2 Economics of Water Productivity in Managing Water for Agriculture

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Abstract

Water is an extremely complex resource. It is both a public and a private good; it has multiple uses; the hydrology requires that we examine potential productivity gains at both the farm and the basin levels; both quantity and quality are important; institutions and policies are typically flawed. For a given situation, economists often disagree on how to value water and on the best strategy for increasing water productivity. This fact notwithstanding, growing scarcity increases the need, if not the demand, for sound economic analyses.

The purpose of this chapter is to lay down some of the concepts and complexities in economic analyses related to increasing water productivity, to provide some examples and to see what this implies regarding the potential for increasing water productivity. We hope that this will help set the stage for productive discussions and the identification of research needs.

The chapter is divided into three main sections. The first section discusses the relationship between efficiency, productivity and sustainability, and emphasizes the confusion in definitions. The second section provides examples at plant, farm, system and basin levels, relating water productivity to both economic efficiency and sustainability. Closely related to this, in the third section we discuss the potentials for increases in water productivity and economic efficiency through incentives created by policy and institutional reforms.

Failure to include the potential for recycling or reuse of water diverted for irrigation in the measurement of irrigation efficiency has led to the widely accepted view that public irrigation systems are poorly managed and that there is considerable scope for increasing water productivity. Water savings do not necessarily lead to higher water productivity and, similarly, higher water productivity does not lead to greater economic efficiency.

A distinction can be made between those measures that increase water productivity by increasing crop yield for a given evapotranspiration (ET) or diversion as opposed to reducing the water-diversion requirements. Measures to increase crop yield for a given ET translate into water-productivity gains at the system and basin levels. However, the management of water to reduce water-diversion requirements is riddled with off-site effects and externalities. Thus, whether water-management practices or technologies designed to increase water productivity and economic efficiency at the farm level translate into water-productivity and economic-efficiency gains at the system or basin level needs to be determined. The basin is a hydrological unit as opposed to an administrative unit. It is only at this level that we can capture and include in our analysis the off-site effects (or, in economic jargon, internalize the externalities).

The growing scarcity and rising value of water in a basin induce farmers to seek ways to increase water productivity and economic efficiency. Recycling or reuse of water is prominent among the prac-

Water Productivity in Agriculture: Limits and Opportunities for Improvement (eds J.W. Kijne, R. Barker and D. Molden)

tices adopted to increase water productivity, and greater attention needs to be focused on managing surface water and groundwater for conjunctive use. We need a better understanding of biophysical and socio-economic changes in basins over time and improved measures of basin-level efficiencies before we can determine in a given situation the potential for increasing water productivity through policy and institutional reforms.

Finally, as basins become closed, overexploitation of groundwater resources is accompanied by a serious decline in water quality and other problems of environmental degradation. Decisions on basin-level allocations among sectors cannot be based strictly on economic efficiency but they must involve value judgements as to how best to benefit society as a whole. This will include setting priorities in the management of water resources to meet objectives such as ensuring sustainability, meeting food-security needs and providing the poorer segments of society with access to water.

Introduction

Water is an extremely complex resource. It is both a public and a private good; it has multiple uses; the hydrology and externalities require that we examine potential productivity gains at the farm, system and basin levels; both quantity and quality are important in measuring availability and scarcity; and the institutions and policies that govern the use of water are typically flawed.

Given these complexities, it is small wonder that there is little agreement among scientists, practitioners and policy makers as to the most appropriate course of action to be taken to improve the management of water resources for the benefit of society. This fact notwithstanding, the growing scarcity of water increases the need and demand for sound economic analyses.

The purpose of this chapter is to lay down some of the concepts and complexities in economic analyses related to increasing water productivity, to provide some examples and to see what this implies regarding the potential for increasing water productivity. We hope that this will help set the stage for productive discussions and the identification of research needs.

This chapter is divided into three main sections. The first section discusses the relationship between efficiency, productivity and sustainability, emphasizing the confusion in definitions and distinguishing between engineering, biological and economic concepts. The second section provides examples – at the plant, farm, system and basin levels – relating water productivity (WP) to economic efficiency (EE) and to sustainability. Closely related to this, in the third section we discuss the potentials for increases in WP and EE through policy and institutional reforms.

Definitions and Concepts of Efficiency, Productivity and Sustainability

In this section we begin with a discussion of definitions of water-use efficiency (WUE), irrigation-efficiency (IE) and WP. We then define EE and relate EE to IE and WP. We conclude with a brief discussion of WP, EE and sustainability.

Water use and irrigation efficiency

In general terms, we define IE as the ratio of water consumed to water supplied. WP is the ratio of crop output to water either diverted or consumed, the ratio being expressed in either physical or monetary terms or some combination of the two. There are four areas of confusion related to the concept of efficiency.

First, WUE as used in the literature, including the economics literature (e.g. Dinar, 1993) and plant-science literature (e.g. Richards *et al.*, 1993), most commonly refers to what we have defined above as WP: that is to say, it is defined as the ratio of crop output to water input. We believe that in these instances WP is the more appropriate term.

Secondly, the conventional wisdom that irrigation systems in the developing world typically operate at a low level of efficiency

(30–40%) is based on what Seckler *et al.* (Chapter 3, this volume) refer to as classical irrigation efficiency (IEc) or the water consumed divided by the water supplied. IEc is defined in terms of differences between the point of water diversion and the ultimate destination of the water in the root zone of the plant.

> IEc = (crop ET − effective rainfall)/(vol. of water delivered − change in root-zone water storage)

IEc at the project level is typically subdivided between conveyance efficiency (water distribution in the main and secondary canals) and field-application efficiency (water distribution to the fields being irrigated). The water diverted but not used for evapotranspiration (ET) includes seepage and percolation, spillover and land preparation, all of which are treated as losses. Classical efficiency decreases as one moves from the field towards the reservoir and conveyance losses are combined with field losses. A high level of IEc may not reflect good management but simply water scarcity. Some scholars prefer to use the term relative water supply (RWS), the inverse of IEc, to avoid the connotation associated with the word 'efficiency'.

Much of the so-called 'losses' in IEc (seepage, percolation and spillovers) can be captured and recycled (for example, by use of tube wells) for use elsewhere in the system. Conversely, many of the so-called 'water savings' practices, such as those that reduce seepage and percolation (e.g. lining canals), are not saving water at all but simply redistributing the water – robbing Peter to pay Paul. The only real losses to the hydrological system are from bare soil and water evaporation (much of which can occur during land preparation) or from flows to the sea or to sinks.

The concepts of neoclassical irrigation efficiency (IEn) or effective irrigation efficiency (Keller and Keller, 1995, 1996; Seckler *et al.*, Chapter 3, this volume) take into account return flows:

> IEn = (crop ET − effective rainfall)/(vol. of waters delivered − change in root-zone water storage − vol. of water returned or recycled)

Taking into account return flows results in a higher estimate of IE, which leads to the conclusion that the scope for improving IE is much less than is normally assumed.

Thirdly, we must distinguish between IE and WP at the farm and basin level. To understand this distinction, we need to turn to water-accounting procedures and include non-agricultural water uses (Molden and Sakthivadivel, 1999). This represents another significant step away from the concept of IEc. The operational terms used here (and there are many more) are beneficial depletion and non-beneficial depletion. At the basin level, a potentially wide range of factors can deplete water. Beneficial depletion would include consumption (ET) by the crop being irrigated as well as, for example, beneficial consumption by trees. Non-beneficial depletion includes evaporation and flows to sinks such as the sea. A higher level of efficiency can be achieved by lowering non-beneficial depletion.

Finally, a high efficiency, defined here as a large percentage of beneficial depletion, does not imply a high level of productivity or of economic return. The same degree of beneficial utilization may have substantially different values for the productivity of the water (Seckler *et al.*, Chapter 3, this volume). For example, the same amount of water depleted in the irrigation of cereal crops may have a much higher value in vegetables and fruits or in non-agricultural uses. Furthermore, as water flows through the basin, economists would want to know the benefits and costs associated with various alternatives for reducing diversions and for recycling water.

Economic efficiency and irrigation efficiency

Economic efficiency (EE) takes into account values of output, opportunity costs of inputs and externalities and is achieved when scarce resources are allocated and used such that the net value or net returns (returns minus costs) are maximized. Unlike IE, which is a ratio by definition, EE is a criterion that describes the conditions that must be satisfied to guarantee that resources are being used to generate the largest possible net benefit (Wichelns, 1999).

EE is often consistent with IE. For example, as water becomes scarce and the value of water is high in semi-arid regions, a high IE (although not necessarily the result of improved irrigation management) is consistent with EE. Alternatively, when off-farm impacts can be ignored and water is abundant with low opportunity cost, EE can be achieved even at low IE.

EE in a production setting involves technical and allocative components. A producer is technically efficient when producing the maximum amount of output with a given set of inputs. The producer is allocatively efficient if he/she produces at the point dictated by the prices of outputs and inputs that will maximize returns. A producer is said to be economically efficient if he/she is both technically and allocatively efficient.

Of concern to many economists is the fact that the farm-level price or charge for irrigation water and power for pumping water do not typically reflect the true value of water and would appear to encourage waste. However, farmers and irrigation-system managers will make adjustments in response to water scarcity without price incentives. Furthermore, at the basin level, while analyses based on economic optimization may be useful to policy makers, allocations must take into account the fact that water is a public as well as a private good. Allocations among competing uses involve value judgements as to how to achieve the highest benefit for society as a whole.

Productivity and partial water productivity

The term water productivity (WP) is also defined and used in a variety of ways. There is no single definition that suits all situations. As mentioned previously, in general terms, productivity is a ratio referring to the unit of output(s) per unit of input(s).

The most encompassing measure of productivity used by economists is total factor productivity (TFP), which is defined as the value of all output divided by the value of all inputs. But the concept of partial factor productivity (PFP) is more widely used by economists and non-economists alike. Partial productivity is relatively easy to measure and is commonly used to measure the return to scarce or limited resources, such as land or labour. For example, in the early stages of economic development, agricultural labour is often in surplus and land is the scarce resource. (There are notable exceptions, including many parts of Africa.) Where land is the limiting resource, the greatest economic benefits are achieved by increasing output per unit of land. Therefore, emphasis is placed on technologies that increase yield per hectare (e.g. high-yielding varieties and fertilizer). The change in PFP measured in yield per hectare is a useful indicator of the economic performance of the agricultural sector.

But, as an economy develops, the labour force in agriculture declines and more and more labour is pulled to the non-farm sector. When agricultural labour is in short supply the emphasis shifts to labour-saving technologies (e.g. tractors and mechanical threshers). PFP measured in output per worker is now a better indicator of the economic performance of the agricultural sector.

Until recently, water was not considered a scarce resource. Now, with mounting water shortages and water-quality concerns, there is growing interest in measures to increase WP, which is a specific example in the general class of PFPs. WP is most commonly measured as crop output per cubic metre of water.

Partial water productivity can be expressed in physical or economic terms as follows (Seckler *et al.*, Chapter 3, this volume):

1. Pure physical productivity is defined as the quantity of the product divided by the quantity of the input. Examples include crop yield per hectare or per cubic metre of water either diverted or consumed by the plant. For example, the International Water Management Institute (IWMI) sees as one of its primary objectives 'increasing the crop per drop'.

2. Productivity, combining both physical and economic properties, can be defined in terms of either the gross or the net present value of the product divided by the amount of the water diverted or consumed by the plant.

3. Economic productivity is the gross or net present value of the product divided by the value of the water either diverted or consumed by the plant, which can be defined in terms of the value or opportunity cost in the highest alternative use.

Economic measures of WP (2 and 3 above) are difficult to estimate. While the net value is more satisfactory than the gross value of the product, the valuation of inputs must be treated in a uniform manner across sites. This can be difficult for land, labour and water (which are also usually the most important inputs). Valuing water is at best a difficult and unsatisfactory process, considering that the marginal value of water varies throughout the season, between seasons, by location, by type of use and by source of water.

There is also the matter of scale or the area over which productivity is measured. Do measures to increase WP at the farm level translate into increases in WP at the system or basin level? Water-accounting procedures that take into account externalities resulting from a farm-level change in water-management practices can be used to measure WP at the system or basin level. Through this process we can determine whether an intervention leads to real water savings (taking into account all return flows, as in IEn). However, at this level, beneficial depletion includes benefits from water use other than for the crop being irrigated, such as water for the environment and other non-agricultural needs.

A distinction can be made between those measures that increase WP by increasing crop yield for a given ET or diversion and those that reduce the water-diversion requirements. In the former case, savings at the plant and field level are realized at the system and basin level. In the latter case, whether increased WP at plant and field level translates into increased productivity at system and basin level needs to be determined. For example, although the water saved in one farming area may be reallocated to higher-value, non-agricultural uses, a reduction in seepage and percolation losses from this area may be at the expense of farmers elsewhere in the system.

However, as the term ‘partial’ in PFP implies, it tells only part of the story. In general, functions relating output to input (e.g. water, fertilizer) are nearly always concave because the use of higher levels of input is eventually subject to diminishing returns. Under these circumstances, a high WP (or a high IE) in a system or basin may simply reflect a shortage of water rather than good management or EE. In fact, when such a function is purely concave, PFP is maximized by using as little of the input as possible, even when it results in large declines in output (because, as input use declines towards zero, productivity increases towards infinity). Thus, the appropriate goal should be to optimize WP, not maximize it.

Despite the above arguments, many people view higher WP (or higher fertilizer productivity or higher yields) as an inherently good idea. But it is easy to see why measures that show an increase in PFP of water or any other input may provide a misleading result from the perspective of the farmer, as well as from that of the economy as a whole. A technology or management practice that increases water productivity may require the use of more labour and other inputs. For example, a reduction in water application in rice could increase the amount of weeding required. Also, a shift to drip irrigation saves water but also requires capital investment, which might not be cost-effective. Unfortunately, the concept of PFP gives very few guidelines regarding optimization. In fact, without considering the economic and social values of all inputs and outputs, it will be difficult to make progress on this issue. Thus, we now turn to a discussion of the concept of net returns.

Net returns and water productivity

In this section we build on the concept of EE, distinguishing between net private returns and net social returns and relating net returns to WP. Net private returns are defined as the market value of all outputs minus the cost of all inputs, taking into account the opportunity cost of family labour, land and any other inputs that are not purchased on the market. If the net returns to a practice are positive, then it will be beneficial for farmers to adopt the practice. If net returns are negative, it will be disadvantageous for the farmer to adopt the practice and, no matter how large the increase in WP due to the practice, it is unlikely that the farmer will adopt it.

Alternatives for improving net private returns can be categorized as follows (Wallace and Batchelor, 1997):

- agronomic improvements (for example, improved crop husbandry, cropping strategies and crop varieties);
- technical improvements (for example, improved and lower-cost technologies for extracting groundwater);
- managerial improvements (for example, improvements in farm-level resource management or system operation and maintenance (O&M);
- institutional improvements (for example, introduction of water pricing and improvement in water rights).

The first two categories relate to innovations or new technologies that lower costs or increase output per unit of water. The third category, improved management, refers to an increase in technical efficiency or increased output per unit of input with existing levels of technology. The fourth category relates principally to allocative efficiencies encouraged by the creation of market incentives.

Economic theory shows that if a new practice does not have any effects on third parties off the farm (known as technological externalities in the jargon of economics), then the adoption of this practice is advantageous for society as a whole, not just for the farmer. Unfortunately, water management is riddled with externalities, so this theory provides little guidance as to whether or not it is advantageous for society to encourage the adoption of a specific new water-management technology based only on the magnitude of net returns to farmers.

In order to assess whether or not a new technology available to farmers is beneficial to society, one needs to calculate net social returns instead of net private returns. The two concepts are identical, except that net social returns value all inputs and outputs at social prices, not market prices. Social prices are identical to market prices when well-functioning markets exist. When well-functioning markets do not exist, as is almost always the case with water, then one must attach a social value to water, which is defined as the value of the water in the best alternative use (at the margin).

While this opportunity cost is relatively easy to define, it is much harder to measure. For example, one could assign to water a societal value equal to its current value in industrial use. However, if one hypothetically begins to shift water from agriculture to industry, the marginal value of additional water in industry will eventually decline. Thus, in contemplating large transfers of water out of agriculture (as opposed to small, marginal transfers), it is not valid to assume that the per-unit value of the water transferred is equal to the current per-unit value of water in industrial uses.

Furthermore, the concept of net social returns is silent on issues of equity, and most people would agree that equity is important in making decisions on the desirability of implementing policies or technologies that affect WP.

Although it is difficult to measure the net social returns due to the implementation of a policy or technology, it is useful to keep this concept firmly in mind when making judgements about practices that improve WP. At a minimum, this concept reminds us of our ignorance and what specific missing information is desirable for an assessment of new technologies, institutions or policies. Although we shall use the term WP in subsequent discussions, it is always important to bear in mind how much it will cost to increase WP and that not all increases in WP are desirable.

Water productivity, environmental degradation and sustainability

Irrigated agriculture not only competes for water but often contributes to the major degradation of water resources. Consider, for example, those regions of rapidly falling water tables due to groundwater mining or alternatively regions of rising water tables leading to waterlogging and salinity. In the latter case, the social cost may be in the form of environmental degradation or, if corrective measures are taken, the cost to some segments of society may be for appropriate disposal of drainage water. The net social benefit is the difference between returns to the farmer and the cost to society associated with drainage-water pollution (Dinar, 1993).

Ultimately, we must address the issue of sustainability. Unfortunately, there are many definitions of sustainability and sustainable development, ranging from the very broad to the very narrow, which create a potential for misunderstanding (Dixon and Fallon, 1989). We define sustainability as the ability to continue extracting net positive social returns from a resource for an indefinite period of time. Notice that it is not inconsistent with some degree of environmental degradation, i.e. it is not always true for all ecosystems that the optimal rate of degradation is zero, just as it is not always true that the optimal rate of oil extraction from a particular deposit is zero.

One viewpoint in the sustainability debate holds that high-industrial-input agricultural systems are inherently unsustainable (Lynam and Herdt, 1999). Proponents of this view have shifted the debate away from production and income distribution to environmental degradation and input use. The focus on ecosystems by environmentalists and on watersheds by hydrologists has carried the debate substantially above the commodity-based farm and farming-systems level to land, water and other highly valued natural and environmental resources.

Lynam and Herdt (1999) argue that:

> sustainability of common resource systems necessarily incorporates value judgements on multiple criteria over how the community wishes to utilize resources; moreover sustainability of the system will depend more on social institutions controlling access and use than on production technologies.

Relating Water Productivity and Economic Efficiency: Some Examples

Molden *et al.* (2001, Appendix A) provide a comprehensive list of alternatives for increasing WP and Molden *et al.* (Chapter 1, this volume) illustrate how various alternatives can be applied at the crop, farm, system and basin levels. At each of the first three levels, we provide an example illustrating the relationship between WP and EE. At the basin level, we emphasize the relationship between WP and sustainability.

Plant level: increasing water productivity through varietal improvement

The concept of WP used by plant physiologists, molecular biologists and plant breeders refers to the crop output (either grain or biomass) per unit of transpiration by the plant. (This is typically referred to as WUE.) There has been steady improvement in grain yield per hectare through plant breeding in rainfed and, most particularly, in irrigated areas. The development of short-season varieties, reducing the growing time from 5 months to 3.5 to 4, has also been a major source of water savings (more crop per drop per day). The development of water-storage facilities and expansion of the irrigated area in the dry season have allowed these savings to be translated into increases in WP. Thus, there is no question that, over the past three decades, varietal improvement through plant breeding (aided by investments in irrigation and advances in fertilizer technology) has been the major source of increase in WP (Richards *et al.*, 1993).

However, the increase in grain productivity is in some ways deceptive (Richards *et al.*, 1993). In almost all crops, the greater grain yield is not due to an increase in biomass but almost entirely to an improved ratio of grain to biomass (harvest index). As the potential ceiling value for the harvest index is rapidly approaching in many crops, the only way to maintain increases in yield will be to increase biomass (Richards *et al.*, 1993). There appears to be considerable potential for increasing biomass by selecting cultivars for increased WP, defined in this case as the rate at which water lost in transpiration results in the photosynthetic assimilation of carbon in the plant. In many Middle Eastern countries, a very high level of WP has already been achieved. There is thus great hope that research in plant breeding and molecular biology will increase WP in other parts of the world. In other areas, gains in productivity may be achieved through varieties tolerant to saline soil and water conditions.

One of the important features of varietal improvement is that it is relatively less site-specific in terms of potential benefits than most management interventions. Much of the research is funded by international and national agencies. Numerous studies have emphasized the high returns to investment in varietal-improvement research in the past (Evenson *et al.*, 1991; Alston *et al.*, 1995) – although in many instances the benefits ascribed to research may include contributions from irrigation and advances in fertilizer technology. In setting research priorities, a key issue is the size of the geographical area as well as the size of the population upon which the varietal improvement is likely to have an impact. This will determine the benefits of the research relative to its costs. As water scarcity becomes more acute, the potential benefits of this research will increase.

Farm level – adoption of yield-increasing and water-saving technologies: the case of SRI

In promoting the adoption of new technologies, researchers and extension agents often focus on the higher yield potential, ignoring the opportunity cost of family labour and the increased management requirements. This point is illustrated in a draft report on a study of the adoption of the System of Rice Intensification (SRI) in Madagascar (Moser and Barrett, 2003). The paragraphs below are based on this report.

SRI was developed in the early 1990s in Madagascar as a seemingly ideal low-external-input sustainable agriculture (LEISA) technology. The method requires almost no external cash inputs, such as chemical fertilizers, pesticides and seeds. The SRI method involves seeding on dry beds, transplanting younger than 20-day-old seedlings with one seedling per hill, spacing of at least 20 cm × 20 cm, frequent weedings and controlling of the water level to allow aeration of roots during the growth period of the plant. However, the technology requires approximately 50% more labour. Using this method, farmers have repeatedly obtained yields two to three times higher than the 2–3 t ha^{-1} obtained using traditional practices. Owing not only to higher yields but also to the water-saving irrigation practices, the gains in water productivity at the field level could be very high, although water accounting would be required to determine the basin-level impacts of farm-level water savings.

The study undertaken by Moser and Barrett (2003) surveyed 317 households in five villages. Approximately one-third of the farmers adopted SRI but most practised it on only a portion of their land. The adopters tended to have higher education, belong to farmer associations and have higher wealth and income. In contrast, the non-adopters were unskilled agricultural labourers, who, lacking the financial resources to carry them through the 'hungry season', depended on the agricultural wages they received daily. Thus, they cannot afford to spend the extra time required for adopting SRI on their own farms because they are busy working on other people's farms. More importantly, many of those who adopted SRI have since abandoned the technology, often after trying SRI for only one season (Table 2.1). Apparently, the significantly higher yields were not enough to offset the substantially higher labour costs and management requirements.

System level: benefit–cost analysis

We have observed that water savings *per se* may or may not lead to increases in WP. Likewise, an increase in WP may or may not result in higher economic or social benefits. Following the general concepts in our discussion of net returns at the system level, economists assess the merits of an investment by measuring the benefits and costs (B:C) ratio or the internal rate of return (IRR). These are measures of the performance of investments or the productivity of capital. These two terms are defined mathematically as follows:

Table 2.1. SRI adoption and non-adoption patterns in Madagascar, 1993–1999 (from Moser and Barrett, 2003).

	Ambatovaky	Iambara	Torotosy	Anjazafotsy	Manandona	Average[a]
Households trying the method, 1993–1999 (%)	48	16	27	28	21	25
Households using the method in 1999 (%)	26	7	0	13	17	15
Adopters who disadopted (%)	46	53	100	49	19	40

[a] Average is weighted to account for different numbers of households at each site.

B:C ratio:

$$\frac{\sum_{t=1}^{t=n} \frac{B_t}{(1+i)^t}}{\sum_{t=1}^{t=n} \frac{C_t}{(1+i)^t}}$$

The IRR is the discount rate *i* such that:

$$\sum_{t=1}^{t=n} \frac{B_t - C_t}{(1+i)^t} = 0$$

For the B:C ratio, a social discount interest rate is chosen, typically 10%. If the B:C ratio exceeds 1, then the project has a positive social benefit. If the IRR is greater than the social discount rate (often assumed to be about 10%), then the project has a positive social benefit. While an assessment of environmental costs is now frequently included in the analyses, as with farm-level analyses, this is largely a commodity-oriented approach. Benefits of a given project are typically measured in terms of higher yield and net returns to the farmer for irrigating a specific set of crops.

One of the most well-studied irrigation projects in Sri Lanka is the Gal Oya Water Management Project (Uphoff, 1992; Murray-Rust *et al.*, 1999). A deteriorated irrigation system, the Gal Oya Left Bank Irrigation System, was rehabilitated in the period 1982–1985, using a combination of physical and institutional interventions.

A time-series, impact-assessment model was used to describe the trends and impacts in the system as a whole, as well as in different parts of the system (Amarasinghe *et al.*, 1998; Murray-Rust *et al.*, 1999). The data from 1974 to 1992 covered the period both before and after the rehabilitation. Significant gains have been made in WP for the system as a whole. The tail-end farmers, even though they were less intensively organized, showed the best overall performance in terms of water use, crop production and WP.

Did benefits exceed costs? The project completion report conducted in 1985 estimated an IRR of between 15 and 30% (Project Completion Report, 1985). A subsequent study by Aluwihare and Kikuchi (1991) reported an IRR of 26%. While investment in the construction of new systems in Sri Lanka is no longer profitable, among the major rehabilitation projects conducted in recent years, Gal Oya has had the highest IRR (Table 2.2).

But there are two caveats. First, some of the gains made were at the expense of other water users (D.H. Murray-Rust, personal communication). Prior to rehabilitation, water in the drains was being used by farmers outside of the Left Bank Irrigation System. With this water no longer available, many farmers simply went out of business. We do not know to what degree these 'hidden' costs would lower the IRR. However, this example of off-site effects or externalities emphasizes the need to adopt a basin perspective.

Secondly, although the area irrigated by groundwater is still small, the recent IRR estimates for largely private agro-well and

Table 2.2. Rates of return on irrigation investments in Sri Lanka in recent decades: new irrigation construction and rehabilitation based on 1995 constant prices (Kikuchi *et al.*, 2002).

	C:B ratio	International rate of return (%)
New construction projects[a]		
1980	0.8	12
1985	1.1	9
1990	1.5	7
1995	2.0	5
Major rehabilitation projects[b]		
TIMP 1984	1.04	10
Gal Oya 1987	0.37	26
VIRP 1990	1.09	9
ISMP 1992	0.60	17
MIRP 1994	1.02	10
NIRP 1999	0.88	11

TIMP, Tank Irrigation Modernization Project; VIRP, Village Rehabilitation Project; ISMP, Irrigation System Management Project; MIRP, Major Irrigation Rehabilitation Project; NIRP, National Irrigation Rehabilitation Project.

[a] For the technology level 'New improved varieties, N = 140 kg'.

[b] Years after the names of projects stand for the years when the projects were completed.

pump investments in Sri Lanka are much higher than for public investments in rehabilitation (Kikuchi *et al.*, 2002). But changes in the management of surface water can have a major impact on the groundwater aquifer and overexploitation of groundwater can have negative consequences for both the supply and quality of groundwater. This raises the issue of how best to coordinate the development and management of surface water and groundwater.

Basin level: response to water scarcity and sustainability

As the competition for water increases and river basins become closed for all or part of the year, WP and EE are typically increased by shifting to higher-valued crops, where feasible, and by reallocation of water to industry and domestic uses. Also, water scarcity and the rising value of water can bring forth a response in terms of the development and adoption of new technologies and institutions that can raise water productivity. In economics, these latter changes are explained by the theory of induced innovation (Hayami and Ruttan, 1985). For example, with reference to the Green Revolution, the theory implies that the development of high-yielding, fertilizer-responsive cereal-grain varieties was a response to both rising food-grain and falling fertilizer prices, which made this technology highly profitable. Applying this theory, we see that situations of water shortage and the rising value of water are inducing new techniques, improved management practices and institutional reforms that will raise the productivity of water. The profitability, the feasibility and hence the order of these changes will vary from site to site, depending on local circumstances.

Recent studies of the Gediz basin in Turkey (IWMI and General Directorate of Rural Services, Turkey, 2000), the Chao Phraya basin in Thailand (Molle, Chapter 17, this volume) and the Rio Lerma basin in Mexico (Scott *et al.*, 2001) illustrate the endogenous adjustments that have occurred at both the farm and system levels in response to water shortages.

In the case of the Gediz basin, the adjustments were in response to a prolonged drought from 1989 to 1994. A change was made in the way water was allocated, shifting from a demand- or crop-based system to a supply-based system, with water rationed from the reservoir downward. The result was a significant increase in basin-level irrigation efficiency. To adapt to the dramatically reduced length of the irrigation season, farmers, with the assistance of the government, developed groundwater resources. The shift in cropping pattern over the past decade away from cotton to grapes and orchards is partially explained by the drought, but the entry into the European Customs Union was the overriding factor.

In the Chao Phraya basin, irrigation efficiency has been gradually raised by the use of grating drains, conjunctive use of groundwater, pumped water from ponds and low-lying areas and improved management of dams. Farmers have responded to water shortage and unreliable deliveries in the dry season by sinking tube wells and diversifying crop production and through a spectacular development of inland shrimp farming. This has occurred despite the fact that there are considerable technical constraints and risks in diversification. The centralized water-allocation system has handled the issue of allocation of water to non-agricultural uses relatively well. Basin-level efficiency is high and there appears to be relatively little scope for achieving further productivity gains.

In the Rio Lerma–Chapala basin, water-shortage problems gained prominence with precipitous declines in Lake Chapala (the main source of water for Guadalajara) in the 1980s. IWMI studies have shown the distribution and extent of aquifer depletion (2 m year^{-1}) and growth in agricultural water demand. The Lerma–Chapala Consejo de Cuenca, established in 1993, is the oldest river-basin council in Mexico. It has responsibility for water allocation among users, improving water quality and WUE and conserving the basin ecosystem. However, agricultural, industrial and domestic demand has been rising rapidly, and there is simply not enough water to meet all demand without further overdraft of the aquifer. Water for Lake Chapala and Guadalahara has priority and 240 million m^3 of water formerly used for irrigated agriculture have been reallocated to Lake Chapala. Farmers are beginning to demand that Guadalahara pay for the 240 million m^3.

In summary, in all three basins there has been a response by farmers and irrigation organizations to water shortage that has raised WP and basin-level efficiency and there appears to be relatively little scope for further gains. The non-agricultural demand for water will continue to rise and declining water quality already presents a serious problem. But each of the three basins is at a different stage with respect to basin closure and chronic water shortage. The situation in Mexico is clearly unsustainable. The reduction in irrigated area and, where possible, the shift to high-valued crops on the remaining land can help alleviate the problem.

Allan (1998) has coined the term 'trade in virtual water' to show how international trade can help alleviate water scarcity and increase WP. Mexico provides an interesting example of trade in virtual water (Barker *et al.*, 2000). Over the past 30 years, both fruit and vegetable exports and cereal-grain imports have been increasing rapidly. Figure 2.1 shows that, over the 5 years from 1991 to 1996, the value of fruit and vegetable exports exceeded the value of grain imports by US$1.0–1.5 billion. At the same time, the water saved by the import of cereal grains was about six times the water used for fruit and vegetable production.

Policies and Institutions

There are those who argue that water in large, publicly managed, irrigation systems is being poorly managed and that policy and institutional reforms are needed to create the environment and incentives for saving water and increasing WP. Charges for water or for power for lifting water (if they exist at all) are rarely adequate to cover O&M expenses. As a result, irrigation infrastructure is deteriorating at a rapid rate and overexploitation of groundwater resources is leading to a decline in the water table and in the quality of water.

Others argue that there is much less scope for increasing WP than is commonly believed. Traditional measures of irrigation efficiency are incorrect. Water scarcity, particularly the closing of a basin, creates its own incentive for reforms, leading to changes in

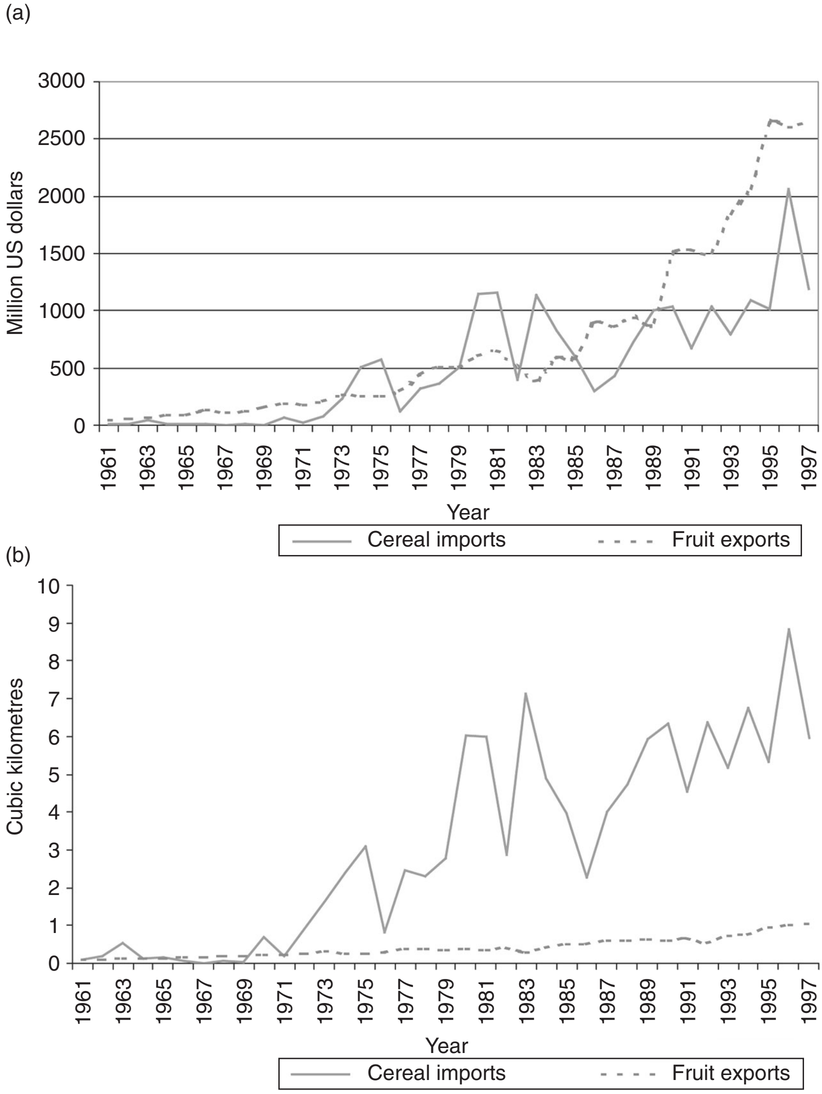

Fig. 2.1. Cereal imports and fruit and vegetable exports in Mexico ((a) US dollars and (b) virtual water, assuming water productivity of 1.2 kg m^{-3} crop evapotranspiration for cereals and 4 kg m^{-3} for fruit and vegetables). Source: Barker *et al.*, 2000.

water-management practices at the farm, system and basin level designed to sustain production. One such example is the spread of pumps and tube wells, largely through private investment, for exploiting groundwater and recycling water from drainage ditches.

There is a strong element of truth on both sides of the argument. As suggested in the previous section, we need much more accurate information on the dynamics of change in water basins over time, noting in particular the changes that occur as water scarcity increases and a basin becomes closed for all or a portion of the year. As competition for water increases, decisions on basin-level allocations among sectors must involve value judgements as to how best to benefit society as a whole. This will include setting priorities in the management of water resources to meet objectives such as ensuring sustainability, meeting food-security needs and providing the poorer segments of society with access to water. These objectives can be incorporated as assumptions or constraints in economic-cum-hydrological optimization models (McKinney *et al.*, 1999).

Faced with growing water shortages, many national policy makers, backed by international experts, have called for improved management of canal irrigation systems. The steps required include: (i) reforms in pricing and charging users for water or water services; (ii) greater participation in the O&M of systems by local user groups; and (iii) the establishment of water rights. In this section, we discuss the first of the two most widely promoted reforms, water-pricing policy and irrigation-management transfer (IMT), and one less publicized area, management for conjunctive use, which appears to offer potential for gains in economic efficiency, equity and WP. We should emphasize that the appropriate policy and institutional reforms will vary depending on the biophysical and socio-economic environment at a given site.

Water-pricing policy

In developed as well as developing countries, there is disagreement regarding the appropriate means by which to price water and the appropriate level of water charges. The pricing of water may involve different objectives, such as cost recovery (who has benefited from the investment in irrigation and who should pay), financing the irrigation agency or reducing wastage of water. Politics also enters heavily into water-pricing decisions. Moreover, many countries lack the tradition, experience and appropriate institutions for pricing irrigation water.

The World Bank has recently undertaken a comprehensive study, ‘Guidelines for Pricing Irrigation Water Based on Efficiency, Implementation, and Equity Concerns.’ As a part of that study, Johansson (2000) has conducted an exhaustive literature survey on pricing irrigation water. More concise treatment of the issues can be found in Tsur and Dinar (1997) and in Perry (2001). The authors emphasize the fact that water (particularly water used in irrigation) is a complicated natural resource, a complicated economic resource and a complicated political resource. Moreover, while water supplied is a proper measure of service in domestic and industrial uses, water consumed is the appropriate measure in irrigation, and this is particularly difficult to measure.

Tsur and Dinar (1997) discuss several different pricing methods for irrigation water and their implementation costs. These include pricing based on area irrigated, volumetric pricing according to the water used or consumed, output or input pricing, fixed- and variable-rate pricing and water markets. The necessary and sufficient conditions for markets to operate, especially defined and enforceable water rights, are, in most cases, not yet in place. Variable-rate pricing is often suggested in charging for electricity for pumps.

Bos and Wolters (1990) investigated irrigation agencies representing 12.2 million ha of irrigated farms worldwide. They found that water authorities charged on a per-unit area basis in more than 60% of the cases, on a volumetric basis in about 25% of the cases and a combination of area and volumetric methods in 15% of the cases.

Water-pricing methods are most pronounced through their effect on cropping pattern – more so than their effect on water demand for a given crop (Tsur and Dinar, 1997). The various methods differ in terms of amount and type of information and the administrative costs needed in their implementation. The most economically efficient method will depend on physical conditions, such as conveyance structures, water facilities and institutions. If the objective is allocation and not cost recovery, rationing (i.e. assigning water to specific uses) represents an alternative mechanism for coping with water shortages where demand exceeds supply (Perry, 2001).

An example of volumetric-cum-area pricing is found in the Zhanghe irrigation system (ZIS) in Hubei, China (Dong *et al.*, 2001). The province determines the price for water for different uses and water is rationed among sectors when supplies are short. The water-user groups or villages pay the water fee to ZIS on a volumetric basis. The fee for the total volume paid by the group is then divided by the area, and individual farmers are charged according to their irrigated area. Even though farmers pay an area fee, they are well aware that, if they use less water as a group, their fees will be reduced. The savings in water use at the farm level through improved water-management practices, as well as through higher crop yields, have led to an increase over time in the productivity of water for irrigation (Hong *et al.*, 2001). There is also an incentive to save water at the system level. Over the past three decades, water has been diverted to higher-valued, non-agricultural uses, greatly increasing the productivity of ZIS water resources. However, the decrease in water seepage and runoff resulting from water-saving practices (including the lining of canals) may have reduced the water available in downstream tanks within the Zhanghe Irrigation District but outside ZIS, and the negative impact of this is not known.

Participatory irrigation management and irrigation management transfer

In the area of institutional reform, the devolution of management and financial responsibility from irrigation-system managers to local user groups has gained prominence. The popular terms for this are participatory irrigation management (PIM) and IMT. These terms are defined as follows (Groenfeldt and Svendsen, 2000):

- PIM usually refers to the level, mode and intensity of user-group participation that would increase farmer responsibility in the management process.
- IMT is a more specialized term that refers to the process of shifting basic irrigation-management functions from a public agency or state government to a local or private-sector entity.

The interest in transfer of responsibility to user groups rests, in large part, on the desire of many governments to reduce expenditures on irrigation. Among proponents, it is also argued that handing responsibility to local user groups will result in better O&M and increased productivity. PIM/IMT has become one of the cornerstones of the World Bank water-management policy (Groenfeldt and Svendsen, 2000). Recent experience in PIM and IMT seems to suggest that there has been considerably more success in transferring management responsibilities in more advanced countries, such as Turkey and Mexico, than in the developing countries of Asia (Samad, 2001). Where implementation has been successful, government expenditures and the number of agency staff have declined and maintenance has, in some cases, improved, but there is little evidence yet that PIM/IMT has led to an increase in the productivity of irrigation water.

While, under IMT, government responsibility for water management in the lowest level of the irrigation system is being reduced, at the same time water scarcity requires increased government involvement at the highest level of management (Perry, 1999). For example, China has recently centralized control over water diversions from the Yellow River because upstream users were taking so much water that the river often ran dry before reaching the sea. This centralization seems to have increased stream flows in the river. Important areas of centralized management at the basin and sector levels include water allocation among sectors, flood control, drought planning, water-quality regulation and enforcement and groundwater depletion.

Conjunctive use of surface water and groundwater

Historically, the development of the technology of surface-water irrigation preceded that of tube wells, based on compact diesel and electrical power. In fact, the introduction of tube wells in the Indus basin and perhaps in the North China Plain was motivated by concern over the waterlogging and salinization that occurred when canal irrigation caused the water table to rise (O'Mara, 1988). Public drainage wells were installed to lower water tables and reduce waterlogging. A boom followed in tube-well investments for irrigation by individual farmers in south Asia and by communes (and, more recently, by private farms) in north China. Because of the greater convenience and reliability of groundwater, many farmers within surface-irrigation command areas have dug wells or tube wells.

The rate of increase in new areas irrigated by surface water has levelled off. But the irrigated area served by the ever-cheaper tube-well technology has continued to expand to the point where, in India, over half of the area irrigated is from groundwater. The massive investment in tube wells has completely transformed the use of water resources in these regions and has raised problems of resource management that are beyond the grasp of existing irrigation bureaucracies. The overexploitation of groundwater, particularly in the semi-arid areas, is leading to declines in both quantity and quality of water, affecting not only agriculture but also domestic supplies and human health. Often, in many large-scale irrigation systems, tail-end farmers have to supplement surface-water supplies with lower-quality drain water or shallow groundwater (Murray-Rust and Vander Velde, 1994).

One of the greatest potentials for increasing WP lies in the management of surface-water and groundwater resources for conjunctive use, provided this leads to better distribution of water. For example, loss of yield due to salinity could be greatly reduced with improved conjunctive management of surface-water and groundwater resources, especially by better distribution of canal water to maintain optimum levels of water table and salt balances, even in the tail reaches of canal commands (Hussain *et al.*, Chapter 16, this volume). This requires close monitoring of any adverse effects on soil and water quality, as has occurred in irrigation management in the People's Victory Irrigation Canal in the Yellow River basin of China. It has been suggested (M. Wopereis, personal communication, 1998) that farmers in the Senegal River valley, an area with severe soil salinization (e.g. Raes *et al.*, 1996), be equipped to monitor salinity levels themselves. Cheap field conductivity meters can be used for this purpose and such equipment should be within the financial reach of farmers' cooperatives.

Summary and Conclusions

Initially, we addressed the confusion in the definitions of IE, WUE and WP. IE is measured by the ratio of water consumed to water supplied, whereas WP is a ratio of crop output to water either diverted or consumed, measured in either physical or economic terms or some combination of the two. Then we discussed the relationship between WP and EE. Just as water saving does not necessarily result in higher WP, so also higher WP does not necessarily result in higher EE (e.g. the case of SRI).

Measures to increase crop yield for a given ET translate into WP gains at system and basin levels (e.g. through varietal improvements). However, the management of water to reduce water-diversion requirements is riddled with off-site effects or externalities (e.g. the case of Gal Oya). Thus, whether water-management practices or technologies designed to increase WP and EE at farm level result in higher WP and EE at system or basin level needs to be determined. The basin is a hydrological, as opposed to an administrative, unit. It is only at this level that we can capture and include in our analysis the off-site effects (or, in economic jargon, internalize the externalities).

The growing scarcity and rising value of water in a basin induces both farmers and irrigation organizations to seek various ways to increase WP, EE and net returns (e.g. the basin cases in Turkey, Thailand and Mexico). Recycling or reuse of water, particularly through the exploitation of groundwater, is prominent among the practices adopted to increase WP. Greater attention needs to be focused on managing water for conjunctive use.

We need a better understanding of biophysical and socio-economic changes in basins over time and improved measures of basin-level efficiencies before we can determine, in a given situation, the potential for increasing WP through policy and institutional reforms and which reforms are most suitable. Finally, as basins become closed, measures to increase water productivity and exploit groundwater resources are leading to a serious decline in water quality and other problems of environmental degradation. Decisions on basin-level allocations among sectors must involve value judgements as to how best to benefit society as a whole. This will include setting priorities in the management of water resources to meet objectives such as ensuring sustainability, meeting food-security needs and providing the poorer segments of society with access to water.

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