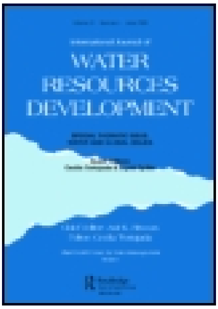

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Water Accounting to Assess Use and Productivity of Water

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ABSTRACT *A methodology is demonstrated to account for the use and productivity of water resources. This water accounting methodology presents useful information to water resource stakeholders and decision makers to better understand the present use of water and to formulate actions for improvements in integrated water resources management systems. Based on a water balance approach, it classifies outflows from a water balance domain into various categories to provide information on the quantity of water depleted by various uses, and the amount available for further use. The methodology is applicable to different levels of analysis ranging from a micro level such as a household, to a macro level such as a complete water basin. Indicators are defined to give information on the productivity of the water resource. Examples from Egypt's Nile River and a cascade of tanks in Sri Lanka are presented to demonstrate the methodology.*

Introduction

With increasing competition for a limited and often scarce water resource, there are great demands to get the best use out of water. A growing population and increased urbanization mean increased water demand for cities and industries. There is increased awareness of the need for adequate water resources to maintain the environment. Competition is further complicated by other broad societal objectives such as equity in access to water and food security. In contrast with land resources, there is a high interdependency among water users simply because of the movement of water within the hydrologic cycle. As a result of these and other factors, more attention is placed on improving the integrated management of water resources.

As large consumers of water, developments in irrigation have profound impacts on basin-wide water use and availability. Often, a higher value is placed on water for industries, cities and the environment than for agriculture. It is most probable that in the future irrigated agriculture will have to produce more with less water. Yet, planning and implementation of irrigation interventions often take place without consideration of other water uses. Similarly, water resources development for other uses does not sufficiently consider the effects on irrigation.

There is a clear need to think of irrigation water supply within a broader context of basin-wide water resources. One difficulty, however, is that we do not have adequate means to describe how irrigation water is used in relation to

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other uses. Irrigation efficiency is the most commonly used term to describe how well water is being used. But local increases in irrigation efficiency do not always lead to reduced competition for water or increases in overall basin productivity of water.

Irrigation within a basin context has been dealt with by several researchers (Wright, 1964; Bagley, 1965; Bos, 1979; Willardson, 1985; Bos & Wolters, 1989; Wolters & Bos, 1990; Van Vuren, 1993; Palacios-Velez, 1994), many of whom point out possible misconceptions about using irrigation efficiency terms. Alternative terms were proposed to describe use of water within basins: Keller & Keller (1995), with effective efficiency, Willardson *et al*. (1994) with the use of fractions, and Jensen (1993) with a consumptive use coefficient. Recently, works by Seckler (1992, 1993, 1996), Keller (1992), Keller *et al*. (1996), and Perry (1996) describe many of the considerations to be dealt with in describing irrigation in the context of water basins.

One purpose of developing this water accounting framework is to present the terminology and measures to describe the use and productivity of water resources. This paper is based on the water accounting framework presented by Molden (1997) and is expected to evolve with more field application. This work is developed from an irrigation perspective so that we can better understand the impacts of irrigation interventions at a water basin scale, and the impacts of other water uses on irrigated agriculture. It is developed in a general manner to describe any water resource use in order to enhance communications among practitioners in different water resource fields.

Objectives

The primary objective of water accounting is to present concepts and definitions to account for water use, depletion and productivity. The accounting procedures developed here are designed to be universally applicable for evaluating water management among all water use sectors. A goal of this approach is to develop a generic, common language for accounting uses of water. This conceptual framework provides terminology and a procedure that can be applied to describe the present status and consequences of water resources-related actions carried out in agriculture and other water use sectors. The water accounting methodology is developed in a manner such that it can be generically employed for irrigation, municipal, industrial, environmental or other uses of water. The concepts are used to describe the means to achieve water savings in irrigated agriculture, and the means to increase the productivity of water in irrigated agriculture. The emphasis of this paper is on quantities of water. Water quality, while critically important in water resource analysis, is not addressed here.

Levels of Analysis

Researchers in agriculture, irrigation and water resources work with spatial scales of greatly different magnitudes: irrigated fields, irrigation systems, municipal and industrial (M&I) supply and treatment, and water resource systems that integrate several uses of water. Three different levels of water use are defined for which water accounting procedures are developed:

Macro level: *Basin* or *sub-basin level*, often encompassing multiple uses and service schemes, such as irrigation and municipal water supply systems sharing the same water resource.

Mezzo level: *Service level* of analysis within a basin area typically involving multiple users who share common water supply, treatment, distribution, or disposal facilities such as an irrigation service, water supply service, or environmental service.

Micro level: *Use level*, such as an agricultural field, a household, or a particular industrial process.

An understanding of the interactions among these levels of analysis helps us to understand the impacts of our actions. A perceived improvement in water use at the farm level may improve overall productivity of water in a basin, or it may reduce productivity of downstream users. Only when the intervention is placed in the context of a larger scale of analysis can the answer be known. Similarly, basin-wide studies may reveal general concepts about how water can be saved or productivity of water increased, but field-level information on how to achieve savings or increase water productivity is required.

Water Balance Approach

The water accounting methodology is based on a water balance approach where, based on conservation of mass, the sum of inflows must equal the sum of outflows plus any change in storage. An initial and critical step is to define a *water balance domain* by specifying spatial and temporal boundaries of the domain. The domain could be the root zone of an irrigated field for an irrigation application, or it may cover the entire water basin, including surface and groundwater, over a period of several years. Clear specification of the vertical dimension is required to capture the interrelationship between groundwater and surface water. Water accounting involves classifying domain inflows and outflows according to their uses and productivity.

Conceptually, the water balance approach is straightforward, though many of the components of the water balance cannot be directly measured or are difficult to estimate. For example, groundwater inflows and outflows are typically impossible or difficult to measure. Estimates of actual crop consumptive use at a regional scale are questionable. And drainage outflows are often not measured, as more emphasis has been placed on knowledge of inflows to irrigation systems or municipal water supply systems. In spite of the limitations, experience has shown that even gross estimates of water balances can be quite useful to water managers and researchers. Water balances have been used successfully to study water use and productivity at the basin level (for example Hassan & Bhutta, 1996; Owen-Joyce & Raymond, 1996), at the irrigation service level (for example, Helal *et al.*, 1984; Perry, 1996; Kijne, 1996;), and at the field level (for example, Bhuyian *et al.*, 1995; Mishra *et al.*, 1995; Rathore *et al.*, 1996; Tuong *et al.*, 1996). Binder *et al.* (1997) use a regional balance quantifying municipal, industrial and irrigation process uses to provide early recognition of changes in quantity and quality of water. Often, first-order estimates provide the basis for more in-depth analysis that provides important clues on increasing water productivity.

Water Accounting Definitions

Water accounting involves classifying water balance components into water-use

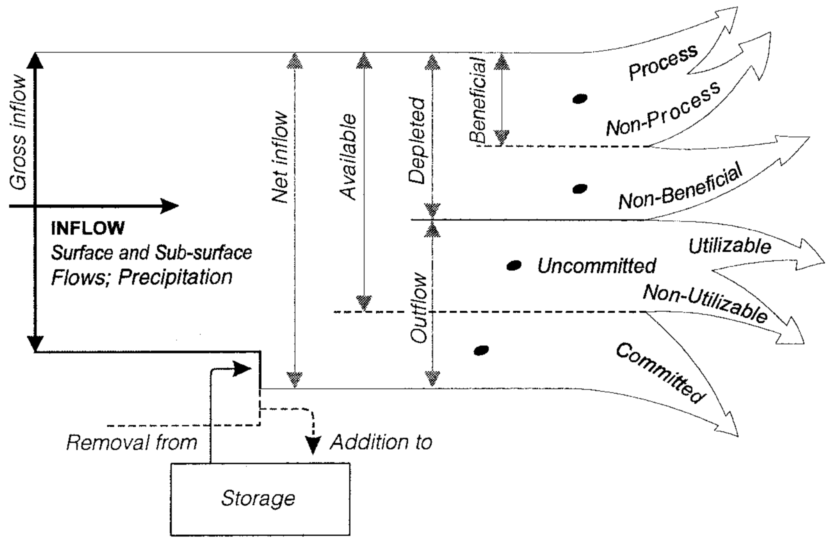

Figure 1. Water accounting.

categories that reflect the consequences of human interventions in the hydrologic cycle. Water accounting integrates water balance information with uses of water as visualized conceptually in Figure 1. Inflows into the domain are classified into various use categories as defined below.

Gross inflow is the total amount of water flowing into the water balance domain from precipitation, and surface and subsurface sources.

Net inflow is the gross inflow plus any changes in storage. If water is removed from storage over the time period of interest, net inflow is greater than gross inflow; if water is added to storage, net inflow is less than gross inflow. Net inflow is either depleted or flows out of the water balance domain. Sustainability may be in question when net inflow differs from gross inflow over a long period of time.

Water depletion is a use or removal of water from a water basin that renders it unavailable or unsuitable for further use. Water depletion is a key concept for water accounting, as it is often the productivity and the derived benefits per unit of water depleted that are of primary interest. It is extremely important to distinguish water depletion from water diverted to a service or use, because not all water diverted to a use is necessarily depleted. Water is depleted by four generic processes (Keller & Keller, 1995; Seckler, 1996; Molden, 1997): *Evaporation,* where water is vaporized from surfaces or transpired by plants; *flows to sinks*, when water flows into a sea, saline groundwater, or other location where it cannot be economically recovered for reuse; *pollution,* when water quality is degraded to an extent that it is not suitable for certain uses; *incorporation into a product* by a process such as incorporation of irrigation water into plant tissues.

Beneficial depletion occurs when water is depleted in providing an input to produce a good such as an agricultural output, or providing a need such as drinking or bathing water, or in any other manner deemed beneficial such as supplying water for environmental uses. Beneficial depletion can be further classified as *process* or *non-process depletion. Process depletion* is that amount of water diverted and depleted to produce an intended good. In industry, this includes the amount of water vaporized by cooling or converted into a product. For agriculture, it is crop-consumptive use plus that amount of water incorporated into plant tissues. *Non-process depletion* occurs when water is depleted by a natural use such as evaporation from forest cover or when diverted water is depleted, but not by the intended process (shown in Figure 1). An example is when trees consume water meant for irrigation, but the community places beneficial value on the trees.

Non-beneficial depletion occurs when no benefit or a negative benefit is derived from the depletion of water. Examples are evaporation from fallow land, discharge into sinks in excess of environmental requirements, deep percolation into saline aquifers, or evaporation from waterlogged areas. Care must be taken to distinguish between non-beneficial and beneficial depletion of water. Often evaporation from trees or free water surfaces is classified as non-beneficial, but this may not be the case if this depletion meets environmental needs.

Committed water is that part of outflow that is allocated to other uses. For example, downstream water rights or needs may require that a certain amount of outflow be realized from an irrigated area. Or water may be allocated to environmental uses such as minimum stream flows, or outflows to sea to maintain fisheries.

Uncommitted outflow is water that is neither depleted nor committed, is available for a use within a basin or for export to other basins, but flows out due to lack of storage or operational measures. For example, waters flowing to a sea in excess of requirements for fisheries, environmental or other beneficial uses are uncommitted outflows. With better management of existing facilities or additional storage, this uncommitted outflow can be transferred to process uses such as irrigation or urban uses. Uncommitted outflow can be classified as *utilizable*, or *non-utilizable*. Outflow is utilizable if, by improved management of existing facilities, the water could be beneficially used. *Non-utilizable* outflow exists when there are insufficient facilities to capture the outflow. An example of non-utilizable outflow is the large part of the Ganges outflow during the monsoon season that is in excess of environmental needs, but flows out due to lack of storage capacity.

In a *fully committed basin*, there are no usable uncommitted outflows. All inflowing water is allocated to various uses. In this case, the major options for future development are reallocation among uses, or decreasing non-process and non-beneficial depletion of water, or importing water into the basin. A 'closed basin', as described by Seckler (1992), is one which is fully committed, whereas an 'open basin' has uncommitted outflows.

Available water is the net inflow less the amount of water set aside for committed uses and less non-utilizable uncommitted outflow. It represents the amount of water available for use at the basin, service or use levels. In situations where there are unsustainable withdrawals from storage, such as aquifer mining, available water should be adjusted to reflect acceptable withdrawal rates. Available water can be increased by adding more facilities to divert and store water up to an economic limit of *potentially available water*.

Non-depletive uses of water are uses where benefits are derived from an intended use without depleting water. In certain circumstances, hydropower can be considered a non-depletive user of water if water diverted for another use such as irrigation passes through a hydropower plant. Often a major part of instream environmental objectives can be non-depletive when outflows are used downstream.

Water Accounting Indicators

Three types of indicators are presented: physically based indicators expressed as fractions, beneficial utilization indicators and water productivity indicators. Physically based indicators are meant to provide information about the flow paths of water, how much water is being depleted and which use is depleting the water. They are not meant to give a value judgement about the use of water (a bigger fraction is not necessarily better than a smaller fraction). In contrast, beneficial utilization indicators answer an important question: how much water is beneficially utilized? Water productivity indicators tell how beneficial the water use is. Ideally, water productivity indicators should be used for policy guidance, but these terms are often difficult to estimate. Indicators of beneficial utilization provide an intermediate step between physical indicators and water productivity indicators, and are meant to be useful for performance assessment and policy guidance.

Physically based indicators are presented in the form of depleted and process fractions to avoid misinterpretations brought about by use of the term efficiency (Jensen, 1993; Willardson *et al.*, 1994). They are meant to characterize a system rather than being a statement of the performance of the system.

Depleted fraction (DF) is that part of the inflow that is depleted by intended process uses. Defined in terms of gross inflow, depleted fraction is:

$$DF_{gross} = \frac{\text{Depleted}}{\text{Gross inflow}} \tag{1}$$

DF indicates the amount of gross inflow that is depleted at the use or service or basin level. For example, a DF_{gross} of 0.30 for municipal use tells us that, of the supply, 30% is depleted, and the remaining 70% is potentially available for downstream use. It does not give information on whether this is good or desirable, rather it is meant to supply useful information. Depleted fraction can be defined in terms of net inflow (DF_{net}) and available water ($DF_{available}$). Similarly, a process fraction (PF) is defined as the ratio of process depletion to gross inflow (PF_{gross}), net inflow (PF_{net}), available water ($PF_{available}$), or depleted water ($PF_{depleted}$). PF is useful to distinguish the percentage of water depleted by intended uses. For example, $PF_{depleted}$ gives information on how much depleted water is depleted by intended process uses.

Beneficial utilization (BU) indicates the percentage of water beneficially depleted. In terms of available water, it is:

$$BU_{available} = \frac{\text{Beneficially depleted}}{\text{Available water}} \tag{2}$$

Beneficial utilization (BU) can be defined in terms of gross inflow ($BU_{gross\ inflow}$), net inflow ($BU_{net\ inflow}$), and depleted water ($BU_{depleted}$). To estimate BU, we must decide which depletive uses are beneficial and which yield low, zero or negative benefits. Both process and non-process depletion can be divided into beneficial and non-beneficial. Often, irrigation services intended mainly for crops provide water for other non-process beneficial uses such as fisheries, domestic water supplies and trees. In contrast with fractions, beneficial utilization is explicitly meant to evaluate the performance of water use. Beneficial utilization, however, does not tell us how beneficial the depletive use of water is. This is handled by productivity of water terms.

Productivity of water (PW), expressed in terms of available water, is:

$$PW_{available} = \frac{\text{Productivity}}{\text{Available water}} \tag{3}$$

In general, productivity can be expressed as the benefits derived through the use of water, less the costs (excluding water costs) in producing the benefit. Within a single use such as agriculture, productivity can also be defined in other units such as mass of production, or gross value of production. Productivity of water is more readily defined where marketable output is produced. It is less easily defined in non-marketable uses such as domestic or environmental uses. Productivity of water can also be defined in terms of gross inflow (PW_{gross}), net inflow (PW_{net}), depleted water ($PW_{depleted}$), or process water ($PW_{process}$), and it is important to clearly state which productivity indicator is being used.

$PW_{process}$ in agriculture is similar to a water use efficiency term (Viets, 1962; Howell *et al.*, 1990), which relates production of mass to transpiration. For water accounting, productivity of water takes on a broader meaning, as it can be related to several crops, or even to non-agricultural uses. A comparison of irrigation systems is made by comparing gross value of crop production per unit ET in Sakthivadivel *et al.* (this issue).

Where multiple uses of water are concerned, we can define a term that considers multiple uses. The total water productivity should consider the sum of the net benefits obtained from agriculture, fisheries, navigation, environment, industrial, municipal and other uses. An expression for basin- or service-level productivity of water is:

$$PW_{available} = \frac{\sum_{\text{Uses}} (\text{benefits} - \text{costs})}{\text{Available water}} \tag{4}$$

Here the numerator is in terms of the net value derived from the use. The denominator is the available water for use within the basin, sub-basin, or service. Estimation of productivity of water across several uses is likely to be quite difficult, in which case it may be desirable to track only selected uses. For comparing various water use tradeoffs, estimating incremental changes in productivity is useful.

Examples of Water Accounting

The first example accounts for water in the Nile Irrigation System in Egypt below the High Aswan Dam and includes non-irrigation uses of water. The second example illustrates a cascade of tanks in Sri Lanka, and is illustrative of basin water use in a humid region with irrigation as the primary user.

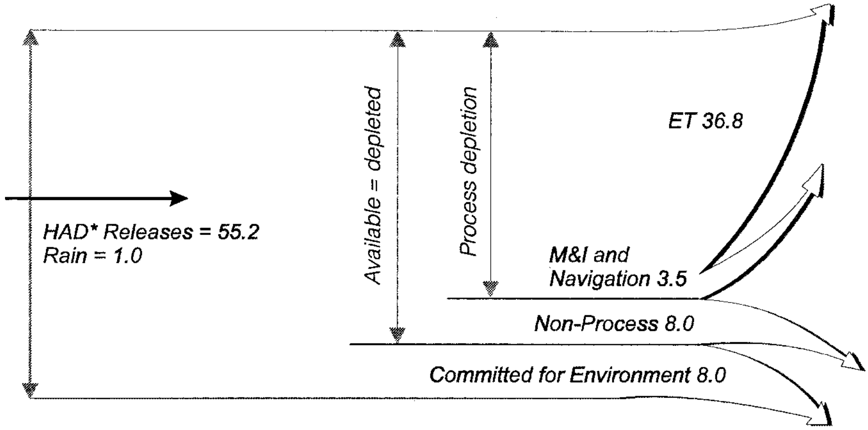

Figure 2. Water accounting for Egypt's Nile River for the agricultural year 1993–94. *Note:* *High Aswan Dam. All figures are in km^3. *Source of data:* Zhu *et al.* (1995); Molden *et al.* (1998).

The Nile River in Egypt

Water accounts are shown for the Nile River downstream of the High Aswan Dam in Egypt (Figure 2). Figures used in the accounts are based on water balance studies by Zhu *et al.* (1995) for the water year 1993–94, and the water accounting study by Molden *et al.* (1998). While some of the water balance terms are under debate, the information provides a sufficiently adequate profile to characterize water use and productivity of Egypt's Nile River. The gross inflow into the Nile system is 56.2 km^3 consisting of 55.2 km^3 of releases from the High Aswan Dam (HAD) plus 1.0 km^3 of precipitation. It is assumed that over the one-year time period there are no storage changes, so gross inflow is equal to net inflow. Major process uses of Nile water are for municipal, industrial, agricultural and navigation uses. The total water consumed by crop evapotranspiration is estimated at 36.8 km^3, while process consumption by municipal and industrial (M&I) uses[1] is estimated at 2.3 km^3. During much of January, when the Nile irrigation system is closed for maintenance, 1.2 km^3 of outflow goes to the Mediterranean Sea because water has been released to the Nile to keep levels high enough to allow navigation. This amount is categorized as beneficial process depletion by navigation.

Some water is required to flow out of the Nile basin to the sea for environmental reasons: to drain out salts, to carry out pollutants that would otherwise concentrate in the Nile waters, and to maintain fisheries in coastal estuaries. With our present knowledge it is difficult to give an estimate for the volume of outflow required, but there are indicative values (Emam & Ibrahim, 1996; Strategic Research Program *et al.*, 1996; Zhu *et al.*, 1996). A first estimate of minimum outflow in the order of 8 km^3 is made here for illustrative purposes, but it is recognized that further research is required to quantify this number. This minimum outflow requirement is classified as committed water. Subtracting committed water from the net inflow yields a value of 48.2 km^3 for available water.

The majority of the outflow is through the drainage system. Some of this can be considered as water meeting the environmental commitment discussed above. The remainder of the water is considered a non-beneficial drainage outflow. In 1993–94, the amount of drainage outflow to the Mediterranean Sea, the northern lakes, and the Fayoum Depression was 13.0 km^3. Subtracting 8 km^3 of committed outflow from the drainage outflow yields 5.0 km^3 leaving the domain classified as non-beneficial.

Other non-beneficial depletion occurs as evaporation from fallow land, evaporation from free water surfaces, and evaporative use by phreatophytes and other non-agricultural vegetation. Certainly, some of this depletion is beneficial as it leads to the desirable green belt along the Nile. There may be other subsurface outflow into sinks, such as flow from the Nile Delta to the Qatara depression (Bastiaanssen & Menenti, 1990) where further research is required, but here the value is assumed to be negligible. It was estimated that there was 2.9 km^3 non-process evaporative depletion during the time period of interest. Assume that 1.5 km^3 of this evaporative depletion is non-beneficial. Adding this to the 5 km^3 of non-beneficial drainage outflow yields a total non-beneficial depletion of 6.5 km^3.

The beneficial utilization of basin water resources is 87% (the sum of beneficial depletions, $36.8 + 2.3 + 1.2 + 1.4$, divided by the available water, 48.2). This shows that most of the water available for use is depleted beneficially indicating good performance. It should be noted that, if the boundaries included Lake Nasser, the $BU_{available}$ would be less, as evaporation from the lake would be considered a non-beneficial depletion of water. The gross value of production of the Nile system in 1992–93 was reported at US$7.5 billion (Agricultural Economics Research Institute, 1993). The productivity of gross inflow is US$0.13/m^3, while the productivity per unit of evapotranspiration is US$0.20/m^3, a value that compares well with other irrigation systems, especially considering the size of the entire Nile system (Sakthivadivel *et al.*, this issue).

How can productivity of water be increased? First, it is worth noting that there are no utilizable, uncommitted outflows remaining to be tapped. There exists some non-beneficial depletion, the largest component of which is the drainage outflow to the sea in excess of environmental requirements. Cost-effective methods to reduce this drainage outflow and convert it into a process use will result in increases in water productivity. Other opportunities lie in increasing the productivity of water consumed by agricultural crops through activities that increase the value of production per unit ET, such as improved varieties, switching from low- to high-value crops, and better agronomic or irrigation practices.

A Cascade of Tanks in Sri Lanka

In the dry zone landscape of Sri Lanka, tank (reservoir) irrigation systems are generally arrayed in cascades (Figure 3). A tank cascade is a connected series of tanks organized within the meso-catchment draining to a common reference point of a natural drainage course, thereby defining a sub-watershed unit with a definite watershed boundary.

Makichchawa cascade is one of 314 cascades in the Anuradhapura District situated in the Malwatu Oya river basin. The total cascade area is 2816 ha with 15 tanks, of which six are breached and thus presently not used for irrigation. The total tank water-spread area and tank command area are 170 ha and 295

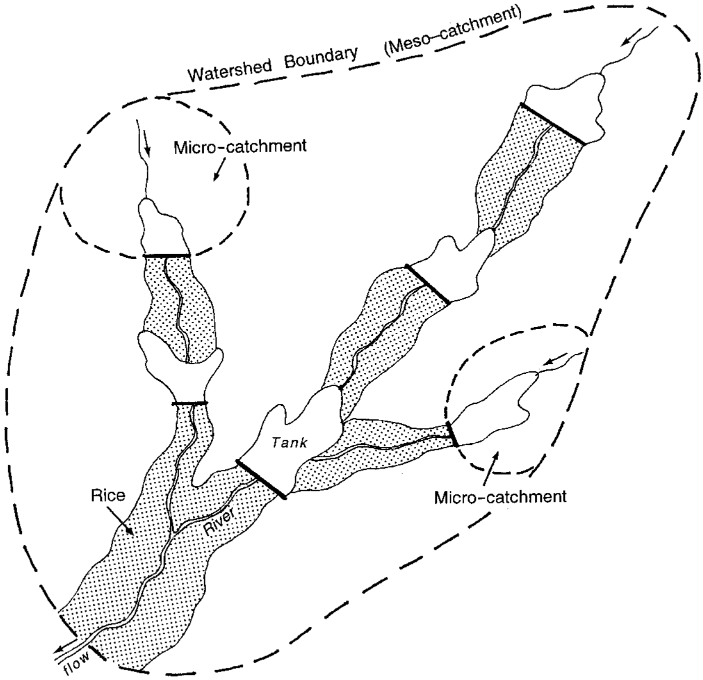

Figure 3. A typical tank cascade in Sri Lanka.

hectares, respectively. Mean annual rainfall in this cascade is 1587 mm. Only one crop, rice, is grown during the rainy season with an average cropping intensity of 79%. There are 11 agrowells each of which provides on average 4000 to 7000 m^3 of well water annually to grow dry season vegetables and other field crops. The water accounting for a typical tank within the cascade and the cascade as a whole is presented in Table 1. The information presented is based on a cascade simulation model that makes use of data gathered from secondary sources as well as from topographic maps, and rapid assessment and farmer participatory sessions (Sakthivadivel *et al.*, 1997; Sakthivadivel & Brewer, this issue).

Three levels of analysis are presented:

- a macro point of view that captures the entire catchment area;
- irrigation in the cascade by defining the domain as the service area of the tank cascade, including the tanks, the canals and the irrigated fields;
- an analysis, still at the mezzo level, showing a typical tank service area within the cascade, including the tank itself and the irrigated area.

First, consider a single tank. Only 6% of the gross inflow of 103 ha-m is consumed by irrigated crop ET ($PF_{gross} = 0.06$). But much of the outflow from the service area is utilizable and an estimated 26 ha-m is classified as committed to downstream uses,[2] leaving 77 ha-m as the available water that can be depleted by the tank service area. The depleted fraction of this available water is 0.60 (60%

Table 1. Water accounting for a cascade of tanks in the Anuradhapura District, Sri Lanka

	Service area boundary		Basin boundary
	Single tank service	Cascade of tanks	Cascade of tanks
Total area (ha)	20.6	465	2816.2
Irrigated service area (ha)	12.1	294.6	294.6
Inflow (ha-m)			
Gross inflow			
Surface inflow	79	747	
Rain on tank & area	25	616	4469
Gross inflow	**103**	**1362**	**4469**
Tank storage change	0	0	0
Net inflow	**103**	**1362**	**4469**
Depletion (ha-m)			
Process (Crop ET)	6	148	148
Non-process depletion			
Evaporation from tank(s)	17	284	284
Evap from soils, vegetation	23	566	3674
Total depleted	**46**	**998**	**4106**
Outflow (ha-m)			
Committed water	26	224	224
Utilizable outflow	31	140	140
Total outflow	**57**	**363**	**363**
Available water (ha-m)	77	1139	4246
Indicators			
Depleted fraction (dimensionless):			
of gross inflow	0.45	0.73	0.92
of available water	0.60	0.88	0.97
Process fraction (dimensionless):			
of gross inflow	0.06	0.11	0.03
of available water	0.08	0.13	0.03
of depleted water	0.14	0.15	0.04
Gross value of crop production ($)	3010	73310	73310
Gross value of crop production per			
Gross inflow ($/m^3)	0.003	0.005	0.002
Available water ($/m^3)	0.004	0.006	0.002
Process consumed water ($/m^3)	0.05	0.05	0.05

Source: Sakthivadivel *et al.* (1997).

of the available water is depleted). The process fraction of depleted water is 0.14, meaning that only 14% of the water depleted by the tank irrigation service is consumed by crop ET, and the remaining 86% is evaporated from free water surfaces or non-crop vegetation, although much of this may be considered beneficial.

The cascade of tanks is an ancient adaptation to the climatic conditions of the region to conserve and utilize water for agriculture. The depleted fraction of available water increases as the service area increases, with a depleted fraction of 0.60 for a single tank and 0.88 for a cascade of tanks. Similarly, the process fraction of available water is 0.08 for a single tank and 0.13 for a cascade. This demonstrates the function of the cascade, to capture and use the water for agriculture. It also demonstrates the need to consider different levels of analysis in planning and evaluation.

For the entire sub-basin analysis, including the catchment area of the tanks, the first point of interest is the amount of evaporation from vegetation other than irrigated agricultural crops. There is considerable forest and shrubs within the area, and a limited area under rain-fed cultivation. After evaporative consumption of the 4469 ha-m of rainfall water in the catchment area, 1362 ha-m remains for irrigated agriculture either as runoff or direct rainfall on the service area. After passing through the cascades, 92% of the water is depleted ($DF_{gross} = 0.92$) through evaporation and transpiration. Crop consumptive use is only 3% of the gross inflow into the catchment area ($PF_{gross} = 0.03$). The beneficial fraction of available water in the basin is not estimated, as the beneficial depletion of water by the non-crop land cover was not estimated.

The productivity per unit of ET is quite low at US\$0.05/m^3 compared with other systems in Sri Lanka (reported values range from US\$0.05 to US\$0.11/m^3) and worldwide (reported values are between US\$0.05 and US\$0.62; Molden *et al.*, 1998, Sakthivadivel *et al.*, this issue). Similarly, productivity related to available water and gross inflow appears quite low.

This analysis indicates general ways to increase productivity of water. The first is to improve irrigation and agricultural practices. The major constraints to improving water productivity are the unpredictability of rains and poor irrigation management practices (Sakthivadivel *et al.*, 1997). Second, during the monsoon, the basin has uncommitted outflows to the ocean; thus there is scope to consume more water by agriculture. This can be done by increasing storage and expanding area, and/or increasing the cropping intensity. This must be carefully planned taking into consideration the entire cascade rather than one individual tank.[3] In contrast with this example, there are a number of cascades in Sri Lanka where there are no more uncommitted utilizable flows to tap and no scope for augmenting the water supply at a particular tank. Third, through watershed management techniques, there may be ways to maintain the forest cover as well as to increase and maintain the water availability for agriculture.

Improving the Productivity of Water in Agriculture

As shown in Figure 1, there are four major outflow categories: beneficial depletion, non-beneficial depletion, uncommitted outflows and committed water. General strategies for improving productivity can be identified, pertaining to each of these categories:

(1) increasing the productivity per unit of beneficial depletion (crop transpiration in agriculture);
(2) reduction of non-beneficial depletion, including reduction of pollution;
(3) reduction of uncommitted outflows either through improved management of existing facilities or through development of additional facilities;
(4) reallocation of water to higher valued uses.

Within each of these broad strategies, more detailed strategies can be identified as listed below. The choice of strategy for increasing water productivity will be guided by economic and social factors. Existing water rights will often constrain choices, especially when there are options of reallocation. Local availability of water may be an important consideration that may dictate irrigation strategy. Among various strategies, cost-effectiveness must be considered. For example, it may be more cost-effective to reuse water through pumping than to modernize existing infrastructure to increase beneficial depletion of available water.

Increasing Productivity per Unit Transpiration

In many cases, water available for agriculture will decrease in the future as water is reallocated to industrial and urban sectors. An important means of achieving increased productivity will be to get more from the amount of water that is beneficially depleted by agriculture. This can be done by:

- *Changing crop varieties.* Plant breeding plays an important role in developing varieties that yield more mass per unit transpiration. Keeping transpiration constant, more mass can be obtained resulting in increased water productivity. Alternatively, for the same mass of production, transpiration can be reduced, yielding water that can be made available for other uses.
- *Crop substitution.* Switch from a more to a less water-consuming crop, or switch to a crop with higher economic or physical productivity per unit of water consumed by transpiration.
- *Deficit, supplemental or precision irrigation.* With sufficient water control, it is possible to achieve more productivity per unit of water by irrigation strategies that may not meet full ET requirements, but instead increase returns per unit of ET.

Reducing Non-beneficial Depletion

In both open and closed basins, it is worthwhile to consider opportunities to reduce non-beneficial depletion of water and use this water saved for beneficial purposes. General means of achieving this are:

- *Reduction of non-beneficial evaporation by:*
  - — reducing evaporation from water applied to irrigated fields (reducing the evaporation part of ET) through special irrigation technologies like drip irrigation, or agronomic practices such as mulching, or changing the planting date to match with periods of less evaporative demands;
  - — reducing evaporation by controlling evaporation from fallow land, decreasing area of free water surfaces, decreasing phreatophytes and controlling weeds.

- *Reduction of flows to sinks* by interventions that reduce deep percolation and/or surface runoff where this water presently flow to sinks.

- *Pollution control* by:
  - — reducing flows through saline soils or through saline groundwater to reduce mobilization of salts into irrigation return flows;
  - — shunting saline or otherwise polluted water directly to a sink and avoiding the need to dilute it with freshwater;
  - — utilizing a basin-wide irrigation strategy that limits reuse of return flows.

Tapping Uncommitted Outflows

It is often the case that facilities exist to utilize water resources, but these facilities are not managed to their fullest extent and, as a result, utilizable outflows in excess of downstream commitments exist. Improvement in management of these facilities is an important consideration in reducing utilizable outflows. Alternatively, it may be more cost-effective to place additional storage, diversion or reuse facilities (including groundwater pumping) to utilize this water. General means of tapping these outflows are to:

- improve management of existing facilities to obtain more beneficial use from existing water supplies. There are a number of policy, design, management and institutional interventions that will allow for an expansion of irrigated area, increasing cropping intensity, or increasing yields within the service areas;
- add storage facilities and release water during drier periods. The storage could take many forms besides impoundment behind reservoirs, including storage in groundwater, and storage in small tanks and in ponds on farmers' fields;
- reuse return flows to increase irrigated area through gravity and pump diversions.

Reallocating Water between Uses

Productivity of water can be dramatically different between uses. The value of water for municipal and industrial (M&I) uses is generally much greater than that for agriculture. An option for increasing productivity of water is to reallocate water from lower to higher value uses. As a result, downstream commitments may change, and any reallocation of water is likely to have serious legal, equity and other social considerations that must be addressed.

Summary and Conclusions

The water-accounting methodology developed in this paper provides a terminology to describe water use and productivity at use, service and basin levels. Accounting indicators were presented to characterize use at these levels. Examples from a humid region in Sri Lanka and an arid region in Egypt were presented to demonstrate the methodology. Water-accounting concepts were then used to describe means of increasing the productivity of water in agriculture.

The water-accounting concepts and procedures presented are useful in characterizing and summarizing water use, and are meant to be useful tools in the planning and evaluation of water resource systems. For evaluation and performance assessment, they can provide a good overview, and point to where in-depth studies are required. For planning, water accounting gives some key information that is useful in deriving strategies for water savings and increasing water productivity. At present, we have limited examples of this water methodology, and it is expected that these concepts and methodologies will undergo further testing, scrutiny and revision.

Water accounting calls for different ways of conceptualizing and studying irrigation in the context of basins. It is recognized that measuring diversions and deliveries is important to understand how to better provide irrigation services. Beyond this, water accounting calls for improved understanding of depletions and the consideration of the downstream use of return flows.

While there has been substantial research in the field of hydrology to quantify water balance terms, cost-effective methodologies for measuring and separating the amount of water diverted to and depleted by various uses are required. A significant area requiring more research is valuing the uses of water within a basin.

The need for improved integrated water resources management is widely accepted as a means to achieve sustainable and equitable increases in productive use of our water resources. Concepts and methodologies developed here are meant to provide tools to help us achieve better integration of irrigated agriculture within the broader context of water use in basins.

Notes

1. The depleted fraction for M&I used was assumed to be 30% for the Nile Valley and 20% for the Nile Delta. That is, in the Nile Valley, 30% of the water diverted for M&I use is depleted through evaporative consumption, or through disposal outside the domain.
2. Water committed for downstream uses was estimated at 5% of the mean annual rainfall over the catchment area of the tank or the cascade of interest.
3. Sakthivadivel *et al*. (1998) developed a methodology for cascade planning taking into consideration the array of tanks. See also Sakthivadivel and Brewer, this issue.

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