Water Productivity in Agriculture:

Looking for Water in the Agricultural Productivity and Efficiency Literature

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Abstract. Expectations are that the agricultural sector will have to expand the use of water for irrigation to meet rising food demand, given population and income growth. At the same time, the competition for water resources is growing in many regions. Increasing water productivity in agriculture is widely seen as a critical response to help address these challenges. Yet much of the public debate is vague on the meaning of agricultural water productivity—often emphasizing "more crop per drop" as if water were the only input that mattered—, and approaches for assessing and increasing water productivity are seldom addressed systematically. This paper discusses conceptual issues that should be kept in mind when assessing agricultural water productivity, and presents findings from what may be the first survey of the agricultural productivity and efficiency literature with regard to the explicit inclusion of water aspects in productivity and efficiency measurements. The survey includes studies applying single-factor productivity measures, total factor productivity indices, frontier models, and deductive models. A key finding is that most studies either incorporate field- and basin-level aspects but focus only on a single input (water), or they apply a multi-factor approach but do not tackle the basin-level aspects. It seems that no study on agricultural water productivity has yet presented an approach that accounts for multiple inputs and basin-level issues. However, deductive methods provide the flexibility to overcome some of the limitations of the other methods.

Key words: Agricultural water productivity, irrigation efficiency, single-factor productivity, total factor productivity, frontier models, deductive methods
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1. Introduction

It is increasingly acknowledged that without advances in water management and more integrated policy making in both developed and developing countries, water-related problems will significantly worsen over the next several decades. Among the key factors influencing this situation are water management issues in the agricultural sector. Agriculture is by far the largest user of water, with irrigated agriculture accounting for about 70 percent of total freshwater withdrawals worldwide (Molden, 2007). Water use in agriculture also tends to have relatively low net returns as compared to other uses. As water becomes scarcer, other users tend to turn to agriculture as a potential source of water (Young, 2005). At the same time, it is expected that the agricultural sector will have to expand the use of water for irrigation due to continued population growth, rising meat and dairy consumption, and expanding biofuel use. Projections indicate that agricultural production in 2050 would have to be 60 percent higher than in 2005/2007 to meet the likely demand (Alexandratos and Bruinsma, 2012). In many parts of the world, the availability of irrigation water may become a major factor in this regard, especially when the impacts from climate change are taken into account (World Bank, 2012).

In order to help address these challenges, it is often recommended that efforts should focus on improving water productivity in agriculture. Given the large amounts of water involved, and the widely held perception that water use in agriculture is relatively inefficient, even small improvements in agricultural water productivity are believed to have large implications for local and global water budgets. Such improvements would allow higher agricultural production with the same amount of water, or the same amount of agricultural production with less water. The water savings from the latter case could be reallocated to other higher-value uses. In line with this thinking, many influential international institutions concerned with water management issues are promoting increases in agricultural water productivity as an important policy goal (Seckler, 1996; UNESCO, 2009; FAO, 2012; and World Bank, 2013).

Yet much of the public debate uses the term agricultural water productivity quite vaguely. If a definition is given or implied, it is usually along the lines of "more crop per drop", emphasizing water as if it were the only input that mattered.[1] Partly due to this lack of a clear conceptual framework, approaches for assessing and increasing water productivity and/or efficiency, and water conservation, are seldom systematically discussed. Nevertheless, large public and private investments are being made for

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[1] For example, an address of the United Nations Secretary General to a summit of the "Group of 77" developing countries stated: "…we need a Blue Revolution in agriculture that focuses on increasing productivity per unit of water, or ' more crop per drop'" (Annan, 2000).

increasing agricultural water productivity, in both developed and developing countries. A frequently applied intervention is to support farmers in the switch to more capital-intensive on-farm irrigation technologies. For the United States, for example, several studies have shown that such interventions may reduce on-farm water applications, but do not necessarily provide real water savings, i.e. they do not reduce water consumption[2] and thus do not free up water resources for other uses (Scheierling *et al.*, 2006; and Ward and Pulido-Velazquez, 2008). Yet the Environmental Quality Incentives Program, first authorized in the 1996 farm bill, continues to help farmers buy more capital-intensive irrigation equipment, such as sprinklers and pipelines, to save water. Since 1997 subsidies of about $1 billion have been used to increase the "efficiency" of irrigation water use. Farmers who received subsidy payments have been shown to use some of their "water savings" (which occur mostly in terms of water applications) to expand the irrigated area or grow thirstier crops, and thus increase consumption (Nixon, 2013).

In this paper we argue that many of the complexities in the discussion about assessing and increasing agricultural water productivity and efficiency are related to two key issues: The first is the unique characteristics of water (Young, 2005). Because water is mobile, exclusive property rights are relatively difficult and expensive to establish and enforce. Water is also rarely completely consumed in the course of its "use". In crop production, it is not unusual to find that 50 percent or more of the water withdrawn from a water source is returned to the hydrologic system in the form of surface runoff or subsurface drainage. The quantity, quality and timing of return flows often affect downstream users. These physical externalities make it difficult to derive insights from what is observed on a field (or farm or irrigation system level) to the overall effects at the basin level.

The second issue is the multi-disciplinary nature of the topic. Among the disciplines involved are hydrology and hydrogeology, civil and irrigation engineering, agronomy and crop physiology, and economics. Each discipline tends to understand the terms productivity and efficiency in a different way, and even within disciplines various productivity and/or efficiency terms are used or newly coined depending on the focus of study and the approach employed. In civil engineering, for example, conveyance efficiency (defined as the ratio of the water received at the farm gate relative to the water withdrawn from a water source) is an important term. In irrigation engineering, application efficiency (defined as the ratio of the water stored by the irrigator in the root zone, and ultimately consumed, relative to the water delivered to the farm) and irrigation efficiency (defined as ratio of the water consumed

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[2] In crop production, the consumption of water is also called evaptranspiration (ET). This is the amount of water that is actually depleted by the crops, i.e. lost to the atmosphere through evaporation from plant and soil surfaces and through transpiration by the plants, incorporated into plant products, or otherwise removed from the immediate water environment.

relative to the water applied or withdrawn) are classical concepts (Jensen, 2007). Agronomists and crop physiologists often use the term water use efficiency, and apply different definitions (such as the ratio of plant biomass or yield produced relative to transpiration, or the ratio of yield relative to water consumed or water applied) (Hsiao *et al*., 2007). In economics, the productivity of a firm is defined as the ratio of its output to its input, while the efficiency is a comparison between observed and optimal values of its output and input (Fried *et al*., 2007).

In the irrigation literature, covering mostly engineering and agronomy studies, such efficiency terms have dominated the discussion for many decades. A particularly important term has been irrigation efficiency, which can be increased significantly by a switch to more capital-intensive on-farm irrigation technologies. Productivity measures have become more widely used after Seckler (1996) pointed out that irrigation efficiency was inadequate to guide demand management at the basin level because it only addresses water delivery aspects for a farm or irrigation system; it implies that water not consumed by crops is wasted (or, vice versa, that water savings are achieved with an increase in irrigation efficiency) which is not necessarily the case in the context of basins where return flows are an important water source for downstream users. Thus local improvements in irrigation efficiency may not translate into basin-wide efficiency gains. In order to achieve real water savings, Seckler recommended to focus on water productivity in irrigated agriculture. Without further defining the term, he advocated measures for improving it, such as increasing output per unit of water consumed, reducing water losses to sinks, reducing the pollution of water, and reallocating water from lower valued to higher valued uses. Subsequently, the term has been used increasingly in the irrigation literature. Many different definitions have been suggested and applied, mostly along the lines of "crop per drop" (and thus similar to some of the definitions of water use efficiency in agronomy).

In the economics literature, including in agricultural production economics, productivity and efficiency aspects are defined in different ways, and the analysis is carried out with a range of methods. Following Ruttan (2002), the methods can be distinguished into three main groups: single-factor (or partial) productivity (SFP) measures, total factor productivity (TFP) indices, and frontier models.

SFP measures relate output to only one input. They are relatively easy to calculate. Yet, the production economics literature pointed out early on that SFP ratios or indices are affected by the intensity of use of the excluded inputs;[3] they thus give an incomplete picture of the underlying drivers of productivity change—especially when used in isolation. Furthermore, they are not marginal, but average

[3] For example, Heady and Dillon (1961) in an inter-country comparison of production function estimates from farm samples emphasized that "the resultant average [computed as the mean output divided by the mean input of a resource] includes the product returns of all inputs, not simply the product return attributable to the single resource" (p. 590).

products (Wichelns, 2014) and do not account for the possibility of input or output substitution (Latruffe, 2010). Because of these limitations, the economics literature on agricultural productivity and efficiency mainly employs the other two groups of methods, TFP indices and frontier models (Coelli *et al*., 2005). TFP indices are particularly concerned with the incorporation of all inputs of the production process.[4] They compare a single output or an aggregate output index to an aggregate input index, and different ways of aggregation lead to different TFP indices. The indices require quantity and price information for the outputs and inputs included, and assume implicitly that all firms are efficient. TFP changes over time are attributed to technological change. The third group of method, frontier models, measure efficiency as a potential input reduction or potential output expansion, relative to a reference "best practice" or efficient frontier, constructed from observed inputs and their output realizations. Techniques for defining the frontier can be classified into parametric and non-parametric methods. Parametric methods rely on specifying a production frontier and estimating its parameters econometrically (with deterministic frontier analysis assuming that any deviation from the frontier is due to inefficiency, and stochastic frontier analysis also allowing for statistical noise [5]). Non-parametric methods, on the other hand, use mathematical programming techniques to construct piece-wise a surface (or frontier) over the output-input space and then calculate the level of inefficiency as the distance to the frontier. The most popular method to do this is data envelopment analysis (DEA) (Latruffe, 2010).

In addition to these three groups of methods, there is a fourth group that is not much discussed in the agricultural productivity and efficiency literature but constitutes an important part of the agricultural and irrigation water economics literature. Following Young (2005), this group can be termed deductive methods, and includes residual imputation methods, mathematical programming, hydroeconomic models, and computable general equilibrium (CGE) models. In contrast to the parametric methods, which employ inductive logic (in this case econometric procedures) to infer generalizations from individual observations, the approach of the deductive methods involves reasoning from general premises to particular conclusions. Deductive methods require construction of models comprising a set of behavioral postulates (such as profit maximization) and data that typically include assumptions about technology of production and the relevant prices. The data may be provided by empirical studies of production processes, published government reports, and expert opinions. Deductive methods are often based on "representative farm models" that can portray a farm scenario or aggregate a regional total, and

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[4] Because of the difficulty of capturing all inputs (and outputs) that interact in the production process, TFP indices are also referred to as multifactor productivity (MFP) indices.

[5] This is modeled through a composed error structure, with a one-sided component measuring inefficiency and a two-sided symmetric term capturing statistical noise.

incorporate producers' resources (including water and all other inputs) and technological options based on realistic assumptions about productivity of resources, market availability, and managerial capability. Thus deductive methods do not focus on inefficiencies, but they can take into account technological change. They can be constructed to reflect any future economic and technological conditions, which makes them useful for policy analysis and project planning.

This paper aims to contribute to the increasing debate on water productivity in agriculture on two fronts: first, by discussing conceptual issues that should be kept in mind when assessing agricultural water productivity and, second, by presenting findings from a survey of the agricultural productivity and efficiency literature with regard to the explicit inclusion of water aspects in productivity and efficiency measurements. To our knowledge, this is the first attempt to undertake a review and analysis of this type. The focus is on studies that apply either SFP measures, TFP indices, frontier models, or deductive methods, and make an effort to incorporate water aspects. Given the extensive literature on agricultural productivity and efficiency, the survey does not attempt to be exhaustive. A key finding is that most studies presented in the agricultural productivity and efficiency literature either incorporate field- and basin-level aspects but focus only on a single input (water), or they apply a multi-factor approach but do not tackle basin-level aspects. It seems that no study on agricultural water productivity has yet presented an approach accounting for both multiple inputs and basin-level issues. However, deductive methods—while not inherently equipped with a basin-level framework—do provide the flexibility to overcome some of the limitations of the other methods.

The remainder of the paper is organized as follows. Conceptual issues are further elaborated in section 2, providing a framework to the literature survey in section 3. Section 3.1 reviews studies, mostly from the irrigation literature, that employ single-factor approaches. Section 3.2 examines studies with multi-factor approaches, comprising TFP indices and frontier models, from the agricultural production economics literature. Deductive methods from the irrigation water economics literature are presented in section 3.3. This is followed by section 4 with a discussion and conclusions.

2. Conceptual Issues

In discussing conceptual issues, we present some of the dimensions that need to be considered when assessing agricultural water productivity, but tend to be neglected when the emphasis is on a simple ratio such as "crop per drop". We start out with a production function for one output and one input, and provide a brief exposition of the definitions of efficiency and productivity in economics and of the sources of productivity increases, and also show some of the limitations of (average) crop per drop ratios (figure 1). We then distinguish between different measures of water and how they affect crop per drop ratios, including how the ratios change as a result of an intervention, such as a switch to a more capital-intensive irrigation technology (figure 2). Also illustrated is the importance of the scale at which water productivity issues are tackled, i.e. limited to the field (or farm or irrigation system) level, or incorporating basin level aspects and taking into account return flows (figure 3). Finally, a situation with the inclusion of other inputs besides water, and their prices, is presented (figure 4).

To illustrate the different sources of productivity increases, figure 1 shows a single input-single output case ($Y = f(X)$), with X representing the water input, Y crop yield, and f the production frontier. Initially the firm is operating at point A. Productivity may improve through (i) increased technical efficiency, i.e. the same level of output is produced with less input (move from point A toward point B') or more output is produced with the same level of input (move from point A toward point B) which, in both cases, involves a move toward the production frontier; (ii) economies of scale, i.e. operating at the point of (technically) optimal scale where the ray from the origin is a tangent to the production frontier (move from point B to point C); and (iii) technological change, which may be represented by an upward shift in the production function (move from f to f'). If not only physical quantities and technical relationships are included in the analysis but also prices (and a behavioral assumption), another source of productivity change can be considered: allocative efficiency. In input selection it would involve selecting that mix of inputs that provides a given quantity of output at minimum cost.

A ray through the origin in figure 1 has the slope y/x, and thus provides a measure of average productivity, as in the SFP measure "crop per drop". More crop per drop could be achieved by any of the moves described above. Thus, even in the single input-single output case, an increase in that ratio could be the result of different sources, and be associated with less or more water use; without further analysis these underlying causes would not be obvious.

When assessing agricultural water productivity, it is useful to distinguish between three water measures: water withdrawal, the amount of water removed from a source; water applied, which differs from water withdrawn by the amount of water lost in transit from the point of withdrawal to the point of delivery; and consumptive use, the amount of water depleted by the crops (footnote 2). Depending on which measure is represented on the X axis of figure 1, the crop per drop ratios may differ. This is shown in figure 2.

An irrigated area is initially assumed to produce 100 kg of a particular crop. Water is withdrawn from a river and delivered to the area in a canal. About 10 percent of the water withdrawn is lost in the canal to seepage. Seepage and water not consumed by the crop are assumed to return via a shallow aquifer to the river. In case (i), on-farm irrigation efficiency (defined as the ratio between water consumed and water applied) is 40 percent. Water consumption amounts to 36 m^3, composed of 24 m^3 of beneficial consumption (which is necessary for plant growth) and 12 m^3 of non-beneficial consumption (which may comprise, for example, evaporation from soil surfaces). Thus 90 m^3 of water would have to be applied to the irrigated area, and 100 m^3 withdrawn from the river. Depending on the underlying water measure in the crop per drop ratio, the values for agricultural water productivity may range from 1 to 2.8.

Case (ii) shows the effects from an improvement in on-farm irrigation efficiency to 60 percent (because the farmer moved to a more capital-intensive irrigation technology, for example, from a gravity system to sprinklers). Water application could then be reduced from 90 m^3 to 60 m^3, and withdrawals from 100 m^3 to 67 m^3. The respective crop per drop values increase significantly.[6] Yet because water consumption does not change[7], the value for agricultural water productivity in terms of water consumed would stay the same, as would the river flow downstream of the irrigated area.

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

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

Going beyond the field level, figure 3 shows a basin with several water users. Building on cases (i) and (iii) of figure 2, two additional irrigated areas with similar features and a city requiring 40 m^3 of water consumption are now assumed to be located downstream. Initially, as in case (i), the three irrigated areas operate with an on-farm irrigation efficiency of 40 percent, with each producing a yield of 100 kg. Under these circumstances the city can be supplied with the necessary water of 40 m^3, and the river flow downstream amounts to 52 m^3which would be considered sufficient for environmental purposes. If, as in case (iii), the irrigated areas switch to an on-farm irrigation efficiency of 60 percent and continue to

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[6] In terms of the framework presented in figure 1, with the X axis representing water withdrawn or applied, this increase would be the result of the improved technology used by the farmer (i.e., a shift in the production frontier), not the efficiency with which a given technology is used (i.e., the distance to the production frontier).

[7] With constant crop yield, a constant level of water consumption is assumed regardless of the level of water application. This assumption is also made in the following cases.

withdraw the same water amounts (because the water rights are formulated in terms of withdrawals, for example), they can spread the water on more land and increase their combined yield from 300 kg to 450 kg (see the numbers in brackets). However, the return flows from the irrigated areas would decrease and the city would now have water problems. Even if the city withdrew all the water left in the river, it would only receive 38 m^3. In such a situation negotiations between upstream and downstream users may help to resolve the problem. The city could, for example, subsidize the farmers in the irrigated areas to adopt additional agronomic measures to reduce non-beneficial consumption by two- thirds. This would guarantee the city's water needs, but the environmental uses further downstream might still be negatively affected.

While figures 1 to 3 are able to illustrate some of the limitations of crop per drop ratios as productivity measures at the field and basin level, they are still based on a conceptual framework that suffers from three shortcomings: only one input (water) is considered; productivity increases stem only from technological progress, and possible efficiency gains are not considered; and prices are not included. Figure 4 strives to address these shortcomings by illustrating a multi-factor framework which also allows for the concepts of technical efficiency and allocative efficiency to be discussed. It represents the situation where a farmer, originally at point A, produces a given crop in the quantity Y by applying irrigation water in the amount of W_A (with a traditional technology, say a gravity system) and all other inputs in the amount of W_A.[8] Following Karagiannis *et al.* (2003), the water-specific technical efficiency is measured by the ratio of two distances $[X_A C]/[X_A A] = W_C/W_A$. This measure determines the minimum amount of water applied (W_C), and also the maximum potential reduction in water applied ($W_A - W_C$) that would still allow the production of Y while keeping the other inputs at X_A. Input-oriented technical efficiency would imply a move to point B where the quantity of water applied would decrease to W_B. This potential reduction ($W_A - W_B$) is smaller than ($W_A - W_C$), with the latter considered as an upper bound. Taking into account the prices of inputs, the farmer could strive to be efficient from an allocative point of view, reaching a level of water applied of W_E or W_D (with $W_E > W_D$) depending on the price of water, P_{W-} or P_{W+} (with $P_{W-} < P_{W+}$), respectively.

More generally, points such as D and E represent an allocatively efficient use of water and other inputs contingent on the ratio of the prices of water and the other inputs. According to standard production theory, least cost production of output Y is achieved when the ratio of the marginal products of water and the other inputs equals their price ratio (MP_W/MP_X) = (P_W/P_X) for any point (or combination

[8] The other inputs X in figure 4 is assumed to be a composite of all the other inputs except water that can be modified by the farmer in the short-run, typically during a cropping season. The level of capital used, including the type of irrigation technology, is assumed to be constant during this timeframe.

of inputs) on the isoquant, with P_W and P_X giving the full opportunity costs of using water and the other inputs, respectively. The marginal product of water can then be written as $MP_W = (P_W/P_X)\ MP_X$. This implies that a SFP measure for agricultural water productivity, when expressed not as an average product as in "crop per drop" but as a marginal product, should be expected to be high when the price of water is high, the cost of other inputs is low, and the marginal product of the other inputs is high. It is important to note that the focus in this case is on water applied, and return flow issues are neglected.

Overall, the illustrations presented in figures 1 to 4 provide insight into some of the key issues that the agricultural water productivity and efficiency literature on seeks to address. The survey of the literature below starts out with a look at the irrigation literature, followed by the economics literature.

3. Water in the Agricultural Productivity and Efficiency Literature

3.1 Single-Factor Approaches: SFP Measures

The use of single-factor productivity measures is dominant in productivity-related studies in the irrigation literature. Its origin can be traced to Seckler (1996) who recommended focusing less on improving irrigation efficiency and more on increasing the productivity of water in irrigated agriculture. Subsequently, other authors—mainly affiliated with the International Water Management Institute (IWMI)—suggested definitions for the term (Molden, 1997; Molden and Sakthivadivel, 1999; and Molden and Oweis, 2007) which were then refined and applied in numerous articles in the irrigation literature. Usually, agricultural water productivity was understood as agricultural output per unit volume of water. The numerator of the ratio could be in physical terms, such as kilograms of agricultural production or marketable crop yield; or, in "economic" terms, such as gross or net value of product. The denominator could be expressed as water supplied or water depleted (such as consumed by evapotranspiration and/or lost in a sink where it cannot be readily reused). Thus, when choosing a particular numerator and denominator, a decision had to be made about 'which crop' and 'which drop' to include, taking into account factors such as the relevant scale (i.e. field, farm, irrigation system, or basin level), the stakeholders, and data availability (Molden *et al.*, 2003).

A review of the single-factor studies shows that various methods have been used to measure agricultural water productivity across crops, basins, countries, regions and time periods, with the aim of identifying critical factors to articulate recommendations for policy reform and interventions to "close the gap" in the water productivity findings and, thus, help alleviate rising water scarcity. Substantial differences in spatial and temporal water productivities have been documented—depending on the particular definition of "water productivity" chosen, but also with the same definition. For example, water productivity for wheat in terms of kilograms of yield relative to cubic meters of evapotranspiration among farms in an irrigation district in Iran varied from 0.76 to 0.98, while in terms of kilograms of yield relative to cubic meters of transpiration it ranged from 1.11 to 1.26 (Vazifedoust *et al*., 2008).[9] Most studies use such findings to argue that a large scope exists to increase yields and/or save water and, thus, to improve water productivity. The identified policy implications tend to be wide-reaching, but often not supported with robust evidence from the analyses carried out. In an early critique, Barker *et al*. (2003), for example, pointed out that while a higher water productivity tends to be viewed as inherently better than a lower one, this may not be the case from the perspective of the farmer or the economy as a whole. To illustrate, a management practice that increases water productivity may require more labor and other inputs, and therefore might not be cost-effective.

Traditionally, agricultural water productivity has been derived by measurements of crop yields and water use at experimental stations and farmer fields. Such studies typically try to control for other relevant inputs. They tend to be time- and resource-intensive, and their results cannot be easily extrapolated to other conditions. An example for this type of study is by Arbat *et al*. (2010) who examine the effect of subsurface drip irrigation emitter spacing on water productivity (defined as corn grain yield with 15.5 percent wet-basis moisture content divided by total crop water consumed) in Kansas, and find no significant impact.

Based on a literature review of 84 publications with data from field experiments, Zwart and Bastiaanssen (2004) compared measured water productivity values (in terms of marketable crop yield over actual evapotranspiration) of major crops. They find wide ranges, amounting to 0.6-1.7 kg m^{-3} for wheat, 0.6-1.6 kg m^{-3} for rice, and 1.1-2.7 kg m^{-3} for maize, and interpret these to indicate "tremendous opportunities for maintaining or increasing agricultural production with 20-40 percent less water resources" (p. 115). Without more in-depth analysis, they discuss three factors that influence the soil-plant-water relationship as key for explaining the large variations, including climate, irrigation water management, and soil management.

More recently, a range of studies used agrohydrological models in combination with measured data to estimate crop water productivities. An example is Vazifedoust *et al*. (2008) who applied the soil water atmosphere plant (SWAP) model calibrated with farmers' field data to an irrigation district in Iran. Water productivity indicators were estimated in different physical and "economic" terms for four key

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[9] Some studies thus recommended that further analyses should be carried out to increase the sample size (for example, regarding the number of irrigation schemes, as in Sakthivadivel *et al*., 1999). Also, for better comparisons of estimates, it was recommended that water productivity indicators should be used in a more standardized way (for example, with regard to fresh matter or dry matter for grain yield in the numerator; or the period taken into account in the denominator, such as the entire growing season or only the time from sowing to harvest), and/or that information on these aspects should at least be provided in the studies (Bessembinder *et al*., 2005).

crops. The authors conclude that the substantial differences between the indicators expressing yield over evapotranspiration and yield over irrigation water applied indicated “the need for replacing the traditional irrigation system with a more efficient one” (p. 101).

Other recent studies have combined agrohydrological modeling with remote sensing and geographical information systems (GIS) data to assess water productivity at larger scales. For example, van Dam *et al.* (2006) used the SWAP model, together with geographical and satellite data, to calculate water productivity using different definitions in a district in India. The authors found that the ratio of yield per m^3 of evapotranspiration for key crops, such as wheat and rice, could be derived relatively cheaply by remote sensing; but more resource-intensive modeling allowed them to estimate additional definitions of water productivity, and also assess the effects of alternative management scenarios on the ratio of yield over evapotranspiration for the key crops. Better crop management, for example, was found to increase the ratio.

Some studies also modeled crop water productivities on a global scale. Liu *et al*. (2007) integrated GIS into the environmental policy integrated climate (EPIC) crop growth model in order to extend the model for wheat on a global scale, addressing spatial variability of yield and evapotranspiration as affected by climate, soil, and management factors. Simulated yields were compared to FAO statistical yields and found to be in good agreement. Estimated crop water productivities differed significantly within and across countries. Western European countries had relatively high values (>1.2 kg m^{-3}), whereas low values (<0.4 kg m^{-3}) prevailed in most African countries. According to the authors, the differences “suggest that global water use could be reduced through food trade” (p. 478).

Based on input data sets derived from remote sensing, Zwart *et al*. (2010a, 2010b) developed WATPRO and estimated yield over evapotranspiration. When applying the model to wheat production on a global scale, they found large variations in water productivities, with an average estimate for the ten major wheat producing countries of 0.93 kg m^{-3}. The authors argued that results from their model “facilitate the planning of food production in relation to limited water resources for agriculture” (p. 1625).

A few studies with single-factor productivity estimates analyze in a more rigorous manner the effect of other factors on their findings for water productivity. For example, Belloumi and Mattoussi (2006) estimated crop yield functions with irrigation water as one of the explanatory variables (thus assessing the partial effect of the water input on crop yield variations while controlling for the effect of other input variables). They applied a Cobb-Douglas function to cross-section data on date yields in different oasis farms in Tunisia, and a linear function to related values for water productivity (in terms of irrigation water applied). They found water salinity to be a key factor that contributes to both yield and water productivity differences. Another approach based on panel data analysis was used by Alauddin and

Sharma (2013) to explore inter-district differences in rice water productivity (in terms of consumptive use) in Bangladesh. They first applied factor analysis to derive representative dimensions, and identified agricultural intensification and technological diffusion as key explanatory variables. Employing Granger causality tests, they further explored the role of these two factors on water productivity changes, suggesting that technological diffusion was a causal factor of water productivity in the majority of districts in Bangladesh. Then they employed generalized least squares estimates and found that technological diffusion had a positive effect on inter-district water productivity differences while agricultural intensification and policy transition towards deregulated markets decreased water productivity.

3.2 Multi-Factor Approaches: TFP Indices and Frontier Models

Whereas single-factor productivity measures are mostly found in the irrigation literature, multi-factor measures—in particular TFP indices and frontier models—dominate the productivity and efficiency-related literature in agricultural production economics.

TFP indices have been employed in a large number of empirical studies, mostly at the national level but more recently also at subnational levels. The usual TFP indices account for marketed outputs of goods and services but tend to disregard items, such as water, that are usually not marketed. The neglect of nonmarketed goods and services has long been recognized as a problem (see, for example, Antle and Capalbo, 1988; and Gollop and Swinand, 1998).[10] Data limitations may continue to be a factor (Alston and Pardey, 2014), with some authors specifically mentioning that they were not able to account for the contribution of water as a separate input in TFP growth estimates because of a lack of appropriate data (for example, Wang *et al*., 2013).

Studies in two recent books by Alston *et al*. (2010a) and Fuglie *et al*. (2012a) on agricultural productivity patterns at the country, regional and global levels demonstrate approaches allowing inclusion of some water aspects in TFP indices. For example, Fuglie (2010a), in a study on Indonesia, distinguished between irrigated and non-irrigated cropland. In an analysis of China's agricultural productivity, Jin *et al.* (2010) included irrigation costs among the material input costs. When examining the shifting patterns of agricultural productivity in the United States, Alston *et al.* (2010b) distinguished between irrigated and non-irrigated cropland, adding a miscellaneous input category to account for irrigation fees. Fuglie (2010b), in a study of TFP in the global agricultural economy using FAO data,

[10] With a slightly different perspective, Fuglie *et al.* (2012b) point out that it was increasingly recognized that future productivity gains in agriculture need to save not only land, but also a wider array of natural resources, such as water, so as to avoid negative impacts to the environment from agricultural intensification.

divided cropland into rainfed cropland and cropland equipped for irrigation, and included irrigation fees in the cost share of agricultural land. Finally, Zhao *et al*. (2012), in an examination of annual TFP indices for Australia's broadacre agriculture[11] stated that an important reason for their significant fluctuations were variable climatic conditions, including the amount of moisture retained in the soil. These examples illustrate the challenges of including water aspects in studies at national or higher levels. In some cases, irrigation water is indirectly considered through the area of land irrigated. Efforts are made to incorporate irrigation fees, but they may not approximate the price or opportunity cost of water. Not surprisingly, these studies do not provide any conclusions related to the effect of water on agricultural productivity patterns.

A few studies of TFP measurement at the subnational level, such as the provincial and district levels, do incorporate water aspects in more detail. For example, Murgai (1999) provided district-level TFP estimates for the Green and post-Green Revolution period in the Indian Punjab. By distinguishing between availability of canal irrigation and investments in private tubewells (the former as cost associated with the quantity of canal-irrigated area, and the latter as an item in the index of capital accumulation), she was able to identify the water source as an additional factor for the sharp differences in productivity growth across districts and cropping systems over time. Conradie *et al*. (2009) focused on South Africa's Western Cape Province and further disaggregated TFP indices for its regions and districts. They found that water availability (included as a dummy variable to indicate whether a district had a major river running through it) was an important explanatory variable. Districts with rapid TFP growth were those that not only showed water availability, but also the adoption of drip irrigation and a switch to export fruit production (which was made possible by a number of other factors, such as the introduction of an improved marketing system and cold storage facilities at the coast).

Besides TFP indices, multi-factor frontier models are also frequently used in the agricultural production economics literature. The original frontier model was introduced by Farrell (1957) in a seminal paper that lays out a framework to measure economic efficiency, including technical efficiency which represents a firm's ability to reach the maximum potential output, given a given set of inputs and for a given technology; and allocative efficiency which captures the firm's ability to adapt optimally to market conditions by adjusting input use such that for each pair of inputs, the ratio of their marginal products equals the ratio of the input prices. Frontier models have been widely used in the agricultural economics literature over the past few decades, and encompass deterministic frontier models, stochastic frontier models (which are increasingly replacing the former), and DEA.

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[11] Broadacre agriculture includes non-irrigated grains, beef and sheep production.

Bravo-Ureta *et al.* (2007) conducted a meta-analysis of frontier models with a focus on farm-level studies, including 167 articles for the period from 1979 to 2005. We found that 28 of these studies include models that incorporate water. Yet most did so either by including water as one of numerous inputs, or by grouping water with other miscellaneous factors in a combined input. In both cases, water's role in technical efficiency was usually not analyzed further. Only six studies incorporated water in more detail—including two DEA studies (Fraser and Cordina, 1999; and Sarker and De, 2004); three stochastic frontier model studies, with one of them also using a deterministic frontier model (Ekanayake and Jayasuriya, 1987; Ali and Flinn, 1989; and Sherlund *et al*., 2002), and one study employing both DEA and stochastic frontier methods (Wadud and White, 2000). We also identified five additional applications of frontier models to agricultural water management, including two earlier studies that are of particular interest for our purpose (Yao and Shively, 2007; Gedara *et al*., 2012; Gebregziabher *et al*., 2012; McGuckin *et al*., 1992; and Karagiannis *et al*., 2003). Table 1 summarizes key features of the eleven studies, including methods and findings.

One of the findings is that potentially large technical inefficiencies in the application of irrigated water are associated with an inability to adequately control water use, due to, for example, unexpected breakdowns (Ali and Flinn, 1989) and location on irrigation canals (Ekanayake and Jayasuriya, 1987; Yao and Shively, 2007; and Gedara *et al.*, 2012). In addition to improving control and security of water applications, education and training (Sarker and De, 2004; Sherlund *et al.*, 2002; Gebregziabher *et al.*, 2012; and Karagiannis *et al.*, 2003) and improved soil moisture management (McGuckin *et al.*, 1992) are suggested as measures to increase the technical efficiency of water applications.

Stochastic frontier models are found to be preferred to deterministic models because the latter cannot separate random "noise" from deviations arising from technical inefficiency (Ekanayake and Jayasuriya, 1987). Omitted variable bias (e.g. when rainfall, water applications or other environmental factors are omitted) may lead to an upward bias in the estimated technical inefficiency and lack of precision in estimating sources of inefficiency (Sherlund *et al*., 2002). One approach to the problem, taken by Gebregziabher *et al.* (2012), was to use plots matched in environmental characteristics.

Two studies, by McGuckin *et al*. (1992) and Karagiannis *et al*. (2003), emphasize the importance of distinguishing between irrigation efficiency (as used in the irrigation engineering literature) and economic efficiency involving technical and allocative efficiency. They point out that irrigation efficiency is only one dimension of input use, a physical measure of the irrigation technology assuming a level of management, while technical and allocative efficiency are measures of management capability.[12]

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[12] As McGuckin *et al.* (1992) put it: "Compared to a furrow system, a sprinkler irrigation system could reduce water use and increase irrigation efficiency but at the expense of an increase in capital. With very low cost water, the sprinkler would be

Karagiannis *et al*. (2003), referring to McGuckin *et al*. (1992) as well as Farrell (1957), proposed to define irrigation water efficiency not along the lines of the engineering-oriented concept of irrigation efficiency but instead to use the concept of water-specific technical efficiency, defined as "the ratio of the minimum feasible water use to observed water use, conditional on the production technology and observed levels of output and other inputs used" (p. 58). The cost saving related to the adjustment of irrigation water to a technically efficient level—while holding all other inputs and output at observed levels—will vary with prices. Furthermore, "relatively inefficient water use in a physical sense can be relatively efficient in a cost sense, and *vice versa*" (p. 60). Thus, while the measures of output-oriented and input-oriented technical efficiency do not identify the efficient use of individual inputs, "water-specific technical efficiency" is an input-oriented single-factor measure that provides information on how much water use could be decreased without altering the output produced, the technology (including the irrigation technology) utilized, and the quantities of other inputs used. Empirical results indicate that water-specific technical efficiency is on average much lower than output-oriented technical efficiency, indicating that farmers could become significantly more efficient in irrigation water use, given the present state of technology and input use. Furthermore, modern greenhouse technologies, education, and extension are the main factors associated positively with the degree of water-specific technical efficiency.

Both McGuckin *et al*. (1992) and Karagiannis *et al*. (2003) include irrigation water as a continuous variable (in terms of water applied), and are concerned with farmers' irrigation water savings. However, the "water savings" discussed are in the form of reduced water applications, not consumption—and therefore potential externalities beyond the farm level in terms of return flows were not explicitly considered.

3.3 Deductive Methods

The agricultural productivity and efficiency literature mostly relies on TFP indices and frontier models to focus on the role of specific factors in productivity growth, and to identify approaches to increasing economic efficiency in production. Deductive methods form a parallel class of techniques important in the agricultural and (irrigation) water economics literature. Similar to TFP indices and frontier models, deductive methods belong to the category of multi-factor approaches. They are flexible with regard to scale, and can be applied from field, farm and irrigation system to the basin and national levels, sometimes in combination with other methods.

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allocatively inefficient. More subtly, a sprinkler could also be technically inefficient. With improved management, a sprinkler system might use as much water as the furrow system and thus be technically inefficient compared to the well-managed furrow system" (pp. 306-307).

The residual imputation method and its variants are frequently used for evaluating policies on water use in agricultural production (Young, 2005). In its basic form, for a single-product case, it can be derived from the neoclassical theory of the firm, in particular the product exhaustion theorem. In general terms, if the production function and the quantities of all other inputs are known, and accurate prices can be assigned to all inputs but one (in this case, water), invoking the production exhaustion theorem allows the imputation of the remainder of total value of product to that input. This allows to derive a point estimate of the producer's net income attributable to the optimally applied input water. This approach provides the building block for more complex approaches that incorporate changes in water supply and multi-product cases. Foremost are mathematical programming models that can represent the optimum allocation of water and other resources so as to maximize net income, subject to constraints on resource availability or to institutional arrangements. They are advantageous where a wide range of alternative productive technologies (formulated as alternative activities) is to be studied, including alternative levels of inputs to produce a given output, alternative products, alternative production technologies, or all of the above. Solutions of a mathematical programming model for a range of water supply constraints trace out a set of net total income points, from which a set of value marginal water productivity points can be then derived.

Residual imputation methods have been applied extensively since the 1960s. An early application is the linear programming model of Hartman and Whittlesey (1961) to study the adjustments of three "typical farms" in western Colorado to changes in water supply. They find that, besides factors such as input and output prices, the kind of adjustments farmers can make determines the value marginal productivity of water. Moore and Hedges (1963) formulated linear programming models for farms of different sizes in California's San Joaquin Valley with a total of 54 production activities representing combinations of alternative crops, irrigation treatments, and soil grades. Yaron (1967) performed linear programming studies for kibbutz and household farms in two regions in Israel, and finds that the incorporation of flexible crop irrigation practices significantly raises estimates for value marginal water productivity. In a study based on a linear programming model of 3,220 equations, Heady *et al.* (1973) dealt with the optimum allocation of water and land resources in 51 water supply regions and 27 market regions of the United States. In a framework of interregional competition and comparative advantage, they examined the effect of alternative water prices, population levels, farming technology, and agricultural policies.

The early linear programming studies typically used constant output prices. This may be problematic, particularly during periods of acute water stress or potential output disruptions. Allowing crop prices to depend on output can be accommodated, as demonstrated in the quadratic programming model used by Howitt *et al*. (1980) to estimate agricultural production and short-run irrigation water use in 14 regions of California.

While the solution of linear programming models (even if they are large) is straightforward, their calibration often is not (Booker *et al.*, 2012). Naïve models rarely result in solutions that reflect observed crop patterns or technology choices under representative water supply and output price conditions. This is typically ascribed to a myriad of producer constraints and hidden costs which may not be evident to the modeler. Calibration is then often carried out using complex sets of linear inequality constraints, which may lead to rigidities in terms of the models' ability to respond to policy scenarios. To circumvent this problem, an approach originally proposed and implemented by Howitt (1995) that recognizes the existence of unobserved costs and incorporate these into a self-calibration procedure called positive mathematical programming is now increasingly used (see, for example, Medellin-Azuara *et al*., 2009).

Deductive methods can also be used to incorporate physical externalities, such as those illustrated in figure 3. Such approaches that explicitly incorporate an empirical hydrologic structure are called hydroeconomic models (Harou *et al*., 2009; Booker *et al.*, 2012). Such integrated models are particularly useful for assessing, for example, the effects of improved on-farm irrigation efficiency through more capital-intensive irrigation technology. That water withdrawals and applications are likely to decline, while consumptive use and hence basin-wide water depletion may remain the same or even increase, was demonstrated in theory by Huffaker and Whittlesey (2003) and with integrated modeling by Scheierling *et al*. (2006) and Ward and Pulido-Velazquez (2008). More generally, hydroeconomic models seek to incorporate the notion that water users are potentially linked through complex physical processes, including those between ground and surface water. For example, Bredehoeft and Young (1970) explored intertemporal allocation options for improved irrigation outcomes in a linked stream-aquifer system where farmers could draw from both ground and surface water. The explicit treatment of return flows as an externality is addressed by Taylor *et al*. (2014).

While including key physical linkages, hydroeconomic models are mostly partial equilibrium models from an economic perspective: linkages with key related economic sectors (e.g., labor markets) are likely to be absent. General equilibrium approaches are needed to include feedback from farm-level changes to the wider economy, and vice versa. Roe *et al*. (2005) provide a discussion of the issues, and an application of such a computable general equilibrium (CGE) model to irrigation water management. In moving towards CGE models, however, many of the key physical linkages and distinctions between, for example, water application and depletion are often lost, and some of the data limitations which challenge TFP studies may reemerge.

4. Discussion and Conclusions

When looking for water in the agricultural water productivity and efficiency literature, it becomes apparent that many studies have examined the question of agricultural water productivity from various perspectives. The irrigation literature, on the one hand, is dominated by studies using single-factor productivity measures. They allow the incorporation of different measures of water use (such as water applied and water consumed) and various scales, ranging from the field to the basin and even global levels. They find large variations in agricultural water productivity, yet usually do not proceed to empirically investigate the factors that might explain the different findings. The use of such single-factor productivity measures, where all variations in output are attributed to the water input, is problematic—especially when they form the basis of policy recommendations for improving agricultural water productivity. These measures disregard the effects of linkages with other inputs (including environmental influences), do not incorporate prices or costs, and do not consider the different sources of productivity.

The agricultural economics literature on productivity and efficiency, on the other hand, has relied on inductive methods, such as TFP indices and frontier models. As multi-factor approaches, these methods avoid some of the key problems of single-factor productivity measures, but have their own shortcomings when it comes to incorporating water aspects and providing insights into how water could be used more productively. TFP studies at the national level tend to not include water as a separate input, often due to data problems. A few TFP studies at subnational levels, such as the district level, capture water aspects as dummy variables and may show, for example, that water availability (in connection with other factors) is an important input associated with TFP growth.

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

Overall, our review of the agricultural productivity and efficiency literature indicates that studies employing inductive methods either incorporate field- and basin-level aspects but focus only on a single input (water), or they apply a multi-factor approach but do not tackle basin-level issues. Based on this albeit partial review of the literature, it seems that no study on agricultural water productivity has yet presented an approach accounting for both multiple inputs and basin level issues. Deductive methods—while, strictly speaking, not part of the agricultural productivity and efficiency literature, but often applied in irrigation water economics—provide the flexibility to address some of the shortcomings of the inductive methods. They are multi-factor (and multi-output) approaches that can be applied at any scale and, if linked with hydrological modeling, can incorporate basin-level issues.

Concluding, while the need to improve agricultural water productivity is widely emphasized in reports and public communications, its meaning often remains ill-defined. This survey of the agricultural productivity and efficiency literature—to our knowledge the first of its kind—indicates that there is an abundance of studies applying a wide range of definitions and methods (and also advocating a wide range of interventions), but it seems that no single approach has yet been able to tackle the complexity of the various aspects of agricultural water productivity. Going forward, it will be important to achieve progress on several fronts. Since water productivity improvements in agriculture may mean many different things, studies should lay out much clearer the objectives they are pursuing in a particular case and be more transparent about their respective limitations, especially if partial approaches are being pursued. Efforts to gather more data on the different measures of agricultural water use need to intensify, even though the special characteristics of water makes this a more difficult and costly endeavor compared to most other factors involved in the agricultural production process. And, last but not least, more intensive collaboration between the various concerned disciplines may well help to arrive at more integrated approaches.

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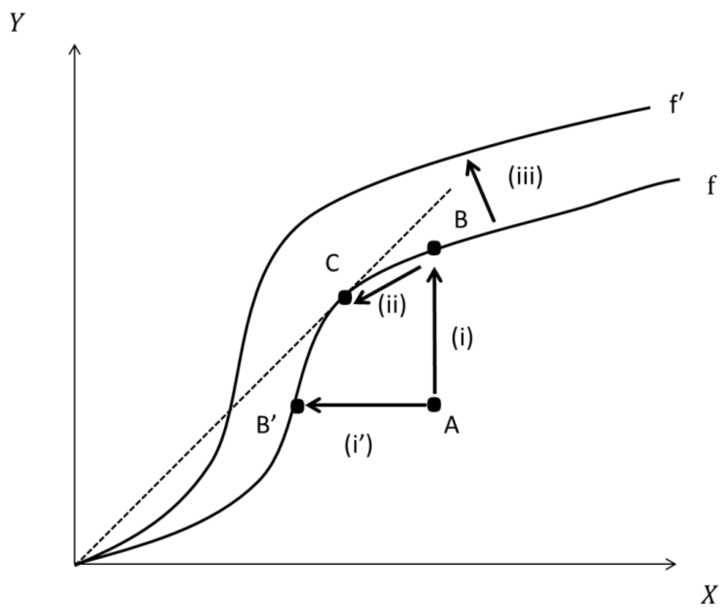
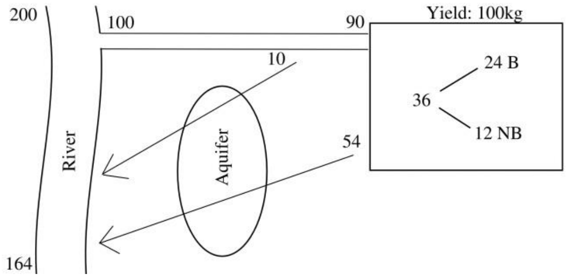


Figure 1. Sources of Improvements in Productivity

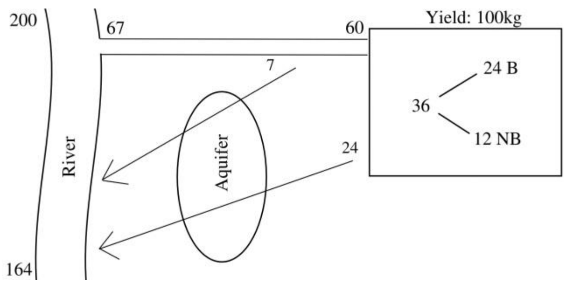
Source: Based on Coelli *et al.*, 2005.

Case (i): 40% Irrigation Efficiency



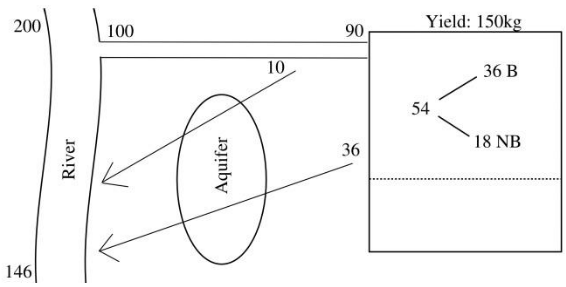
	Water Measure (m^3)	Crop per Drop (kg/m^3)
Water		
Withdrawn	100	1
Applied	90	1.1
Consumed	36	2.8

Case (ii): 60% Irrigation Efficiency, No Water Spreading



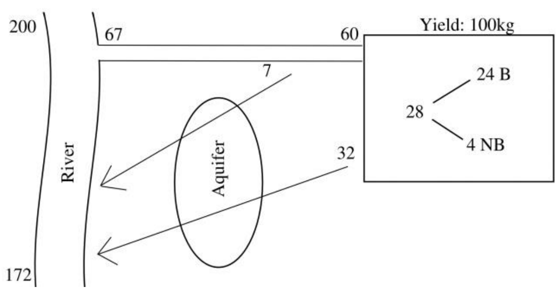
	Water Measure (m^3)	Crop per Drop (kg/m^3)
Water		
Withdrawn	67	1.5
Applied	60	1.8
Consumed	36	2.8

Case (iii): 60% Irrigation Efficiency, Water Spreading



	Water Measure (m^3)	Crop per Drop (kg/m^3)
Water		
Withdrawn	100	1.5
Applied	90	1.7
Consumed	54	2.8

Case (iv): 60% Irrigation Efficiency, No Water Spreading, Reduction of Non-Beneficial Consumptive Use (NB) by 66%



	Water Measure (m^3)	Crop per Drop (kg/m^3)
Water		
Withdrawn	67	1.5
Applied	60	1.7
Consumed	28	3.6

Figure 2. Effects of Improved On-Farm Irrigation Efficiency and Water Spreading on Agricultural Water Productivity (Defined in Terms of Yield Divided by Water Withdrawn, Water Applied, and Water Consumed) and on River Flow.

Source: Authors.

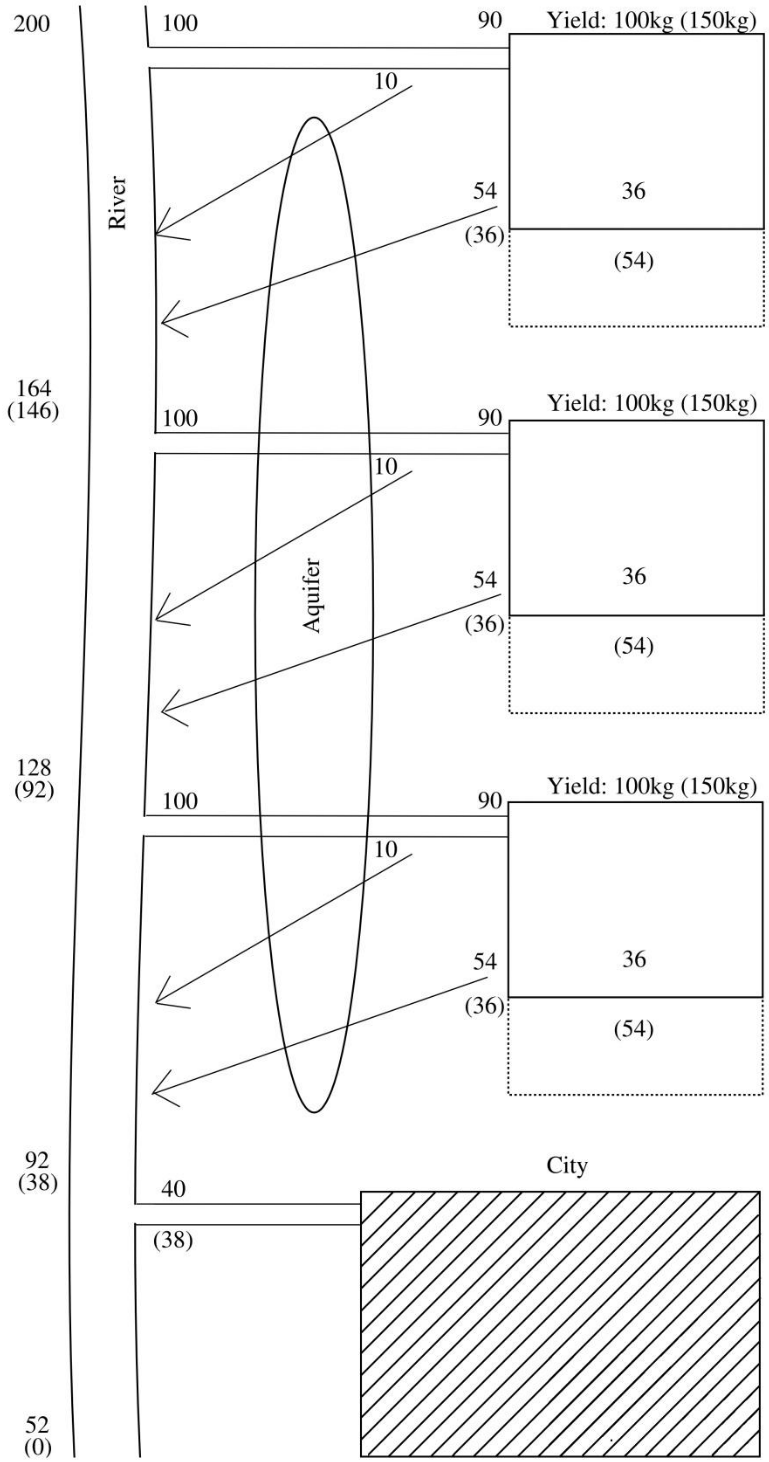


Figure 3. Basin-wide Effects of an Increase in On-Farm Irrigation Efficiency from 40% to 60% with Water Spreading (in Brackets)

Source: Authors.

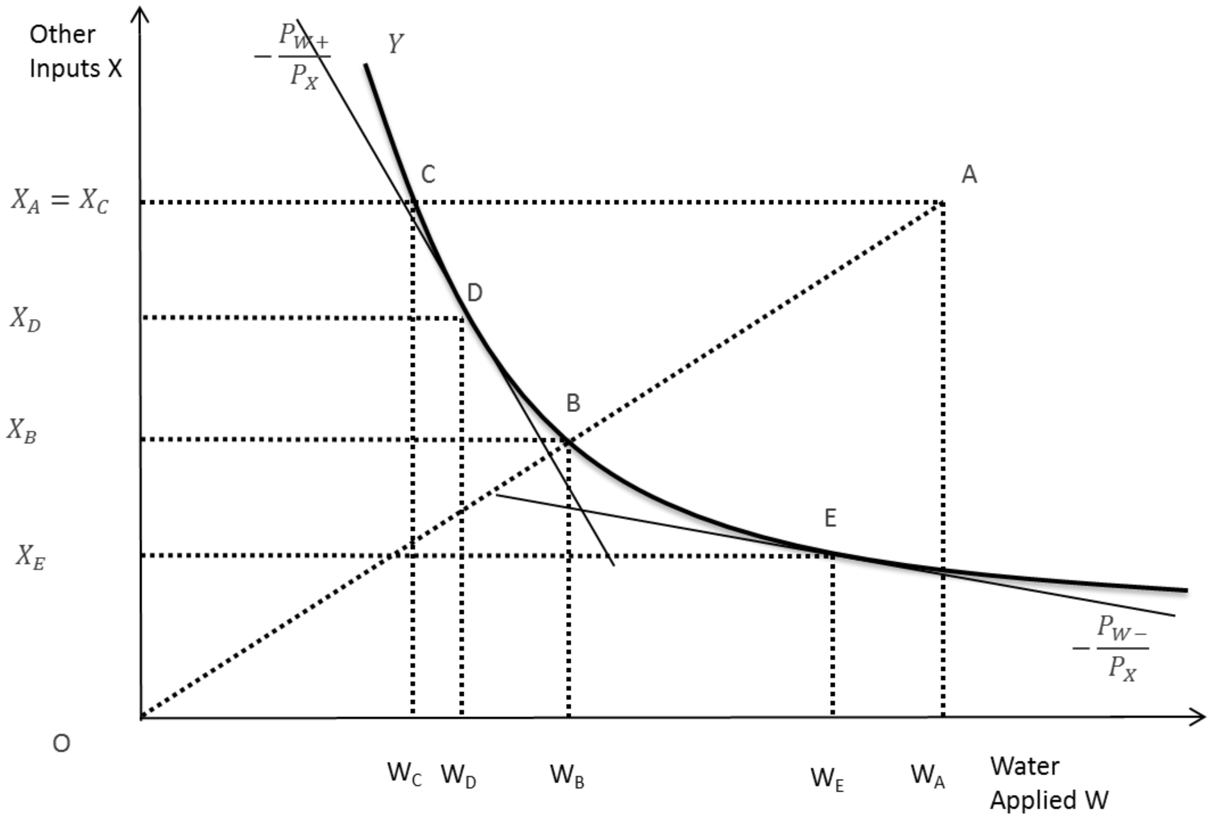


Figure 4. Effects of Input-Oriented Technical Efficiency, Water-Specific Technical Efficiency, and Allocative Efficiency on Water Applied and Other Input Use

Source: Authors.

Table 1. Features of Frontier Model Studies with the Inclusion of Water

Authors (Year of Publication)	Method	Location	Farm Type	Water Specification	Efficiency Findings
Fraser and Cordina (1999)	Data envelopment analysis	Australia	Dairy farms	Irrigation water application	Efficient farm operation could reduce water applications by one-sixth
Sarker and De (2004)	Data envelopment analysis	West Bengal, India	Paddy farms	"Technological advancement" at village level, measured by high incidence of irrigation and high yielding paddy varieties	Little difference in technical efficiency level between villages
Ekanayake and Jayasuriya (1987)	Deterministic and stochastic frontier models	Mahaweli Development Project, Sri Lanka	Rice farms	"Head" vs. "tail" of irrigation canal	Deterministic model overestimates inefficiency; water shortages at "tail" cause real inefficiencies
Ali and Flinn (1989)	Profit frontier approach	Two Punjabi villages, Pakistan	Basmati rice producers	Unexpected water cutoffs due to electrical and tubewell breakdowns and canal closures	Cutoffs cause profit losses; rural workshops to allow timely repairs would reduce losses
Sherlund *et al.* (2002)	Stochastic frontier model	Côte d'Ivoire	Smallholder rice plots, rainfed	Total rainfall and number of rainy days	Including water measures (and other environmental conditions) lowers estimated technical inefficiency
Wadud and White (2000)	Stochastic frontier model with data envelopment analysis	Bangladesh	Rice farms	Irrigation infrastructure (i.e. diesel-operated irrigation schemes)	Presence of irrigation infrastructure reduces technical inefficiency (as does rural electrification)
Yao and Shively (2007)	Time varying stochastic frontier model	Philippines	Rice farms	Level of irrigation development, dry season irrigation	Irrigation development reduces technical inefficiency; increasing distance to canals and canal siltation increase inefficiency
Gedara *et al.* (2012)	Stochastic frontier model	District level, Sri Lanka	Rice farms, village reservoir	Length of irrigation period (minutes), position (head, middle, tail)	Reducing inefficiencies could increase production by 28%
Gebregziabher *et al.* (2012)	Stochastic frontier model	Tigray, Ethiopia	Smallholder plots	Matched rainfed and irrigated plots	Irrigated plots had large inefficiencies; rainfed plots had only small inefficiencies
McGuckin *et al.* (1992)	Stochastic frontier model	Nebraska, United States	Corn producers	Supplemental water application by gravity or sprinkler	Presence of soil moisture sensors most important in reducing inefficiency
Karagiannis *et al.* (2003)	Stochastic frontier model	Crete, Greece	Greenhouse vegetable cultivation	Water application	Water-specific technical efficiency is much lower than output-oriented technical efficiency