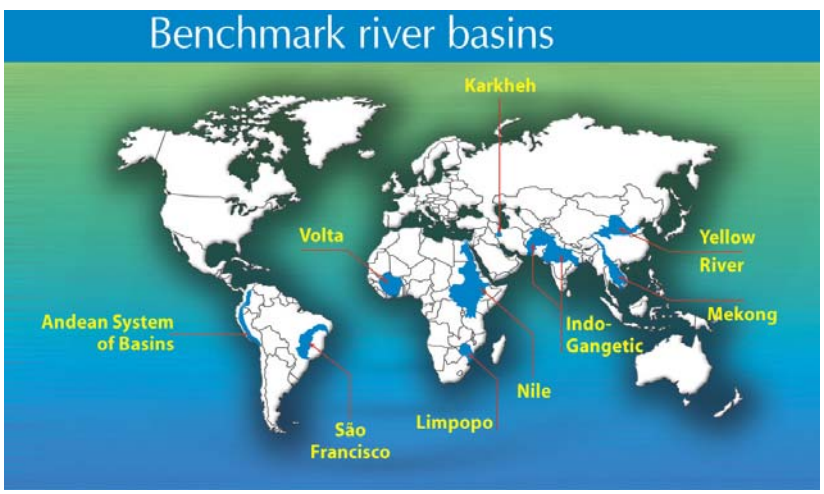
AGRICULTURAL WATER PRODUCTIVITY: Issues, Concepts and Approaches

Basin Focal Project Working Paper No. 1

CGIAR Challenge Program on WATER & FOOD

WORKING WITH PARTNERS TO ENHANCE AGRICULTURAL WATER PRODUCTIVITY SUSTAINABLY IN BENCHMARK RIVER BASINS



DISCLAIMER

This is an advance edition of the *Agricultural Water Productivity: Issues, Concepts and Approaches* and is a **draft version** of a working paper to be published formally by the Challenge Program on Water and Food. This report contains less than fully polished material. Some of the works may not be properly referenced. The purpose is to disseminate the findings quickly so as to invigorate debate.

The findings, interpretations, and conclusions expressed here are those of the author(s) and do not necessarily reflect the views of the Challenge Program.
Comments and additional inputs that could contribute to improving the quality of this work are highly welcomed.

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Agricultural Water Productivity: Issues, Concepts and Approaches

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1 Introduction

The world has finite water resources, which are under increasing stress as the human population and water demand per capita both increase. These problems are not new but are now becoming more widespread and their impacts more devastating. This has provided additional impetus for the search for solutions to problems arising from the mismatch between demand and supply in terms of water quantity, quality and timing. Increasing water productivity has been identified as one of the global challenges that requires urgent attention.

This document examines issues, concepts and approaches to assessing water productivity in agriculture. Section 2 presents a set of concepts and issues for improving our understanding of the complexities associated with assessing and improving water productivity. Section 3 presents approaches in assessing agricultural water productivity and highlights the challenges in quantifying and valuing inputs and outputs. Section 4 presents the rationale for increasing water productivity from the global, basin, irrigation system and farm level perspectives.

2 Concepts and issues

2.1 Water scarcity: a driver for increasing water productivity

Although globally there are adequate water resources to meet the needs of the current and future world population, locally there are many areas experiencing water scarcity (see Box 1).

Box 1: Symptoms of growing water scarcity.

Declining dry season river flows have become a common phenomenon in many rivers. The ecological implications of decline in dry season river flows include (a) insufficient quantity of water to flush sediments leading to siltation problems; (b) insufficient quantity of water to dilute water pollutants leading to permissible pollution levels being exceeded; (c) reduced flows into estuaries result in a rapid advance of a saline front, which extends the extent of the estuary, damages the aquatic ecosystem and threatens bio-diversity. When such ecological changes occur, livelihoods of downstream communities are adversely affected leading to conflicts.

Groundwater depletion. Studies in the Indo-Gangetic plains of northern India show that groundwater tables are dropping by 0.5 to 0.7 meters a year and that 25 per cent of India's grain harvest is threatened by unsustainable use of groundwater. Postel (1999) estimated that globally groundwater is overused by 200 km3/year. The most serious over pumping occurs in India, the United States, Mexico, the Mediterranean countries and China. Over-depletion of groundwater in the coastal areas of Gujarat state in India has lowered the groundwater levels to a point where salt water intrusion is contaminating the supplies of drinking water (Postel, 1993).

Water pollution arising from agricultural and non-agricultural sources is a major contributor to water scarcity. Water erosion transports soil particles and nutrients and deposits them in water bodies contributing to loss of reservoir capacity and eutrophication of water bodies. Intensification of crop and livestock production systems is a major contributor of pesticides and fertilizer pollutants of surface and groundwater resources. Discharge of untreated or partially-treated waste water into river systems aggravates the problem with some rivers becoming virtual sewers. For example, Yamuna river, which passes through New Delhi, receives 200 million litres of untreated sewage per day and has coliform counts as high as 25 million per 100 milliliters (Clarke, 1993).

Inequitable allocation of water resources, combined with poor enforcement of permitted water withdrawals leads to conflicts among uses and users of water.

Water scarcity exists when the demand for water exceeds the supply and it can be classified based on the context as: (a) physical water scarcity in which water availability is limited by natural availability; (b) economic water scarcity when human and financial resources constraints availability of water; (c) managerial water scarcity where availability is constrained by management limitations; (d) institutional water scarcity where water availability is constrained by institutional short-comings; and (e) political water scarcity where political forces bar people from accessing available water resources (Molle and Molinga, 2003). These types of scarcity can occur concomitantly, increasing both the severity and impacts of water scarcity.

Molden *et al.* (2003) estimated that by 2020 approximately 75% of the world's population will live in areas experiencing physical or economic water scarcity. Most of these areas happen to be where most of the poor and food insecure people live. Meeting their food needs with locally produced food presents enormous challenge. Hence, the need is to increase water productivity of agricultural production systems that the poor people in water scarce areas depend on.

2.2 Production function and technical and allocative efficiency

Agricultural production involves the combination of inputs to produce agricultural outputs. For each agricultural production system a generic production function (input-output relationship) can be derived:

$$O = f(I1, I2, I3, \ldots In) \quad (1)$$

Where O is the output and I1, I2, I3, and In are the production factors (land, labor, water, capital, energy and other inputs used in the production).

As production resources become scarce, producers seek ways to enhance the productivity of the resources and of the entire production system. Understanding the production function is a pre-condition for identifying opportunities for improving the performance of a production system. Increases in productivity can be achieved by two approaches: (a) by increasing technical efficiency through more efficient utilization of production inputs; and (b) increasing allocative efficiency by producing outputs with the highest returns. Here below, we illustrate how these two approaches can be used in identifying opportunities for enhancing productivity.

The level of output produced when production resources are used most efficiently defines the technical efficient limit. For example, in Figure 1 the line A-B defines the limits of technical efficiency. Points below the curve are technically inefficient because the same level of yield could be attained with less water. Points above the line are not technically feasible. The single factor production function presented in Figure 2 denotes the production possibilities for a given level of technical efficiency and of other production inputs. From Figure 2, we note that the output per unit input decreases at higher levels of input. In the case of crop production, a decrease in crop yield at higher levels of water input is mainly attributed to inhibited uptake of oxygen by the roots under water-saturated soil conditions.

An analysis of a single factor production function enables us to assess opportunities for maximizing returns from the use of this factor. Let us take a case where the only way of increasing crop yield is by increasing the water input. To optimize the production system, one must understand how output increases with increase in water input. The contribution of water to the production process can be described on both average and marginal (incremental) basis as shown below at different levels of water input.

$$Average\ Product\ of\ Water = \frac{Output}{Water\ Input} \tag{2}$$

$$Marginal\ Product\ of\ Water = \frac{Change\ in\ Output}{Change\ in\ Water\ Input} \tag{3}$$

At low levels of input, marginal product is higher than average product and the average product is increasing. The average product equals the marginal product when the average product reaches its maximum. At high levels of inputs marginal product decreases and becomes negative when one additional input results in a

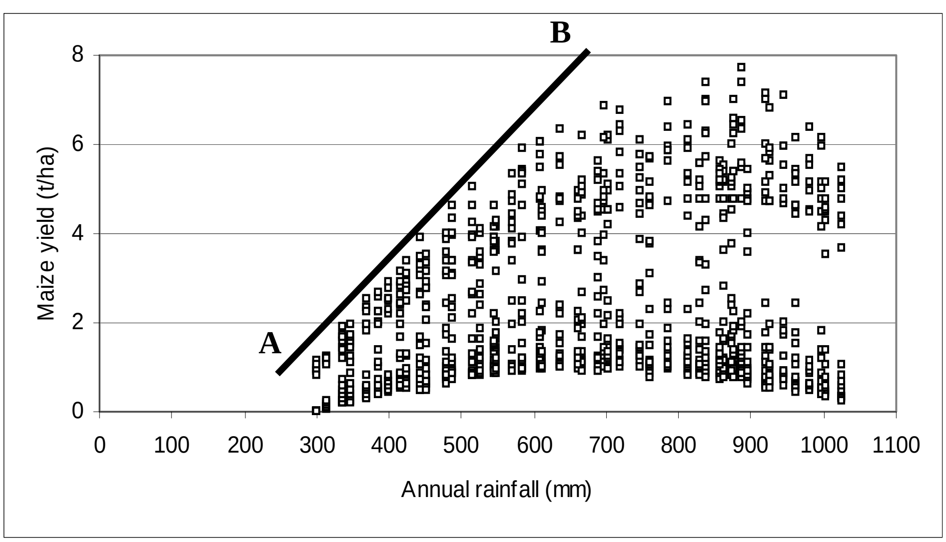

Figure 1. Maize yield as a function of annual rainfall in Ewaso Ngiro Basin Kenya (Source: NRM3, 2000)

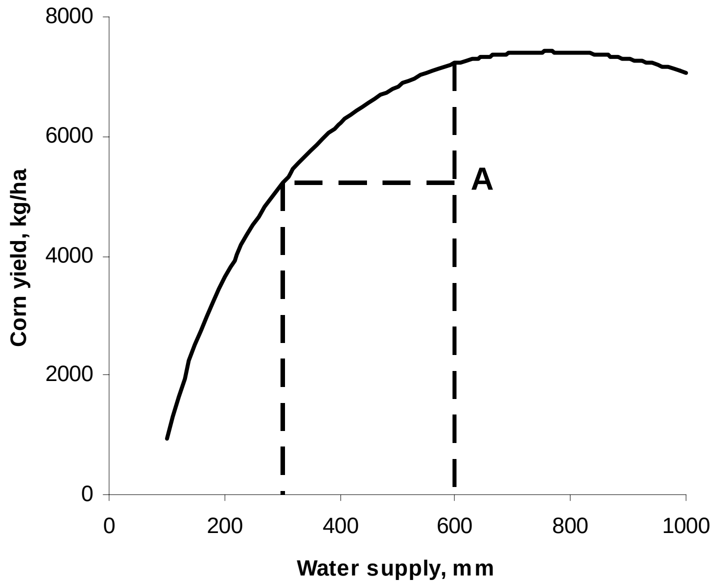

Figure 2. Crop-water production function for irrigated corn in Brazil. At point A, a yield of 5210 kg/ha was achieved with the application of 600mm water. The technically efficient water application for this yield is 300mm. Data from Frizzone *et al.* (1997).

decrease in total output. Marginal product concept can be used to aid farmers in deciding what is the optimal level of a given input to apply.

How much production input is allocated to competing uses? The production resources available to farmers are limited and have competing uses. The farmers therefore have to choose the most desirable mix of agricultural outputs that they can produce with the resources at their disposal and with their state of technical know-how. They know that some outputs can only be produced if they forego others in keeping with the opportunity cost principle (see Figure 3). Take a case of a farmer who has to allocate a given quantity of water W to producing two crops, product A and product B. The production possibility curve for this enterprise shows how much of product A and product B he/she can produce for a given level of water input. Increasing the output of product A can only be achieved by reducing product B for that level of water input and production technology. Increasing the amount of water input will enable him to produce more of product A and product B at a higher production possibility curve.

The concept of allocative efficiency is used here to illustrate how a farmer could make a decision on what and how much to produce with a given level of input. The slope of the production possibility curve presented in Figure 3 is the rate at which crop A is substituted for crop B and is called the marginal rate of transformation (MRT). The farmer maximizes his returns if the marginal rate of transformation of crop A to crop B is equal to the price ratio of the two crops.

$$MRT_{AB} = \frac{P_A}{P_B} \qquad (4)$$

What combination of input levels minimizes production costs? A given level of crop yield can be attained using different combination of production inputs. Hence farmers are confronted with the challenge of substituting one production input for another. The concept of marginal rate of technical substitution illustrates how this could be done.

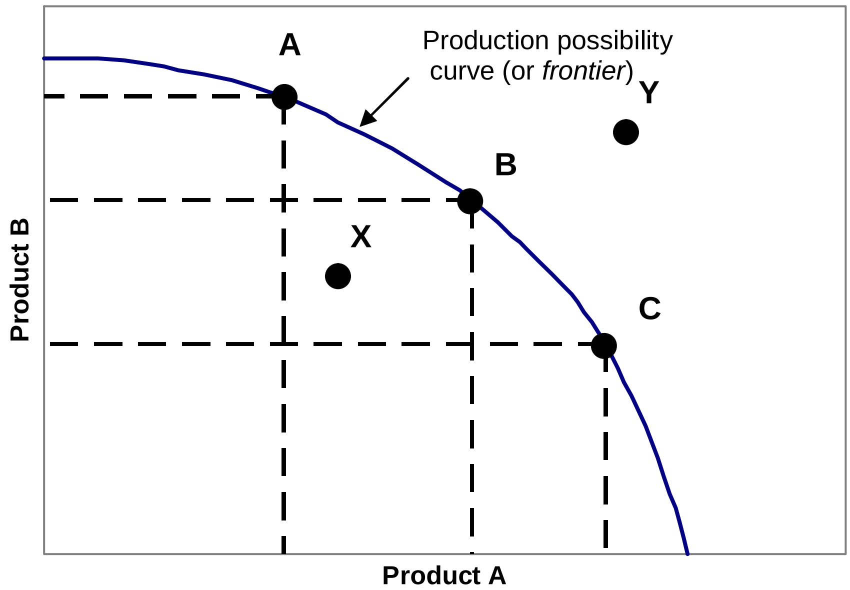

Figure 3. Product possibility curve (PPC), which depicts all maximum output possibilities for two (or more) goods with a given a set of inputs (resources, labor, etc.). The PPC assumes that all inputs are used efficiently. Points A, B and C all represent points at which production of both product A and product B is most efficient. At point X resources are not being used efficiently in the production of both products, while point Y cannot be attained with the given inputs.

Isoquants are curves that show all possible combination of inputs that yield the same level of output. An isoquant map is a combination of several isoquants in a single graph that describe how levels of output vary with different combination of input levels. Isoquant maps are used to assess input substitution as the slope of the isoquant indicates how the quantity of input can be traded off against the quantity of other inputs, holding the output constant. This slope is called the marginal rate to technical substitution (MRTS). As more and more of one input replaces the other, its productivity decreases as that of the other input becomes more productive. For example, the marginal rate of technical substitution (MRTS) of fertilizer for water in a crop production system is the amount by which the input of water can be reduced when one extra input of fertilizer is used, holding the crop output constant. MRTS tells the farmers the nature of the trade-offs involved in adding fertilizer and reducing the level of water input. The decision on how much water and how much fertilizer to use depends on the relative cost of these inputs. Optimum production is achieved when the following conditions hold

$$MRTS_{FW} = \frac{MP_F}{MP_W} = \frac{P_F}{P_W} \qquad (5)$$

Where P_F and P_W are the unit prices of fertilizer and water respectively and MP_F and MP_W are marginal products of fertilizer and water respectively. MP_F/P_F is the additional output that results from spending an additional dollar on fertilizer. Similarly MP_w/P_w is the additional output that results from spending an additional dollar on water. The above equation therefore tells us that the farmer would minimize cost by choosing the quantities of inputs so that the last dollar's worth of any input added to the production process yields the same amount of extra output. We illustrate this point with a numerical example.

Suppose that the unit costs of fertilizer and water are \$10 and \$2 respectively. If an additional unit of water would increase output by 20 units, then the additional output per dollar of water input is 20/\$2 = 10 units per dollar and an additional unit of fertilizer increases output by 4 units. Because a dollar spent on water is five (20/4) times more productive than a dollar spent on fertilizer, the farmer wants to use more water than fertilizer. If he reduces fertilizer and increases water, the marginal product of fertilizer will rise and the marginal product of water will fall. Eventually, a point will be reached where the production of an additional unit of output costs is the same regardless of which additional input is used. At that point the farmer minimizes his costs.

2.3 Producers versus social net benefits

Farmers seeking to maximize benefits will use water and other inputs at levels where the incremental value generated is at least equal to the incremental cost. Farmers choose cropping patterns that maximize net benefits over time subject to their resource endowment, relative input and output prices and market opportunities. In places where water is scarce relative to available land, farmers will choose crops that maximize net returns to their limited water supplies. The way that they manage the water resources will depend on the cost and availability of water together with the technologies and management practices available for improving water productivity.

From society's perspective, the goal for managing public water resources can be described as maximizing the present value of net benefits over time. Net benefits include farm-level net returns minus the cost of water delivery, while accounting for the opportunity cost and externalities. Opportunity costs are the incremental values water might have in alternative uses, for example the value that it might generate for a downstream user. In addition to the spatial dimension (is the water worth more somewhere else?), opportunity costs can also have a temporal dimension (would the water be worth more at some time in the future?) In these examples, opportunity costs must be discounted by the cost of conveying the water to the alternative site or the losses during storage. Society's objectives in increasing water productivity are to meet the ever-increasing demands on a finite water resource. They fall into the following categories:

- Food security for all;
- Poverty alleviation;
- Employment creation – jobs/m^3;
- Equity and
- Meeting environmental demands (for example, flows needed to maintain wetlands).

Externalities are the off-farm effects of water use that impose costs or benefits on other water users. Positive externalities are any benefits that accrue, for example the generation of usable runoff to a desirable wetland area. Negative externalities are short- and long-term damage caused by runoff and deep percolation, for example, waterlogging and salinization.

2.4 Performance assessment

2.4.1 Rationale for performance assessment

Under conditions of increasing scarcity of resources, performance measures can play an important role in identifying opportunities to improve performance. Performance measures of similar (sub-) systems in different geographic locations or those tracking the performance of a particular (sub-) system over time can provide answers to strategic questions, such as: "What types of systems get the most return from limited water and land resources?" At the same time, they provide a cost-effective means of tracking performance in individual systems and valuable information that can be used by:

- Planners to evaluate how efficiently and effectively land, water, labour and capital resources are being used;
- Agricultural producers and managers of water systems to identify long-term trends in performance for use in setting reasonable overall objectives and to measure progress;
- Researchers to compare systems and identify factors that lead to better performance; and.

- Policy makers and development facilitators (donor agencies, private sector and NGOs) to assess the impact of their interventions so that they can be designed to be more effective.

One of the challenges to improve the performance of water in agricultural systems is to answer the questions:

- How well should a system be performing;
- How well is it performing; and
- How can its performance be improved in a cost-effective way?

Such performance analysis implies the need for:

- Performance standards that will be used for comparison;
- Tools and methods for assessing performance and any shortfalls in performance that there may be; and
- The ability to analyze critically the performance data and the determinants of those performance shortfalls that are modifiable.

2.4.2 Challenges of evaluating highly diverse production systems

A river basin comprises of a mosaic of highly diverse agricultural production systems whose outputs include crop, tree, livestock and fish products and a vast multitude of ecological goods and services. The bio-physical, socio-economic and institutional settings under which these production systems operate and the multiple and sometimes conflicts goals of the key actors present additional challenges.

The decisions made by agricultural producers and managers of water systems determine the levels of technical and allocative efficiency of the water resources available in the basin. Their decisions are influenced by the policy and regulatory instruments and by the level of complementary interventions such as infrastructural development. We therefore consider increasing water productivity to be a shared responsibility, however here we focus on the perspective of the agricultural producers. They have multiple objectives upon which they assess the performance of their production systems, namely the productivity, profitability, stability, diversity and time-dispersion (see Box 2 for brief definitions of each). The relative importance of each of these objectives depends on whether their production system operates at subsistence level or is partially commercial or fully commercial.

The most important objective for a commercial farmer is to maximize profit. Productivity, stability, diversity and time-dispersion may be important underlying factors for achieving higher levels of profitability but are generally not taken as desirable objectives in themselves. Farmers generally view productivity as a necessary condition to achieve higher profits but not as a sufficient condition in itself (McConnell and Dillon, 1997).

Box 2. Multiple objectives of an agricultural producer.

Productivity: Ratio of output to input that serves as a measure of the relative suitability of a farming system or an activity within the system.

Profitability: Net benefit accruing from the farming system.

Stability: The absence or minimization of season-to-season or year-to-year fluctuations in the level and/or the value of output of a farming system.

Diversity: Risk minimizing strategy associated with: (a) diversification of the farming system – crop, livestock, trees, fisheries on a given farm; (b) diversity of outputs from a given farming system, for example milk, meat and draft power from cattle production; (c) diversity of the ways that the produce is used – consumed, sold, stored, processed; and (d) diversity of income sources.

Time dispersion: The degree to which production inputs, output and income are spread over time.

Adapted from McConnell and Dillon (1997)

The most important objective for a subsistence farmer is a reliable and well-distributed source of livelihood. Subsistence farmers therefore put more weight on time-dispersion, diversity and stability of their farming system. Subsistence farmers tend to be more diversified and produce more numerous and important by-products, which invariably complicates assessment of productivity. Subsistence farmers diversify to reduce risk of income loss or food insecurity and/or to increase the level of output and profitability through better use of available resources. Increased diversity improves stability, but in some cases reduces profitability.

2.5 Water productivity and efficiency

Productivity is a measure of performance expressed as the ratio of output to input. Productivity may be assessed for the whole system or parts of it. It could account for all or one of the inputs of the production system giving rise to two productivity indicators (Molden, 1997):

- total productivity – the ratio of total tangible outputs divided by total tangible inputs; and
- partial or single factor productivity – the ratio of total tangible output to input of one factor within a system. In farming systems the factors could be water, land, capital, labor and nutrients.

Water productivity (WP), like land productivity, is therefore a partial-factor productivity that measures how the systems convert water into goods and services (Molden *et al.,* 2003). Its generic equation is:

$$Water\ Productivity\ (WP) = \frac{Output\ Derived\ from\ Water\ Use}{Water\ Input} \qquad (6)$$

WP was introduced to complement existing measures of the performance of irrigation systems, mainly the classic irrigation and effective efficiency (Keller *et al.*, 1996). Classic irrigation efficiency focuses on establishing the nature and extent of water losses and included storage efficiency, conveyance efficiency, distribution efficiency and application efficiency. These measures are particularly useful for managers of water system who use them to (a) assess how much water they were losing in the storage, conveyance, distribution, and application sub-systems; and (b) identify interventions to improve performance.

In assessing the performance of water use in a large system, a basin or sub-basin, classic efficiency fails to capture the water re-use aspect. It ignores the beneficial use put to water re-captured and re-used in one part of the basin as a consequence of deep percolation and/or runoff losses that takes place elsewhere in the basin. To address this problem, Keller *et al.* (1996) introduced the concept of effective efficiency, which takes into account the quantity of the water delivered from and returned to a basin's water supply. In an irrigation context, effective efficiency is the amount of beneficially-used water divided by the amount of water used during the combined processes of conveying and applying that water.

The introduction of measures of water productivity makes it possible to undertake a holistic and integrated performance assessment by:

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

2.6 Water productivity and water saving

Real water saving is defined as the process of reducing non-beneficial water uses and making the water saved available for a more productive use. In situations where water is scarce, reducing non-beneficial uses becomes one of the main ways for reducing water scarcity. Improving water productivity seeks to get the highest benefits from water and hence can be viewed as a major contributor to water saving.

Real water saving by reducing non-beneficial depletion can be accomplished through:

- Reducing flows to sinks and
- Reducing non-beneficial evaporation.

For example, improving irrigation efficiency is considered to be the most appropriate way to reduce non-beneficial depletion and save water. Before this can be done, it is important to understand the water pathways of non-beneficial water use and its re-use. For example seepage losses may be the main way in which shallow groundwater aquifers used for downstream irrigation and domestic water supply are recharged. By failing to take a basin perspective when planning and implementing water interventions, we run the risk of not achieving real water saving and of having a negative impact on water quality, drinking water supply, groundwater balance, and downstream human and ecological users.

Guerra *et al.* (1998) noted that in most cases the arguments regarding water saving do not address other important factors that determine water saving such as the cost of water development and recovery. Increasing water productivity often requires greater use of other resources such as labor, capital and management.

Hence, at the basin level it is important to address the following key questions:

- What happens to the water that is lost through runoff and deep percolation?
- What effect does reducing non-beneficial use have on systems that were dependent on the water that it provided?
- What happens to the water that is saved through reduced runoff and deep percolation losses?

Box 3: Definition of terms used in the water accounting framework.

(Source, Molden *et al.*, 2003; IWMI, 2006.)

Gross inflow is the total amount of water flowing into the study area from precipitation, rivers and subsurface sources (groundwater).

Net inflow is the gross inflow less any increases in storage in the surface soil or groundwater.

Available water represents the amount of water available for use that is the net inflow minus the committed and non-utilizable outflow.

Water depletion is a use of water within the system that renders it unavailable for further use.

Process depletion is that amount of water diverted for use that is depleted to produce a human-intended product.

Non-process depletion occurs when water is depleted, but not by a human-intended process.

Non-beneficial depletion occurs when water is depleted through evapotranspiration that is not beneficial. Classification as beneficial or non-beneficial requires a value judgment and is a good entry point for discussions with stakeholders.

Committed outflow is that part of outflow from the study area that is committed to other uses such as downstream environmental requirements or downstream water rights.

Uncommitted outflow is that part of outflow that is not committed and is therefore available for a use within the study domain, but flows out of the basin due to lack of storage or sufficient operational measures. Some of the uncommitted outflow can be non-utilizable.

The water-accounting framework is summarized graphically in Figure 4.

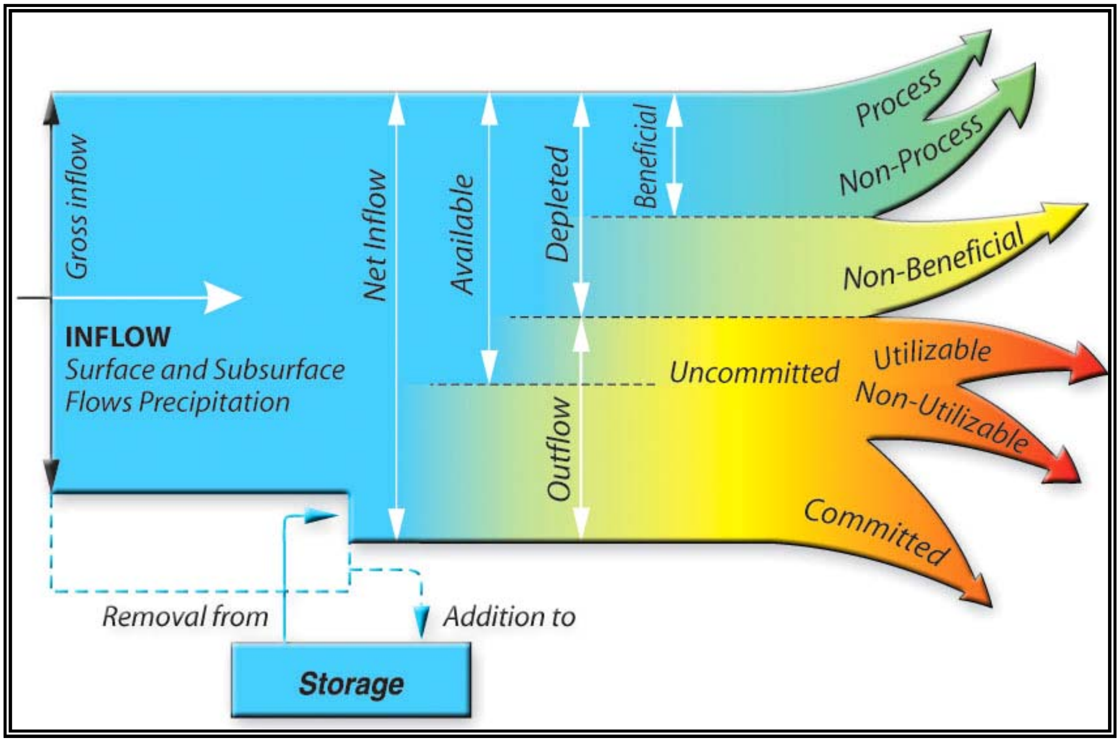

Figure 4. Water depletion accounting. (Source, Molden *et al.*, 2003).

3 Approaches in assessing water productivity

3.1 Assessing the water input

Water accounting is a pre-condition for assessing the water input into a production system. A water accounting framework tracks the water pathways and quantifies inflows, depletions and outflows. It uses a 'water balance' approach to quantify the amount of water entering and leaving a system. The inflows include precipitation, surface and groundwater inflow and any changes in storage. There are two main pathways through which water leaves the system; depletion and outflow (see Box 3).

The amount of water used in production can be interpreted differently depending on the system boundaries and the level of detail. Based on a water accounting methodology developed by Molden *et al.* (2003), the denominator can be, in decreasing order of scale:

- Gross inflow into a given field or catchment area;
- Net inflow;
- Available water;
- Depleted water, which is the amount of water removed from the system by both beneficial and non-beneficial depletion.
- Beneficially depleted water, which is the amount of water depleted through process and non-process beneficial use; and
- Process depleted water, which is the amount of water depleted through process beneficial use.

3.2 Assessing the outputs

Outputs in this context are benefits derived from using water. They can be quantifiable or non-quantifiable and can be generated either through depleting or non-depleting uses of water. Assessing different categories of outputs shown in Figure 5 is particularly challenging due to the following:

- Water provides a wide range of benefits, with quantifiable and non-quantifiable elements;

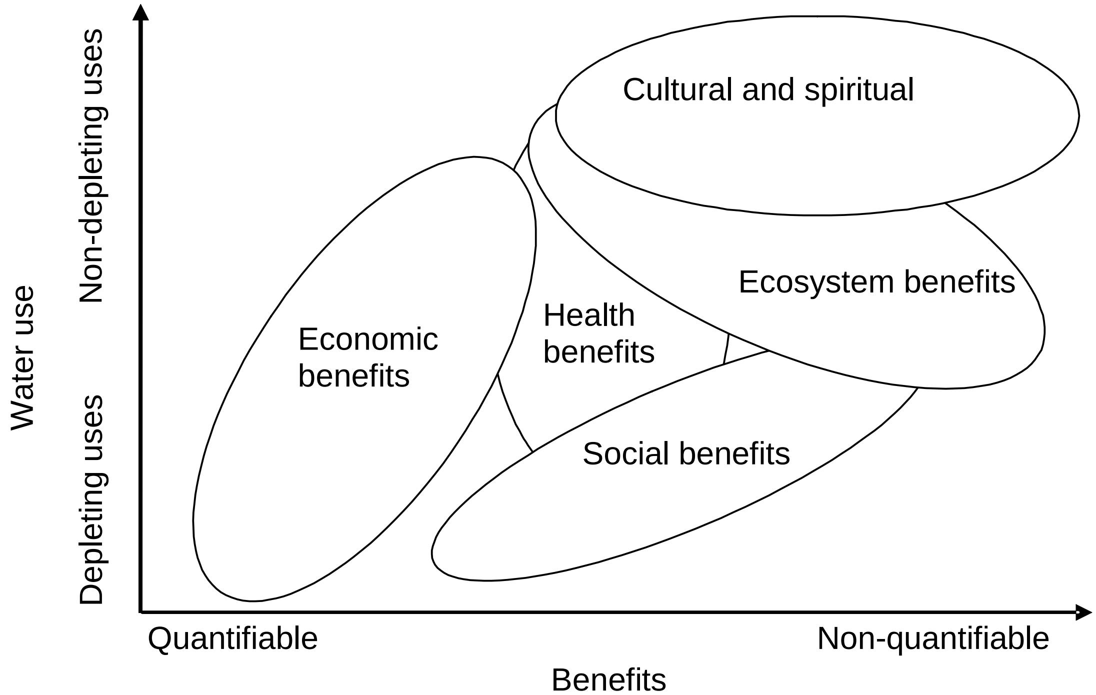

Figure 5. Water use and associated benefits.

- No common objective measure applies to all water benefits;
- Water benefits reflect human value judgments that may vary from person to person and also over time;
- Benefits can be synergistic, for example income generation may improve health through adequate nutrition. Conversely, benefits may also involve trade-offs, such as the loss of ecosystem services that may occur as a result of excessive outtake of water for irrigation;
- In some cases, water may also cause harm through the introduction of hazards such as flooding, soil erosion, water-logging, salinization, as well as a wide the range of water-vectored health risks; and
- Benefits may be valued from different perspectives such as increased food security, reduced climatic risk, stabilization of income, etc.

An agricultural production system may be perceived as providing benefits of primary and secondary goods and services as shown in Table 1. Many secondary goods produced in agricultural systems are complementary to one another. For example, crop production systems may sequester carbon in some circumstances but in other circumstances they may release carbon. In most cases, the improved function of a system comes from complementarities in space and time. The difficulty is to compare parallel benefits from a range of water users.

We now focus on agricultural output, which can be evaluated for physical, nutritional or monetary benefit, within the bounds of the scale and time period being considered. Difficulties arise when outputs are difficult to value or when output quantities are expressed in different units. Crop production, for example, may produce a range of significant outcomes, including grain yield, fodder for livestock and organic matter for soil quality improvement. The first is measured in kg of grain/ha, the second in kg of gain in animal live weight/ha and the third in kg of organic matter accumulated/ha. It is little wonder then that past assessments of agricultural benefits have focused mainly on primary benefits of a given production systems and assessed the benefits as shown in Table 2. The table shows that even when focusing on primary output, there are still many

Table 1. Some agricultural production systems and their benefits.

Agricultural production system	Benefits		
	Primary goods	Secondary goods	Services
Crop production	Harvestable yield	Crop residue for livestock feed	Soil cover to reduce erosion, enhancing agro-biodiversity, carbon sequestration
Livestock production	Meat, milk and eggs	Draft power, manure, leather	
Tree production	Timber, fuel wood	Food	Bio-diversity, water catchment protection, carbon sequestration
Fish production	Meat	Manure	Bio-diversity of aquatic ecosystems

Table 2. Agricultural production systems and their primary goods and indicators

Agricultural production system	Primary output	Indicator	
		Physical/nutritional	Economic
Crop production	Harvestable yield	• Total above ground biomass (marketable and non-marketable) at standardized water content (kg) • Total harvested product at the water content at which it is consumed (kg) • Nutritional content (kcal, or grams of protein, vitamin or micro-nutrient content)	Value of output or gross margin of output
Livestock production	Meat, milk and eggs	• Live weight of animal (kg) • Meat (kg) • Milk (kg or liters) • Eggs (number or kg) • Nutritional content (kcal, or grams of protein, vitamin or micro-nutrient content)	Value of output or gross margin of output
Tree production	Timber, fuel wood	• Timber (kg) • Fuel wood (kg)	Value of output or gross margin of output
Fish production	Meat	• Meat (kg) • Nutritional content (kcal, or grams of protein, vitamin or micro-nutrient content)	Value of output or gross margin of output

ways in which the output can be quantified. This presents an enormous challenge when comparing total water productivity of different agricultural production systems.

Current approaches to assessing the agricultural water-use benefits generally ignore secondary goods and services. In some cases these could be important. For example, in rainfed farming systems, grain is only one output of value to the farmer; others are green and dry fodder (grazing during early crop growth and straw and stubble after harvest). In pastoral systems, the value of green biomass varies at different stages of growth so that it is usual to convert green and dry biomass into digestible dry matter to account for this variability. Additionally, the value of a product may vary according to its position within often-complex farming systems.

These benefits often have relevance for broader water management goals and should be acknowledged in any attempt to define water productivity. Hence, the need to develope methodologies that take the following into consideration:

- Non-grain benefits of water use in crop production such as the use of crop residues as fodder and/or mulch.
- Benefits from by-products of livestock and fish production and their role as food supplements for livestock and fish production systems or as inputs to enhance soil fertility.
- Benefits from ecosystem goods and services (biodiversity, ecosystem integrity, habitat maintenance) and socio-cultural benefits, such as aesthetics and cultural importance, derived from hydrologic flows in agricultural water use systems.

3.3 Indicators of water productivity

Water productivity is a very robust measure that can be applied at different scales to suit the needs of different stakeholders. This is achieved by defining the inputs of water and outputs in units appropriate to the users' indicator needs.

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

- Physical output, which can be total biomass or harvestable product;
- Economic output (the cash value of output) either gross benefit or net benefit.

The water input can be specified as volume (m^3) or as the value of water expressed as the highest opportunity cost in alternative uses of the water.

The combination of the different numerator and denominator parameters yield a wide range of water productivity indicators as illustrated in Table 3.

We now consider how the different indicators could be used to assess water productivity for a cropping system at different scales:

- **Crop scale**: is of interest to crop physiologists to assess how efficient a particular crop or cultivar of a crop is in converting water into biomass. At this scale the output can be quantified either as total biomass or crop yield (harvestable produce). The water input that is relevant for this assessment is the water used in transpiration, which here we call process depleted water.
- **Field scale beneficial use**: is of interest to the farmer, agronomist and water specialist to assess how efficiently a particular cropping system converts water into beneficial output. At this scale the output can be quantified as total biomass or crop yield and the water inputs are the amount of water that was used in process depletion (transpiration).
- **Field/farm scale beneficial and non-beneficial use**: is of interest to the farmer, agronomist and water specialist to assess the opportunities of saving water lost through non-beneficial use. At this scale the output can be quantified as total biomass, crop yield (kg), crop value ($) while the water input is the amount of water depleted from the system through (a) evaporation, (b) flows to sinks that are not recoverable, (c) pollution to levels that render it unfit for use and (d) incorporation into the product.
- **Irrigation system scale**: is of interest to the irrigation system manager in assessing how productively the water available to the irrigation system is being used. At this scale the manager takes into consideration both the amount of water depleted and that which is recaptured for re-use downstream. At this scale the output can be quantified in physical and economic terms and the water can be accounted for in either volume or in value terms.
- **Sub-basin scale**: is of interest to planners and river-basin managers in assessing options for increasing water productivity at this scale. The output can be quantified as either biomass or

Table 3. Range of water productivity indicators and the units that can be used.

Water input parameters (m³ or $ value)	Output parameter					
	Physical measures		Physical/economic measures		Economic measures	
	Biomass (kg)	Harvestable yield (kg)	Gross value ($)	Net value ($)	Gross value ($)	Net value ($)
Gross inflow	kg/m^3	kg/m^3	$\$/m^3$	$\$/m^3$	($/$)	($/$)
Net inflow	kg/m^3	kg/m^3	$\$/m^3$	$\$/m^3$	($/$)	($/$)
Available water	kg/m^3	kg/m^3	$\$/m^3$	$\$/m^3$	($/$)	($/$)
Depleted water	kg/m^3	kg/m^3	$\$/m^3$	$\$/m^3$	($/$)	($/$)
Beneficially depleted water	kg/m^3	kg/m^3	$\$/m^3$	$\$/m^3$	($/$)	($/$)
Process depleted process water	kg/m^3	kg/m^3	$\$/m^3$	$\$/m^3$	($/$)	($/$)

harvestable produce in kg or their cash value in $. The water input becomes the net inflow, which is difficult to value in monetary terms and therefore generally assessed as volume. It is particularly useful in assessing the opportunities for investing in water infrastructure.

- **Basin scale**: is of interest to river-basin managers and planners in assessing the productivity of the renewable water that enters the basin, mainly as rainfall. The output includes all the water benefits derived by water as it moves across the basin landscape and could even include the value of near-shore marine life.

3.4 Aggregating multiple outputs water productivity

One of the advantages of the water productivity concept is that it allows us to assess the productivity of multiple-use systems such fish production in irrigation canals, or where crop residue is an important source of livestock feed. Under such conditions there are multiple benefits arising from using the same quantity of water. To calculate water productivity of depleted water in a multiple-use system we could use the formula:

$$Waterproductivity(WP)_{Depletedwater} = \frac{\sum_{j=1}^{p} \sum_{i=1}^{n} Y_{ij} A_{ij}}{\sum_{j=1}^{p} \sum_{i=1}^{n} W_{ij} A_{ij}} \tag{7}$$

Where *Yij* is the amount of output for production system *j* on field *i* (kg/ha),
Wij is the amount of water depleted (m^3/ha),
Aij is the production area,
p is the number of production system and
n is the number of fields

Molden *et al.* (1998) proposed an approach for standardizing crop benefit by using the standardized gross value of production indicator within an area, computed as:

$$SGVP = \left(\sum_{i=1}^{N} A_i Y_i \frac{P_i}{P_b} \right) P_w \qquad (8)$$

Where A_i is the area cropped with crop *i*,
Y_i is yield of crop *i*,
P_i is local price of crop *i*,
P_b is the local price of base crop (the main locally-grown, internationally-traded crop) and
P_w is the value of the base crop traded at world prices and N is the number of crops grown.

Where data exist, SGVP for other agricultural produce (fish, livestock and trees) may be assessed using a similar procedure. The equation can also be expanded, at least in principle, to include the value of other goods and services. These might include value society places on other ecosystem services generated by the hydrologic flow of water through the system such as biodiversity, ecosystem integrity, habitat maintenance, aesthetics, etc.

4 Rationale for increasing water productivity

4.1 Global imperatives

The global population, which reached 6 billion in 1999 and is expected to reach 7.8 billion in 2025, is putting enormous pressure on the finite renewable water resources as the demand for food and other water-dependent goods and services increases. Irrigated agriculture, which accounts for 72% of global and 90% of developing countries' water withdrawal will have to increase its productivity to mitigate the growing water crisis (Cai and Rosegrant, 2003). Other agricultural water uses will also have a role to play. It is estimated that increases of 30 and 60% in water productivity from rainfed and irrigated agriculture, respectively will be required to meet the demands for food security. To achieve sustainable agricultural growth necessary for food security, Kofi Annan, Secretary General of the United Nations in his Millenium Report to the General Asembly, April, 2000 and repeated in his report to the Millenium Conference in October, 2000 called for a "*Blue Revolution in agriculture that focuses on increasing productivity per unit of water – 'more crop per drop"* (Annan, 2000). This formed the basis for setting global target for reducing water use in agriculture that is stated as (CPWF, 2002):

> *"Maintaining the level of global diversions of water to agriculture at the level of the year 2000, while increasing food production, to achieve internationally-adopted targets for decreasing malnourishment and rural poverty by the year 2015, particularly in rural and peri-urban areas in river basins with low average incomes and high physical, economic or environmental water scarcity or water stress, with a specific focus on low-income groups within these areas."*

4.2 Basin-level rationale

At the basin level, the rationale for increasing water productivity lies in the need to:

- Increase water availability to users and uses that are disadvantaged. For example the need to increase water productivity in the upper reaches of rivers so as to reduce water depletion and hence increase water availability in downstream reaches;
- Reduce overall water demand and develop additional water resources (dam development, groundwater exploitation and water transfers from regions with excess water to regions that experience water scarcity); and
- Increase total basin level water benefits through more productive use of the available water resources.

Several basins are exploring options for enhancing water productivity to achieve various social, economic and environmental goals. For example, the Yellow River basin, which is currently experiencing severe water shortages in the dry seasons, has set a target of reducing water use in agriculture by 4 billion m^3 by 2010 so as to meet the needs of urban development.

4.3 System level rationale

At the level of the irrigation system, increases in water productivity may be required to:

- Secure water for downstream farmers who experience water shortages;
- Reduce operation and maintenance costs associated with desilting and water outtake including the costs of pumping;
- Make water available for expansion of the irrigated perimeter where the cost of saving water through increasing water productivity is less than the cost of developing additional water resources; and
- Comply with water permit and pollution regulations to ensure adequate provision of safe water for non-agricultural users.

4.4 Farm level rationale

At the farm level, increases in water productivity are required to:

- Reduce water costs (costs of pumping, delivering water or water fees);
- Reduce loss of land productivity associated with soil erosion, waterlogging and salinization;
- Expand irrigated areas with the same amount of irrigation water available; and
- Increase agricultural output, food security and profitability.

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