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SWIM Paper

Accounting for Water Use and Productivity

David Molden

SWIM

IIMI

System-Wide Initiative for Water Management

SWIM Papers

In an environment of growing scarcity and competition for water, increasing the productivity of water lies at the heart of the CGIAR goals of increasing agricultural productivity, protecting the environment, and alleviating poverty.

TAC designated IIMI, the lead CGIAR institute for research on irrigation and water management, as the convening center for the System-Wide Initiative on Water Management (SWIM). Improving water management requires dealing with a range of policy, institutional, and technical issues. For many of these issues to be addressed, no single center has the range of expertise required. IIMI focuses on the management of water at the system or basin level while the commodity centers are concerned with water at the farm and field plot levels. IFPRI focuses on policy issues related to water. As the NARS are becoming increasingly involved in water management issues related to crop production, there is a strong complementarity between their work and that of many of the CGIAR centers that encourages strong collaborative research ties among CGIAR centers, NARS, and NGOs.

The initial publications in this series cover state-of-the-art and methodology papers that assisted the identification of the research and methodology gaps in the priority project areas of SWIM. The later papers will report on results of SWIM studies, including intersectoral water allocation in river basins, productivity of water, improved water utilization and on-farm water use efficiency, and multiple uses of water for agriculture. The papers are published and distributed both in hard copy and electronically. They may be copied freely and cited with due acknowledgment.

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SWIM Paper 1

Accounting for Water Use and Productivity

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Acronyms

CGIAR	Consultative Group on International Agricultural Research
CIAT	Centro Internacional de Agricultura Tropical
CIMMYT	Centro Internacional de Mejoramiento de Maize y Trigo
ET	Evapotranspiration
ICRAF	International Council for Research in Agroforestry
IIMI	International Irrigation Management Institute
IRRI	International Rice Research Institute
M&I	Municipal and Industrial uses
NARS	National Agricultural Research System(s)
NGOs	Nongovernmental Organizations
SGVP	Standardized Gross Value of Production
SWIM	System-Wide Initiative on Water Management
TAC	Technical Advisory Committee of the CGIAR

CGIAR Centers

CIAT	Centro Internacional de Agricultura Tropical
CIFOR	Center for International Forestry Research
CIMMYT	Centro Internacional de Mejoramiento de Maize y Trigo
CIP	Centro Internacional de la Papa
ICARDA	International Center for Agricultural Research in the Dry Areas
ICLARM	International Center for Living Aquatic Resources Management
ICRAF	International Centre for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFPRI	International Food Policy Research Institute
IIMI	International Irrigation Management Institute
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IPGRI	International Plant Genetic Resources Institute
IRRI	International Rice Research Institute
ISNAR	International Service for National Agricultural Research
WARDA	West Africa Rice Development Association

Glossary

Available water: the amount of water available to a service or use, which is equal to the inflow less the committed water.

Basin or sub-basin accounting: the macro scale of water accounting for all or part of water basins, including several uses of water.

Closed basin: a basin where utilizable outflows are fully committed.

Committed water: the part of outflow that is reserved for other uses.

Depleted fraction: the fraction of inflow or available water that is depleted by process and non-process uses. Depleted fraction can be related to gross inflow (Depleted Fraction of Gross Inflow), net inflow (Depleted Fraction of Net Inflow), or available water (Depleted Fraction of Available Water).

Domain: the area of interest where accounting is to be done, bounded in time and space.

Equivalent yield: a yield value for a base crop derived from a mixture of crops by using local prices to convert yields between crops.

Fully committed basin: a water basin that has been developed to the extent that all water has been allocated or, in other words, all outflows are committed.

Gross inflow: the total amount of inflow crossing the boundaries of the domain.

Net inflow: the gross inflow less the change in storage over the time period of interest within the domain. Net inflow is larger than gross inflow when water is removed from storage.

Non-depletive uses of water: uses where benefits are derived from an intended use of water without depleting water.

Non-process depletion: depletion of water by uses other than the process that the diversion was intended for.

Open basin: a basin where uncommitted utilizable outflows exist.

Process depletion: that amount of water diverted and depleted to produce an intended good.

Process fraction: the ratio of process depletion total to depletion (Process Fraction of Depleted Water) or available water (Process Fraction of Available Water).

Productivity of water: the physical mass of production or the economic value of production measured against gross inflow, net inflow, depleted water, process depleted water, or available water.

Standardized gross value of production: a standard means of expressing productivity in monetary terms by converting equivalent yield of a base crop into monetary units using world prices.

Uncommitted outflow: outflow from the domain that is in excess of requirements for downstream uses.

Use level accounting: the micro scale of water accounting such as an irrigated field, a household, or a specific industrial process.

Utilizable water: outflow from a domain that could be used downstream.

Water depletion: a use or removal of water from a water basin that renders it unavailable for further use.

Water services level accounting: the mezzo scale of water accounting for water services such as irrigation services or municipal services.

Foreword

Water accounting is a procedure for analyzing the uses, depletion, and productivity of water in a water basin context. It is a supporting methodology useful in assessing impacts of field level agricultural interventions in the context of water basins, the performance of irrigated agriculture, and allocation of water among users in a water basin. It is being developed as one of the activities of the System-Wide Initiative on Water Management (SWIM) of the CGIAR. The purpose of the first phase of this SWIM Water Accounting Project is to develop standardized water accounting procedures. The specific objectives of the project are to:

1. Develop and formalize accounting standards for tracking water depletion within water basins.

2. Develop, jointly with the major commodity centers, an accounting procedure for determining the status of, and measuring changes in, the sustainable output per unit of water effectively depleted by various crops.

3. Apply and test the procedures for water use and depletion by irrigated agriculture as a component of selected SWIM and NARS research projects.

4. Disseminate the accounting procedures to NARS operating in both water resources planning and crop research.

This paper is aimed at fulfilling the first two objectives. It is to be used as a tool to disseminate information about standardized water accounting procedures both for CGIAR centers and for NARS, including those involved in managing irrigation and water resources. IIMI will coordinate activities with IRRI, ICRAF, CIAT, and CIMMYT. A second phase of water accounting and other SWIM projects will use the procedures developed here in more detailed investigations. Ultimately, it is intended that water accounting will evolve into a set of generally accepted and standardized practices.

David Molden

Abstract

This paper presents a conceptual framework for water accounting and provides generic terminologies and procedures to describe the status of water resource use and consequences of water resources related actions. The framework applies to water resource use at three levels of analysis: a use level such as an irrigated field or household, a service level such as an irrigation or water supply system, and a water basin level that may include several uses. Water accounting terminology and performance indicators are developed and presented with examples at all the three levels. Concepts and terminologies presented are developed to be supportive in a number of activities including: identification of opportunities for water savings and increasing water productivity; developing a better understanding of present patterns of water use and impacts of interventions; improving communication among professionals and communication to non-water professionals; and improving the rationale for allocation of water among uses. It is expected that with further application, these water accounting concepts will evolve into a robust, supporting methodology for water basin analysis.

Accounting for Water Use and Productivity

David Molden

> *All science depends on its concepts. These are ideas which receive names.*
> *They determine the questions one asks, and the answers one gets.*
> *They are more fundamental than the theories which are stated in terms of them.*
>
> *Sir G. Thompson*

Background

With growing population and limited water resources, there is an increasing need worldwide to manage water resources better. This is especially true when all or nearly all water resources in a basin are allocated to various uses. Effective strategies for obtaining more productivity while maintaining or improving the environment must be formulated. Wastes and nonproductive uses must be carefully scrutinized to identify potential savings. Effective allocation procedures that minimize and help resolve conflicts must be developed and implemented. To assist in accomplishing these tasks, improved procedures to account for water resource use and productivity are required.

Due to vastly different types and scales of use, communicating about water between professionals and non-water professionals is quite difficult. Policy decisions are often taken without a clear understanding of consequences on all water users. As competition for a limited supply of water increases, it becomes increasingly important to clearly communicate about how water is being used, and how water resource developments will affect present use patterns.

As irrigation is a large consumer of water, developments in irrigation have profound impacts on basin-wide water use and availability. Yet, planning and execution of irrigation interventions often take place without consideration of other uses. One of the main reasons for this restricted view of irrigation workers is inadequate means to describe how irrigation water is being used. Irrigation efficiency is the most commonly used term to describe how well water is being used. But increases in irrigation efficiency do not always coincide with increases in overall basin productivity of water.

Irrigation within a basin context has been dealt with by several researchers. Bagley (1965) noted that failure to recognize the boundary characteristics when describing irrigation efficiency can lead to erroneous conclusions, and noted that water lost due to low efficiencies is not lost to a larger system. In the field of water rights, there is often a clear distinction between consumption and diversion from a hydrologic cycle (Wright 1964). Bos (1979) identified several flow paths of water entering and leaving an irrigation project, clearly identifying water that returns to a water basin and is available for downstream use. Willardson (1985) noted that efficiency of a single irrigation field is of little importance to the hydrology of a basin, except when water quality is considered, and concluded that “basin-wide effects of increasing irrigation efficiency may be negative as well as positive.” Bos and Wolters (1989) pointed out that the portion of water diverted to an irrigation project that is not consumed, is not necessarily lost from a river basin, because much of it is being reused downstream. It was shown that high reuse actually increases overall efficiency (Wolters and Bos 1990). Van Vuren (1993) listed several constraints on the use of irrigation efficiency and pointed out situations when lower efficiencies are tolerable. Palacios-Velez (1994) argues that “water that is lost is not always necessarily wasted.”

While these works recognized weaknesses in using efficiency terms, and scale effects in moving analysis from farm to irrigated area and to river basin, an alternative means of describing water resource use was not presented. Working at about the same time, alternative terms were proposed to describe use of water within basins by Keller and Keller (1995) with effective efficiency, and by Willardson et al. (1994) with the use of fractions. Recently, works by Seckler (1992, 1993, 1996), Keller (1992), Keller et al. (1996), and Perry (1996b) describe many of the considerations to be dealt with in describing irrigation in water basins.

At this time, a common framework is required to describe water use in basins. A framework and common language to describe the use and productivity of water resources are presented in the paper. This work is developed from an irrigation perspective so that we can better understand the impacts of irrigation interventions at a water basin scale. It is developed in a general manner to describe any water resource use in order to enhance communications between practitioners in different water resource fields.

Objectives

This paper presents concepts and definitions necessary to account for water use, depletion, and productivity. The accounting procedures and standards given here are designed to be universally applicable for evaluating water management within and among all sectors. A goal of this approach is to develop a generic, common language for accounting for uses of water. This conceptual framework provides:

1. the 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 sectors;
2. a common means for reporting results of water-related agronomic trials and irrigation interventions so that impacts can be better understood in a water basin context; and
3. examples of water accounting at three levels to test and demonstrate the utility of the methodology.

Levels of Analysis

Researchers in agriculture, irrigation, and water resources work with spatial scales of greatly different magnitudes. Agricultural researchers often focus on a field level or a plot level dealing with crop varieties and farm management practices. Irrigation specialists focus on a set of fields tied together by a common resource—water. Water resource specialists are concerned with other uses of water beyond agriculture, including municipal, industrial, and environmental uses.

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. Therefore, three different levels of water use are defined for which water accounting procedures are developed:

- *Macro level:* basin or subbasin level covering all or part of a water basin, including several uses of water
- *Mezzo level:* water services level, such as irrigation or municipal water services
- *Micro level:* use level, such as an agricultural field, a household, or an environmental use

The water accounting methodology is developed in a manner such that it can be generically used for irrigation, municipal, industrial, environmental, or other uses of water. But the focus of this paper will be on irrigation services and use of water, and emphasis will be on quantities of water at the field and irrigation service levels. In the future phases, concepts and examples will be presented from multiple uses of water and water quality.

Water Balance Approach

The water accounting methodology is based on a water balance approach. Water balances consider inflows and outflows from basins, subbasins, and service and use levels such as irrigation systems or fields. An initial step in performing a water balance is to identify a domain of interest by specifying spatial and temporal boundaries of the domain. For example, a domain could be an irrigation system bounded by its headworks and command area, and bounded in time for a particular growing season. Conservation of mass requires that for the domain over the time period of interest, inflows are equal to outflows plus any change of storage within the domain.

In a purely physical sense, flows of water are depicted by a water balance. To develop and use water resources for their own needs, humans change the water balance. Water accounting considers components of the water balance and classifies them according to uses and productivity of these uses.

Conceptually, the water balance approach is straightforward. Often though, many of the components of the water balance are difficult to estimate or are not available. For example, groundwater inflows and outflows to and from an area of interest are 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 a gross estimate of water balances for use in water accounting can be quite useful to managers, farmers, and researchers. Water balance approaches have been successfully used to study water use and productivity at the basin level (for example, Owen-Joyce and Raymond 1996; and Hassan and Bhutta 1996), at the irrigation service level (for example, Perry 1996b; Kijne 1996; and Helal et al. 1984), and at the field level (for example, Mishra et al. 1995; Rathore et al. 1996; Bhuyian et al. 1995; and Tuong et al. 1996). Binder et al. (1997) use a regional balance technique quantifying municipal, industrial, and irrigation process uses to provide an early recognition of changes in quantity and quality of water. Often, first order estimates provide the basis for a more in-depth analysis that provides important clues on increasing water productivity.

Water Accounting Definitions

The art of water accounting is to classify water balance components into water use categories that reflect the consequences of human interventions in the hydrologic cycle. Water accounting integrates water balance information with uses of water as visualized 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 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 water is either depleted, or flows out of the domain of interest.

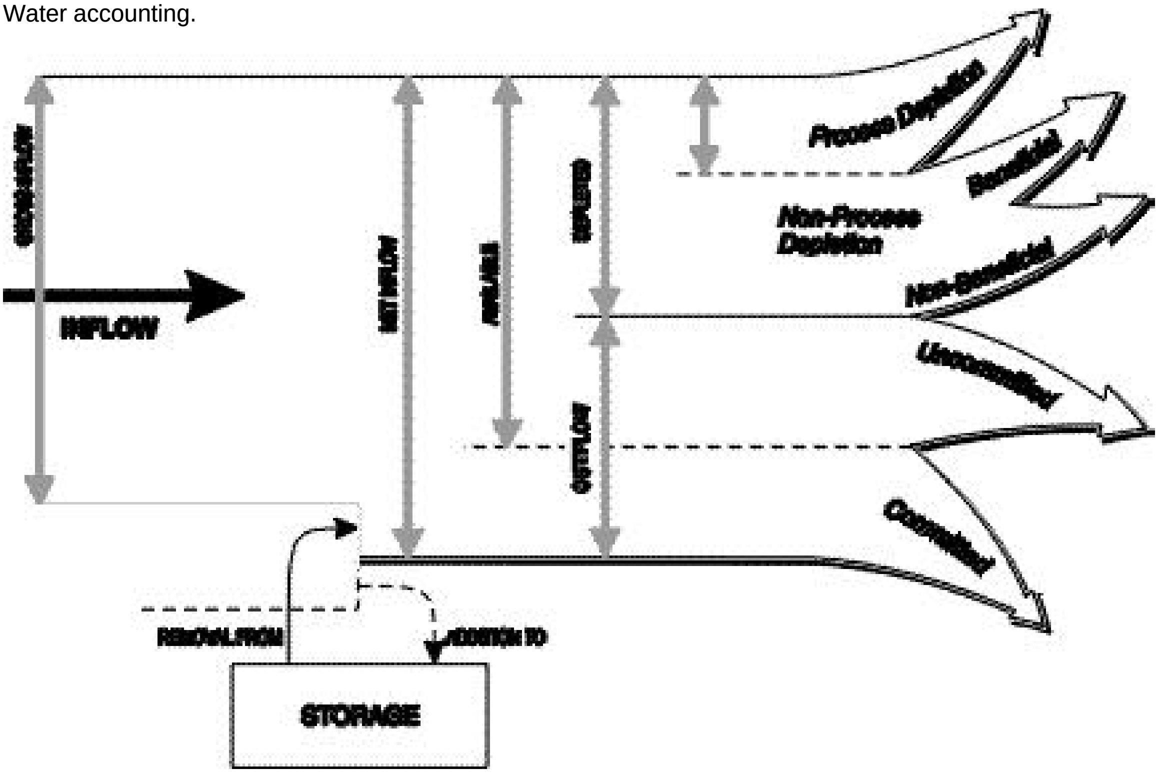
Water depletion is a use or removal of water from a water basin that renders it unavailable for further use. Water depletion is a key concept for water accounting, as it is often the productivity and the derived benefits per unit of water depleted we are interested in. It is extremely important to distinguish water depletion from water diverted to a service or use, because not all water diverted to a use is depleted. Water is depleted by four generic processes, the first three described by Seckler (1996) and Keller and Keller (1995). A fourth type of depletion occurs when water is incorporated into a product.

The four generic processes are:

- Evaporation: water is vaporized from surfaces or transpired by plants

- Flows to sinks: water flows into a sea, saline groundwater, or other location

FIGURE 1.
Water accounting.



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: by a process such as incorporation of irrigation water into plant tissues

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 water transpired by crops plus that amount incorporated into plant tissues.

Non-process depletion occurs when diverted water is depleted, but not by the process it was intended for. For example, water diverted for irrigation is depleted by transpiration (process), and by evaporation from soil and free water surfaces (non-process). Outflow from coastal irrigation systems and coastal cities to the sea is considered non-process depletion. Deep percolation flows to a saline aquifer may constitute a non-process depletion if the groundwater is not readily or economically utilizable. Non-process depletion can be further classified as beneficial or non-beneficial. For example, a village community may place beneficial value on trees that consume irrigation water. In this case, the water depletion may be considered beneficial, but depletion by these trees is not the main reason why water was diverted.

Committed water is that part of outflow that is committed 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 committed to environmental uses such as minimum stream flows, or outflows to sea to maintain fisheries.

Uncommitted outflow is water that is not depleted, nor committed, and is thus 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 that is in excess of requirements for fisheries, environmental, or other beneficial uses are uncommitted outflows. With additional storage, this uncommitted outflow can be transferred to a process use such as irrigation or urban uses.

A closed basin[1] (Seckler 1992) is one where there are no utilizable outflows in the dry season. An open basin is one where uncommitted utilizable outflows exist.

In a *fully committed basin*, there are no uncommitted outflows. All inflowing water is committed to various uses. In this case, major options for future development are reallocation among uses, or importing water into the basin.

Available water is the net inflow less the amount of water set aside for committed uses and represents the amount of water available for use at the basin, service, or use levels. Available water includes process and non-process depletion, plus uncommitted 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 from these uses do not enter the sea.

Performance Indicators

Performance indicators for water accounting follow depleted fraction and effective efficiency concepts presented by Willardson, et al. (1994) and Keller and Keller (1995). Water accounting performance indicators are presented in the form of fractions, and in terms of productivity of water.

Depleted Fraction (DF) is that part of the inflow that is depleted by both process and non-process uses. Depleted fraction can be defined in terms of net, gross, and available water.

1. $DF_{net} = \frac{\text{Depletion}}{\text{Net Inflow}}$

2. $DF_{gross} = \frac{\text{Depletion}}{\text{Gross Inflow}}$

3. $DF_{available} = \frac{\text{Depletion}}{\text{Available Water}}$

Process Fraction (PF) relates process depletion to either total depletion or the amount of available water.

4. $PF_{depleted} = \frac{\text{Process Depletion}}{\text{Total Depletion}}$

5. $PF_{available} = \frac{\text{Process Depletion}}{\text{Available Water}}$

The process fraction of depleted water ($PF_{depleted}$) is analogous to the effective efficiency concept forwarded by Keller and Keller (1995) and is particularly useful in identifying water savings opportunities when a basin is fully or near fully committed. When there is no uncommitted water, process fraction of depleted water is equal to the process fraction of available water.

Productivity of Water (PW) can either be related to the physical mass of production or the economic value of produce per unit vol-

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[1] This water accounting definition differs from a strict hydrologic definition of a closed basin where outflows go only to internal seas, lakes, or other sinks.

ume of water. Productivity of water can be measured against gross or net inflow, depleted water, process depleted water, or available water. Productivity of water has a broader basis than water use efficiency (Viets 1962), which relates production of mass to process depletion (transpiration or evapotranspiration for irrigated agriculture). Here it is defined in terms of net inflow, depleted water, and process depletion.

6. $PW_{inflow} = \frac{\text{Productivity}}{\text{Net Inflow}}$

7. $PW_{depleted} = \frac{\text{Productivity}}{\text{Depletion}}$

8. $PW_{process} = \frac{\text{Productivity}}{\text{Process Depletion}}$

The following relationships exist between productivity and water indicators.

9. $PW_{depleted} = \frac{PW_{\text{net inflow}}}{DF_{net}}$

10. $PW_{process} = \frac{PW_{depleted}}{PF_{net}}$

For an irrigated service area, these are external indicators of system performance relating the output of irrigated agriculture to its main input, water. IIMI's external indicators (Perry 1996a and Molden et al., forthcoming) draw from this water accounting list for a minimum set of indictors and include the productivity of water related to process depletion.

Accounting Components at Use, Service, and Basin Levels

Field Level

The use level of analysis for irrigation is taken at the field level with inflows and outflows shown in table 1. This is the level where crop production takes place—the process of irrigation. Agricultural research at this level is often aimed at increasing productivity per unit of land and water and conserving water. The key question is: Which water? Again, it is important to understand the category of water against which production is being measured, or the category of water that is being conserved.

At the field level, the magnitudes of the components of the water balance are a function of crop and cultural practices. Different crops, and even different varieties of crops, will transpire water at different rates. Irrigation techniques influence evaporative losses, and volumes of deep percolation and surface runoff. For example, drip irrigation minimizes these components, while surface application induces depletion by evaporation. Also, the amount of water delivered influences runoff and deep percolation. Other cultural practices such as bunding, mulching, and crop spacing affect the amount of water stored in the soil, and the amount of runoff and deep percolation. Water accounting procedures attempt to capture the effects of different crop and cultural practices on how water is used and depleted at the field level.

At the field level, it is sometimes impossible, and oftentimes unnecessary to know the fate of outflows. Only when moving up to the service and basin levels can we determine whether to classify outflows as committed or uncommitted. By accounting for water use at the field level, then placing it in the context of irrigation service and basin levels, it is possible to match field level interventions with requirements at the irrigation service level, or water basin level, or both.

TABLE 1.
Water accounting components at field, service, and basin levels.

Field	Irrigation service	Basin/subbasin
Inflow		
* irrigation application * precipitation * subsurface contributions * surface seepage flows	* surface diversions * precipitation * subsurface sources * surface drainage sources	* precipitation * trans-basin diversions * groundwater inflow * river inflow into basin
Storage change		
* soil moisture change in active root zone	* soil moisture change * reservoir storage change * groundwater storage change	* soil moisture change * reservoir storage change * groundwater storage change
Process depletion		
* crop transpiration[a]	* crop transpiration	* crop transpiration * municipal and industrial uses * fisheries, forestry, and other non-crop depletion * dedicated environmental wetlands
Non-process depletion		
* evaporation from soil surface, including fallow lands * weed evapotranspiration	* evaporation from free water and soil surfaces, weeds, phreatophytes, and other non-crop plants	* evaporation from free water and soil surface, weeds, phreatophytes, and other non-crop plants
* lateral or vertical flow to salt sinks * flow to sinks (saline groundwater, seas, oceans) * water rendered unusable due to degradation of quality	* flow to sinks (saline groundwater, seas, oceans) * evaporation from ponds/playas * water rendered unusable due to degradation of quality	* flow to sinks (saline groundwater, seas, oceans) * evaporation from ponds/playas * water rendered unusable due to degradation of quality * ET from natural vegetation
Outflow		
* deep percolation * seepage * surface runoff	* instream commitments such as environment and fisheries * downstream commitments * for M&I use within irrigation service * uncommitted outflows	* instream commitments such as environment and fisheries * downstream commitments * outflow commitments to maintain environment * uncommitted outflows

[a] Crop evapotranspiration may be considered process depletion when it is impractical to separate evaporation and transpiration components, or when separation of terms does not add to the analysis.

Notes: M&I = Municipal and industrial uses.   ET = Evapotranspiration.

Irrigation Service Level

At the service level, the focus is on irrigation service analysis (table 1). Similar water accounts could be developed for municipal and industrial uses.

The boundaries for an irrigation system typically include groundwater underlying the irrigated area, whereas for the field level the boundary would be taken as the bottom of the crop root zone. Changes in storage take place in the soil, the groundwater, and surface storage. As compared to the field level, there are more opportunities for non-process depletion, such as evaporation from free water surfaces and phreatophytes.

Water diverted primarily for irrigation often provides the source of water for other uses such as for fisheries, drinking, bathing, and industrial use. Some of this water may be committed to these uses and not available for crop transpiration. Municipal uses of irrigation service water are typically not large, but they may represent a significant proportion of depletion during low flow periods and have an important impact on operating rules. Another commitment is to ensure that water is delivered to meet downstream rights or requirements. It is very common to have downstream irrigation diversions dependent on irrigation return flows and water rights can be violated when these outflows are not available. These outflows, whether remaining in canals or flowing through drains, can be considered committed uses of water. The water available at the irrigation service level is the diversion to irrigation less the committed uses.

Basin and Subbasin Levels

At the basin level, several process uses of water are considered, including agricultural, municipal and industrial uses (table 1). The major inflow into a basin is precipitation. Other inflows could be river inflows into a subbasin, trans-basin diversions, or groundwater originating from outside the basin. At the outflow of a basin, it is important to consider commitments such as water required to remove salts and pollutants from the basin, and water required to maintain fisheries.

Through water accounting, changes in water use patterns can be analyzed. For example, changes in watershed vegetation can have a profound impact on basin-wide water accounts. Reducing forest cover may reduce evaporation but induce non-utilizable or even damaging flood flows unless surplus storage is available. Converting a forest to agricultural use with water conservation practices may make water available in water-deficit seasons, or drought years. Converting from agricultural land to native vegetation may have the impact of reducing downstream flows. Using water accounting to note these factors allows decision makers to start to understand the consequences of their actions and to indicate where more in-depth studies would be most profitable.

Examples of Water Accounting

To illustrate water accounting, three examples are chosen from the use, service, and basin levels. The use level and service level examples are taken from the Bhakra system in India, and the basin level example is drawn from the Nile River in Egypt.

Field-Level Accounting Example

As a field-level example, results of modeling trials based on field experiments (Bastiaanssen et al. 1997) carried out in the Hisar and Sirsa Circles of the Bhakra command area in India are reported in a water accounting format (table 2). In this area, the water duty falls short of potential crop requirements as water is scarce relative to land. In response, farmers typically have a strategy of deficit irrigation, or giving less water than the potential crop requirement, thus giving them the opportunity to irrigate more land.

For both crops, nearly all of the irrigation and rainwater applied is depleted leading to a depleted fraction of nearly 1.0. The process fraction of depleted water is quite high at 0.73, due to small amounts of evaporation. On an annual basis, there is

TABLE 2.
Field-level water accounts of Sirsa Circle of the Bhakra system in India: 1991 wheat-cotton rotation.[a]

	Wheat (mm)	Cotton (mm)	Annual (mm)
Inflow			
Irrigation	324	393	717
Precipitation	42	206	252
Subsurface	0	0	0
Lateral seepage flows	0	0	0
GROSS INFLOW	366	599	969
Storage Change	+14	+22	+24
NET INFLOW	352	577	945
Depletion			
Transpiration (process)	291	401	692
Evaporation (non-process)	60	175	251
TOTAL DEPLETION	351	576	943
Outflow			
Surface runoff			
Deep percolation	1	1	2
TOTAL OUTFLOW	1	1	2
Performance			
Depleted Fraction (gross)	351/366=0.96	576/599=0.96	943/969=0.97
Process Fraction (depleted)	291/351=0.83	401/576=0.70	692/943=0.73
Production (kg/ha)	4,000	2,380	
Production per unit net inflow (kg/m^3)	4,000/3,520=1.14	2,380/5,770=0.41	
Production per unit total depletion (kg/m^3)[b]	4,000/3,510=1.14	2,380/5,760=0.41	
Production per unit process depletion (kg/m^3)	4,000/2,910=1.37	2,380/4,010=0.59	

[a] Treatment: Computer simulation of typical on-farm water management practices.

[b] Depletion includes process depletion of transpiration and non-process depletion of evaporation.

TABLE 3.
Service level accounts of sirsa circle of the Bhakra system in India: 1977–1990.

	Component value (mm/year)	Total (mm/year)
Inflow		
Gross Inflow		652
Surface diversions	402	
Precipitation	191	
Subsurface sources from outside domain	59	
Surface drainage sources from outside domain		
Storage change		98
Surface	n.a.	
Subsurface	98	
Net Inflow		554
Depletive use		
Process depletion, (ET)	533	
Non-process depletion		n.a.
Flows to sinks	n.a.	
Other evaporation	n.a.	
ET from non-crop vegetation	n.a.	
Total Depletion		533
Outflow		
Total utilizable outflow		21
Surface outflow	21	
Subsurface outflow	n.a.	
Committed water		21
Domestic use	n.a.	
Industrial use	n.a.	
Environmental use	n.a.	
Downstream uses	21	
Uncommitted water		0
Available water		533
Indicators		
Depleted fraction (gross)		533/652 = 0.82
Depleted fraction (net)		533/554 = 0.96
Depleted fraction (available)		533/533 = 1.00
Process fraction (depleted)		533/533 = 1.00
Process fraction (available)		533/533 = 1.00

Notes: ET = Evapotranspiration. n.a. = Data not available.

some rainfall between seasons, and some evaporation from fallow land.

Yields were reported as 4.0 tons per hectare for wheat and 2.38 tons per hectare for cotton while relative transpiration (the ratio of actual to potential transpiration) for wheat and cotton was, 0.78 and 0.60, respectively, lower than 1.0 as a result of the practice of deficit irrigation used. In this case, transpiration and evaporation are reported separately so that productivity per total depletion and per process depletion can be computed.

It is meaningful to compare values of mass of production per unit of water diverted or depleted, when comparing like crops. But when different crops are compared, mass of output is not as meaningful. There is a clear difference between 1 kg of strawberries and 1 kg of rice produced per cubic meter of water depleted. One approach is to convert yields into value of production using local prices. A second approach is to use Standardized Gross Value of Production (SGVP). SGVP is used to measure economic productivity to allow comparisons across different agricultural settings by using world prices of various crops (Perry 1996a, Molden et al., forthcoming). To calculate SGVP, yield of a crop is converted into an equivalent yield of a predominant, traded field crop using local prices. Then this mass of production is converted into a monetary unit using world prices.

Service-Level Accounting Example

Inflow sources for irrigation include sources that originate from outside the irrigation system. Accounts for the Sirsa Circle serving 430,000 ha in the Bhakra command area (Boels et al. 1996) are shown in table 3. They are based on computer simulations calibrated to local situations. Crop

TABLE 4.
Basin-level accounts of the Nile River downstream of the High Aswan Dam:1989–1990 agricultural year.

	Component value (km^3)	Total (km^3)
Inflow		
Gross Inflow		53.7
Surface diversions	53.2	
Precipitation	0	
Subsurface sources from outside subbasin	0.5	
Surface drainage sources from outside subbasin		
Storage change		0
Surface	0	
Subsurface	0	
Net Inflow		53.7
Depletive use		
Process depletion		36.4
Evapotranspiration	34.8	
M&I	1.6	
Non-process depletion		
Flows to sinks	n.a.	3.2
Other evaporation (phreatophytes, free water surface)	3.2	
Total Depletion		39.6
Outflow		
Total Outflow		14.1
Surface outflow from rivers	1.8	
Surface outflow from drains	12.3	
Subsurface outflow	0	
Committed Water		9.8
Navigation	1.8	
Environment maintenancea (assumed)	8.0	
Uncommitted Outflow	14.1–9.8	4.3
Available Water	53.7 – 9.8	43.9
Available for irrigation	43.9–1.6 (M&I)	42.3
Indicators		
Depleted fraction (gross and net)	39.6/53.7	0.74
Process fraction (depleted)	36.4/39.6	0.92
Process fraction (available)	36.4/43.9	
Gross value of production (1992 US$)[b]	6,450 million	
Productivity per unit of water depleted by irrigation	6.45/36.3	0.19
Productivity per unit of water available to irrigation	6.45/41.9	0.15
Productivity per unit inflow	6.45/55.3	0.12

[a] This estimate is made by the author and is made for illustrative purposes.

[b] *Source:* Ministry of Agriculture and Land Reclamation, 1990.

Notes: ET = Evapotranspiration. M&I = Municipal and industrial uses.

evapotranspiration was considered as the process depletion. No information was available on non-process depletion and productivity. It was assumed that all the outflow was required by downstream users, and thus is shown as committed water.

Striking in this example is the relatively high depleted fraction. This is in part due to the on-farm practice of deficit irrigation illustrated in the example above. In this example, there is no uncommitted water, so available water is equal to depleted water. Because non-process depletion was not separated from process depletion (evapotranspiration) and no other non-process depletion was identified, the process fraction of depleted water is 1.0.

The change of storage term stands out as 15 percent of the gross inflow and was added to groundwater storage over the period 1977 to 1990. In fact, it is estimated that over this area, groundwater is rising at an average rate of 0.6 m per year. For long-term sustainability, this situation of a rising water table has to be dealt with. In general, over time periods of several years, a large positive or negative change of storage represents issues of sustainability corresponding to a rise in water table or mining from groundwater.

Basin-Level Accounting Example

Water accounts are shown for the Nile River downstream of the High Aswan Dam in Egypt (table 4). Figures used in the accounts are based on data presented by Abu-Zeid (1992) and estimates presented by Keller (1992) for the water year 1989–1990. Many of the figures and estimates require further scrutiny, and the example is presented to illustrate the use of water accounting.

The inflow is derived almost entirely from releases from the High Aswan Dam and was recorded at 53.2 km^3 (cubic kilometers). Inflow from groundwater was estimated at 0.5 km^3, while rainfall and other sources were negligible during this year. The storage change of the groundwater was assumed to be zero for the annual cycle. Evapotranspiration was estimated at 34.8 km^3. Depletive use by municipal and industrial (M&I) uses was estimated at 1.6 km^3 by assuming that 20 percent and 30 percent of diversions are depleted in the Nile Delta and Valley, respectively. There is considerable return flow from M&I back to the Nile water system. Other non-process depletion considered was evaporation from free water surfaces, fallow land, and phreatophytes, estimated at 3.2 km^3. The total depletion of the net inflow of 53.7 km^3 is 39.6 km^3.

Measured outflows are 1.8 km^3 from the Nile River to the sea, and 12.3 km^3 from the drains to the sea. But 1.8 km^3 of this outflow during that particular year was committed to maintain water levels for navigation. Some drainage outflow is required to maintain the environment at present levels, and is roughly estimated here at 8 km^3 based on the need to remove salts and pollutants from the Nile, and to maintain freshwater fisheries. With this estimate for environmental commitments, the remaining uncommitted outflow is 4.3 km^3.

The depleted fraction of net and gross inflows for the basin is 0.74 (in this case gross inflow equals net inflow). The process fraction of depleted water is 0.92 and the process fraction of available water is 0.83. A very high percentage of both depleted and available water is depleted by the intended processes.

The Water Accounting Research Agenda

The terminology and framework presented here are developed for general use under a variety of conditions. The concept is meant to be supportive for a number of activities, including identification of opportunities for water savings and increasing water productivity; support of the decision process for water allocation; general water audits and performance studies; and conceptualizing and testing interventions. A few examples were provided here for illustration, but for the procedures and terminology to develop into standards these need to be tested and refined under a variety of conditions.

Water accounting requires water balances. Some important shifts in irrigation water measurement programs are required. Measurement of irrigation water is often focused on diversions. Yet to complete the water balance, better knowledge is required of the drainage outflow. Estimates of non-process depletion of water are rarely made at the irrigation system and basin levels.

Critical in the water accounting process is the estimation of evaporation and transpiration. Our uncertainty about results increases when shifting from use level to service level to basin level. New technologies and techniques of remote sensing show promise in improving estimates of evaporation and transpiration and for separating process and non-process evaporation (Bastiaanssen, forthcoming).

The interaction between water accounts at the field level and at the irrigation service and basin levels needs to be better illustrated. Claims of water savings based on field trials should be made by placing the consequences of field-level practices in terms of service and basin-level analyses. Reporting of field-scale results in a water accounting format will assist researchers and designers to point out appropriate field-level strategies that will achieve water savings and increases in water productivity.

At the service and basin levels, there is a need for documentation on the depletion of water by other nonagricultural users of water, and the returns from that depletion. It is widely known that within irrigated areas and within basins, there are other important uses of water. Oftentimes, we know the diversion to these uses, but we have no idea how much is depleted. Some detailed case studies should shed light on the depletion of water by these uses.

Quality of water plays an extremely important role in water depletion and water productivity. A means of accounting for depletion due to pollution is required. This is particularly true in basins where water is fully or near fully committed. Often, in these cases, recycling intensifies and dilution is not a viable option. While recycling of water is a viable water saving strategy the effects of pollution loading on productivity, the environment, and health require clear accounting beyond the water quantity estimates presented here.

In the field of financial accounting, there exist accepted, standardized procedures for performing audits, and auditing of accounts is a widely accepted practice. This is not true in the water field. There will be an increasing pressure for accountability for water use with increasing scarcity of water. One direction for further research starting from water accounting is the development of standardized, widely accepted procedures for performing water audits.

Water accounting will assist in a better understanding of present patterns of water use, improving communication among professionals and communication to non-water professionals, improving the rationale for allocation of water among uses, and for identification of means to achieve water savings and increases in water productivity. It is expected that over a short period of time this framework will develop into commonly applied practices and presentations to help us better utilize our water resources.

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