and discusses the contributions to broader development objectives. Based on these, and considering the broader literature, Chapter 4 presents a set of key lessons and insights from two decades of research on water productivity. Chapter 5 concludes by highlighting how a focus on agricultural water productivity has brought greater attention to critical water scarcity and management issues. Important strategic opportunities remain, however, for continued improvements in technologies and management practices, data sources, and interdisciplinary research to develop and apply more comprehensive approaches to address water scarcity concerns and, ultimately, make progress towards broader development objectives.

This reflection on past research, lessons learned, and future opportunities to improve the understanding of the role of water in agricultural production and productivity is timely given the adoption of the United Nations Sustainable Development Goals (SDGs) in 2015. Specifically, Goal 6.4 aims to, "by 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity" (United Nations 2015, 21). This is the first time the efficiency with which water is used has a place on the mainstream development agenda. We hope that some of the insights and opportunities presented in this report will also inform the development and application of appropriate indicators and measures to meaningfully track progress towards the achievement of this goal.

2. Origins of the Concept and Methodological Developments

IWMI's focus on water productivity originated in large part from a concern over increasing water scarcity and longer-term trends in water supply and demand. Cautioning that the problems with water management may be much more severe than commonly acknowledged, Seckler (1996, 5) pointed out the "increasingly difficult problems facing water management," including growing demands for, and competition over, scarce water resources, as well as the physical, economic and environmental constraints to developing additional supplies. With agriculture being the largest user of water resources worldwide, there was a need to identify ways to achieve *real* efficiency gains and *real* water savings, and, thus, "opportunities for increasing the productivity of water" (Seckler 1996, 10). This idea was later formulated as growing more food with the same or less amount of water, a concept that became popularly known as 'more crop per drop'.[3]

This chapter presents in more detail the evolution of the concept of agricultural water productivity, its influence on a "new era" of water research at IWMI and elsewhere, and related methodological developments that supported its operationalization.

2.1 From Irrigation Efficiency to Agricultural Water Productivity

By the early 1990s, a wide body of research from different disciplines—including agronomy, plant physiology, and irrigation engineering—already existed on opportunities to increase *irrigation efficiency* and *water-use efficiency*. Box 2 presents some of the key terms and definitions. As a background to the definitions, it is useful to keep in mind the different measures of water quantity (Young 2005):

- *Water withdrawal*. This measure refers to the amount of water removed (or diverted) from a surface water or groundwater source.
- *Water application*. Water applied (or delivered) differs from water withdrawn by the amount of water lost in transit from

[3] For example, in 2000, Kofi Annan, the then UN Secretary General referred to the need for a "'Blue Revolution' in agriculture, focused on increasing productivity per unit of water, or 'more crop per drop'" (Annan 2000, 2).

the point of withdrawal to the point of use. This delivery (or conveyance) loss usually stems from leakages (for example, from unlined earthen canals).

- *Water consumption*. This measure (also called consumptive use, crop evapotranspiration, or depletion) refers to the amount of water that is actually depleted by the crops, i.e., transferred to the atmosphere through evaporation from plant and soil surfaces and through transpiration by plants, incorporated into plant products, or otherwise removed from the immediate water environment.

Box 2. Terms and definitions.

Classical irrigation efficiency

The term refers to the ratio of water consumed by crops relative to water applied or, in some instances, relative to water withdrawn from a source. The numerator sometimes takes into account effective precipitation, by deducting it from the water consumed. To assess losses in the conveyance and application of irrigation water, the terms *conveyance efficiency* (ratio of water received at the farm gate relative to the water withdrawn from the water source) and *application efficiency* (ratio of water stored in the root zone and ultimately consumed by crops relative to the water delivered to the farm gate), respectively, are used.

Sources: Israelsen 1932, 1950; Keller and Keller 1995; Burt et al. 1997; Cai et al. 2006; Jensen 2007.

Water-use efficiency

The term refers to the ratio of plant biomass (or yield) relative to the water consumed (or, in some instances, transpired). In the field of agronomy and plant physiology, it is typically expressed in kilograms per cubic meter (kg/m^3).

Sources: Viets 1962; Molden 1997; Renault and Wallender 2000; Howell 2001; Hsiao et al. 2007; Perry et al. 2009.

Effective irrigation efficiency

The term is defined as the ratio of water consumed, minus effective precipitation, relative to the effective use of water. Effective use of water is the difference between water inflow to an irrigation system and water outflow (with both flows discounted for the leaching requirements to hold soil salinity at an acceptable level). The term was developed to address some of the limitations of classical irrigation efficiency by taking into account the quantity of water delivered from, and returned to, a water supply system (as well as the leaching requirements).

Sources: Keller and Keller 1995; Keller et al. 1996; Cai et al. 2006; Jensen 2007.

Water productivity

The term refers to the ratio of physical production (in terms of biomass or crop yield) or, in some instances, 'economic value' of production (in terms of gross or net value of product) relative to water use (in terms of water withdrawn, applied or consumed). It is, therefore, expressed in kilograms per cubic meter (kg/m^3) or US dollars per cubic meter (USD/m^3). The selection of the numerator and denominator depends on the scale and focus of the analysis.

Sources: Molden 1997; Molden et al. 1998b; Molden and Sakthivadivel 1999; Jensen 2007.

The different disciplines often understand the terms ‘efficiency’ and ‘productivity’ in different ways, and also tend to focus on different measures of water. For example, the classical notion of *irrigation efficiency* was developed in irrigation engineering, and commonly measures the ratio of water consumed to water applied or withdrawn from a source. Plant physiologists and agronomists often use the term ‘*water-use efficiency*’ and apply different definitions, such as the ratio of plant biomass or yield to transpiration, or the ratio of yield to water consumed.[4] A further confounding factor is the range of scales (both spatial and temporal) at which the terms can be defined and applied, e.g., from field-scale, seasonal measures of grain biomass per unit of water transpired to basin-scale, annual estimates of the economic value obtained per unit of water applied in the agriculture or other sectors (Kijne et al. 2003a; Bouman 2007; Molden et al. 2007b).

Starting in the mid-1990s, Seckler (1996) and others (e.g., Keller and Keller 1995; Keller et al. 1996) argued that “efficiency” was a tricky concept in the context of a mobile resource such as water, and highlighted a need for metrics that account for the capture and reuse of water within broader hydrologic systems, such as river basins. As stated by Keller and Keller (1995, 7), “The classical concepts of irrigation efficiency have been appropriate for farmers making irrigation management decisions and for planners designing irrigation conveyance and application systems. But applying classical efficiency concepts to water basins as a whole leads to incorrect decisions and, therefore, to faulty public policy.”

To demonstrate this point, Keller and Keller (1995) and Keller et al. (1996) used the case of the Nile Valley, where deep percolation either returns to the river or recharges groundwater supplies. Classical efficiency concepts do not account for such return flows and their subsequent reuse. Thus, in this case, applying irrigation efficiency concepts alone could lead to the conclusion that significant opportunities existed for efficiency gains. In reality, however, despite local irrigation inefficiencies, the scope for improved efficiency at the sub-basin or basin scale (and thus for *real* water savings) is limited due to the reuse of the return flows elsewhere in the Nile Valley. Moreover, because of the opportunity to recharge groundwater aquifers through return flows, a strategy involving over-watering on the fields and allowing seepage losses from conveyance canals may be preferable to promoting local (application or conveyance) efficiency gains in this situation.

Several modifications were proposed to address the limitations to classical efficiency concepts. This includes the term ‘effective irrigation efficiency’ to account for leaching requirements and return flows (Keller and Keller 1995), and the concept of ‘fractions of water use’ to break down consumptive and non-consumptive uses and analyze the purposes for which water is consumed (Willardson et al. 1994; Frederiksen and Perry 1995; Molden 1997). These refinements to the irrigation efficiency terminology, and the underlying principles, contributed to the conceptual development of *water productivity*.[5]

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4 Hsiao et al. (2007) showed that the ‘efficiency’ concept can be used for an array of steps that may be involved in converting an input into a final end product. They applied the chain of efficiency approach to systematically quantify and integrate the complex steps involved to convert water into an agricultural output. When the production of an output is complicated and an input (such as water) goes through a chain of sequential steps ending in the output, the overall efficiency of the process can be quantified in terms of the efficiency of each of the component steps. The output in any step in the chain is the input in the following step. For example, if water is withdrawn from a reservoir for irrigated crop production, the efficiency of the first step would be conveyance efficiency, calculated as the ratio of water received at the farm gate to the water withdrawn; the second step would be farm efficiency, calculated as the ratio of water at the field edge to the water at the farm gate, and so on. In all, the authors present a chain with three engineering-related and five agronomy-related efficiencies, with the last one being yield efficiency, defined as the ratio of harvested yield to the plant biomass. At each efficiency step, different interventions could be made to improve the respective efficiency measure, yet the effects would extend to the whole process.

5 It is interesting to note that the term ‘water productivity’ dates back, at least, to the nineteenth century, when it was used in connection with water management for agriculture in the Indus River Basin, and defined as the number of farm holdings per unit of available water (Renault and Wallender 2000).

Productivity is conventionally understood as a ratio that refers to output per unit of input. *Water productivity*, like land and labor productivity, is a single-factor productivity metric applied in a multi-factor production process. In its basic form, water productivity measures production per unit of water use. The denominator, water use, may be measured in terms of water withdrawn, applied, or consumed. The numerator can also be expressed in different forms. In the case of *physical* water productivity, expressed in kilograms per cubic meter (kg/m^3), the numerator is defined as the physical mass of production (such as biomass or crop yield). In the case of *economic* water productivity, expressed in US dollars per cubic meter (USD/m^3), the numerator is usually expressed as gross value of output (yield multiplied by price). Other formulations for the numerator have also been used in the literature; an example is water productivity in *nutritional terms*, expressed in protein grams or kilocalories ($kcal/m^3$) (Molden 1997; Molden and Sakthivadivel 1999; Renault and Wallender 2000). The water productivity concept is thus applied for different purposes and at a range of scales (field, farm, irrigation system, and basin).

The next section describes how the evolution and development of the water productivity concept inspired a "new era" of water research at IWMI. This included a shift from an earlier focus on farm- and irrigation system-level irrigation efficiency to one focused on ways to grow more food with the same or less amount of water—with the aim of alleviating water scarcity, achieving food security and placing less strain on the environment (Rijsberman and Molden 2001).

2.2 A "New Era of Water Resources Management"

IWMI Research Report 1 (Seckler 1996) introduced the concept of water productivity and related strategies for its improvement to promote "real solutions" to complex water management problems. The report aimed to inspire new and creative concepts that could address key food security and environmental challenges—and thus initiated a "new era of water management" (Seckler 1996, 3). The focus was on three fundamental points:

- Classical notions of irrigation efficiency overlook the fact that so-called "losses" in water conveyance and application may be reused, or "recycled", elsewhere in a river basin.[6] Thus, measures of irrigation efficiency do not take into account the **recycling opportunities** for irrigation water.
- Because of these recycling opportunities, there is the need to distinguish between **real water savings** (e.g., due to a reduction in consumptive water use) and **reallocation of water** (e.g., where water is redistributed from one user to another). Because of the extent of water recycling at the basin scale, the actual scope for real water savings is often less than imagined. For example, a water conservation strategy that simply reduces the amount of drainage water that would otherwise be reused downstream does not result in real water savings. By contrast, if the excess drainage water would have otherwise flowed into saline shallow groundwater, real water savings are possible.
- When considering water productivity or, more generally, water management strategies, **context** is important. If a basin is closing or *closed* (i.e., no usable water leaves the basin), identifying opportunities to increase water productivity becomes increasingly important. By contrast, in an *open* basin (i.e., a basin with uncommitted utilizable outflows), other water management objectives may be more appropriate—such as increasing the supply of water to a particular sector, transferring water to another basin with more

[6] Seckler later referred to this as the "water multiplier effect", which can enhance the productivity of the water inflow into a basin (Seckler et al. 2003).

pressing water needs, or reserving water for environmental services.

Taking the above points into consideration, Seckler (1996) highlighted four basic basin-scale water management strategies to promote improved water productivity and achieve *real efficiency gains* in both open and closed basins:

(i) Increase the output per unit of evaporated water.

(ii) Reduce losses of water to sinks and evaporation.

(iii) Reduce the deterioration of water quality.

(iv) Switch from lower-value to higher-value uses of water.

Seckler described the potential for increasing water productivity and efficiency from water use as enormous, but also highlighted the equally enormous conceptual and practical challenges in doing so, a challenge which he encouraged IWMI and others to overcome.

2.3 Water Accounting and Water Productivity Indicators

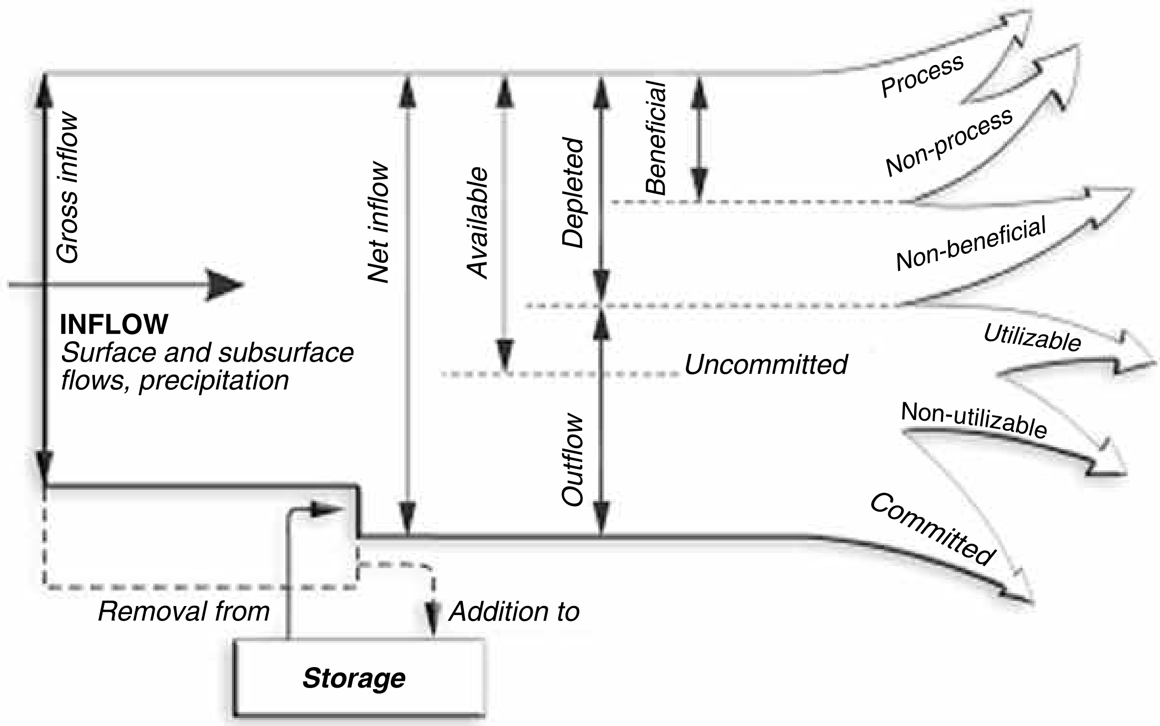
In the years following the publication of IWMI Research Report 1 (Seckler 1996), the Institute's research concentrated on developing a common framework and set of indicators to assess and measure water productivity across a range of uses and scales. The SWIM and CA programs were a fundamental part of this effort, laying the foundation for the concept's operationalization. Below is a summary of some of the key developments in this regard.

2.3.1 Water Accounting and Performance Indicators

To place water productivity in context, the first SWIM Paper focused on the development of a water accounting framework to identify possible strategies to achieve real water savings and improve water productivity (Molden 1997). The framework, illustrated in Figure 1, is based on a water balance approach and a categorization of water based on how it is (re)used (Molden 1997; Molden et al. 1998a; Molden and Sakthivadivel 1999; Jensen 2007; Perry 2007):

- *Inflow* into the domain of interest is classified as *gross* inflow (i.e., the amount of water flowing into a sub-basin from precipitation and surface and subsurface sources) and *net* inflow (i.e., gross inflow plus any changes in storage).
- *Available water* is the net inflow less the amount of water set aside for committed outflows (such as for downstream water rights and non-utilizable outflows), and includes depleted water (i.e., water withdrawn that is unavailable for further use) and uncommitted utilizable outflows.
- *Depleted water* includes:
    - *Beneficial* depletion, such as (i) *process* depletion (i.e., for an intended process; for example, in agriculture, the water transpired by crops plus the amount incorporated into plant tissues); and (ii) *non-process* depletion (i.e., for a process other than the one for which the diversion was intended; for example, the water transpired by trees along an irrigation canal); and
    - *Non-beneficial* depletion (such as water flows to sinks).
- *Outflow* from the domain comprises:
    - *Uncommitted* outflows, both *utilizable* and *non-utilizable* (i.e., water that is not depleted and in excess of requirements or storage or operational capacity); and
    - *Committed* outflows for other purposes downstream (e.g., downstream water rights, minimum streamflows, offshore fisheries).

FIGURE 1. Water accounting framework.



Source: Adapted from Molden et al. 2003.

The water accounting framework was developed as a means to demonstrate how much water is actually depleted in a given domain, where and for what purpose, compared to what is available. It provides a means to generalize about water productivity and use across scales—such as the crop, field, farm, irrigation system or the basin level—depending on the purpose and users of the analysis (Table 1).

TABLE 1. Water productivity at different scales.

Scale	Crop	Field	Farm	Irrigation system	Basin
Purpose	Assessing energy conversion, biomass or harvestable yield from a particular crop or cultivar	Assessing biomass or harvestable yield from a particular cropping system	Assessing harvestable yield or economic return from a farm's crop production	Assessing irrigation system performance in terms of harvestable yield or economic return	Assessing water allocation, including use of water in agriculture as compared to other sectors
Users	Plant physiologists, farmers	Soil and crop scientists, farmers	Agriculturalists, farmers	Irrigation engineers, water managers	Water managers, hydrologists

Sources: Adapted from Molden 1997; Molden et al. 2003, 2007b; Cook et al. 2006.

The aim of the water accounting framework was to provide first-order estimates of water use within and across crops (or sectors), as well as insights into opportunities for real water savings and improvements in water productivity. Some of the advantages of the framework include its ability to:

- identify total water depletions (beneficial and non-beneficial),
- distinguish between process (e.g., agriculture, cities, and industry) and non-process (e.g., forests, grassland and water bodies) beneficial depletions,
- estimate the components of beneficial and non-beneficial depletions, and
- account for downstream commitments.

To complement the framework, IWMI introduced a set of performance indicators to characterize the various uses of water in a given domain (Molden 1997; Molden et al. 1998a). These indicators built on the notions of *effective irrigation efficiency* and *fractions of water use* (Willardson et al. 1994; Frederiksen and Perry 1995), described earlier, and were organized into three main groups as follows:

- *Depleted Fraction* (DF) is the proportion of process and non-process depletion in relation to net inflow, gross inflow or available water:

  DF_{net} = depletion/net inflow

  DF_{gross} = depletion/gross inflow

  $DF_{available}$ = depletion/available water

- *Process Fraction* (PF) is the proportion of process depletion in relation to inflow, total depletion or available water:[7]

  PF_{net} = process depletion/net inflow

  PF_{gross} = process depletion/gross inflow

  $PF_{depleted}$ = process depletion/total depletion

  $PF_{available}$ = process depletion/available water

- *Productivity of Water* (PW) is the physical mass of production (or the economic value of production) per unit of water in terms of net inflow, gross inflow, depletion, process depletion, or available water:

  PW_{net} = productivity (kg or USD)/net inflow

  PW_{gross} = productivity (kg or USD)/gross inflow

  $PW_{depleted}$ = productivity (kg or USD)/depletion

  $PW_{process}$ = productivity (kg or USD)/process depletion

  $PW_{available}$ = productivity (kg or USD)/available water

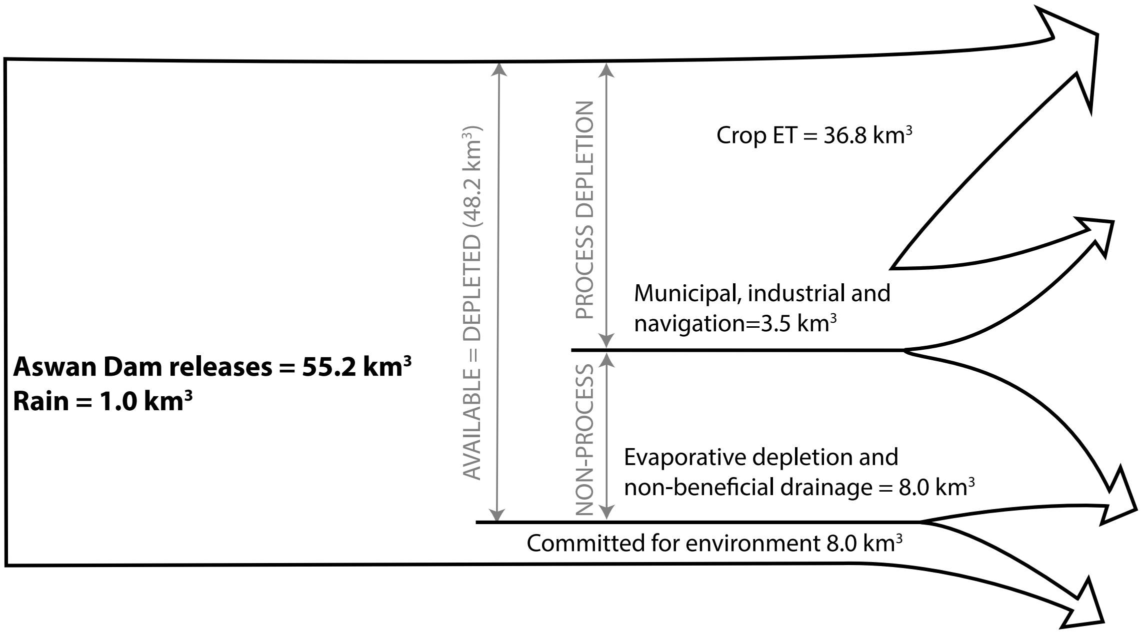
For more complex comparisons across multiple crops and multiple countries, an approach to standardize water productivity measures was proposed. This involved the conversion of physical output to value of output through the use of a standardized gross value of production indicator (Molden et al. 1998b; Sakthivadivel et al. 1999). Where data were available, the indicator could also be used for other agricultural products besides crops, such as fish and livestock (Cook et al. 2006).

IWMI applied the water accounting framework and the related indicators in a variety of locations at different scales to understand current conditions and opportunities to achieve water savings and increase water productivity in irrigated agriculture. An example of the water accounting framework applied to the Nile River below the High Aswan Dam, drawing from water balance studies carried out between 1993 and 1994, is provided below (Figure 2 and Table 2).

This example illustrates a case where a large proportion of depleted water (84%) is used for intended ("process") purposes, including crop production, and municipal, industrial and navigational uses.

[7] The process fraction of depleted water is similar to the concept of effective irrigation efficiency.

FIGURE 2. Water accounting framework for the Nile River below the High Aswan Dam (1993-1994).



Source: Based on Molden and Sakthivadivel 1999.

Note: ET = Evapotranspiration.

TABLE 2. Water accounting components for the Nile River below the High Aswan Dam (1993-1994).

Indicator	Components	Indicator value
Depleted Fraction		
$DF_{net} = DF_{gross}$[1]	48.2 km^3/(55.2 + 1.0) km^3	86%
$DF_{available}$	48.2 km^3/48.2 km^3	100%
Process Fraction (all uses)		
$PF_{depleted}$	(36.8 + 3.5) km^3/48.2 km^3	84%
$PF_{available}$	(36.8 + 3.5) km^3/48.2 km^3	84%
Process Fraction (irrigated agriculture)		
PFavailable[2]	36.8 km^3/(55.2 + 1.0 - 8.0 - 3.5) km^3	82%
Productivity of Water[3]		
PW_{gross}	USD 7.5 billion/56.2 km^3	USD 0.13/m^3
$PW_{depleted}$	USD 7.5 billion/48.2 km^3	USD 0.15/m^3
$PW_{process}$	USD 7.5 billion/36.8 km^3	USD 0.20/m^3

Sources: Adapted from Molden et al. 1998a; Molden and Sakthivadivel 1999.

Notes:

[1] Assumes no change in storage, therefore gross inflow equals net inflow.

[2] Water available for irrigation equals total water available less committed water (for the environment, and municipal, industrial, and navigational uses).

[3] Assumes gross value of production (in 1993 USD) equals USD 7.5 billion.

In this case, converting the non-beneficial portion of the remaining non-process depletion (e.g., non-beneficial drainage that is in excess of environmental requirements) could allow for improvements in the productivity of water (Molden et al. 1998a).

Similar studies were carried out at irrigation system and basin scales in Sri Lanka (Molden et al. 1998b; Molden and Sakthivadivel 1999), India (Elkaduwa and Sakthivadivel 1999; Bastiaanssen et al. 1999a, 1999b; Hussain et al. 2000, 2003), Pakistan (Hussain et al. 2000; Tahir and Habib 2000), China (IWMI 2003; Roost 2003), Turkey (Kite and Droogers 2000a; IWMI and GDRS 2000), Iran (Murray-Rust and Droogers 2004), and Central Asia (Murray-Rust et al. 2003).

2.3.2 Beyond "More Crop per Drop"

Early reflections on water productivity and the related indicators highlighted several limitations to a restrictive "crop per drop" interpretation and the need for methodological advances to assess the broader implications from, including the costs and benefits of, improved water productivity. Restricting the interpretation and application of water productivity to crop outputs, for example, ignored important non-crop outputs such as fisheries, livestock, environmental services and other benefits (and costs) from the use and reuse of water (Rijsberman 2006). In some circumstances, non-process uses (such as environmental services) may provide as much value or more than the process uses (Renault and Wallender 2000; Murray-Rust and Turral 2006).

Several studies conducted by the SWIM and CA programs further aimed to identify and, as far as possible, quantify the range of benefits (both process and non-process) from the use (and non-use) of water (e.g., Bakker et al. 1999; Bakker and Matsuno 2001; Meinzen-Dick and Bakker 1999, 2001; Renwick 2001; Meinzen-Dick and van der Hoek 2001; Hussain et al. 2007; Molden et al. 2007b). These studies highlighted that conventional "crop per drop" indicators of water productivity may not provide reasonable estimates of the overall benefits or value of water as they do not account for the broader uses as well as the direct and indirect costs and benefits of water at various levels, and how these values may vary significantly across time, space and user (Hussain et al. 2007). As described by Bakker et al. (1999, vii), "to ensure efficient, equitable, and sustainable water use, to reduce poverty and improve the well-being of the community, irrigation and water resources policies need to take into account all uses and users of water within the irrigation system."

Moreover, even while many argued that improving water productivity was an inherently good idea, IWMI researchers cautioned early on that a focus on a single-factor productivity metric in agricultural production processes with multiple factors (or inputs) may provide misleading results from the perspective of the farmer, as well as from the economy as a whole (Barker et al. 2003). An example would be researchers and extension agents who focus on potential water productivity gains (either in physical or "economic" terms) without considering the often significant, additional costs involved. Yet, improvements in agricultural water productivity may require more labor, better management, or other additional inputs, and the changes in these inputs and the related costs and benefits (economic, financial, social and environmental) tend not to be incorporated into single-factor productivity metrics. A greater understanding of these broader costs and benefits would be needed to inform policy and investment advice for enhancing water productivity to address food security, environmental sustainability and poverty alleviation objectives (Barker et al. 2003; Kijne 2003).

Since the early 2000s, these reflections prompted IWMI and others to broaden the definition of agricultural water productivity and related metrics to include a wider perspective on water use—such as crop and non-crop and other livelihood and ecological benefits and costs from improving water productivity. IWMI argued that water productivity must be understood in the "widest possible sense" with the ultimate objective of increasing yields, fisheries, ecosystem services and direct social benefits at less cost (social, ecological) per unit of water consumed (Rijsberman 2006; Molden et al. 2010). A review of some of the applied research on agricultural water productivity further demonstrates this evolving thinking by IWMI and its partners.

3. Applied Research

Since the launch of the SWIM program in 1995, IWMI and its partners have carried out numerous case studies applying the concept of water productivity and the related tools described above. These case studies differed in scale and context (such as agroecosystem, and socioeconomic and institutional setting), and applied different approaches, including advanced modeling and remote sensing methods, to address data constraints. Many of the case studies were initiated by the four IWMI-led programs (SWIM, CA, CPWF and WLE), and included global analyses as well as regional (basin- and irrigation system-level) assessments in South and Southeast Asia, sub-Saharan Africa, North Africa and Central Asia, and Central and South America. Over the last 20 years, this body of research has generated over 300 reports and publications. In this chapter, some of the research studies and findings are highlighted under three thematic areas: water productivity analysis and mapping; pathways to increase water productivity; and water productivity and broader development objectives.

3.1 Water Productivity Analysis and Mapping

The water accounting methodology and related performance indicators described in section 2.3.1 provided an overarching framework to assess water inflows, uses and outflows across different spatial scales, and helped to overcome some of the limitations of the classical irrigation efficiency concepts by incorporating other uses besides crop water uses and making more explicit the interactions between different uses, including agricultural and non-agricultural uses. The methodology allowed for an analysis of total water depletion—for beneficial and non-beneficial purposes—to assess strategies to improve water productivity, identify opportunities for real water savings, and assess the net benefits (in terms of changes in the water productivity indicators) from water reallocation (Murray-Rust and Turral 2006).

Although the performance indicators had intentionally been kept simple, the availability of primary data and the related cost and time challenges as well as methodological constraints often hampered their application in field-based studies (Sakthivadivel et al. 1999; Murray-Rust and Turral 2006). Even more problems were encountered at the scale of the irrigation system or the basin. To ease these constraints, IWMI tested the use of integrated crop and hydrologic modeling—later in combination with remote sensing tools—to simulate the process of water flows and measure water productivity in its various forms and at various scales (e.g., Kite and Droogers 2000b; Droogers and Kite 2001a, 2001b; Ines et al. 2002; Aerts and Droogers 2004). Modeling allowed researchers to extrapolate and generate scenarios to complement data derived from field studies.

An example is the study in the Gediz Basin, Turkey, where researchers applied the Soil-Water-Atmosphere-Plant (SWAP) model for the analysis at the field and irrigation system scale, combined with the Semi-Distributed Land Use-Based Runoff Processes (SLURP) model for the analysis at basin scale, to estimate the water balance and calculate different water productivity indicators in physical terms (Droogers and Kite 2001a). Table 3 illustrates yields and the resultant water productivity indicators at mid-basin and tail-end fields, and at the irrigation system and basin scales. The fields located further upstream performed better in terms of yield and water productivity indicators than those at the tail end—in part due to its location but also due to different climate conditions. Yield and water productivity indicators at the basin scale were considerably lower than at the field and irrigation system scales because of large areas in the basin with other ‘less-productive’ land cover.

In other studies, models were developed, calibrated, and then applied to assess the effect of various inputs on yield, productivity and the water balance, with the aim of supporting resource allocation and policy

TABLE 3. Water productivity indicators in the Gediz Basin, Turkey (averaged over the nine-year period [1989-1997]).

Scale	Yield (kg/ha)*	PW_{inflow} (kg/m^3)	$PW_{depleted}$ (kg/m^3)	$PW_{process}$ (kg/m^3)
Field (mid-basin)	2,800	0.30	0.39	0.54
Field (tail end)	2,289	0.24	0.24	0.38
Irrigation system	2,614	0.30	0.32	0.40
Basin	874	0.16	0.16	0.21

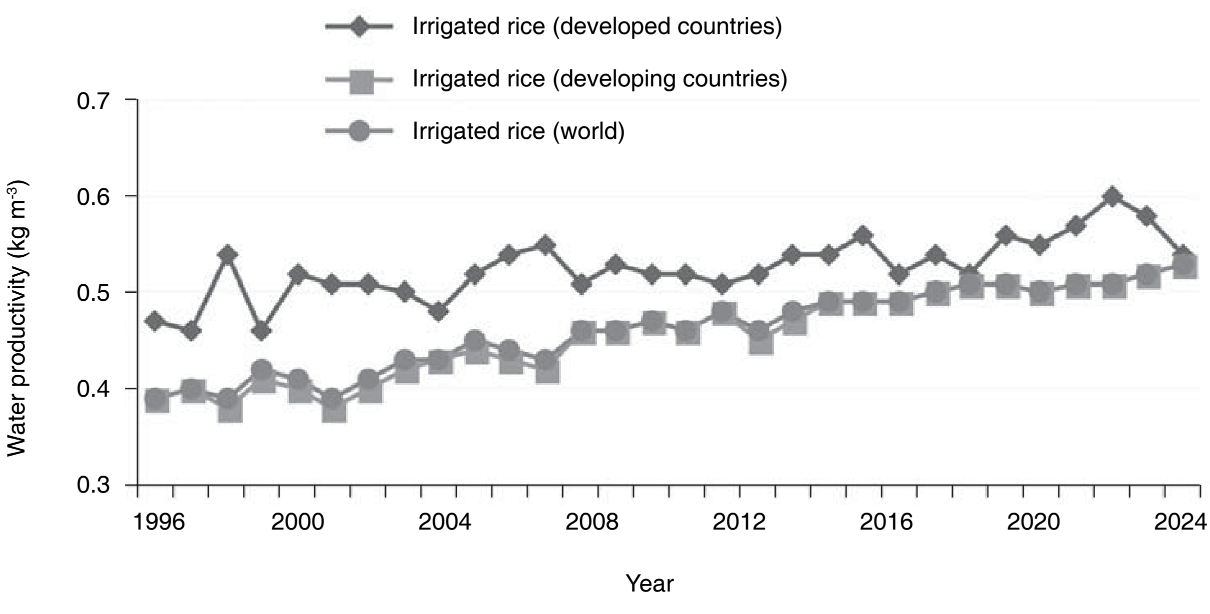
Source: Droogers and Kite 2001a.

Notes: * Yield is the simulated yield for cotton at field scale, for irrigated crops at the irrigation system scale, and for agricultural and non-agricultural production at the basin scale.

PW_{inflow} = yield/net inflow, $PW_{depleted}$ = yield/depletion, and $PW_{process}$ = yield/process depletion, all expressed in kg (yield) per m^3 (water).

decisions at higher scales (Murray-Rust and Turral 2006). As part of the CA program, for example, the IMPACT-WATER model (combining the International Model for Policy Analysis of Agricultural Commodities and Trade [IMPACT] model with a water simulation model) was used for the analysis of various water productivity scenarios for irrigated rice globally and regionally; and for projections taking into account possible impacts from technology and management improvements, investments in agricultural infrastructure and research, and increased environmental flow requirements (Cai and Rosegrant 2003). Figure 3 presents water productivity estimates for irrigated rice (as ratios of yield relative to water consumed) for developing and developed countries, and for the world, based on the IMPACT-WATER model. Estimates indicate that developed countries have higher water productivity values than developing countries and the world. However, the values converge over time due to a projected higher rate of increase in irrigated yield and increase in water-use efficiency for irrigated crops in developing countries during the period under analysis.

FIGURE 3. Water productivity estimates for irrigated rice (1995-2025).

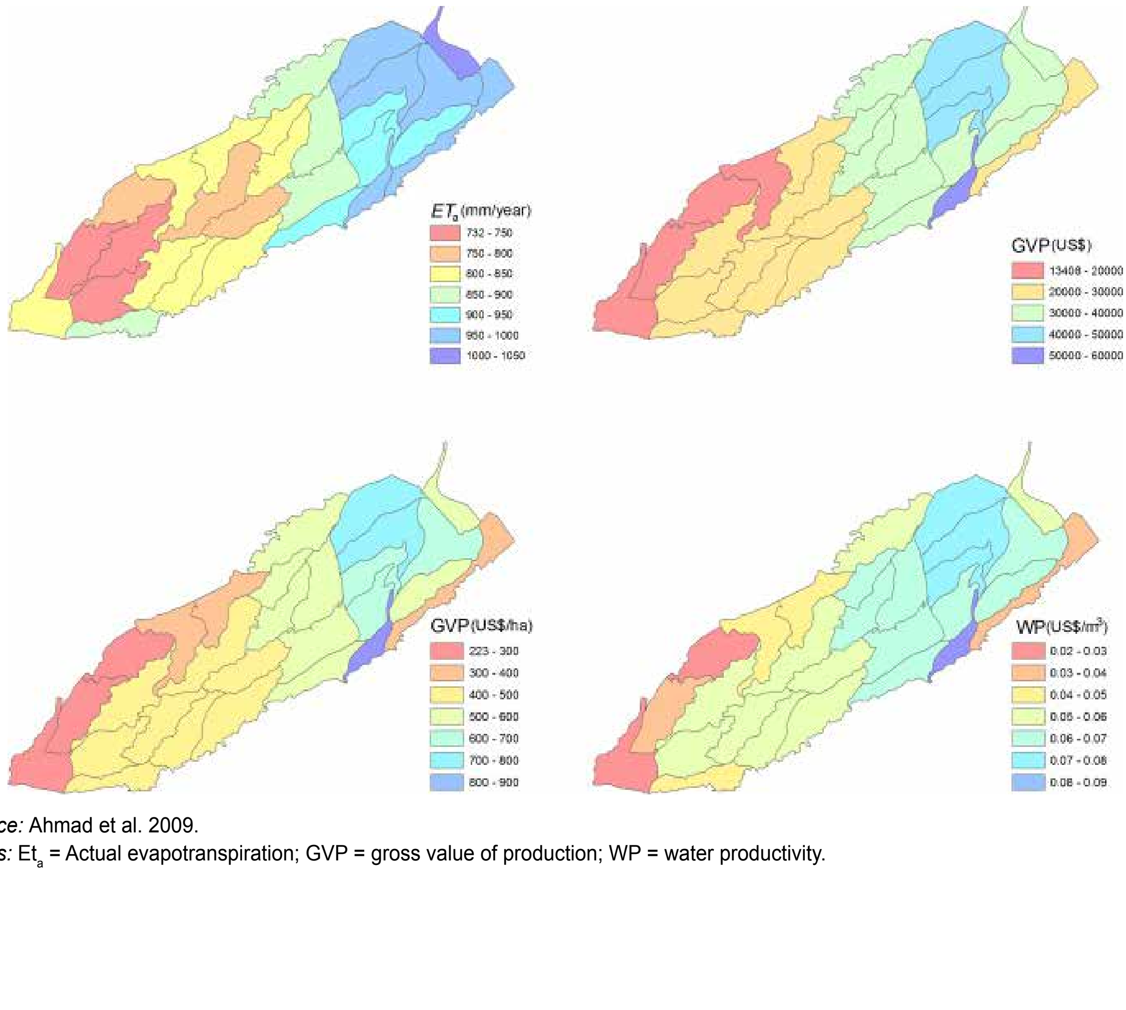


Source: Cai and Rosegrant 2003.

In many cases, the availability of data for modeling purposes, particularly at different spatial and temporal scales, continued to be an issue (Droogers and Kite 2001a). The coupling of remote sensing with integrated (crop-hydrologic) modeling helped to overcome some of these challenges. Remote sensing provided important additional data inputs, such as estimates on land use and water consumption, and supported model calibration (Karimi 2014). From the early 2000s, IWMI placed significant emphasis on the development and application of remote sensing technologies combined with crop and hydrologic modeling tools to map and assess water productivity and simulate scenarios at multiple scales.

In the Rechna Doab Basin in Pakistan, for example, the Surface Energy Balance Algorithm for Land (SEBAL) model (Bastiaanssen et al. 1998a, 1998b) was combined with secondary agricultural production data to estimate water productivity, assess irrigation performance variability and, based on that, identify opportunities to improve overall performance (Ahmad et al. 2009). The values for land productivity were calculated as the gross value of production per hectare, and water productivity values were calculated as the gross value of production per unit of consumptive use (actual evapotranspiration)—for summer and winter cropping seasons as well as annually. Figure 4 shows the spatial variation in annual values for actual evapotranspiration, gross value of production, and land and water productivity in the basin. Among the reasons for the differences across the basin are the quality and reliability of surface water and groundwater supplies, and farmers' crop choices. The study demonstrated how remote sensing-based estimates of water consumption combined with secondary agricultural production data can provide estimates of land and water productivity, and indicate opportunities for improving water productivity at different spatial and temporal scales.

FIGURE 4. Spatial variation in annual values for actual evapotranspiration, gross value of production, and land and water productivity in the Rechna Doab Basin, Pakistan (May 2001-May 2002).



Source: Ahmad et al. 2009.

Notes: Et_a = Actual evapotranspiration; GVP = gross value of production; WP = water productivity.

Not only did remote sensing techniques help to fill data gaps, but they also contributed to further developments in the water accounting framework. The recently developed *Water Accounting Plus* (WA+) framework uses remote sensing to incorporate more details in the processes of water use and the mechanisms to achieve water productivity improvements (Karimi et al. 2012, 2013a). WA+ uses satellite-derived estimates of land use, rainfall, evaporation, transpiration, interception, water levels of open water bodies, biomass production, crop yield and measured basin outflow to produce a water account. These data are supplemented with the outputs of global hydrological models on surface water networks and aquifers. The use of the WA+ framework allows the following:

- Link land use and evapotranspiration to assess the impact of land-use change on exploitable water resources.
- Distinguish between managed and manageable depletions in a basin (i.e., depletions defined as evapotranspiration processes that are or could be manipulated by land use, cultivation practices and water use) and non-manageable depletions.
- Differentiate between surface water and groundwater systems to consider different management options and legal regulations.
- Estimate changes in evapotranspiration (difference between withdrawals and return flows) for different land-use categories and water user groups to assign benefits and costs from changes in managed water depletion.

Over the past 20 years, advances in mapping, modeling and remote sensing techniques have eased some of the challenges in assessing water productivity and its variation in different contexts, and have also contributed to a better framework for water accounting. Technical and methodological challenges remain, however, in the accuracy and interpretation of water productivity and accounting measures (Molden et al. 2010; Cai et al. 2011; Karimi and Bastiaanssen 2015; Karimi et al. 2015). For example, a recent study on the combination of remote sensing and water accounting found that, while the majority of estimates of WA+ parameters and indicators have a coefficient of variation of less than 20% (an accuracy that is on par with field measures), some uncertainty remains with regard to the estimates of overall basin depletion and groundwater flows (Karimi and Bastiaanssen 2015; Karimi et al. 2015).

Even with these technological advances, IWMI researchers have emphasized that water productivity measures on their own do not necessarily provide sufficient information to determine whether improving water productivity is desirable and if so, what specific actions need to be taken (Lautze et al. 2014; Wichelns 2014a, 2014b). This requires an understanding of different intervention pathways, the context in which the pathways are introduced, and their related production, livelihood and ecological benefits and costs—as further elaborated in the next section.

3.2 Pathways to Increase Water Productivity

Building on the four basic, basin-scale water management strategies (Seckler 1996) discussed in section 2.2 and the water accounting framework presented in section 2.3.1, four main pathways with different interventions for increasing water productivity at the irrigation system or basin level were identified by the 2000s (Molden et al. 2001a, 2003, 2007b):

(i) Increase yield per unit of water consumed by, for example:

  - improving water management by providing better timing of water supplies to reduce stress at critical crop growth stages or by increasing the reliability of supplies to enable farmers to invest more in other agricultural inputs;
  - improving non-water inputs that increase production per unit of water consumed and agronomic practices, such as laser land leveling and fertilization; and

- changing to new or different crop varieties with higher yield per unit of water consumed.

(ii) Reduce non-beneficial depletion by, for example:

- increasing the proportion of water applied that is used beneficially by crops, by (a) reducing evaporation from water applied to irrigated fields through more capital-intensive technologies (such as drip irrigation) or better agronomic practices (such as mulching or changing crop planting dates to match periods of less evaporative demand); and (b) restricting evaporation from bare soil through conservation agriculture (such as land leveling or zero tillage);
- lessening evapotranspiration from fallow land by reducing the area of free water surfaces, decreasing non-beneficial or less-beneficial vegetation, and controlling weeds;
- reducing water flows to sinks by decreasing irrecoverable deep percolation and surface runoff, by such measures as canal lining and precision irrigation;
- minimizing salinization (or pollution) of recoverable return flows, by minimizing flows through saline (or polluted) soils and groundwater; and
- shunting polluted water to sinks to avoid the need for dilution with water of usable quality.

(iii) Tap uncommitted flows by, for example:

- adding water storage facilities, including reservoirs, groundwater aquifers, tanks and ponds, on farmers' fields;
- improving management of existing facilities to obtain more beneficial use of existing water supplies; and
- reusing uncommitted return flows through gravity or pump diversions to increase irrigated area.

(iv) Reallocate water among uses by, for example:

- reallocating water from lower- to higher-value uses within or between sectors, while addressing possible effects on downstream uses.

While not emphasized in the earlier literature, it should be noted that the different pathways implicitly target different formulations of water productivity: the first pathway focuses on achieving more yield per unit of water consumed, and the fourth pathway is about improving water productivity expressed in "economic" terms (US dollars per cubic meter [USD/m^3]). The second and third pathways aim to increase the amount of water available for beneficial use.

The sections below present key research highlights addressing each of the four pathways, and the related interventions and water productivity indicators. As will be seen, however, many studies incorporated elements from more than one pathway to increase water productivity.

3.2.1 Increase Yield per Unit of Water Consumed

IWMI and its partners have assessed a number of water-related interventions to increase crop yield per unit of water consumed. A frequent focus was on improving the timing of water supplies using supplemental irrigation or deficit irrigation. In dry regions, moisture availability, especially during critical periods, is frequently the most significant factor limiting agricultural production. Research carried out through the SWIM, CA and subsequent programs explored the extent to which supplemental irrigation, often coupled with rainwater harvesting, can enhance yields as well as water productivity in arid and semi-arid regions (e.g., Oweis et al. 1999; Wani et al. 2009; Hessari et al. 2012).

Several longer-term studies, conducted at experimental sites of the International Center for Agricultural Research in the Dry Areas (ICARDA) in northern Syria, found that rainfall supplemented by irrigation increases water productivity in wheat systems. Supplemental irrigation contributed to the alleviation of moisture stress during the most sensitive stages of crop growth and thus to an increase in yield per unit of water consumed (or evapotranspiration) (Oweis et al. 1999; Zhang and

Oweis 1999; Oweis and Hachum 2003). Table 4 shows the results of a study where mean water productivity of bread-wheat grains, measured over 5 years (1991-1996), increased from 0.96 to 1.11 kg/m^3 as a result of supplemental irrigation. Supplemental irrigation on its own would have been insufficient to support crop production. However, when combined with rainfall, it led to an increase in water productivity in most years, particularly in the drier years. The study also shows that when rainfall is ignored and only irrigation water is considered, water productivity estimates are significantly higher.

Similar increases in water productivity for the combination of rainfall and irrigation water were documented in Burkina Faso and Kenya, where supplemental irrigation was applied to rainfed crops (Rockström et al. 2003; Rockström and Barron 2007).

Deficit irrigation is another practice that can increase yield per unit of water consumed. Using this technique, crops are deliberately exposed to water stress (mostly through reduced irrigation water applications in non-critical periods) resulting in some yield reductions. With well-timed applications, consumptive water use can be reduced more than yield, resulting in water productivity increases. In field trials with wheat carried out by ICARDA in semi-arid northern Syria from 1994 to 2000, supplemental irrigation combined with deficit irrigation improved yields (compared to rainfed conditions) and also led to an increase in water productivity from 0.53 to 1.85 kg/m^3 ET. With full irrigation, water productivity was 0.70 kg/m^3 ET (Oweis and Hachum 2003; Zhang and Oweis 1999).

While these cases illustrate the potential for water productivity improvements, it is not clear if productivity gains in the form of increased yield per ET at the field or irrigation system level translate to improved productivity at sub-basin or basin scale. Cost and risk considerations would also need to be taken into account. Deficit irrigation, for example, requires precise management in terms of scheduling water and other inputs, information on rainfall amounts and distribution, and specialized agronomic knowledge on crop water use and crop response to factors such as water deficits, planting dates and nitrogen application (Oweis and Hachum 2003). The costs, risks, and overall net benefits would need to be assessed before recommending the adoption of such practices to farmers for the purpose of improving water productivity (Kijne 2003).

3.2.2 Reduce Non-Beneficial Depletion

Reducing non-beneficial depletion involves reducing "waste" and generating real water savings (Molden et al. 2003). Two key areas of research have focused on the introduction of:

TABLE 4. Rainwater productivity (WP_R), combined rainfall and irrigation water productivity (WP_{R+I}), and irrigation water productivity (WP_I) for bread-wheat grains in northern Syria (1991-1996).

Year	Rainfall (R) (mm)	WP_R (kg/m^3 ET)	Supplemental irrigation (I) (mm)	WP_{R+I} (kg/m^3 ET)	WP_I (kg/m^3 ET)
1991-1992	351	1.04	165	1.16	1.46
1992-1993	287	0.70	203	1.23	2.12
1993-1994	358	1.08	175	1.17	1.43
1994-1995	318	1.09	238	1.08	1.06
1995-1996	395	0.91	100	0.90	0.73
Mean WP		0.96		1.11	1.36

Source: Oweis and Hachum 2003.

Notes: WP = Water productivity; ET = evapotranspiration.

- capital-intensive technologies, such as sprinkler, drip and other micro-irrigation technologies (e.g., Sally et al. 2000; Rockström et al. 2003; Indu et al. 2008; Kumar et al. 2009; Namara et al. 2005, 2007); and
- agronomic practices, including land leveling and zero tillage (e.g., Ahmad et al. 2006, 2007a, 2007b, 2014), and alternate wet and dry irrigation of rice (Dong et al. 2004; Loeve et al. 2002, 2004a, 2004b).

While many studies identified a potential to reduce non-beneficial depletion, a recurrent recommendation has also been the need to consider context, scale and hydrology in the interpretation and potential application of the results. It is often assumed, for example, that micro-irrigation technologies will result in less evapotranspiration (or consumptive water use) than surface irrigation. This is not necessarily the case. Rather, the outcome depends on the context (both biophysical and institutional), as well as the specific technologies or agronomic practices applied and how they are managed (Seckler 1999; Molden et al. 2001b, 2007b; Kendy et al. 2003; Kijne 2003).

Research conducted by the CA program in the rice-wheat zone of Pakistan's Indus Basin illustrates this point. Ahmad et al. (2006, 2007a, 2007b, 2014) examined the impact of two "resource conservation" technologies (laser leveling of fields and zero tillage) on water application, water productivity, and real water savings. The study, carried out in the Rechna Doab Basin in the semi-arid Punjab Province, involved a survey of 223 small-, medium- and large-scale farmers, field measurements, and remote sensing to assess the factors influencing the adoption of the technologies in rice-wheat cropping systems, and the impacts on water use and "savings" at field, farm and irrigation system level.

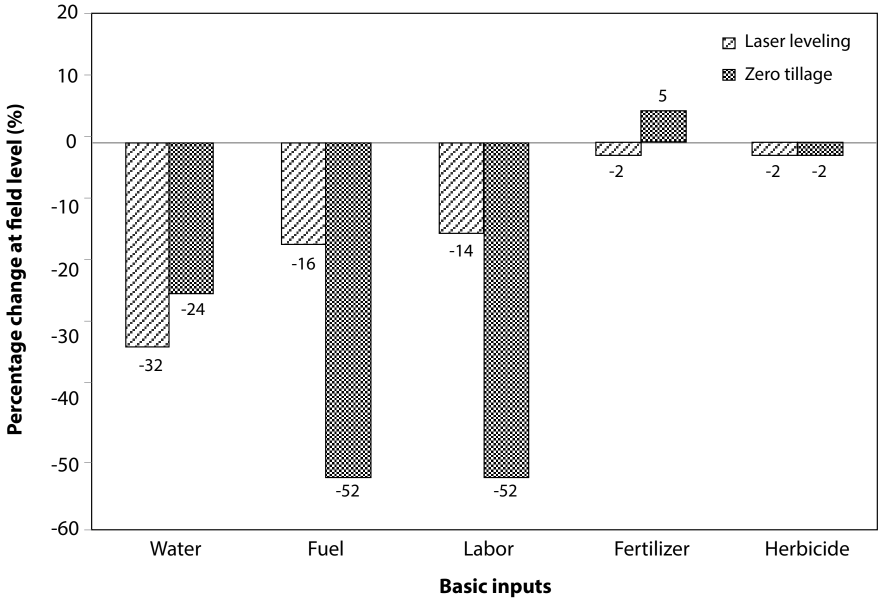
According to the study, the main factors influencing farmers' adoption of each of the technologies were increased yields and reduced input costs. Figure 5 shows the changes in the use of key inputs at the field scale as a result of the introduction of laser leveling and zero tillage technologies. The reductions in water application amounted to approximately 24% and 32% for laser leveling and zero tillage, respectively.

As Ahmad et al. (2014) pointed out, whether the reduced water applications translate into reduced water consumption and real water savings at the larger scales depends on the water balance in a given setting and the broader hydrologic system, and the adjustments farmers make in response to the "saved" water. In the case of the Rechna Doab Basin, the increased profitability following the adoption of the technologies allowed many farmers—in particular, medium- and large-scale farmers with better access to land and the necessary machinery—to expand the cultivated area or increase cropping intensity. Table 5 shows the estimated increase in annual crop evapotranspiration (consumptive water use) at each of the different farm sizes, with a more significant change in the winter dry (*Rabi*) season than in the summer monsoon (*Kharif*) season based on the monsoon.

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. The study estimated that overall water consumption at the system scale increased by 59 million cubic meters (Mm^3)/year following the adoption of "resource conservation" technologies. Thus, improvements in field-scale water productivity (in terms of water application) did not result in reduced water use (in terms of consumptive use) at the farm or larger scales. Ahmad et al. (2014) stressed that, in different contexts (e.g., where additional land cannot be brought under irrigation, highly saline groundwater conditions limit groundwater recycling, or institutional arrangements restrict additional water applications), the outcome could be different, further highlighting the range of factors that can influence the outcomes from water productivity interventions.

In this case, the introduction of "resource conservation" technologies reduced water applications at the farm scale.

FIGURE 5. Impacts of laser leveling and zero tillage technologies on field-scale water application and the use of other inputs as reported by farmers surveyed in the Rechna Doab Basin, Pakistan (2004).



Source: Ahmad et al. 2014.

Note: Data for zero tillage and laser leveling refer to wheat and the mean of various crops, respectively.

TABLE 5. Change in crop evapotranspiration as a result of the adoption of "resource conservation" technologies in the Rechna Doab Basin, Pakistan (2004).

Average farm size under each category (ha)	Change in potential crop evapotranspiration (%)		
	Rabi	*Kharif*	Annual
2.83 *(small)*	1.5	-1.1	0.2
7.69 *(medium)*	5.0	3.7	5.0
33.18 *(large)*	7.7	5.0	8.1

Source: Ahmad et al. 2014.

Note: The data represent the combined impact of adopting zero tillage (for wheat cultivation in the *Rabi* season) and laser leveling for various crops (in the *Rabi* and *Kharif* seasons).

However, improved water productivity (in terms of yield and income per unit of water applied) encouraged farmers, who had access to fallow land (generally medium- and large-scale farmers), to expand their irrigated area. Conversely, smallholder farmers, in general, had little additional land for expansion. While all farmers benefitted from the intervention in terms of increased cropping intensity, the medium- and large-scale farmers received a disproportionate share of the benefits by being able to expand their irrigated area. This is not to say that improving productivity necessarily further increases inequity, but it is important to consider the potential for differential outcomes across different socioeconomic groupings.

3.2.3 Tap Uncommitted Flows

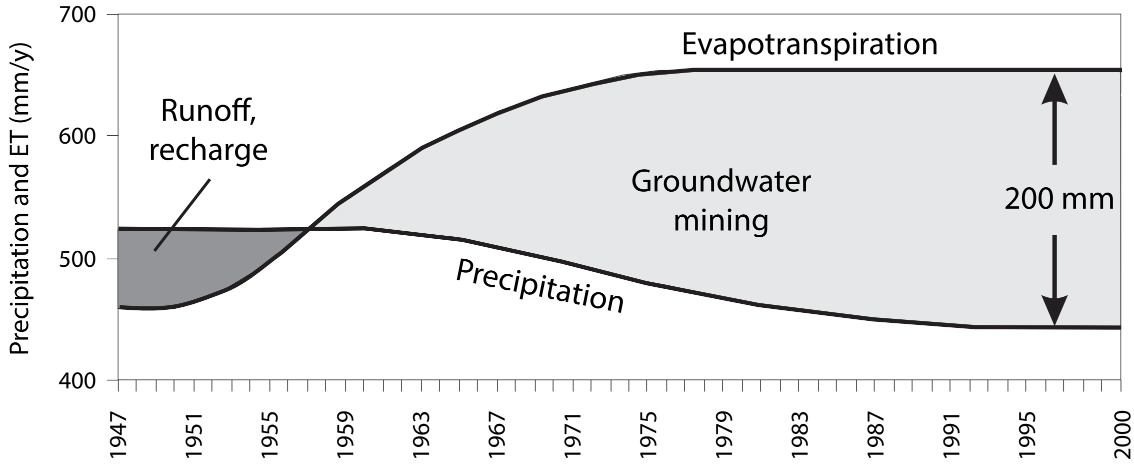
In many locations, additional storage of water above or below ground is key to accessing uncommitted flows. Section 3.2.1 discussed water productivity gains that may result from access to additional surface storage (such as rainwater harvesting) for supplemental irrigation. Access to groundwater in aquifers is another pathway to tapping uncommitted flows or reusing return flows. Since the 1950s, with the advent of the modern pump and tube wells, groundwater irrigation has increased dramatically (Shah 2014).

Research suggests that—at least in terms of water applied—irrigation with groundwater may be more productive than irrigation with surface water, both in terms of physical and "economic" water productivity. In Spain, for example, groundwater irrigators apply less water than surface water irrigators and achieve higher returns for their output per unit of water applied, resulting in an economic water productivity, on average, of over USD 3/m^3, compared with less than USD 1/m^3 for surface water irrigators (Shah 2014). In India, physical crop water productivity (in terms of yield - kilograms per cubic meter [kg/m^3] of water applied]) on groundwater-irrigated farms can be between one and three times greater than on farms irrigated with surface water. Similar findings have been documented in other studies in South Asia (DebRoy and Shah 2003). Overall, the higher water productivity achieved with groundwater irrigation may be the result of several factors, including lower water applications, production of higher-value crops, increased capacity to control timing of irrigation applications, and a tendency for groundwater farmers to invest more in complementary inputs (such as fertilizers and high-yielding seed varieties) given the greater reliability of groundwater (DebRoy and Shah 2003).

However, increases in water productivity resulting from tapping uncommitted flows may be associated with significant costs. Depending on the hydrologic context, and the underlying definition for water productivity, costs may occur in various forms, including in terms of groundwater depletion, reduced water quality, and greater carbon emissions. An example of this draws from IWMI's research on groundwater use and management in China, conducted in Luancheng County of Hebei Province (Kendy et al. 2003). The North China Plain has traditionally been a key agricultural production center and a critical region to help achieve the country's food security goals. To support the increase in agricultural production, groundwater has been used as the primary source of irrigation water since the 1960s—mainly to supplement the region's unpredictable rainfall patterns. In Luancheng County, a growing industrial sector coupled with the local government's focus on expanding wheat production led to increasing competition for groundwater supplies. In response, the agriculture sector moved toward improving irrigation efficiency (more specifically, application efficiency) through the adoption of "water-saving" technologies in order to reduce groundwater use. Subsequently, groundwater pumping rates declined by more than 50% between the 1970s and 2000. However, despite these gains in irrigation efficiency, groundwater levels continued to decline over that same time period.

Kendy et al. (2003) discussed this outcome in the context of the local hydrology. The local shallow aquifers in Luancheng County are replenished by rainfall and runoff, and depleted by water consumption (evapotranspiration). As illustrated in Figure 6, if precipitation is higher than evapotranspiration in a given year, runoff and groundwater recharge occurs. If, however, evapotranspiration starts to continually exceed annual rainfall, groundwater is mined. The focus on food self-sufficiency led to a significant increase in the region's irrigated area, and thus crop evapotranspiration. Since about 1960, the levels of evapotranspiration were higher than precipitation and continued to increase until the mid-1970s. Since then up to the conclusion of the study in 2000, annual evapotranspiration remained constant. With a progressive decline in precipitation from the 1960s, groundwater mining increased to 200 mm per year in the 1990s. Overall, while groundwater pumping declined and irrigation efficiency improved, the proportion of groundwater pumped that was consumed by crops

FIGURE 6. Annual evapotranspiration, precipitation and groundwater recharge/mining in Luancheng County, China (1947-2000).



Source: Based on Kendy et al. 2003.
Note: ET = evapotranspiration.

increased significantly and return flows to the aquifers declined (Kendy et al. 2003; Frederiksen et al. 2012).

Frederiksen et al. (2012) used the example of Luancheng County as part of a larger discussion on the need for precision in water use definitions and terminology (e.g., water application versus water consumption), and how imprecision can lead to faulty decision making and unintended consequences. According to the authors, the lessons from this case prompted the Chinese authorities to shift their focus from reducing water applications to reducing water consumption.

3.2.4 Reallocate Water among Uses

Reallocating water from lower- to higher-value uses is one of the means to increase "economic" water productivity (Molden et al. 2003; Molle 2003b). Reallocations can occur within the agriculture sector (e.g., from staple grains to horticulture crops) or across sectors (e.g., from agriculture to the municipal or industrial sector). Within the agriculture sector, values of "economic" water productivity (especially in the conventional definition of gross value of product relative to water applied) for most major grains are much lower than for vegetables and fruits. Thus, farmers who reallocate water and shift part or all of their land to higher-value crops tend to improve their agricultural returns and "economic" water productivity, with the extent dependent on market and other conditions (Molden et al. 2003, 2007a).

Reallocating water from agriculture to other sectors with higher-value water uses is often emphasized as a way of reducing problems of water stress and contributing to broader societal goals. It is seen as a pillar of water demand management, making better use of available resources as opposed to augmenting supplies. In many instances, "irrigation efficiency" tends to be low with a large share of agricultural water withdrawals and irrigation applications not consumed by crops. Thus, it is commonly believed that a focus on improving "irrigation efficiency" could free up substantial quantities of water for reallocation to other sectors that often have much higher water values than agriculture. The CA program provided a better understanding of the potential for shifting water out of agriculture and why this type of transfer may often be problematic (Scott et al. 2001; Molle 2003b; Molle et al. 2007; Molle and Berkoff 2006; Wester et al. 2008).

In a review of the literature and country experiences with intersectoral water reallocations, Molle and Berkoff (2009) pointed out that the conventional view, based on the classical notion of "irrigation efficiency", considers farmers' water use as inefficient and wasteful. However, this ignores the fact that much of the wasted water flows back to the river or an aquifer and—subject to water quality—can be recycled downstream. The economic gains from intersectoral water reallocations may also not be as high as expected. For example, if measured in terms of "economic" water productivity, a comparison of the respective values between the agriculture and industrial sectors can be misleading, since water is only a tiny portion of the overall costs in many industries. Furthermore, in the context of assessing intersectoral water allocations, other social and environmental, but also political, costs associated with transfers are not easily estimated and thus often not included in the calculations.

In an analysis of the economics of water productivity in agriculture, Barker et al. (2003) emphasized that an increase in water productivity as a result of a reallocation of water among users may, or may not, result in higher economic or social benefits. In discussing the complexities in economic analysis in relation to efforts for increasing water productivity, they state, "As the competition for water increases, decisions on basin-level allocations among sectors must involve value judgments as to how best to benefit society as a whole. This will include setting priorities in the management of water resources to meet objectives such as ensuring sustainability, meeting food security needs, and providing the poorer segments of society with access to water" (Barker et al. 2003, 30-31).

Together, the research across the four pathways to increase water productivity has highlighted the importance of grounding water management decisions in the hydrological, social, economic and environmental context, and the need to understand the trade-offs at different scales. Risks and cost considerations (economic, social and environmental) for farmers and for society as a whole may go unnoticed in the promotion of water productivity-enhancing practices. Yet, these costs need to be considered (even if it is only qualitatively) to determine whether improvements in water productivity are desirable or not to achieve broader policy or development objectives (Bakker et al. 1999; Barker et al. 2003; Kijne 2003).

3.3 Water Productivity and Broader Development Objectives

Fundamental to IWMI's overarching mission, and many of the programs led by the Institute, is an effort to understand the extent to which improving agricultural water productivity can help in achieving food security, responding to pressures to reallocate water to cities and for the environment, contributing to economic growth, and alleviating poverty (Molden 2007). Starting in 2000, when David Seckler as Director General led the transition from the International Irrigation Management Institute (IIMI) to the International Water Management Institute (IWMI), the Institute's mandate was to "contribute to food security and poverty eradication by fostering the sustainable increases in the productivity of water through the management of irrigation and other water uses in the river basin" (IWMI 2015b). In the same year, IWMI launched the CA program with an overarching research question of "how can water in agriculture be developed and managed to help end poverty and hunger, ensure environmentally sustainable practices, and find the right balance between food and environmental security" (Molden 2007). The CPWF continued this journey with an explicit focus on the linkages between water productivity and water poverty (Fisher et al. 2014), while WLE has extended these earlier objectives with an additional effort to explore gender and social equity dimensions of water productivity in the context of sustainable intensification and ecosystem values (IWMI 2014).

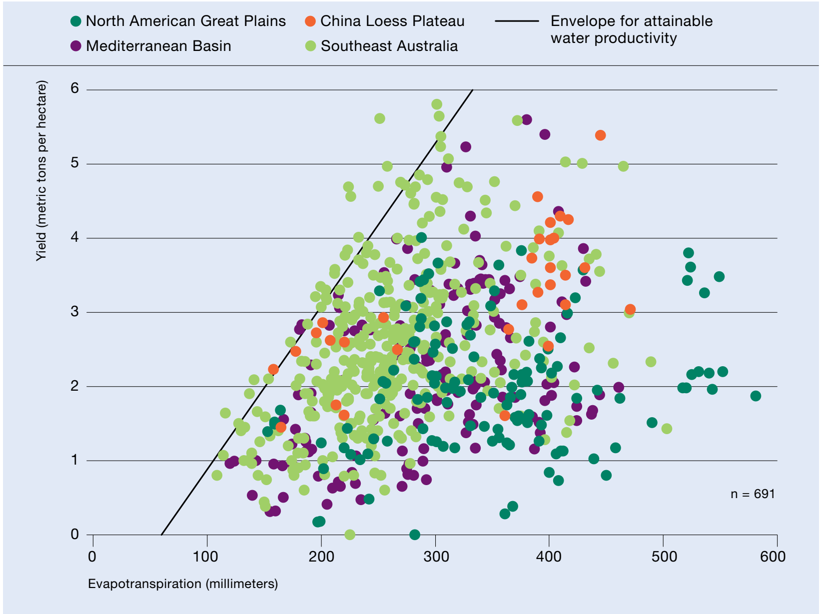
This section presents in more detail how IWMI's research has contributed to understanding the relationship between interventions to improve water productivity and their contribution to different development objectives. Two key objectives are increasing agricultural production to meet rising food demands and reducing agricultural water use to facilitate reallocations to other sectors. Two additional objectives that may be linked to the others are raising farm-level income, and alleviating poverty and inequity in the agriculture sector. In many instances, water productivity interventions have embraced more than one development objective.

3.3.1 Increasing Agricultural Production to Meet Rising Food Demands

Concerns over food security and growing water scarcity were at the heart of the call for improved agricultural water productivity in the mid-1990s. Seckler and his colleagues at IIMI (Seckler 1996; Seckler et al. 1998, 1999) stated that, for many countries, particularly in arid regions, water had become "the single greatest threat to food security, human health and natural ecosystems" (Seckler et al. 1999, 29). World food reserves were at an all-time low. Unstable water regimes (and consequently unstable food supplies and rural livelihoods) fueled social and political instability in parts of sub-Saharan Africa. In India, food security was "crucially" dependent on the development of additional irrigated lands (Seckler 1996). These impressions were given in the context of declining irrigation development investments, and growing competition for water from other sectors (mainly urban and industry) and to meet environmental needs (Seckler et al. 1998). These factors placed a stronger urgency on improving the productivity of existing agricultural water supplies to meet future food demands.

Consequently, a large part of the early IIMI/ IWMI research on water productivity was focused on measures and pathways to increase yield (particularly of staple crops) per unit of water consumed to contribute to rising food demands. Research indicated considerable scope for raising yield relative to water consumption, and promising field results were documented (see section 3.2.1). An illustration is Figure 7, which shows significant variations in the water productivity of wheat measured in terms of water consumed in different regions of the world, suggesting considerable scope for raising the amount of yield relative to ET in different wheat-producing areas.

FIGURE 7. Variations in the water productivity of wheat (kg/ha/ET) in different regions.



Source: Molden et al. 2007b, adapted from Sadras and Angus 2006.

Note: ET = evapotranspiration.

In this regard, research conducted by IWMI and partners also explored the linkages between water productivity and agricultural productivity, and showed that they are not straightforward. Studies carried out by IWMI and the CA (e.g., Hussain et al. 2000, 2003, 2004, 2007; Kumar et al. 2009) made some progress in identifying and quantifying the contribution of the different factors affecting crop yields, but the importance and magnitude of each factor's contribution was found to vary significantly by physical location, and the related hydrologic and climatic setting. More fundamentally, the research findings impressed the point that farm-level decisions regarding cropping pattern and water use are influenced by a range of context-specific (water- and non-water-related) factors. Thus, reliance on water productivity values in isolation can mask important variables affecting agricultural production (Lautze et al. 2014). Consequently, policy actions aimed at improving water management for food security need to consider the range of factors and resource constraints that influence farm-level production and marketing decisions, many of which have no relation to water (Wichelns 2003, 2014b; Lautze et al. 2014).

3.2.2 Reducing Agricultural Water Use to Facilitate Reallocations to Other Sectors

Improving water productivity in agriculture has also been seen as a means to reallocate water to meet the growing demands from other sectors, such as cities, industry and the environment (Molle and Berkoff 2006). Seckler (1996) highlighted the growing number of water-scarce countries turning to water reallocation as a solution. The SWIM and CA programs explored the extent to which improvements in agricultural water productivity can free up water for non-agricultural uses (e.g., Hong et al. 2000; Scott et al. 2001; Molle 2003b; Molle and Berkoff 2006; Molle et al. 2007; Wester et al. 2008). Molle and Berkoff (2006) carried out a review of intersectoral water transfers based on 19 case studies from North America, Europe, South Asia, Southeast Asia, China, the Middle East and Latin America. The study found an overall mixed picture in terms of the success of water reallocations, and apropos to this paper, the extent to which gains in water productivity played a role in this process. Two contrasting cases from IWMI's research carried out in the Yangzte and Yellow river basins illustrate this point (Hong et al. 2000; Loeve et al. 2004a, 2004b, 2007; Molden et al. 2006, 2007a).

In the Yangtze River Basin, the research focused on the Zhanghe Irrigation District in Hubei Province. During the 1990s and early 2000s, the proportion of water received for irrigation (rice production) from the main reservoir declined significantly as the water was reallocated to other sectors, including hydropower, industry and domestic use (Molle and Berkoff 2006). The long-term trends in water releases for irrigation and other uses are provided in Table 6.

TABLE 6. Water inflows and releases from the Zhanghe Reservoir, Hubei Province, China (1966-2004).

Period	Average water use (million m^3 x 100)							Rainfall (mm)
	Irrigation	Industrial	Municipal	Hydropower	Flood control	Evaporation	Inflow	
1966-1978	6.03	0.17	0.00	0.25	0.15	1.24	6.94	952
1979-1988	3.62	0.37	0.09	0.53	2.27	1.19	7.53	967
1989-2001	2.21	0.48	0.16	2.76	1.98	1.22	8.82	945
2002-2004	0.62	0.56	0.24	4.28	0.33	0.80	7.86	868

Source: Loeve et al. 2007

To facilitate reallocations, a suite of complementary technical, managerial and policy interventions was introduced over time. Farmers were charged a volumetric fee for water supplies, on-farm water conservation practices (such as the use of alternate wetting and drying, and recycling of drainage water) were introduced, and ponds were constructed or rehabilitated to capture rainfall and reduce farmers' reliance on the reservoir water. In addition, the irrigation operators responsible for allocating water across sectors received higher water fees from cities and industries. This pricing system incentivized a reduction in allocations for irrigation. At the same time, provincial authorities formally negotiated the water allocations across sectors to ensure sufficient releases for irrigation to meet food production goals.

As shown in Table 7, despite significant reductions in water releases for the Zhanghe Irrigation District and associated declines in planted area, rice production did not similarly decline and yields doubled. As a result, water productivity in terms of yield per unit of water supplied (in this case, water withdrawn) increased significantly. However, the fact that farmers reused drainage water and had access to alternative sources of water (e.g., farm ponds) suggests that water productivity gains may not have been achieved in terms of production per unit of water consumed (Roost et al. 2008). Also unclear are the impacts of the changes in return flows on downstream users. Furthermore, while the reallocation of water across sectors may have been successful and supported by an alignment of various interventions, the extent to which water productivity gains played a role in this process is not clear.

Research on the experience of the Liuyuankou Irrigation District, located in the chronically water-stressed Yellow River Basin, provides a contrasting case. To meet demands from other sectors, surface water allocations for agriculture in the district were reduced from 87% to 63% between 1968 and 2000 (Molle and Berkoff 2006). While the objective of reallocation was the same as in the Zhanghe Irrigation District, the necessary interventions to support it were not in place at the different scales. Farmers paid only a flat fee for surface water supplies, water conservation practices were not promoted, and groundwater as a supplementary source of irrigation water was not included in the official water allocation plans. System managers were accountable only for delivering less surface water to farmers. The fees collected by the managers were based on the amount of the area irrigated, and no fees were received from the other sectors. The outcome was that, while surface water withdrawals for agriculture were reduced, farmers adjusted by pumping additional groundwater. No technical, financial or institutional incentives or other mechanisms were put in place to restrict groundwater use for agriculture, with the result that overall annual groundwater withdrawals for agriculture remained largely unchanged (Molden

TABLE 7. Annual rice production, water supply and water productivity in the Zhanghe Irrigation District, Hubei Province, China (1966-2004).

Period	Rice			Water supply (Mm^3)	Water productivity (kg/m^3)
	Planted area ('000 ha)	Production ('000 tons)	Yield (tons/ha)		
1966-1978	173	698	4.04	850	0.87
1979-1988	149	1,001	6.72	774	1.44
1989-2002	118	934	7.98	396	2.54
2003-2004	107	894	8.34	141	8.76

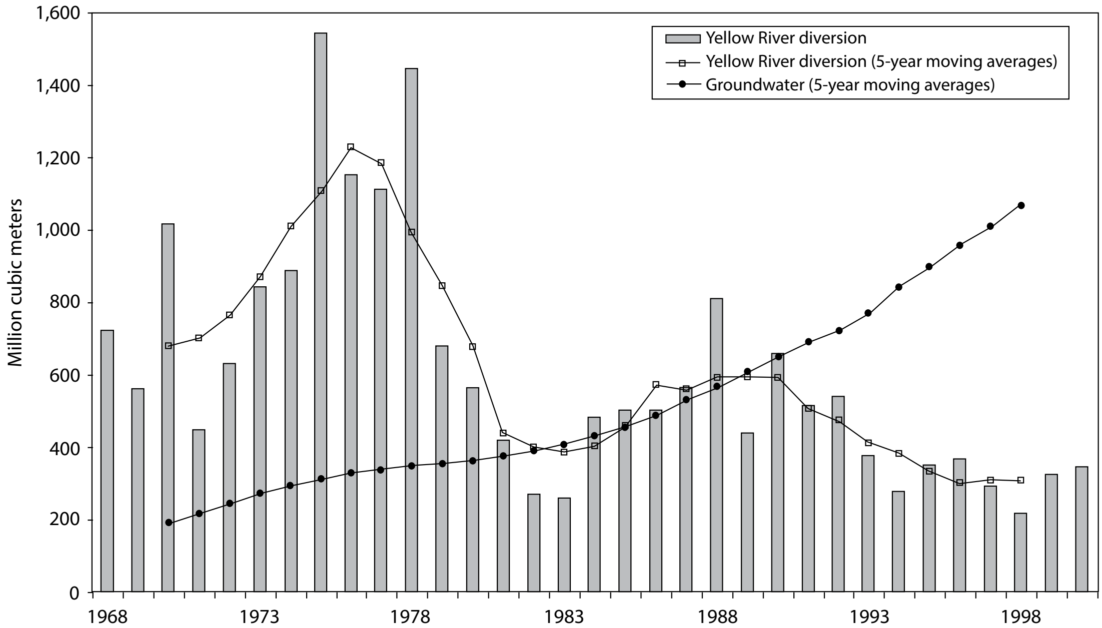
Source: Adapted from Loeve et al. 2007.

Notes: Planted area accounts for multi-cropping in parts of the district. Water productivity is measured as yield per unit of water withdrawn from the Zhanghe Reservoir and other sources under the control of the Zhanghe Administrative Bureau.

et al. 2007a; Loeve et al. 2004b). Figure 8 shows the trends in water diversions from the Yellow River and groundwater withdrawals for the period 1968 to 2000.

Several key points emerge from the research related to the two irrigation systems. First, it is important to be clear how water productivity and associated gains are defined and measured, and how they relate to the pursued objectives. Second, potential trade-offs, such as those resulting from farmers' shift to other water sources and other adjustments, need to be taken into account when assessing outcomes. Third, unless the suite of interventions is complementary, moving water supplies from agriculture to other uses may prove to be difficult and trigger unintended consequences (Molle et al. 2007; Molden et al. 2007a).

FIGURE 8. Water use trends in the Liuyuankou Irrigation System, Henan Province, China (1968-2000).



Source: Based on Molden et al. 2007a.

3.3.3 Raising Farm-Level Income

A third development objective for improving water productivity is to raise farm-level income. This can be done, for example, by increasing production in a given cropping pattern or by changing the cropping pattern with a move to higher-value crops (Molden et al. 2003). For IWMI, a key focus of research was on farm-level economic impacts of technologies that reduce the amount of water withdrawn, applied or consumed. For example, one objective of IWMI's research on "resource conservation" technologies was to explore the impacts of "water-saving" technologies on farm income (Ahmad et al. 2006, 2007a, 2007b, 2014). As noted in section 3.2.2, the main factors contributing to farmers' adoption of the technologies were increased yields and reduced input costs. In a 2004 survey of 168 farmers in the Punjab Province of Pakistan who had adopted zero tillage or laser leveling technologies, the majority (87% for zero tillage and 88% for laser leveling) reported a decrease in production costs (Ahmad et al. 2007b, 2014). With yields also increasing or remaining the same for most of the farmers surveyed, net farm incomes likewise rose.

Table 8 shows the percentage of farmers reporting an increase, decrease or no change in yield, cost of production, and net farm income following the adoption of zero tillage and laser leveling technologies.

Similar research was carried out on micro-irrigation technologies to assess their impacts on, among other things, farmers' incomes. A study in the Indian states of Maharashtra and Gujarat found that investments in micro-irrigation technologies (including drip and sprinkler systems) are generally profitable with farmers able to recoup their initial investment within 1 to 3 years, with available subsidies further improving the returns. Farmers reported that the technologies enhanced water productivity (in terms of water applied) as well as the productivity of other agricultural inputs, thereby reducing the cost of production (Namara et al. 2005).

However, while adopters of micro-irrigation technologies usually reported gains in both yield and profitability, the majority of adopters were wealthier farmers, suggesting that the poverty impact was not substantial. Moreover, in both Maharashtra and Gujarat, micro-irrigation adopters produced more water-intensive crops than non-adopters and also increased cropping intensity. Consequently, Namara et al. (2005) cautioned that improved productivity and profitability following the adoption of micro-irrigation technologies could have important sustainability implications by increasing (rather than decreasing) the demand for irrigation water, particularly when coupled with financial subsidies. Specifically, the authors noted a trend towards year-round cropping, which could result in greater water use in terms of water withdrawals, application and consumption. These findings further highlight the need to consider the range of possible impacts on multiple development objectives when designing or promoting (including with subsidies) interventions to increase water productivity.

3.3.4 Alleviating Poverty and Inequity in the Agriculture Sector

A fourth key development objective for IWMI and its hosted programs has been to examine opportunities for alleviating poverty and inequities in the agriculture sector through irrigation-related interventions, including gains in water productivity. Early research conducted by the CPWF explored the link between water productivity gains and the alleviation of poverty and inequity. The research built on an implicit assumption that the "poor were also 'water poor'" (CPWF 2015).

TABLE 8. Farmers' perceptions of the impact of zero tillage and laser leveling on yield, cost of production and net farm income, Punjab Province, Pakistan.

	Yield	Cost of production	Net farm income
Zero tillage			
Increase	54	6	67
Decrease	30	87	23
No impact	16	7	8
Laser levelling			
Increase	96	8	96
Decrease	0	88	0
No impact	4	4	4

Source: Ahmad et al. 2014.

Note: Based on a 2004 survey of 168 farmers.

Conceptual aspects of this work began in the early 2000s (e.g., Prasad and Watson 2003; Hussain and Giordano 2004; Prasad et al. 2006) and continued in a more applied set of studies in 10 basins located in Asia, Africa and South America (Kemp-Benedict et al. 2011, 2012; Cook et al. 2012). Over time, researchers identified a set of five interlinked aspects that define the relationship between water and poverty (Kemp-Benedict et al. 2011):

- Scarcity (when people are challenged to meet their livelihood goals due to water scarcity).
- Access (when people lack equitable access to water).
- Low water productivity (when people acquire insufficient benefits from water use).
- Chronic vulnerability (when people are vulnerable to relatively predictable and repeated water-related hazards, such as seasonal floods and droughts, or endemic disease).
- Acute vulnerability (when people suffer an impaired ability to achieve livelihood goals as a consequence of large, irregular and episodic water-related hazards).

The research also demonstrated that the nature of these linkages and the role of improved water productivity in addressing them is complex. Kemp-Benedict et al. (2011) argued that the five aspects of water-related poverty must be considered within a broader context of institutions, variability (natural, social and economic), and household and community assets. Specifically, the authors state: "Deprivation as a result of water scarcity reflects a lack of natural assets; equitable access is determined largely by institutions; vulnerability to water-related hazards is largely (although not entirely) due to variability in the natural environment; low water productivity is affected by household and community assets, such as access to markets or knowledge; and loss of livelihood due to change is a consequence of variability in the external natural, economic, and social environment" (Kemp-Benedict et al. 2011, 135). This, in turn, suggests the need for multiple criteria to understand the linkages between water and poverty as well as inequity.

Complementary research conducted by the CPWF suggested that water productivity and poverty are only weakly related, and there is no clear relationship between poverty and water scarcity within a basin (Fisher et al. 2014). Researchers found that the severity of poverty is more dependent on the level of control than the physical endowment of water (Namara et al. 2010); and stronger linkages exist between poverty and other factors, such as access to basic services—ranging from safe drinking water and sanitation to healthcare, education, finance, markets and farm inputs (Fisher et al. 2014; Vidal et al. 2014). Moreover, where relationships were found between the provision of natural resources (such as irrigation water) and livelihood outcomes, these were more closely associated with the level of economic development and institutional factors (Molle 2003a; Cook et al. 2009; Kemp-Benedict et al. 2011; Fisher et al. 2014). In other words, poverty is more dependent on the stage of a basin's economic and institutional development than the availability of water resources (Cook et al. 2012; Vidal et al. 2014). Irrigation may play a role in improving livelihood outcomes, but only alongside improvements in other contributing factors, including access to markets and credit, as well as a supportive institutional environment (Kemp-Benedict et al. 2011).

Complex linkages were also found in relation to water productivity and equity, in that water interventions could either reinforce or reduce inequities (e.g., Clement et al. 2011a, 2011b; Mapedza et al. 2008). Within a community, the benefits derived following the introduction of technologies or practices aimed at improving water productivity could benefit some farmers more than others (Ahmad et al. 2007a, 2007b, 2014). For example, as illustrated in section 3.2.2, the adoption of technologies aimed at improving water productivity can disproportionately benefit some categories of farmers. This is not to say that improvements in water productivity necessarily further increase inequity. However, it is important to identify preexisting inequities in access to water and other resources among farmers and communities in order to better target poor communities, and/or avoid exacerbating inequity in the agriculture sector (Clement et al. 2011b).

Overall, this large body of applied research on water productivity and the broader development objectives has contributed a greater understanding of the role of context and when, how, and for what purpose improvements in water productivity can be desirable. Improving water productivity is not the ultimate goal, but rather can serve as a pathway to achieving broader development aims. The research reinforces the need to be clear about the definition of water productivity to understand the possible trade-offs, and cautions against relying solely on water productivity indicators for decision making. The selected pathway(s) to promote water productivity improvements must consider scale; the hydrologic, socioeconomic, policy and institutional context; and the differing perspectives across actors, the factors influencing them, and related adaptation strategies. Without due consideration of these context-specific elements, well-intended interventions may result in unintended social or environmental consequences.

4. Lessons Learned: Reflecting on Two Decades of Water Productivity Research

Since the 1990s, significant conceptual and methodological advancements and insights have emerged from applied research on agricultural water productivity. Through that research, a more nuanced understanding of the concept has also emerged, highlighting its usefulness and limitations, as well as its operationalization and contribution to broader development objectives. Some of the main lessons learned from the research on water productivity in the literature published by IWMI and others are highlighted below.

Lesson 1: Key terms need to be properly defined and discussed

Agricultural water productivity, introduced in IWMI Research Report 1 (Seckler 1996) in an effort to better address growing water scarcity, stimulated important conceptual developments in the field of water resources management. It challenged researchers and practitioners to think beyond the traditional notions of "irrigation efficiency" in the use of irrigation water, and consider more broadly the net benefits received in agriculture and other sectors from the use of water. The concept and related terms helped to highlight the importance of scale and the notion of recycling water within a river basin, allowing for a better understanding of whether a "piecemeal change" (i.e., increasing irrigation efficiency on a farm) represents a "real" improvement in terms of water saving at the basin scale or not (Seckler 1999).

As alluded to in previous sections, a strong debate and some disagreement continues in the literature on how water productivity and efficiency terms are to be defined and used (e.g., Jensen 2007; Perry et al. 2009; Frederiksen et al. 2012; van Halsema and Vincent 2012; Pereira et al. 2012; Kambou et al. 2014; Heydari 2014; Wichelns 2014a). Some aspects of the debate are new, but to a large extent it comes back to the fundamental conceptual and practical challenges Seckler outlined in his early writings on the topic (e.g., Seckler 1996, 1999). Already in the late 1990s, he characterized the circular debate using a quote from André Gide's *Le traite du Narcisse* of 1891: "Everything has been said before, but since no one listens, one must always start again" (Seckler 1999).

Many reports and much of the public debate continue to be vague on the meaning of "water productivity" and the different notions of efficiency, often using the terms interchangeably—with little discussion on how to define and measure them, what to do for improving them and, importantly, how to monitor and assess changes (Scheierling et al. 2014, 2016). The terms then become generic to label an array of performance indicators and even development objectives. In part, this is due to the multi-disciplinary nature of the topic, with different disciplines using different definitions (and promoting different interventions), and with relatively limited exchange between the disciplines. The CA and its successor programs made progress in bridging disciplinary boundaries. Further discussion would clearly benefit from more intensive interdisciplinary collaboration and outreach to the general public and decision makers.

Lesson 2: Understanding of the hydrological setting and appropriate scale is critical

The concept of agricultural water productivity initially evolved as a means of producing more agricultural output with the same amount or less water. A wide range of interventions has been proposed to promote improved water productivity. To understand where and how productivity gains can be made—and possibly also "real" water savings achieved—requires consideration of the specific hydrological setting, and the appropriate spatial and temporal scale of analysis. There is no 'one-size-fits-all' approach (Seckler et al. 1999). Achieving a desired improvement in water productivity requires an understanding of the water balance in a given domain and a clear definition of "water productivity." With growing water scarcity, the interdependencies among water users increases and gains from the use of water in one location may result in losses in another; for example, the opportunity to beneficially recycle water returning from an irrigated field to a surface water or groundwater source may be reduced, if its quantity or quality is diminished by an intervention on the irrigated field (Seckler 1999). An understanding of the hydrologic setting is also required to ensure that a proposed intervention fits the local context and achieves the desired effects (Molden et al. 2001b; Kendy et al. 2003).

To illustrate, interventions such as the promotion of drip or sprinkler irrigation technologies have gained considerable attention as a means to save water in agriculture—based on the assumption that, by increasing the proportion of water applied that is beneficially used by crops, less irrigation water would be needed (and water can be freed up for other purposes). This may be the case with regard to the amount of water applied at the field level—*if* farmers do not have incentives to apply the same amount of water as before in order to expand the irrigated area or intensify production. Even if the amount of water applied is reduced, the consumptive water use of the crop may stay the same and no "real" water savings would be achieved at the basin scale. In fact, research has shown that such interventions may even increase consumptive water use, and thus overall depletion at the basin scale, unless accompanying measures are undertaken (Ahmad et al. 2007a, 2007b; Ward and Pulido-Velazquez 2008; Dagnino and Ward 2012; Pfeiffer and Lin 2014; Fishman et al. 2015). An example to at least partially address this problem is a measure that was introduced in the Arkansas River Basin, United States, where surface water users were required to return the reductions in water applications (and withdrawals), which were made possible due to the adoption of improved irrigation technologies, to the river (Harvey 2014). Thus, the promotion of such interventions for achieving real water savings should target locations where return flows would otherwise be lost in a sink, or be accompanied by mechanisms that limit the potential increase in consumptive use. Proper water accounting at local and basin scales, coupled with an understanding of the institutions that govern water allocation and application, and consumptive use, are necessary prerequisites for effective water productivity interventions.

Lesson 3: Interventions need to be aligned with the objectives and incentives of various decision makers

At the policy level, improvements in agricultural water productivity are usually called for in connection with the need to meet rising food demand or to reallocate water to other uses. Farmers, though, may be interested in these objectives only insofar as they contribute to maintaining or increasing farm-level income—with water being only one of many often dynamic and context-specific factors affecting crop production and decision making. If, for example, water productivity-enhancing technologies or management practices generate more on-farm costs (including uncertainty or risks) than additional benefits, their adoption may not be a priority for some or all farmers (as the farming community itself is not homogenous). These often conflicting objectives across water users and decision makers at different scales, as well as the different incentives they face, need to be taken into account when designing policies or promoting interventions to enhance water productivity. Otherwise, "farm-level responses to policy parameters may be different than expected, and the goals of water management policies may not be achieved" (Wichelns 2003, 100).

Tools are needed to place these different perspectives in context, so that the various factors influencing different users and decision makers at various levels can be identified, and the costs and benefits generated from improvements in water productivity can be estimated. This should include assessments of how the costs and benefits are likely to be distributed (Barker et al. 2003; Barker and Levine 2012). Studies in water accounting, as well as hydro-economic simulation and optimization models, are increasingly part of the tool kit. Research conducted by IWMI and others is helping to better understand and quantify some of the complex interactions. Recent updates to the *Water Accounting Plus* (WA+) framework, for example, allow users to assess not only water flows, fluxes, stocks and consumption in large, complex river basins, but also the potential impacts of different water management strategies on the agricultural and environmental services these systems provide (Rebelo 2016). The water balance quadrant framework is another recent development aimed at identifying hydrologic contexts in which "water-saving" technologies may be promoted without risking reduced return flows for downstream users (Batchelor et al. 2014). The challenge is to bring these more advanced approaches into the broader policy discussions to improve the design and outcomes of interventions related to water productivity.

Lesson 4: Well-intended interventions may result in unintended consequences

Without due consideration of context-specific elements, well-intended interventions may result in unintended (and often undesirable) consequences, ranging from hydrological to environmental, social and financial/economic changes. An illustration is provided in section 3.2.2 involving the adoption of "resource conservation" technologies in Pakistan, which led to increases in yields, water productivity (in terms of yield per unit of water applied), and farm profits. Among the unintended consequences were higher water consumption as well as an increase in groundwater use at the cost of downstream users and uses, including the environment. Preexisting inequities among farmers with different farm sizes were also exacerbated.

There may be other unintended consequences and trade-offs (Guerra et al. 1998; Barker et al. 2003; Kijne 2003; Hsiao et al. 2007; Sadras et al. 2011). Water productivity improvements involving higher yields may come in the form of more polluted drainage flows due to farmers' more intensive use of fertilizers and pesticides. Furthermore, water productivity improvements associated with investments in better technologies or practices may affect farm-level incomes due to high investments and operational costs, and possibly additional labor or management requirements. This is often used as a rationale for providing public subsidies to facilitate investment decisions. Moreover, yields (and farm-level incomes) may decrease with interventions that aim at reducing the consumptive water use of crops for achieving real water savings, such as deficit (or partial) irrigation. Higher risk is another potential trade-off from adopting "water-efficient" technologies and practices as is increased exposure to market fluctuations through the production of marketable crops. Poor farmers who often have less ability or resources to cope with or manage risk may then be disproportionally affected (van Ittersum et al. 2013). As mentioned in section 3.3.4, depending on the context and preexisting inequities, water productivity interventions can either reduce or reinforce inter-household inequities (Barker and Levine 2012; Clement et al. 2011b). Consequently, estimates of changes in water productivity may not be useful to assess policy interventions unless the possible trade-offs—such as effects on downstream users, increased risk and uncertainty, and rising inequities—are properly incorporated (even if only qualitatively) into the assessments, and efforts are made to minimize them (Bakker et al. 1999; Barker et al. 2003; Kijne 2003; Wichelns 2014a, 2014b).

Lesson 5: Improving water productivity is not a goal in and of itself

Improving agricultural water productivity must not be seen and pursued in isolation. IWMI's research has shown that it is not a "principle objective" or an end in and of itself (Rijsberman 2006; Vidal et al. 2014). Rather, it needs to be integrated with, and contribute to, broader development objectives. As discussed in section 3.3, the four main objectives are: (i) increasing agricultural production, (ii) reducing agricultural water use, (iii) raising farm-level income, and (iv) alleviating poverty and inequity in the agriculture sector.

Research conducted by IWMI and partners has also suggested that the relationship between water productivity and these broader objectives is not straightforward. For example, with regard to the first development objective of increasing agricultural production, it is not clear if a contribution has been made when a water productivity measure increases and more output per input of water is produced. The ratio may have increased due to a reduction in water use (however defined) while output remained constant or even decreased. Furthermore, as Wichelns (2014a) illustrates with typical crop-water production functions, the point of maximum water productivity may be very different from the point of maximum crop yield—even in the simplest case of one output and one input (water). It may also be quite different from the point of maximum net revenue (which has implications regarding the contribution to the third development objective of raising farm-level income). More complications in determining whether a contribution to the first objective has been made arise when water productivity estimates are compared over different crop types and over time. Without further information and analysis, it is not obvious which situation should be preferred over the other and whether the change helped to increase agricultural production or not.

Similarly, when assessing the contribution of improved water productivity to the second development objective of reducing agricultural water use, a number of issues need to be kept in mind. Besides noting whether the change occurred in the numerator or denominator of the ratio, it is important to pay attention to which water measure is used and which scale incorporated. In addition, the context needs to be considered—in particular, whether return flows matter for downstream uses—to determine whether real water savings were achieved. Broadly speaking, when return flows do not matter (for example, if they flow to a salt sink that prevents reuse), a focus on optimizing the share of water applied for crops' transpiration needs may be justified (for example, with the adoption of "resource conservation" technologies, coupled with a limit on the expansion of the irrigated area). If return flows do matter, the focus may need to be on reducing water consumption, because only this reduction could be considered as "saved" water that is available for reallocation without affecting downstream uses.

On the fourth development objective, IWMI's research has shown that there is no simple link between water productivity improvements and poverty or equity. Technology-oriented interventions may even be associated with trade-offs between poverty reduction and equity (section 3.3.4). It is, therefore, important to assess the constraints faced by poor irrigators (not only with regard to access to water, but also to other resources), and properly design and target interventions.

Lesson 6: Limitations of single-factor productivity metrics must be kept in mind

Similar to land productivity or labor productivity, agricultural water productivity focuses on one factor in a multi-factor, and usually also multi-output, production process. In general, single-factor productivity metrics do not give a full picture of the natural, market or policy context in which agricultural production takes place. For example, water productivity ratios expressed in kilograms per cubic meter (kg/m^3) or US dollars per cubic meter (USD/m^3) are often used for making comparisons across users, sectors and over time. It is then important to keep in mind that different water productivity values do not necessarily reflect water-related issues, but may be the result of many other factors and their respective intensity of use, and, depending on the formulation of the ratio, also the result of different outputs and their related prices. Such data can, therefore, provide only an incomplete, and potentially misleading, picture of the underlying drivers of water productivity, especially when used in isolation (Barker et al. 2003, Lautze et al. 2014; Scheierling et al. 2014).

It is these conceptual challenges that Seckler encouraged IWMI and the broader research community to address, so that water management projects are designed and implemented "in a much better way—from all the important technical, economic, social, and environmental perspectives" (Seckler 1996, 3). Early on, IWMI researchers cautioned that a focus on a single-factor productivity metric in agricultural production processes with multiple factors may provide misleading results from the perspectives of the farmer and the economy as a whole. Consequently, IWMI argued for a broadened definition of agricultural water productivity—one that includes a wider perspective on water use and the related benefits, costs and risks that may accompany its improvements (Bakker et al. 1999; Barker et al. 2003; Molden et al. 2007b).

As illustrated in section 3, this broadened definition has likewise faced conceptual challenges, but the related research has also provided greater clarity on both the contributions and limitations of agricultural water productivity metrics. On its own, agricultural water productivity may be considered as a weak proxy variable for the objectives that are indeed of interest (section 3.3). However, when considered in context and as part of a larger suite of indicators, measures of water productivity can give a first approximation of the situation and help to identify outliers. They can also provide a basis to generate and test hypotheses on the underlying causes for the differences and, with further analysis, suggest possible interventions (Fuglie 2014).

Lesson 7: New technologies and data sources should be increasingly used and cross-disciplinary approaches promoted

The creation of water accounting frameworks has been fundamental to the improved application of the water productivity concept. Water accounting has provided a framework to understand how water is used and reused within and across sectors at various spatial scales. Tools such as hydrologic models coupled with crop models, and data generated with remote sensing technologies, have allowed researchers to estimate average current and potential water productivity; identify locations with high and low water productivity; explore possible entry points (technical, managerial or policy) to improve water productivity; and understand the potential consequences within and outside of the agriculture sector, including the effects on ecosystems (Karimi et al. 2012, 2013a, 2013b; Rebelo et al. 2014).

However, data constraints continue to limit the application of even single-factor water productivity metrics—even in developed countries. For instance, the United States Geological Survey (USGS) discontinued calculations to estimate return flows and consumptive water use due to resource and data constraints in 1995; since then, USGS has relied on estimates of water withdrawals rather than water depletions as the basis for its semi-decadal report on water use

(Maupin et al. 2014). Continued development of water accounting and remote sensing tools (e.g., United Nations 2012; Karimi et al. 2013a; Tilmant et al. 2015) is needed to lessen the constraints of data limitations, and enhance the ease and precision with which water productivity estimates can be made at multiple scales.

The development and application of other approaches from related disciplines could also provide new insights and opportunities for improving the definition, assessment and analysis of agricultural water productivity and efficiency. In economics, especially in the field of agricultural production economics, aspects related to productivity and efficiency have been defined and analyzed using more comprehensive approaches, taking into account a range of production factors. A recent survey of the literature on agricultural productivity and efficiency, which explicitly includes water aspects in the measurement of productivity and efficiency, showed that the field offers a number of useful approaches to assess multi-factor production processes, including total factor productivity indices and frontier models (Scheierling et al. 2014). Deductive methods, such as hydro-economic models, which are often applied in irrigation water economics could also be used more specifically to assess agricultural water productivity in a multi-input and multi-output framework (Scheierling and Tréguer 2016). These findings suggest an opportunity to advance economic assessments of agricultural water productivity, and to provide insights, in combination with other disciplinary approaches, on how water could be used better in different contexts and in support of different development objectives.

5. Conclusions

In the preceding sections, we discussed the concept of agricultural water productivity and its evolution from different efficiency concepts; the development of further indicators to assess and measure change across a range of uses and scales, and their applications; the scope for water productivity gains in different contexts and scales, and the related pathways; as well as the rationale and thinking behind the importance of improving water productivity, and the contribution to broader development objectives. The report highlighted the need for precision in defining water productivity terms, and discussed their limitations. The importance of water accounting as an adaptable framework for estimating water uses and identifying opportunities for improvements has been stressed. Progress in the use of remote sensing to generate additional data for use in water accounting, and in integrated crop and hydrologic modeling, at a range of scales has also been discussed.

In the rich body of literature on agricultural water productivity that has evolved over the past 20 years through research conducted by IWMI and partners, a shift becomes apparent from more theoretical deliberations (the need to produce more crops with the same or less amount of water) to a more practical discussion (where, why, and how to achieve this). Based on the methodological developments and applied research, a number of key lessons emerge: scale and context matter, and so do objectives and incentives as well as data and approaches. This body of research suggests that the inherent value of single-factor water productivity metrics may not be as variables to be maximized but rather as initial, albeit imperfect, indicators for regions with increasing water scarcity of the potential for improvements; and as a basis for further analysis of the underlying causes for the differences, the possible interventions (that may or may not be related to water) and their likely impact.

Reflecting on these lessons is particularly relevant given the adoption of the United Nations Sustainable Development Goals (SDGs) in 2015, and the fact that Goal 6.4 emphasizes the importance of increasing water-use efficiency across all sectors, including agriculture. With growing water scarcity in many parts of the world, improvements in agricultural water productivity seem to be desirable as a means to reduce overall water use in the agriculture sector. However, whether gains in water efficiency or productivity measured as single-factor productivity metrics are a relevant indicator at different scales of analysis and in different settings, or whether they contribute to broader development objectives, depends on a number of complex and interrelated factors, and requires more detailed analysis in those specific settings.

The launch of the SDGs provides an important moment to revisit the concepts of water efficiency and productivity—their use and limitations, particularly in relation to water savings—and to consider agricultural water productivity as part of a larger suite of metrics and approaches to help address water scarcity concerns and achieve broader development objectives. More intensive interdisciplinary collaboration would help arrive at more comprehensive approaches. Research presented here offers possible entry points with remote sensing, agronomy, hydrology and economic approaches, in particular from agricultural production economics and irrigation water economics. To conclude, a focus on agricultural water productivity has brought greater attention to water scarcity and management issues and their complexity. There exists now a strategic opportunity to combine the lessons from this large body of research to tackle challenges, improve methods and application, and thus contribute to food and water security, economic growth and poverty alleviation goals.

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Postal Address
P O Box 2075
Colombo
Sri Lanka

Location
127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone
+94-11-2880000

Fax
+94-11-2786854

E-mail
iwmi@cgiar.org

Website
www.iwmi.org

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