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Research Report

Basin-Level Use and Productivity of Water: Examples from South Asia

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and
Zaigham Habib

International Water Management Institute

Research Reports

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Summary

Increasing water scarcity poses a threat to food security and safe domestic water supplies. Irrigated agriculture is a major driver in leading to water scarcity because of its high consumption of water resources. Obtaining more benefits from each drop of water consumed, especially from each drop irrigated agriculture consumes, will be key to mitigating problems of scarcity. The means of improving productivity of water are not always immediately apparent due to the complex nature of water diversions and return flows within basins. The purpose of this report is to discuss and illustrate concepts for identifying ways of improving productivity of water within basins.

We applied a water accounting procedure to four subbasins in South Asia where there are perceived problems of water scarcity: Bhakra in India, Chishtian in Pakistan, Huruluwewa in northern Sri Lanka and Kirindi Oya in southern Sri Lanka. The accounting procedure identifies the quantities and productivity of various uses of water within a basin. This information is used to identify the water-saving potential, and the means of improving the productivity of the managed supplies.

At Bhakra and Chishtian, there is little remaining prospect for water savings, while at Huruluwewa and Kirindi Oya, there is considerable opportunity for water savings and increasing beneficial use. At Chishtian, almost all water is consumed by beneficial uses, but considerable scope remains for improving the productivity of water. In all four of the cases we analyzed, productivity of water that is presently being depleted by agriculture can be improved. The four subbasins are representative of situations that we believe are typical of many other basins worldwide. With the methodology used, we were able to shed light on opportunities to increase water productivity. It appears that the methodology is thorough and robust, and can be applied to other basins.

Basin-Level Use and Productivity of Water: Examples from South Asia

David Molden, R. Sakthivadivel, and Zaigham Habib

Introduction

It is likely that 78 percent of the world's population will live in areas facing physical or economic water scarcity by 2025 (IWMI 2000). In physically water-scarce regions, there is simply not enough water to meet agricultural, industrial, and domestic needs. In economically scarce regions, there has been relatively little water development and substantial investments must be made to increase water supply by at least 25 percent by 2025 to meet basic water needs. Increasing productivity of water to obtain more value for each drop of water used can play a key role in mitigating scarcity. However, special tools and directed actions are needed to most effectively utilize scarce water resources.

Our objective in this report is to illustrate a strategy for increasing the productivity of water under various conditions in South Asia. The examples we present are used to identify various means of targeting development and management efforts to most effectively deal with problems of water scarcity. Concepts of water savings and productivity are discussed. A water accounting methodology is presented and applied in four regions of South Asia to illustrate the concepts and to demonstrate its use for targeting basinwide programs to conserve water and increase water productivity.

Water Savings and Water Productivity

According to a fairly optimistic scenario (including sustained growth in irrigated yields and increases in basin-level effective efficiency) in IWMI 2000,[1] the world's irrigated area would need to be increased by 29 percent from 1995 to meet food and nutritional requirements. This irrigation expansion would require constructing additional storage and diversion facilities to develop 17 percent more of the world's primary water supplies. Furthermore, to accomplish this, irrigated crop yields would also need to be increased by 38 percent over the 30-year period (1995-2025), from a global average of 3.3 to 4.7 tons per hectare.

Water conservation is an appealing option compared to developing new storage and diversion facilities, as these often carry high financial, social, and ecological costs. "Real water savings" (Keller and Keller 1995) imply that we reduce wastage of water in one area to free it up for transfer to a beneficial use elsewhere. In essence, through real water savings, water is redistributed from a use of little or even negative benefit to one that has higher benefit.[2] For example, reducing irrigation drainage water that

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[1] IWMI 2000 presents projections on future demand and supply for water and food, and discusses key issues of water management with which we are confronted. The PODIUM (Policy Dialogue Model), described in detail in the report, is used to create projections under various scenarios. The Base Case Scenario, which relies on fairly optimistic assumptions around existing trends, is used to make estimates of future water use.

[2] Divine (1999) argues that by implementing conservation programs we are not saving water but, rather, we are "freeing up" water from one use so that another can use it.

has a negative downstream environmental impact and redirecting this water to a beneficial purpose, say a drinking water supply, would constitute real water savings at a basin scale.

It is commonly perceived that agricultural water users waste large quantities of water during the irrigation process and thus real water savings could reduce the need to construct additional facilities to tap more water. This perception is derived from common knowledge that on-farm irrigation application efficiencies are often in the order of 20 to 50 percent, implying that the remaining 80 to 50 percent is somehow lost. When we move from an on-farm perspective to a basin perspective, we often find that, because of reuse of "lost" water, there is much less wastage than commonly perceived. This phenomenon, noted by several people in the past, has become known as the IWMI paradigm (Perry 1999).

Increasing productivity of water in agriculture by producing more agricultural output with the same amount of available water is a key strategy for addressing water scarcity. Increasing the global, average, irrigated cereal yield from the 1995 level of 3.3 tons per hectare to 5.8 tons per hectare, as opposed to the 4.7 tons per hectare given in the PODIUM base case (IWMI 2000), will eliminate the need to expand irrigated areas. As a further example, to meet future population demands in India, an approximate doubling of yields from 2.7 tons per hectare to 4.7 tons per hectare would eliminate the need to develop more water for irrigation.

We can think of the productivity of water from various perspectives. Obtaining more crop production from the same amount of water is a means of expressing the physical productivity of water in agriculture. Productivity of water can also be related to economic or social objectives, such as obtaining more value per unit of water used. If the societal objective of water resource development is targeted at eliminating poverty, water benefiting poor people by providing more jobs and income is considered more productive than water benefiting wealthier people even when the value of output produced by rich and poor is the same. Thus, a comprehensive assessment of the productivity of water requires a combined socioeconomic and physical analysis of water resource use.

The following three paths are usually applicable for increasing the productivity per unit of basin-level utilizable water resources, which is all water entering the basin or subbasin that could be tapped:

1. Develop and consume more primary water[3] (by increasing the developed storage and diversion facilities).

2. Deplete more of the developed primary water supply for beneficial purposes[4] (by increasing water savings).

3. Produce more output[5] per unit of water depleted (by increasing unit water productivity).

Various basins, depending on their water resource endowment and level of development, will have differing needs for increasing the productivity of water. In this report, we will address the second and third options, which focus on greater water productivity from existing developed supplies.

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[3] This results in increases in overall production, but not necessarily productivity per unit of water consumed.

[4] We use the term water savings, and refer to "real water savings" as discussed in the document. Some people use "efficiency" or "water conservation" to carry similar meanings, but we have opted not to use these words because of their multiple meanings and interpretations.

[5] Output could be measured in mass of produce or in economic terms as net value.

Accounting for Water Use and Productivity

An accounting procedure was developed to help identify opportunities for water savings and increased productivity of water (Molden 1997; Molden et al. 1999; Sakthivadivel et al. 1997). The procedure uses a water balance approach and classifies different outflow components or flow paths into water accounting categories. Productivity of water is then related to various categories of use. Water accounting definitions are summarized in Box 1, and mathematical relations are given in the Appendix. These concepts and definitions are further illustrated in the examples that follow.

When analyzing a water basin, one of the first questions to answer is whether the basin is open or closed (Keller et al. 1996; Seckler 1996). In completely closed basins, all utilizable water is committed to present uses. An increase in depletive use in one part of a closed basin requires a decrease in another part. For example, an increase in irrigated area that results in increased evaporation in one part of the basin must be offset by a decrease in the area served in another (usually downstream) part of the basin. Concentration of pollutants toward the tail reaches of a system can be a serious problem in closed basins. In fully closed basins, carefully conceived efforts to identify non-beneficial or less-beneficial depletions of water and implement water-saving programs are required to free up water for more beneficial uses elsewhere.

In an open basin, there is uncommitted but utilizable outflow even in low-flow periods. Thus, in open basins, it is possible to increase water consumption without adversely affecting downstream uses or to use the excess water to dilute pollutant loads. In open basins, water managers generally have many more options for increasing overall water production from the water resource than in closed basins. As demands for water increase, basins move from being open to becoming closed basins.

Case Studies

We performed a comparative analysis using information from four subbasins in South Asia, where irrigation is a major user of water, to illustrate the concepts of water accounting. The four subbasins are: Bhakra in northwest India, Chishtian Sub-Division in the Pakistan Punjab, Huruluwewa subbasin in northern Sri Lanka, and Kirindi Oya subbasin in southern Sri Lanka (fig. 1). They are similar in many ways but have important differences. Table 1 presents salient features for each subbasin. The International Water Management Institute (IWMI) and others have done considerable research in each area (Bastiaanssen et al. 1999; Habib and Kuper 1998; IIMI 1995; Renault et al. 1999; Sakthivadivel et al. 1999; and Van Eijk et al. 1999). By comparing and contrasting these subbasins, we were able to draw generic conclusions about the use and productivity of water.

We used a hydronomic zone classification (Molden and Sakthivadivel 1999) for each site to distinguish hydrologic features and physical characteristics that influence water use. At Bhakra and Chishtian, there are regulated recycling zones with the presence of groundwater. This means that drainage flows enter surface drainage and groundwater systems where there are possibilities for reuse that can be regulated. Both of the areas have stagnation zones where there is a lack of adequate drainage for agriculture. In both Bhakra and Chishtian, BOX 1.

Water Accounting Definitions

- *Gross inflow* is the total amount of water entering into the water balance domain from precipitation, and surface and subsurface sources.
- *Net inflow* is the gross inflow plus any changes in storage.
- *Water depletion* is a use or removal of water from a water basin that renders it unavailable for further use. Water depletion is a key concept for water accounting, as interest is focused mostly on the productivity and the derived benefits per unit of water depleted. It is extremely important to distinguish water depletion from water diverted to a service or use as not all water diverted to a use is depleted. Water is depleted by four generic processes:
    - *Evaporation*: water is vaporized from surfaces or transpired by plants.
    - *Flows to sinks*: water flows into a sea, saline groundwater, or other location where it is not readily or economically recovered for reuse.
    - *Pollution*: water quality gets degraded to an extent that it is unfit for certain uses.
    - *Incorporation into a product*: through an industrial or agricultural process, such as bottling water, or incorporation of water into plant tissues.
- *Process consumption* is that amount of water diverted and depleted to produce a human-intended product.
- *Non-process depletion* occurs when water is depleted, but not by the process for which it was intended. Non-process depletion can be either beneficial, or non-beneficial.
- *Committed water* is that part of outflow from the water balance domain that is committed to other uses, such as downstream environmental requirements or downstream water rights.
- *Uncommitted outflow* is water that is not depleted, nor committed and is, therefore, available for a use within the domain, but flows out of the basin due to lack of storage or sufficient operational measures. Uncommitted outflow can be classified as utilizable or non-utilizable. Outflow is utilizable if by improved management of existing facilities it could be consumptively used. Non-utilizable uncommitted outflow exists when the facilities are not sufficient to capture the otherwise utilizable outflow.
- *Available water* is the net inflow minus both the amount of water set aside for committed uses and the non-utilizable uncommitted outflow. It represents the amount of water available for use at the basin, service, or use levels. Available water includes process and non-process depletion plus utilizable outflows.
- A *closed basin* is one where all available water is depleted.
- An *open basin* is one where there is still some uncommitted utilizable outflow.
- In a *fully committed basin*, there are no uncommitted outflows. All inflowing water is committed to various uses.

groundwater use is limited in these stagnation zones because of salinity, and there are pockets of groundwater buildup and waterlogging. The subbasin at Huruluwewa is considered to be a natural recapture zone since outflows from irrigation naturally reenter the river system and are available for reuse downstream. The Kirindi Oya subbasin contains a regulated recapture zone,

FIGURE 1.
Locations of the four case-study sites in South Asia.

TABLE 1.
Salient features of the case-study subbasins.

Description	Bhakra	Chishtian	Huruluwewa	Kirindi Oya
Basin country	India	Pakistan	Sri Lanka	Sri Lanka
Nature of subbasin	Subbasin	Administrative division	Upper-reach subbasin	Lower-reach subbasin
Type of basin	Closing	Closing	Open	Open
Hydronomic zone	Regulated recapture with groundwater and stagnation	Regulated recapture with groundwater and stagnation	Natural recycling and regulated recapture	Regulated recapture and final use zone
Climate	Semi-arid	Arid	Semi-arid	Semi-arid
Gross command area	1.53 Mha	70,590 ha	4,860 ha	8,619 ha
Cropped area	2.95 Mha	100,380 ha	7,750 ha	17,238 ha
Cropping intensity	196%	147%	160%	200%
Rainfall (annual)	595 mm	203 mm	1,267 mm	897 mm
Seasonal reference ET	522 mm (Rabi)	600 mm (Rabi)	762 mm (Maha)	600 mm (Maha)
Actual ETa (average over crops for season)	417 mm (Rabi)	400 mm (Rabi)	762 mm (Maha)	551 mm (Maha)
Year of accounting	1995/96	1993/94	1997/98	1997/98
Main crops grown	Wheat, rice, cotton, grams, oil seeds, vegetables	Wheat, cotton, sugarcane, vegetables	Rice, onion, chili, gram, vegetables	Rice, onion, chili, gram
Groundwater status	Localized areas of both accretion and depletion	Depletion	Stable	Stable

Notes: ET = evapotranspiration; ETa = evapotranspiration (average).

where drainage outflows in the upstream area can be captured by smaller tanks and reused downstream. Kirindi Oya also contains a final use zone in its downstream area where there are no downstream human uses, and drainage water flows to the ocean.

Bhakra and Chishtian are similar in many ways—in both areas rigid irrigation rotation schedules called warabandi irrigation are practiced (Jurriens and Mollinga 1996; Malhotra 1982), water is a more scarce resource than land, groundwater is utilized in both areas, and both have pockets of poorly drained, saline groundwater. However, an important difference is that Chishtian receives less rain than Bhakra. We refer to these two areas as the “Bhakra group.”

Huruluwewa and Kirindi Oya are similar in that they are rice-based systems located in the dry zone of Sri Lanka. In contrast to Bhakra and Chishtian, water is relatively more plentiful compared to land. Huruluwewa is situated in the upper part of the Yan Oya basin with significant irrigation and other uses downstream, while Kirindi Oya is situated in the lower reaches of the Kirindi Oya basin and close to the Indian Ocean. We refer to these two areas as the “Huruluwewa group.”

Accounting for Water Use

We used water balance studies to generate the water accounting components for each of the case-study sites as presented in tabular form in table 2. The data are also presented as a flow diagram for each case-study site in figures 2 and 3. The domain of interest at each site represents a subbasin that includes agricultural, industrial, domestic, and environmental uses of water. Each subbasin is sufficient in size and selected in such a manner so it could be analyzed separately from, but in the context of, the entire basin in which it is located. The water balance domain in each case was selected so the area corresponds to a management unit and the inflows and outflows could be estimated with minimal difficulties. The lower boundary extends to the bottom of the aquifer, while the upper boundary is above the crop canopy. The time period of interest is one year.

Gross inflow consists of the rainfall on the subbasin plus measured surface inflows crossing the boundary.[6] Groundwater inflows and outflows were assumed to be negligible compared to other inflow components, except at Chishtian. Net inflow is the gross inflow plus change in storage within the subbasin. The change in storage over a given time period is the increase or decrease in the amount of water stored in surface reservoirs, groundwater aquifers, or in the unsaturated soil zone between the soil surface and the watertable. We assumed the storage change in the unsaturated soil zone and in internal reservoirs to be zero, except at Huruluwewa, over the time period studied. The measured groundwater-level change was multiplied by the specific yield of the aquifer to obtain the volume of the change in groundwater storage.

The Bhakra group exhibited similar groundwater characteristics. In some areas of good quality water, the groundwater levels fall as a result of pumping. In areas of poor groundwater quality, groundwater levels rise due to percolation from irrigation and lack of drainage. At Bhakra there was a positive storage change, meaning that on average groundwater levels rose. At Chishtian the average groundwater levels declined.

Depleted water is classified into categories of process, beneficial non-process, and non-beneficial non-process, and are shown on the right-hand side of figures 2 and 3. Process water consists of water uses intended by humans and includes evapotranspiration by crops and evaporation from municipal and industrial (M&I) uses. Crop evapotranspiration (ET) was estimated using standard techniques (Doorenbos and Pruitt 1977) for Chishtian, Huruluwewa, and Kirindi Oya. However, for Bhakra the ET was assumed to be equal to the closure term in the water balance. Estimates for municipal and industrial depletions were made by applying a depleted fraction of 0.2 to the gross inflows to these uses. Home garden and forest use was estimated from an assumed crop coefficient (actual ET/reference ET) for each category.

Often water is depleted by beneficial uses, but not those directly intended or managed by irrigation. For example, there are several economically important trees within Kirindi-Oya and Huruluwewa that are beneficial, and are thus characterized as non-process, beneficial users of water. Drainage outflows that discharge directly into a sink and are in excess of downstream requirements are considered non-beneficial, non-process depletion. The drainage flow from Kirindi Oya to the Indian Ocean is considered as a non-process water depletion of agriculture.

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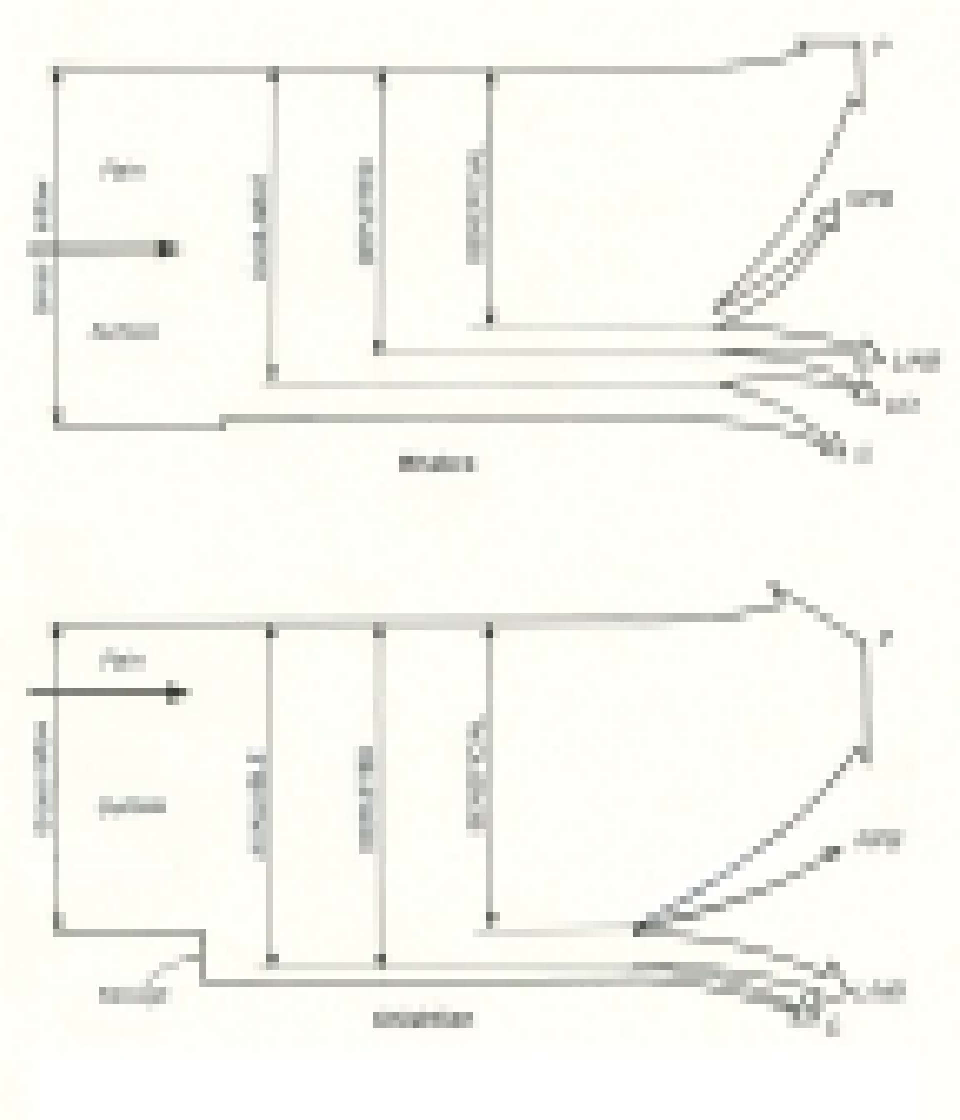
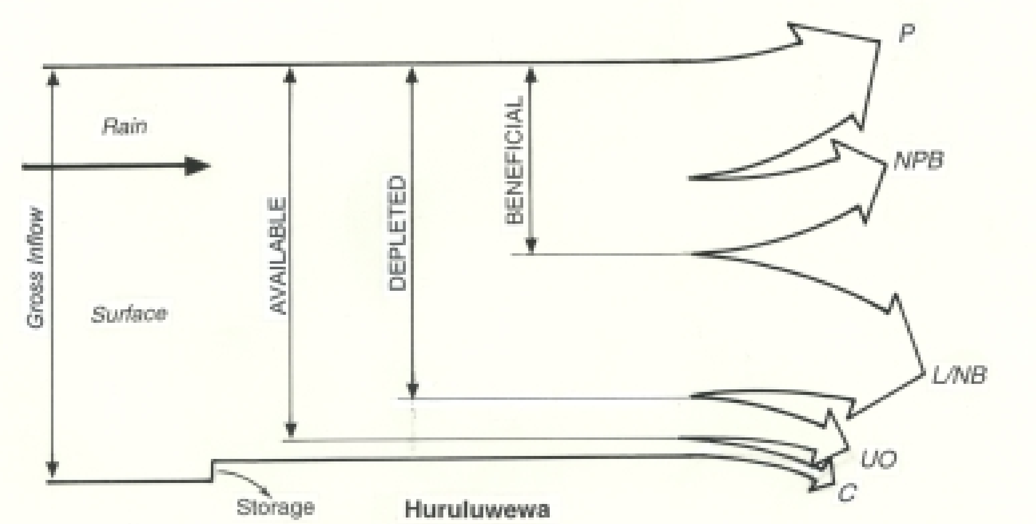
[6] The flow data for the water balances were based on secondary data combined with measurements and estimations. Thus there is considerable uncertainty about terms. A one-year time step was used in the analysis due to lack of water balance data for extended time periods. Confidence intervals around most of the terms are on the order of 20 percent to 30 percent. In spite of the rather large error terms, we feel these initial water balance estimates provide valuable insights that would not be much altered if more detailed investigations were made. However, we recommend that more detailed investigations be made before making investments or taking other actions.

FIGURE 2.
Water accounting diagrams of the Bhakra and Chishtian study areas.

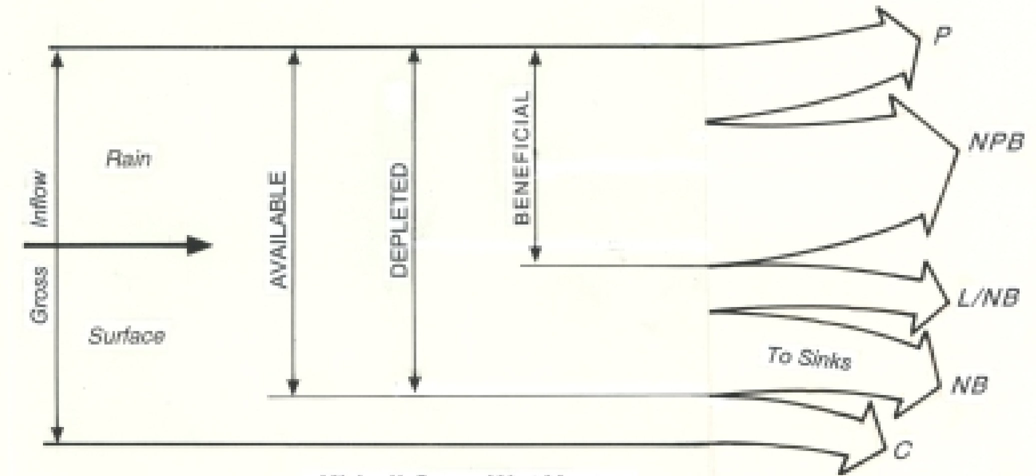


Notes: P = Process consumption (includes crop evapotranspiration plus consumption from domestic and industrial uses)
NP = Non-process depletion
NPB = Beneficial non-process depletion
L/NB = Low or non-beneficial depletion
UO = Uncommitted outflow
C = Committed outflow

FIGURE 3.
Water accounting diagrams of the Huruluwewa and Kirindi Oya study areas.



Huruluwewa



Kirindi Oya—Wet Year

Notes: P = Process consumption (includes crop evapotranspiration plus consumption from domestic and industrial uses)
NP = Non-process depletion
NPB = Beneficial non-process depletion
L/NB = Low or non-beneficial depletion
UO = Uncommitted outflow
C = Committed outflow

TABLE 2.

Water accounting components of case-study sites in million cubic meters (MCM).

Description	Bhakra (1995/96)		Chishtian (1993/94)		Huruluwewa (1997/98)		Kirindi Oya 1998	
	Total	Parts	Total	Parts	Total	Parts	Total	Parts
Gross Inflow	17,920		667		208		475	
Surface diversion		7,447		504		44		245
Precipitation		8,504		143		164		230
River inflow		1,969		0		0		0
Subsurface inflow		0		20		0		0
Storage Change	+ 237		-73		+ 12.6		0	
Surface storage		0		0		0		0
Subsurface storage		+ 237		-73		13		0
Net Inflow	17,683		740		196		475	
Depletion	13,687		725		164		428	
Process	*13,322*		*625*		*60*		*95*	
Irrigation – Crop ET		12,283		595		59		95
M&I		1,039		30		1		-
Non-process, non-beneficial								
Irrigation – flows to sinks		0		0		0		96
Non-process, beneficial								
Home gardens, forest		0		20		42		184
Beneficial	*13,322*		*645*		*103*		*279*	
Low and Non-beneficial		365		80		61		53
Outflow	3,997		15		32		47	
Committed outflow for downstream water rights		2,177		0		0		0
Committed outflow for environment		0		15		0		47
Uncommitted outflow								
utilizable		1,820		0		32		0
non-utilizable		0		0		0		0
Available water at basin level (net – committed – non-utilizable)	15,506		725		196		428	
Available for agriculture	14,467		675		152		244	

Notes: ET = evapotranspiration; M&I = municipal and industrial

The balance of outflow from the domain is either classified as committed or non-committed. Committed outflows are those required to meet downstream environmental or human needs. For both Bhakra and Huruluwewa, committed outflow is required to meet downstream agricultural, domestic, and industrial needs. At Chishtian there are no downstream users and drainage flows are directed toward the desert rather than back into the Indus drainage system. Kirindi Oya lies adjacent to the Indian Ocean, so there are no downstream users but there is an important downstream wetland that requires water; therefore, we estimated an environmental commitment for it. We also estimated an environmental commitment for Chishtian based on the need to remove salts from the subbasin.

There is a lack of definition or knowledge about upstream and downstream water rights or commitments in all the cases, and a general lack of knowledge about downstream environmental requirements. We believe that much more research is required to quantify environmental commitments of water in many areas of the world. For many closed and closing basins, this would be important and necessary information for properly managing scarce supplies to minimize conflicts between environmental and development interests and to control upstream and downstream effects.

The balance of liquid water outflow from the subbasin is classified as un-committed outflow, in that the outflow is in excess of downstream needs. Part of this outflow could have been used within the subbasin and is classified as utilizable outflow. Non-utilizable outflow is that portion that could not be used within the subbasin given the present level of storage and diversion facilities. For example, if there are heavy rains occurring at a time when reservoirs are full, and there is no way to use the excess to recharge groundwater, this water would be classified as non-utilizable. Based on our knowledge of the sites, the non-utilizable outflow during the study period was estimated to be zero in all cases.

The available water is used to indicate how much water can be depleted within the water accounting domain without affecting present downstream uses. Available water is the net inflow minus the sum of any downstream commitments to meet water rights or environmental needs plus any non-utilizable flows.[7] Available water is an important term against which the water-saving potential could be measured. Water should only be depleted up to the limit set by available water.

From figures 2 and 3, it is apparent that for Huruluwewa there is a significant amount of utilizable outflow. Similarly, at Kirindi Oya there is a significant amount of irrigation drainage water that is directed to a sink, in this case the Indian Ocean. This drainage water is thus categorized as depleted water. In both Huruluwewa and Kirindi Oya cases, these outflows could be redirected and put to beneficial use within the respective subbasin. At Bhakra the amount of utilizable outflow is quite small, while at Chishtian it is zero representing a limited opportunity to deplete more water within the subbasin.

Water Accounting Indicators

Table 3 shows a selection of the water accounting indicators we developed for each of the case-study sites. Depleted fraction of gross inflow indicates how much of the gross inflow was depleted by various uses. The minimum amount

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[7] The available water is based on present development conditions. Potentially available water would represent a situation where non-utilizable outflows are reduced to a minimum when all technically and economically feasible water infrastructures are in place. An additional adjustment to the available water could be made to account for allowable removal or addition to groundwater. For example, if groundwater is used as long-term storage, the available water could be adjusted such that over several years there would be little change in groundwater levels. In the case of waterlogging, the available water may be increased to allow for more depletion within the domain.

TABLE 3.
Water accounting indicators for the four case-study sites.

Indicator	Definition	Bhakra	Chishtian	Huruluwewa	Kirindi Oya
Depleted Fraction (gross)	Depleted / Gross inflow	0.76	1.09	0.79	0.90
Depleted Fraction (available)	Depleted / Available	0.88	1.00	0.84	1.00
Process Fraction (available)	Process depletion / Available water	0.86	0.86	0.31	0.22
Beneficial Utilization	Beneficial depletion / Available water	0.86	0.89	0.52	0.65
For irrigated agriculture					
Process Fraction (available)	ET / Available water for agriculture	0.85	0.88	0.39	0.39

Note: ET = evapotranspiration

is 0.76 at Bhakra, meaning that about three quarters of the water entering the domain is depleted within the domain. The maximum value of 1.09, obtained at Chishtian, represents a somewhat extreme case. At Chishtian more water is evaporatively depleted than the gross inflow. The additional water depletion beyond gross inflow is derived from groundwater storage. Based on only a one-year analysis, we are unsure whether or not this is an extreme case of overdraft, but certainly if this imbalance in inflow and outflow persists, the water use patterns are not sustainable.

The next adjustment is to understand how much water available for use is depleted, by using the indicator, depleted fraction of available water. In all cases, the value is over 0.85, indicating that most available water is depleted. At Chishtian and Kirindi Oya, all available water is depleted.[8]

To indicate how much of the available water was depleted by process uses, the process fraction of available water is used. At both Bhakra and Chishtian, the process fraction was quite high at 0.86, indicating that most water was depleted by process uses. In contrast, the process fraction of the available water was much lower at Huruluwewa (0.32) and Kirindi Oya (0.22). This indicates that only a small fraction of the available water was depleted by the intended processes. However, before concluding that there is scope for improvement, we must understand whether non-process uses are beneficial or not.

Beneficial utilization of available water indicates how much of the available water was depleted beneficially by both process and non-process uses.[9] Again, the Bhakra group has a higher beneficial utilization of the available supplies than the Huruluwewa group (0.86 and 0.89 versus 0.52 and 0.65). At Huruluwewa and Kirindi Oya, the major reason for the lower values is that there is substantial evaporation from vegetation and free water surfaces, which were felt to have little or no benefit (Renault et al., Forthcoming). Evaporation from fallow land, free water surfaces, and scrub brush was classified as low benefit or non-beneficial depletion. Evaporation from forests and productive trees like coconut and mango trees was considered beneficial depletion. Classification as beneficial or non-beneficial depletion requires a value judgment and is a good entry point for discussions with stakeholders. But a classification of beneficial does not indicate or qualify how beneficial the use is. Valuation of

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[8] At Chishtian, depletion is probably in excess of available water. In situations of long-term overdraft, it would be best to adjust the term available water to indicate allowable long-term removals from storage.

[9] We consider beneficial utilization of available water as the best term to be used for basin efficiency, in that in most cases it is desirable to increase beneficial utilization. To know the most beneficial means of using basin water though we need to value water in its various uses.

water would provide more precise information, but the advantage of identifying beneficial utilization categories is that it provides an initial rough estimate for identifying uses that clearly have higher values.

A useful adjustment in the water accounting exercise is to isolate agriculture from other uses, especially when agriculture is an important use within the domain of interest. To do this we deduct non-agricultural uses that are beneficial but depletive (such as domestic and industrial uses, and forest cover evaporation) from the available water. This makes agriculture the residual user of the available water after the requirements of M&I and other beneficial uses have been meet. After making this adjustment, the Bhakra group has a higher water process fraction of available water for irrigation than the Huruluwewa group.

Water-Saving Strategies

We are now in a position to answer the question: What is the potential for water savings within the case-study subbasins?

- At Chishtian, water resources are overutilized and so there is no scope for increased consumption. At both Bhakra and Chishtian, there is little or no scope for reducing the outflow through water-saving measures such as recycling water or improving application efficiency. However, there is some non-beneficial evaporative depletion from waterlogged areas that could be reduced. But the opportunity for significant water savings in these subbasins is limited because a high degree of beneficial depletion of the water resources is already taking place.

- Within the Huruluwewa group, there is considerable scope for savings by reducing utilizable outflows, and non-beneficial or less-beneficial depletion of water. At Huruluwewa, the utilizable outflows are 32 MCM while crop evapotranspiration is estimated at 59 MCM. If all utilizable outflows could be converted to crop evapotranspiration (ET), the cropped area could be increased by roughly 50 percent. At Kirindi Oya, the quantity of excess drainage water is about the same as crop ET. Savings could be achieved by either changing the management of existing facilities or by constructing new diversion or storage facilities within the subbasin’s domain. For example, on-farm water management practices could be designed to use rain more effectively to reduce releases from reservoirs so that water could be used in a second cropping season, and recycling could be intensified through downstream pumping. These actions would decrease the utilizable outflow and would lead to increased crop ET.

The destination of the outflow from a subbasin is an important consideration. There is a significant distinction between the destinations of the outflows from Kirindi Oya and Huruluwewa. At Kirindi Oya, the drainage water flows directly to the Indian Ocean and is considered depleted. However, at Huruluwewa there is the possibility of using the drainage outflow water either within the domain of the subbasin or downstream if it is not depleted by uses within the subbasin. The water-saving strategies for Kirindi Oya should be focused on reducing drainage outflows and using the saved water for beneficial uses within the study domain. At Huruluwewa, there are more opportunities for utilizing the water saved because the utilizable outflow could be directed to uses either within upstream or downstream of its domain.

There are important lessons in the way Huruluwewa is operated that could be applied to improve the performance of Kirindi Oya. There are several tanks (small reservoirs) within both subbasins, 21 in Huruluwewa and 5 in Kirindi Oya. There is an important difference in the way the two tank cascades are operated.   The tanks at

Huruluwewa receive only drainage water from upstream areas and runoff from their catchments. Before releasing water for irrigation, the tanks must first be filled by rainfall runoff and the drainage from irrigation of upstream reaches. Thus the upstream farmers at Huruluwewa must begin irrigating first before downstream farmers have access to irrigation water. This cascading system is an effective way of utilizing rain and drainage flows. On the other hand, the smaller downstream tanks in Kirindi Oya are supplied with water directly from the most upstream and much larger Lunugamvehera reservoir. This reduces the available storage of small tanks to catch drainage flows, and inflows from the catchment area. Water in excess of the capacity of the downstream tanks flows into the ocean and is depleted. Kirindi Oya farmers could choose to irrigate the upstream areas first, and use the drainage water to fill the smaller downstream tanks.[10]

Productivity in Irrigated Agriculture

We computed the productivity of land and water for all four of the subbasins following the procedures presented by Molden et al. 1998, Sakthivadivel et al. 1999, and Molden 1997. The results are presented in table 4. A standardized gross value of production (SGVP) is used in order to present agriculture production in monetary units. To obtain the SGVP, we calculated an equivalent yield of rice for all crops in each subbasin (see Appendix). The equivalent yields are based on the farm-gate prices such that if 1 kg of wheat is worth 20 cents and 1 kg of rice is worth 10 cents, then 1 kg of wheat is equivalent to 2 kg of rice. We then converted the equivalent yields to a standardized gross value of production using world market prices. This allows us to draw comparisons within and between systems where multiple crops are grown.[11] The analysis is limited to agricultural water use where production and price data were readily available. For a more complete analysis, the water productivity by other major uses within the subbasins would need to be considered.

Land productivity is similar in all cases, except Chishtian. Chishtian represents an exception, as reported yields are comparatively low (1.4 tons per hectare for rice and 2.1 tons per hectare for wheat). In addition to low yields for rice, the return per unit of irrigated command area is low because the cropping intensity is relatively low (147%).

A comparison of SGVP per unit water consumed by ET within the four subbasins presented in table 4 shows a wide variation from US\$0.17/m^3 to US\$0.07/m^3. The highest value occurs at Bhakra where the land productivity is fairly high and deficit irrigation is practiced. The lowest values occur in Chishtian and also in Huruluwewa. The lowest value in Chishtian is due to low land productivity while in the case of Huruluwewa, it is due mainly to the low cropping intensity and mono-crop cultivation of rice. Productivity per unit crop ET (PW_{ET}) is important in that it gives us the unit productivity of water—for every drop going to ET, it tells us how much is produced. It does not tell us the proportion of available water contributing to crop ET, and so more indicators are needed.

Water productivity per unit of water available for irrigated agriculture ($PW_{available}$) is a basic indicator that incorporates effects of the unit productivity of water (PW_{ET}) and the amount of available water that is consumed by crop ET. If

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[10] This option is difficult because the downstream farmers feel they have the first right to water, as they have been using the water for centuries, while upstream farmers have only recently been settled. Thus downstream farmers take Lunugamvehera water first, and are reluctant to change this situation.

[11] Using gross value as opposed to net value provides a more meaningful perspective for the societal view than for an individual farmer who may be more interested in the net value of production (value of production less production costs).

TABLE 4.
Estimated productivity of water in the four case-study subbasins.

Items	Units	Bhakra	Chishtian	Huruluwewa	Kirindi Oya
Basic values					
Gross command area	ha	1,503,000	70,590	4,858	8,619
Cropped area	ha	2,945,000	103,800	7,750	17,238
Cropping intensity		196%	147%	160%	200%
Rice yield	ton/ha	2.3	1.4	2.2	2.4
Wheat yield	ton/ha	3..0	2.1		
SGVP	Million US$	2,146.30	41.36	5.90	14.52
Productivity indicators					
Land Productivity					
per unit command	SGVP/command	US$1,428	US$586	US$1,214	US$1,684
per unit cropped area	SGVP/cropped area	US$728	US$398	US$761	US$842
Water Productivity					
wheat mass per unit ET	kg/m^3	1.1	0.6	-	-
per gross inflow	SGVP/gross inflow	US$0.12	US$0.06	US$0.03	US$0.03
per available water for irrigation	SGVP/AW irrigation	US$0.15	US$0.06	US$0.04	US$0.06
per process consumption	SGVP/ETa	US$0.17	US$0.07	US$0.10	US$0.15

Notes: AW = available water; ETa = evapotranspiration (average); SGVP = gross value of production

water available for ET does not reach crops, the value for $PW_{available}$ is reduced. $PW_{available}$ is usually a more appropriate indicator of performance than productivity per gross inflow (PW_{gross}), because part of gross inflow is consumed by other uses besides agriculture, and some of the inflow is committed to downstream uses, which varies between systems. Like PW_{ET}, there is a large variation in $PW_{available}$, from US$0.07 to US$0.17.

Within the Bhakra group, PW_{ET} and $PW_{available}$ are similar, but the two values diverge within the Huruluwewa group. The situation is most pronounced at Kirindi Oya where PW_{ET} is US$0.15 but $PW_{available}$ is reduced to US$0.06. When most available water is used for crop evapotranspiration, the productivity of water is fairly high (PW_{ET} = US$0.15). But the divergence of the two values indicates that much of the water available for crop ET does not reach the crops. As indicated in earlier discussion, by redirecting utilizable outflows to crop ET, $PW_{available}$ could be increased.

Within the Bhakra group, there is very little divergence between PW_{ET} and $PW_{available}$ because there is very little water that could be saved. The only chance of increasing $PW_{available}$ is to increase PW_{ET}. It is striking that in similar environments there is a large difference in PW_{ET} at Bhakra (US$0.17) and Chishtian (US$0.07). Both water management and agronomic practices influence PW_{ET}.

We would like to pose the following hypothesis to explain part of the difference in land and water productivity at Bhakra and Chishtian. At both Bhakra and Chishtian, warabandi distribution practices are used. The depth of actual crop ET on the irrigated area is lower at Bhakra, indicating that deficit irrigation is practiced. The cropping intensity at Chishtian is lower (147%) than at Bhakra (196%). These differences are related to the way in which the available water per unit command is distributed. In the case of Chishtian, irrigation provides most of the available water for the crops while in Bhakra a significant part of the available water comes from rain. Pumping groundwater is common at both sites.

In response to the warabandi distribution practice and possibility of rainfall, Bhakra farmers opt to plant as large an area as possible, and supplement rain with irrigation for one or two waterings. They can do this because the reliability of the water supply is high (Perry and Naryanamurthy 1998). In this process, they use deficit irrigation to cover a large area. On the other hand, Chishtian farmers restrict their cropped area because there is little rain, and they tend to supply the full crop water requirement with irrigation water in hopes of obtaining a higher yield. It is riskier to spread water thinly at Chishtian because reliability of the supply is lower. Unfortunately this is the case as the average yields are even lower than at Bhakra. The reason for the yield difference may be salinity, or other non-water factors such as inadequate fertilizer. These factors are not known, and a key to increasing productivity of water would be to better understand why there are such differences.

The case of Chishtian brings out the fact that increased “efficiency” (here taken to mean a high beneficial utilization of available water) does not necessarily lead to better productivity of water. Most of the water is being used for crop ET and there is no scope to save any more water—indeed, consumption must be reduced. It could be erroneously concluded that overall performance is good because “efficiency” is high. But there is considerable scope for improving the productivity of available water supplies by improving yields and the unit productivity of water (PW_{ET}).

General Means of Saving Water and Increasing Water Productivity

We can express various ways of conserving water and increasing water productivity based on the above observations, combined with other experiences (Seckler 1996). These general means follow from four major categories of water accounting: beneficial depletion, non-beneficial or less-beneficial depletion, uncommitted outflows, and committed water (Molden and Sakthivadivel 1999).

The general means of saving water are:

1 Reduce negative, non-beneficial, and low-beneficial depletion.

2. Reduce uncommitted outflows either through improved management of existing facilities or through the construction of additional facilities.

When the saved water is transferred to a beneficial use such as more agriculture, protection of environment, or urban use, an increase in water productivity will be achieved.

The general means of increasing productivity of water without water-saving measures are:

1. Increasing the productivity per unit of process depletion (crop transpiration in agriculture) or other beneficial depletion.

2 Reallocation of water to higher valued uses.

Within each of these broad categories, more detailed strategies are listed in Box 2.

BOX 2.

Means of Saving Water and Increasing Productivity of Water

Increasing the productivity per unit of water consumed:

- *Changing crop varieties*—to new crop varieties that can provide increased yields for each unit of water consumed, or the same yields with fewer units of water consumed.
- *Crop substitution*—by switching from high water-consuming crops to less water-consuming crops,or switching to crops with higher economic or physical productivity per unit of water consumed.
- *Deficit, supplemental, or precision irrigation*—with sufficient water control, higher productivity can be achieved using irrigation strategies that increase the returns per unit of water consumed.
- *Improved water management*—to provide better timing of supplies to reduce stress at critical crop growth stages, leading to increased yields or, by increasing water supply reliability so farmers invest more in other agricultural inputs, leading to higher output per unit of water.
- *Improving non-water inputs*—in association with irrigation strategies that increase the yield per unit of water consumed; agronomic practices such as land preparation and fertilization can increase the return per unit of water.

Reducing non-beneficial depletion:

- *Lessening of non-beneficial evaporation* by reducing:
    - evaporation from water applied to irrigated fields through specific irrigation technologies such as drip irrigation, or agronomic practices such as mulching, or changing crop planting dates to match periods of less evaporative demand
    - evaporation from fallow land, by decreasing area of free water surfaces, decreasing non-beneficial or less-beneficial vegetation, and controlling weeds
- *Reducing water flows to sinks*—by interventions that reduce irrecoverable deep percolation and surface runoff.
- *Minimizing salinization of return flows*—by minimizing flows through saline soils or through saline groundwater to reduce pollution caused by the movement of salts into recoverable irrigation return flows.
- *Shunting polluted water to sinks*—to avoid the need to dilute with freshwater, saline or otherwise polluted water should be shunted directly to sinks.
- *Reusing return flows*.

Reallocating water among uses:

- *Reallocating water from lower-value to higher-value uses*—reallocation will generally not result in any direct water savings, but it can dramatically increase the economic productivity of water. Because downstream commitments may change, reallocation of water can have serious legal, equity, and other social considerations that must be addressed.

Tapping uncommitted outflows:

- *Improving management of existing facilities*—to obtain more beneficial use from existing water supplies. A number of policy, design, management, and institutional interventions may allow for an expansion of irrigated area, in creased cropping intensity, or increased yields within the service areas. Possible interventions are reducing delivery requirements by improved application efficiency, water pricing, and improved allocation and distribution practices.
- *Reusing return flows*—through gravity and pump diversions to increase irrigated area.
- *Adding storage facilities*—so that more water is available for release during drier periods. Storage takes many forms, including reservoir impoundments, groundwater aquifers, small tanks, and ponds on farmers' fields.

The strategy chosen for increasing water productivity will be guided by economic and social factors. Existing water rights will often constrain choices, especially when there are options for reallocation of supplies. Local availability of water may be an important consideration that may dictate irrigation strategy. Among various strategies, cost-effectiveness and other social goals must be considered. In certain situations, the societal preference may be to a use that produces less agricultural output, but benefits disadvantaged groups. As a further example, it may be more cost-effective to reuse water through pumping from drains or groundwater than to modernize existing infrastructure to increase the beneficial depletion of water.

Summary and Conclusions

To meet future needs, development and management efforts should be targeted in a cost-effective and socially desirable way to obtain more value from existing supplies. This is often difficult because of the interaction between different uses within a basin and the complex flow paths of water within a basin. In this report, we present a framework to better understand use and productivity of water. The framework applies to all water uses, but we focused on irrigated agriculture—user of the largest quantities of water of any sector. We presented concepts of water savings and productivity. We also presented an accounting procedure to illustrate and assist in understanding how water is presently being used and opportunities to increase the productivity of water.

The concepts were illustrated using four case studies representing differing subbasin situations in South Asia. We have demonstrated that the water accounting methodology is robust in that it expresses how water is used in these various situations. We have also been able to draw some meaningful explanations on the present status of water use, and have suggested means by which productivity of water could be increased in these subbasins. Of course much more detailed studies would be required before implementing recommendations, but the procedure presented should prove helpful in directing and formulating ideas.

It is clear from the case studies that conservation strategies are site-dependent and there is no one solution that is appropriate for all situations. However, patterns can be identified that are helpful in forming strategies. From these case studies and other experiences, we have presented a general means of identifying water-saving opportunities and increasing water productivity.

We are able to reach the following important general conclusions based on the case studies:

- The choices available for water savings in closed basins with high beneficial utilization, such as in the Bhakra and Chishtian subbasins, are limited. In these cases, efforts should focus on gaining more productivity from water that is being depleted.

- A high rate of beneficial depletion does not necessarily lead to increased water productivity as demonstrated by the analysis of the Chishtian subbasin. Even though existing practices lead to apparently high efficiency there remains considerable scope for increasing water productivity. This illustrates the need to incorporate indicators of water productivity in assessing performance.

- Within the open subbasins of Huruluwewa and Kirindi Oya, many more opportunities for saving water and increasing the productivity of available supplies exist than in the closed and closing subbasins of Bhakra and Chishtian. But, to increase productivity of available supplies, the water conserved must be directed to beneficial and productive uses.

- At all of the case-study sites, the data for water outflows were sketchy and it was not clear how best to interpret the available information. There seemed to be a general lack of knowledge of environmental requirements both within and downstream of study sites and little knowledge on both how much water could or should be depleted within the subbasins and how much water should be committed to downstream uses. This is probably due to having the primary focus on sector-oriented supply management rather than overall management of the water resources within the basin. This indicates a need for more action on overall water resource management, especially when basins become closed, and a need for more research on how to define rights to and commitments for water.

The cases studies illustrate the need to take a basin perspective when considering how to improve water use. It is important to consider various uses of water within a basin, the use and depletion of water by each use, and quantity and nature of downstream water use. This framework allows us to place irrigation within a basin framework, to view irrigation as it interacts with other uses, and to identify means of improving the productivity of water.

Appendix

Mathematical Relationships for Water Accounting

The purpose of this appendix is to show the mathematical relationships used for water accounting that were described in the main text.

Water accounting relies on a water balance for a domain bounded in space and time. The basic water balance equation is:

1. $Q_{in} + R + \Delta S = Q_{out} + E$

Where:$_{in}$

Q_{in} = surface plus subsurface inflows

Q_{out} = surface plus subsurface outflows

R = precipitation

E = evaporation and transpiration

ΔS = change in storage within the domain consisting of changes in groundwater, surface water, or storage changes within the unsaturated zones. A positive sign indicates a removal from storage.

The water accounting terms of gross inflow and net inflow are defined in terms of the water balance as follows:

2. $GI = Q_{in} + R$

3. $NI = GI + \Delta S$

Where:

GI = gross inflow

NI = net inflow

The water accounting outflow terms are:

4. $NI = Q_{out} + E = PD + NPD_b + NPD_{nb} + UO + NUO + C$

Where:

PD = Process depletion = $E_p + S_p$, where E is evaporation and transpiration and S is flows to sinks (places where water is not readily recoverable, like flows to oceans, or deep percolation to groundwater that is very difficult to abstract). The subscript p indicates a process use.

NPD_b = Non-process, beneficial depletion = $E_{npb} + S_{npb,}$ where the subscript npb indicates non-process but beneficial use.

NPD_{nb} = Non-process and non-beneficial or low beneficial depletion, = $E_{npnb} + S_{npnb}$

UO = Utilizable, uncommitted liquid water outflows at the present state of infrastructure development

NUO = Non-utilizable, uncommitted liquid outflows

C = Committed outflows.

Rearranging these terms so that all depletion terms are together, we obtain:

5. $NI = TD + UO + NUO + C$

Where: TD = total depletion = PD + NPD

TD can be split between process and non-process, or beneficial and non-benefical as shown below:

6. $NI = D_b + D_{nb} + UO + NUO + C$, where

7. $D_b = E_p + S_p + E_{npb} + S_{npb}$ and

8. $D_{nb} = E_{npnb} + S_{npnb}$

Available water (AW) at the present state of development is defined as:

9. $AW = NI - C - NUO$

It is important to distinguish between available water at the present time, and available water at a future state, a potential state of water resource development where all technically and economically feasible infrastructures would be constructed. Available water at the potential state of development is:

10. $AW_{pot} = NI - C - NUO_{pot}$

Where the subscript pot represents the potential if all technically and economical feasible structures were built. NUO and NUO_{pot} differ because some outflow cannot be captured and depleted by uses with the present amount of storage and diversion facilities. At full development, $NUO = NUO_{pot}$.

Available water can be defined for agriculture only by subtracting out depletion by other uses. This equation places irrigation as the residual user of water after requirements of all other committed and beneficial uses have been met.

11. $AW_{ag} = NI - C - NUO - (D_b$ of all other non-irrigation uses)

Based on these definitions, water accounting indicators are derived as shown in table A1.

TABLE A1.
Water accounting indicators.

Name	Symbol	Definition
Depleted Fraction of Gross Inflow	DF_{GI}	TD/GI
Depleted Fraction of Available Water	DF_{AW}	TD/AW
Process Fraction of Available Water	PF_{AW}	PD/AW
Process Fraction of Available Water for Agriculture	PF_{AW-ag}	ET/AW_{ag}
Process Fraction of Depleted Water	PF_{TD}	PD/TD
Beneficial Utilization of Available Water or Basin Efficiency	BU or BE	D_b/AW

The water accounting framework allows us to explore and define water productivity. Water productivity can be used in a variety of senses, one of which is the physical productivity derived from water use, such as the number of kilograms of a crop produced per unit of evapotranspiration. As another example, productivity can be used to represent the value of water in various uses. Here we use the symbol P to be a general term for the production derived or value derived from the use of water. The denominator consists of a water term derived from water accounting. One potentially confusing area is the many water terms from which productivity of water could be derived. For example, is the water the supplied water, evapotranspiration, or available water? We try to clearly separate these in water accounting.

For agriculture, production (P_{ag}) could be the mass of produce or, following Molden et al. (1998), it could be the gross value of production or, when costs of production are subtracted, it could represent the net value of production. In this report, we used a standardized gross value of production (SGVP):

12. $$SGVP = \left(\sum_{crops} A_i Y_i \frac{p_i}{p_b} \right) p_{world}$$

Where:

SGVP is the standardized gross value of production

Y_i is the yield of crop i

p_i is the local price of crop i

p_{world} is the value of the base crop traded at world prices

A_i is the area cropped with crop i

p_b is the local price of the base crop

Water productivity indicators are derived by using either the general form of production or value in the numerator and a unit of water in the denominator. Some water productivity indicators are given in table A2.

TABLE A2.
Water productivity indicators.

Name	Symbol	Definition
Productivity of Gross Inflow	PW_{GI}	P/GI*
Productivity of Delivered Water Supply	PW_{del}	P/water deliveries**
Productivity of Available Water	PW_{AW}	P/AW
Productivity of Water Available for Irrigation	PW_{AW-irr}	P/AW_{irr}
Productivity of Process Water	PW_P	P/PD
Unit Productivity of Water in Irrigation	PW_{ET}	P/ET

* P represents production, or value derived from the use of the water. In agriculture, we used SGVP for this report.

**Water deliveries include water diverted from groundwater and surface water sources to uses. It does not include rainfall.

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