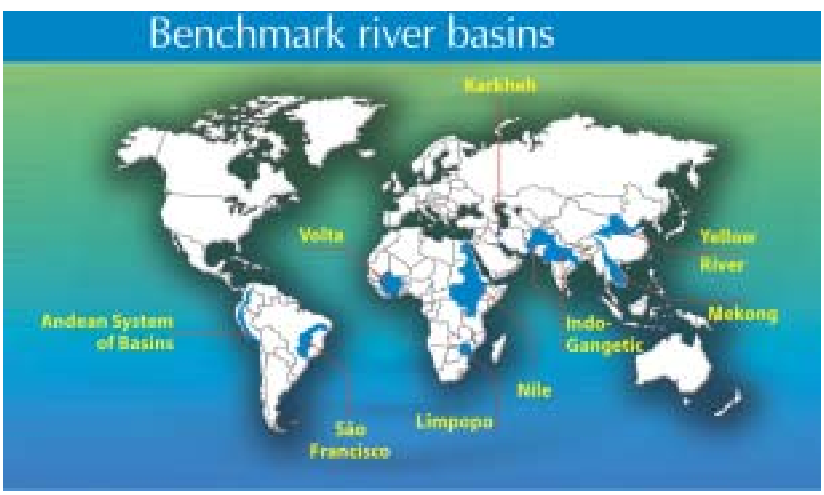
WATER PRODUCTIVITY:
Measuring and Mapping in Benchmark Basins

Basin Focal Project Working Paper No. 2

Estimation at plot, farm and basin scale

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



DISCLAIMER

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

The findings, interpretations, and conclusions expressed here are those of the author(s) and do not necessarily reflect the views of the Challenge Program.

Comments and additional inputs that could contribute to improving the quality of this work are highly welcomed.

They should be sent to the authors:

Simon Cook – s.cook@cgiar.org
Francis Gichuki - f.gichuki@cgiar.org
and
Hugh Turral – h.turral@cgiar.org

This document will be updated as more data and information become available. For the latest update please visit our website
www.waterforfood.org

Paper 2 Agricultural Water Productivity: Estimation at Plot, Farm and Basin Scale

Contents

Basic concept: Water productivity for agricultural production systems

The concept of water productivity (WP) is offered by Kijne *et al.* (2003) as a robust measure of the ability of agricultural systems to convert water into food. While it was used primarily to evaluate the function of irrigation systems – as 'crop per drop' - it seems useful to extend the concept to include other types of livelihood support, such as mixed cropping, pasture, fisheries or forests. The basic concepts and rationale for estimation are described more fully in the first working paper of this series.

The purpose of this paper is to present ideas of methods of estimating WP at a range of scales, and for different agricultural systems. Water productivity of non-agricultural systems is not considered.

A third paper in this series describes how estimates are used to define actionable goals of agricultural water management for poverty alleviation. For now, we assume two basic uses of WP estimates: firstly, WP provides a diagnostic tool to identify low or high water use efficiency in farming systems or sub-systems; secondly, WP provides robust insight into the opportunities for re-distribution of water within basins towards a goal of increased basin-scale and global water productivity.

In practice, measurement of WP over large areas requires approximations and assumptions that can introduce important errors. The subsidiary purpose of this paper is to enable developers to make judgments about how acceptable these errors are and what alternatives there may be to resolve the technical problems.

Basic express ion:

Productivity is a measure of system performance expressed as a ratio of output to input. For agricultural systems, WP is a measure of output of a given system in relation to the water it consumes. Assessment may be required for the whole system or parts of it, defined in time and space.

$$WP = \frac{Agricultural\ Benefit}{Water\ Use}$$

UNITS:

It is normal to represent WP in units of kg/m^3. If production is measured in kg/ha, water use is estimated as mm of water applied or received as rainfall, convertible simply to m^3/ha (1mm = 10m^3/ha). Alternative notations include food (kcal/m^3) or monetary value ($/$m^3$).

DEFINING THE SYSTEM FOR WHICH WATER PRODUCTIVITY IS TO BE ASSESSED:

Water productivity is estimated for an agricultural system or sub-system, defined within a given area and time period. The simplest purpose of WP is to enable rapid comparisons between water use systems in space and time; a WP of 1.5 kg/m^3 might be considered 'good' whereas one of 0.5 kg/m^3 might be thought 'bad'. For this purpose, it is preferable to restrict the concept to *component parts* of a system, rather than try to estimate overall productivity for the entire system.

Systems are defined by plot, field, sub-basin and basin. Estimates of WP for single activities are called partial WPs. WP of larger areas containing complexes of multiple land use requires integration of partial WPs for each activity contained within them.

Changes in water use in the hydrologic pathway will have impacts both upstream and downstream, so it is necessary to analyze the impacts of different interventions in a way that internalizes hydrologic feedback in terms of water quantity and water quality. The best way to do this is to integrate the production system, the hydrology and economics within one modeling framework. This can vary from simple spreadsheets, through suites of hydrologic, allocation and production models; to fully integrated hydrologic and economic models. The precise requirements and solutions will vary according to the basin context and data availability.

Defining the time period for estimation

The time period over which WP is estimated is determined by the cycle of agricultural production that drives the system. Normally, this would include at least one complete crop cycle, extended over a complete year to account for productive and non-productive water use. Assessment may be extended over several years to derive estimates of average, minimum or maximum water productivity within each season.

Complex agricultural systems may require assessment over several years to include all productive and consumptive phases. The value of product may vary according to its position within the farming system it is used, often in quite complex ways. For example, livestock systems in semi-arid regions have developed to cope with fluctuations in water availability in different seasons, so assessment in any one season may not represent productivity of the whole system. Cropping systems provide internal benefits in addition to yield, such as fodder or soil nutrition, which may significantly influence water productivity in subsequent years. Forest products may provide small but critically important gap-filling products.

The fluctuation over time of drivers of productivity such as climate or markets introduces a further source of estimation error. This is because the condition of WP will reflect the state of these drivers at the time of assessment, which may, or may not, be representative of the average situation.

Defining the area for estimation

The first step is to define the boundaries of the system for which WP is to be estimated. This is determined by the definition of production system (field-by-field, farm-scale, multiple administrative units) and the area for which water consumption can be defined (plot, field, sub-basin or basin).

There is a trade-off between accuracy of measurement over small areas and representation of a larger hydrologic system. Measurement of partial WP for a single crop at field or plot level is simplest. However, such an assessment will represent only part of the benefits generated within a farming system. Additional activities within the farming system such as livestock, trees or fish may need to be included to represent essential benefits, but will also introduce major uncertainties.

Yield data exist for many countries as secondary statistics, expressed crop-by-crop according to administrative boundaries. In these cases, manipulation in GIS is required to make the data spatially coherent with water-use data. Techniques of proportional areal estimation are described in standard GIS texts (see Davis, 2003 for a review of methods in relation to poverty mapping).

The effect of spatial scale on variation in water storage should also be considered. In rainfed areas, WP will vary spatially according to varying water storage capacity (Bouman, 2006), such that definition of a particular production system can be over- or under-represented within areas with a high or low storage capacity. Systems in which groundwater flows make a significant contribution to production (either via re-emergent or extracted groundwater) need to be defined over an area large enough for this source of variation to be identified.

Production: Estimating the enumerator

The beneficial outcome of agriculture can be expressed in a range of forms, as yield (kg, Mg, t) or food equivalent (kcal.); income ($) or other agreed measure of well being derived from the goods and services coming from the agricultural system. The common forms of evaluation are listed in Table 1.

Physical measurement of productivity

The simplest option is to consider the water productivity of a principal crop, in kg or t, for an area of known extent for which there exist data on agricultural water use. Primary yield data may be generated from direct measurement or by crop survey. More commonly, crop production data will come from secondary statistics – as total tonnage for a given administrative area (convertible to t/ha if the area dedicated to each crop is known). In some cases, global or national level statistics can be manipulated to provide useful insight (e.g. Falkenmark and Rockström, 2004). This will enable partial water productivity of principal crops to be estimated for large areas. Raw production in kg may be converted to nutritional value (see Rockström *et al.*, 2003).

Remote sensing provides a third option to estimate production over large areas. Wide area estimation of grain yield from the normalized difference vegetation index (NDVI) has been used successfully for basin or national scale estimation of biomass and crop yield for several years. Its accuracy varies widely, depending on the ability for an episodic estimation of reflectance to estimate biomass and final yield. Under good conditions, remotely sensed imagery correlates about 70% with final grain yield.

Local calibration seems essential since in some areas correlation between NDVI-based estimates and actual yield can be extremely low. Remote sensing has also been used to assess total feed value of pastures. In all

Table 1. Possible forms of the numerator for estimating water productivity.

Parameter	Numerator
Physical water productivity at field, farm or system level.	Yield (kg) of total biomass, *or* above ground biomass, *or* grain, *or* fodder.
Economic water productivity at farm level.	Gross value of product, *or* net value of product, *or* net benefit of irrigated production compared with rainfed production.
Economic water productivity at basin scale.	Any of the above valuations including those derived from raising livestock, fish or agro-forestry.
Macro-economic water productivity at regional or national scale.	Monetary value of all direct and indirect economic benefits minus the associated costs, for all uses of water in the domain of interest.

cases, the accuracy of remote sensing techniques is highly dependent on the availability of timely imagery. Remote sensing tends to be most successful in arid and semi-arid regions in which cloud-free imagery is available for the whole growing season.

Ahmad *et al.* (2005) propose a combined remote sensing approach to estimate water productivity at a regional scale, using a variety of scales of imagery (Landsat at 28.5 m pixel to Moderate Resolution Imaging Spectroradiometer (MODIS) at 1km (thermal) and 500m (visible, near- and medium- infrared wavebands)). Ground truth, crop histories, classification, biomass development and yield will be required to understand the relationship between net primary productivity and yield and better assess harvest index as a function of crop condition. Representative areas for survey can be selected from a preliminary analysis of satellite images, and local knowledge.

Economic measures of agricultural productivity

The simplest measure of economic productivity at a field scale is gross margin (GM) for a single product during a single phase of the crop rotation. The system may require estimates of GM from several seasons to cover all phases of a farming system.

For areas that contain different production systems, a composite measure is standardized gross value of product (SGVP) in which the price of the product is converted to the equivalent price of a standard crop, such as rice, then converted to the world market price. Expressed in a formula:

$$SGVP = \sum_{Eachcrop} \left(Area \times Yield \times \left(\frac{local\ price}{base\ price} \right) World\ market\ price \right)$$

The utility of SGVP may be questioned since it includes no estimate of costs, and therefore attributes average total benefit of all farming inputs to water.

The full range of economic benefits from agricultural production extends far beyond the simple measure of local production, to include indirect and broader impacts (Hussain *et al.*, 2005). Multipliers of economy-wide farm / non-farm multipliers vary widely. Estimates in India suggest a multiplier as low as 1.2 for local schemes up to about 3 for the country as a whole. Multipliers tend to be larger in developed economies, estimated as high as 6 for Australia (Hill and Tollefeson, 1996).

Hussain *et al.* (2005) point out that the most meaningful measure is of marginal value, that is, the additional value that is created when water is added (or lost when water is not available). WP assessment is more directly linked to problems in water-scarce or water-costly situations than in systems which are supplied with plentiful, low value water. WP is most meaningful as an indicator as water resources become increasingly scarce. The range of productivity-based indicators is summarized in Table 2 below:

Estimates of marginal value may be necessary where assessment is needed to identify ‘optimal’ distribution amongst contrasting users. Oweis and Hachum (2003) cite the benefit of supplemental irrigation in these terms and demonstrate marginal WP of up to 2.5 kg/m^3. The concept of marginal value is reasonably standard in resource-based economies but data on which to evaluate it is difficult to find beyond research stations. It may be possible to derive crop production functions that estimate the contribution of water to productivity (see, for example, estimates for Rechna Doab in Pakistan; Ahmad *et al.*, 2005).

Assessment to emphasize pro-poor outcomes might also weight assessment to account for the increased value of benefits in low income groups. This argument is made on the basis that

- Income has diminishing marginal utility in purely economic terms;
- If the intention is equitable income distribution, a dollar generated on behalf of a low income earner is worth more than one generated for a richer person and
- On a one-person, one-vote principle the per *person* benefit counts more than the per dollar benefit.

On the basis of this analysis, the relative value of fisheries and forests can be much greater than initial analysis suggests because they are often of great importance to the landless poor and marginalized people.

Table 2. Productivity indicators.

	Indicators
Water productivity-based indicators	Average product per unit of water Average gross value of product per unit of water Average gross margins per unit of water Average gross net value of product per unit of water Value of marginal productivity of water.

Note: Commonly used denominators for calculating water productivity based indicators are amount of water diverted/supplied, water applied, gross inflow of water (rainfall plus irrigation), and crop evapotranspiration (Et).

NON-ECONOMIC MEASURES OF AGRICULTURAL PRODUCTIVITY

Non-economic benefits from water by agriculture can be significant factors to include in assessment of total WP. They can, however, be difficult to evaluate – each type demanding complex methodologies to assess complex benefits. Environmental benefits can include direct product (including protection of fish resources), indirect benefits (e.g. impact on carbon stocks) or environmental flows – namely, flows deemed necessary for proper function of basin processes (Smakthin *et al.*, 2004). The potentials for payment for ecosystem services (PES) appear to be increasing as more effort is put into practical evaluation and implementation (Farber *et al.*, 2002; Kozanayi, 2002). As explained in Paper 1 of this series PES exemplifies the benefit of building social capital through management of common water resources. The final non-economic benefit that we mention here is the political capital that accrues through agreements to share or trade water resources or their products (such as hydro-electric power). Analysis by Wolf *et al.* (2003) of reported events involving trans-boundary basins indicate these predominantly construct political capital.

Valuation systems are inextricably linked to the attitudes people have towards water, ranging from private, depleting uses to common, observable (non-depleting) attributes (Groenfeldt, 2003; Turner *et al.*, 2004). Difficulties in quantification arise when outputs are difficult to value or when output quantities are expressed in different units. Some issues that may require specific attention include:

- Assessment of WP in complex livestock-based farming systems. This would need to include exchange of plant and animal products around the system (see, for example, Peden *et al.*, 2002).
- Forest and agroforestry systems, which may provide ecosystem services, and be of unusual importance culturally or because of biodiversity considerations.
- WP of fisheries and other aquatic systems, for which both output and consumption may be very difficult to quantify, yet provide essential livelihood support to the world's poorest people.

One suggestion is to adopt a broadly-based indicator of water wealth that portrays the income per m^3 on a per capita basis. Per capita income, however, does not estimate the total support provided by water so ultimately does not relate to the problem that more food will need to be produced for more people with less water. For example in the Lakes region of Kenya and Uganda rainfed agriculture supports a very high density of people, each with a small per capita wealth. Total WP is far higher than per capita WP. Another approach may be to take account of the number of people supported by a given water resource and the level to which they are supported, using standard measures of livelihood support, such as Human Development Index (see Maxwell, 1999) or Basic-Needs Index (see Davis, 2003).

Estimating the denominator: Water consumed

A key distinction when computing WP is to differentiate between water input to an agricultural system and water depleted by it. WP is estimated from the amount of water directly consumed by the agricultural system (that is, evaporation and transpiration), not simply the amount of water supplied. This distinction is increasingly important as we move upscale from field to farm to basin, because water that is taken into a system, but not consumed, is available downstream and hence is excluded from calculation (see Molden, 1997). In measuring depleted water, we account for flows not used by the crop and returned to the hydrologic system.

Quality of downstream water is potentially an important factor. Activities that damage water quality effectively reduce or even remove water that would otherwise be available to downstream users.

Estimating water input can be confounded by not being able to define contributions from shallow or deep groundwater, although if available, water table modeling can assist. Another problem is not knowing the extent of run-on to rainfed lands from surrounding catchment areas. It is also possible that there will be varying amounts of soil water carried over between seasons, depending on the year and the timing of rainfall. For example, we would expect all soil moisture in the root zone to be depleted every year in the Karkheh basin, with its strong pattern of winter rainfall and very high rates of potential Et in the dry summer.

Water balance

The basic expression of water balance is (input – output), accounting for change in water stored in the system:

$$Q_{in} = Q_{out} + \Delta S \qquad (1)$$

Where:

Q_{in} includes rain, groundwater and surface-supplied irrigation and run-on,
Q_{out} includes runoff, drainage and evapotranspiration, and
ΔS is change in soil water content.

At the field scale, the key term is evapotransiration, considered as:

$$Et = P + I + G + Q - \Delta S \qquad (2)$$

Where:

Et = evapotranspiration, that is evaporation from soil and water surfaces plus crop transpiration
P = rainfall
I = irrigation inflow
G = net groundwater flow
Q = runon (positive) or runoff (negative)
ΔS = changes in soil water content within the root zone

Some components may not be relevant and be removed to simplify evaluation (e.g., no irrigation in rainfed farming, no run-on (incoming overland flows) or no capillary rise from high water table). Using both actual Et and net water supply as denominators can help define the context and options for management.

Direct and indirect measurement of Et

Et of crops is routinely inferred for large areas from more easily measured climatic variables (for details see Linacre, 1977; Allen *et al*., 1998).

Quantitative estimates of consumptive water use by crops over large areas is possible using the Surface Energy Balance Algorithm (SEBAL) method. This determines Et as a residual of the energy balance using routinely available weather data in conjunction with satellite-sensed thermal radiation.

Remote sensing offers the chance to represent land use and its spatial variation accurately, to determine actual Et (Et_a) and possibly to fill gaps that there may be in the coverage of rainfall data. Et_a is obviously a better measure of water consumption by agriculture than potential Et (Et_p), which assumes water is freely available and that the crop canopy remains fully developed and active. However there are a number of challenges to be addressed:

- SEBAL relies on cloud-free imagery of cropped areas,
- Sub-pixel disaggregation of land use (between crops and between cropped and fallow land), when using 1km or 500m pixel (MODIS or Advanced Very High Resolution Radiometer (AVHRR)) data,

- Corresponding sub-pixel disaggregation and attribution of Et_a to each land use, or alternatively to land use defined by higher resolution imagery (Landsat at 28.5m) and
- The SEBAL procedure needs improved calibration for rainfed, pasture and forest land covers. New research is providing some insight on the estimation errors.

ESTIMATING CONSUMPTIVE WATER USE BY SIMULATION MODELLING

It may be possible to represent the effect of climate variation on rainfed-crop WP by coupling a weather generator with crop simulation models. This has been done for large areas using the MarkSim procedure (Jones *et al.*, 2002) coupled to the Decision Support System for Agrotechnology Transfer models (DSSAT, Hoogenboom *et al.*, 2004) by Díaz-Nieto *et al.*, (2006). Results can be spatialized in GIS using exhaustive parameterization of model inputs. An alternative approach is to establish the spatial distribution of a small number of 'typical' soil profiles for which more exhaustive modeling results exist (Pracilio *et al.*, 2001). The purpose of this would be to identify theoretical benchmarks of crop WP from which may be identified *intrinsic* factors liable to reduce water productivity.

Allocation scenarios can be simulated by changing the balance of land under rainfed and irrigated conditions, or by adjusting water supply inputs through:

- Rainwater harvesting,
- Soil water conservation practices,
- Supplemental irrigation,
- Changing surface or groundwater allocations and
- Conjunctive use policy to balance demands for surface and groundwater.

The estimation of Et from water input data can be complicated by not being able to define contributions from high water table (although water table mapping will assist, if available) and not knowing the extent of run-on to rainfed lands from surrounding catchment areas.

The soil water storage term is normally assumed to make an insignificant contribution to seasonal water use. For example, we would expect all soil moisture in the root zone to be depleted every year in regions with strong patterns of winter rainfall and very high rates of potential Et in summer such as the Karkheh and upper Volta basins. However, it is possible that in some situations there might be carry-over of soil water between seasons in regions such as the Mekong basin, depending on the timing of rainfall between years.

More complex 2- and 3-dimensional modeling may be necessary to understand the consequences of land-use change on water availability and consumptive water use. Where the system is governed by surface water supply with limited groundwater, a simple node-link model like the Stockholm Environment Institute's water evaluation and planning (WEAP) system may be adequate to represent water budgets. If the system is dominated by rainfed agriculture, then a model like the USDA soil and water assessment tool (SWAT), which integrates land use and hydrology may be preferred, although there may be problems in representing groundwater and surface water diversions. Higher-dimensional hydrologic models such as TOPOG (Dawes and Hatton, 1993) may be used to represent water balance within spatially-variable landscapes. More complex process-based models (such as the Danish DHI Water & Environment MIKE-SHE model) integrate all process, but present very serious challenges in calibration and parameterization, due to extensive data requirements, often related to soil characteristics. There are intermediate solutions, such as the New South Wales Department of Land and Water Conservation integrated quality and quantity model (IQQM), which is basically a node-link model with more advanced hydrology options for catchment yield, ungauged inflows and storage (see Hameed and O'Neill, 2005).

A long history of development and application of such models can be found in the literature. However, the data requirements may be daunting. A major lesson seems to be 'proceed with caution', since propagation of error within data-hungry models can render complex results meaningless.

If there is significant groundwater use, and salinity is an important factor, then the integrating model should be a groundwater model, incorporating a salt transport module (e.g. the USGS modular three-dimensional groundwater flow model MODFLOW with the MT3D module). Creating groundwater models is a very time and data intensive exercise, and is usually limited to well-defined areas. It is highly unlikely that groundwater models can be built and calibrated at whole basin scale.

The recent publication by the International Water Management Institute (IWMI) on the Zayendeh Rud basin in Iran (Murray-Rust and Selemi, 2002) provides a good example of the integration of models at different scales using simple spreadsheets as links, although it is a little superficial on the integration of groundwater.

WATER ACCOUNTING

The problem of estimating water consumption becomes more difficult for large, heterogeneous areas that contain complex mosaics of land uses. Discrepancy of meaning between WP of different uses can obstruct comparison of different water users within a single area. To simplify this, the method of water accounting may help track different flow paths of water depletion (Molden, 1997).

Water accounting tracks the movement of water volumes within a field, an irrigation system or a basin according to four basic designations (Figure 1):

- Water inflow (positive)
- Change in storage (positive or negative)
- Depleted water, that is water used or removed in either process (e.g. growing and processing food) or non-process (e.g. depletion by evaporation from soil surfaces and ditches, or deep percolation to groundwater that is non-recoverable) or non-beneficial (transpiration by weeds; washing motor vehicles).

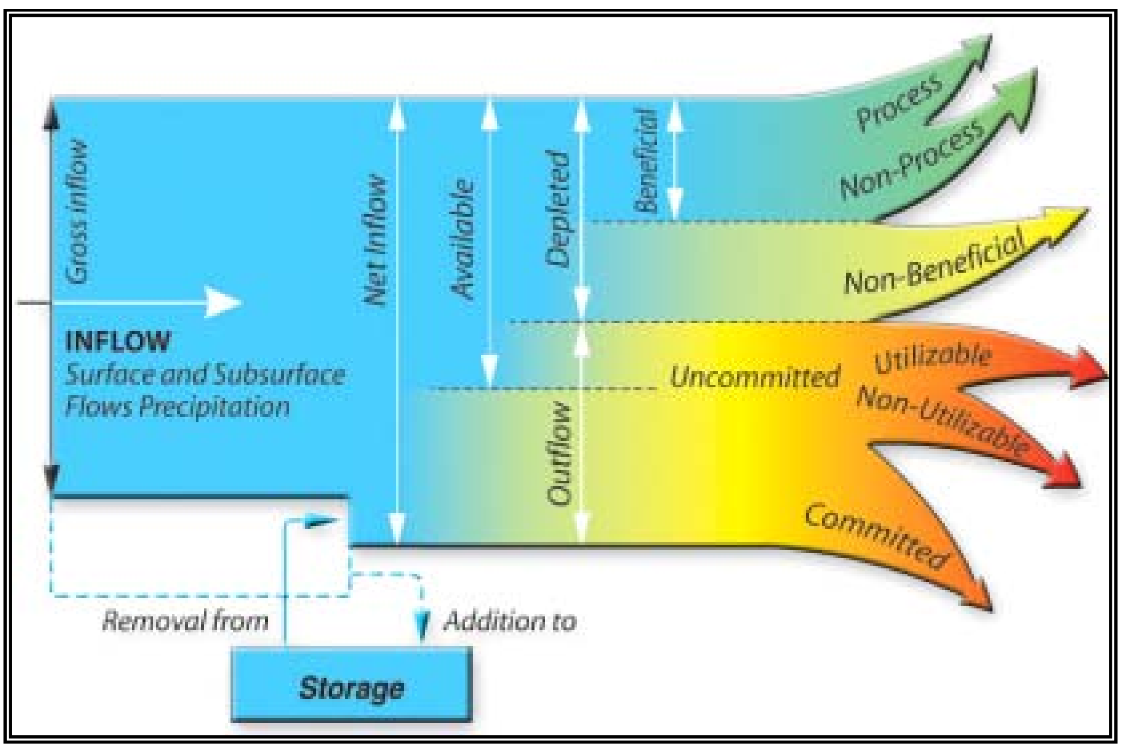


Figure 1. Water accounting framework (Molden *et al.*, 2001).

- Outflow that is either committed as direct input into some downstream application or is available for use downstream (utilizable) or not (non-utilizable, as in the case of saline or contaminated water).

Volumes in each category are measured (e.g. irrigation inflows), inferred by modeling (drainage outflow) or inferred from other data (e.g. use of remote sensing to estimate Et).

WP of rainfed cropping systems

Rockström *et al.* (2003) provide tables of consumptive water use for a range of tropical and temperate crops, based largely on observations from the 1950s to 1970s to compute WP from published values for crop water use efficiency (see also Rockström *et al.*, 1999). Rockström *et al.* (1999) observe a wide range of WP around the universal average of about 0.7 kg/m^3 of green water. (non-irrigation water use by agriculture). Within-field variation in yield is even greater (hence WP), suggesting substantial scope for improvement of WP.

Water use efficiency of dryland crops has been studied for over 90 years. Yield data are widely available and in them attention is generally focused on estimating the denominator WP, the water consumed. At its most basic, consumptive water use (Et) is expressed as growing season rainfall and soil water changes:

$$Et = P_{\text{growing season}} + \Delta S \qquad (3)$$

No account is taken of losses/transfers of water by runoff, nor of losses through deep percolation beyond the rootzone, both of which will reduce WP at any given point. In dryland systems, changes in soil water at the beginning and end of growing season may be assumed to be insignificant, so that water consumption is simply estimated as rainfall during the growing season. The compilation of results of water use by dryland cereal crops by Sadras and Angus (2006, Figure 2), shows several interesting features:

- An intercept of about 60mm (range 80-110 mm according to site characteristics), attributed to evaporative loss,
- An overall maximum conversion efficiency of about 22 kg_{grain}/mm_{water} (equivalent to WP of 2.2 kg_{grain}/m^3, somewhat higher than the estimates of WUE collated by Rockström *et al*, 1999) and
- A large spread of data below the maximum line, demonstrating the potential gains that could be achieved by better agronomic management.

WP of irrigated crops

Molden *et. al.* (2001) analyzed WP of two irrigated systems – Chishtian in the Indus basin in Pakistan and Bhakra in the Ganges basin in India. They showed that there are marked differences in yields, and hence WP, with the system in India reporting higher values (Table 3). They attributed the higher productivity of the Indian system to higher land productivity and deficit irrigation.

A procedure has been developed by scientists at IWMI for determining the water productivity of irrigated crops as follows:

1. Map irrigated areas and crop types within the surface water / groundwater system
    - Identify conjunctive use areas with the irrigation system
    - Map high water table areas (secondary data)
    - Obtain crop yield data through appropriate combinations of secondary (administrative or hydraulic district) data or from primary crop survey.
    - Obtain data on straw and green fodder production and utilization from irrigated crops, (usually from primary survey).
    - Determine livestock holdings and fodder use (by survey)
2. Overlay irrigation networks, and determine flow data for primary, secondary and possibly tertiary canals.

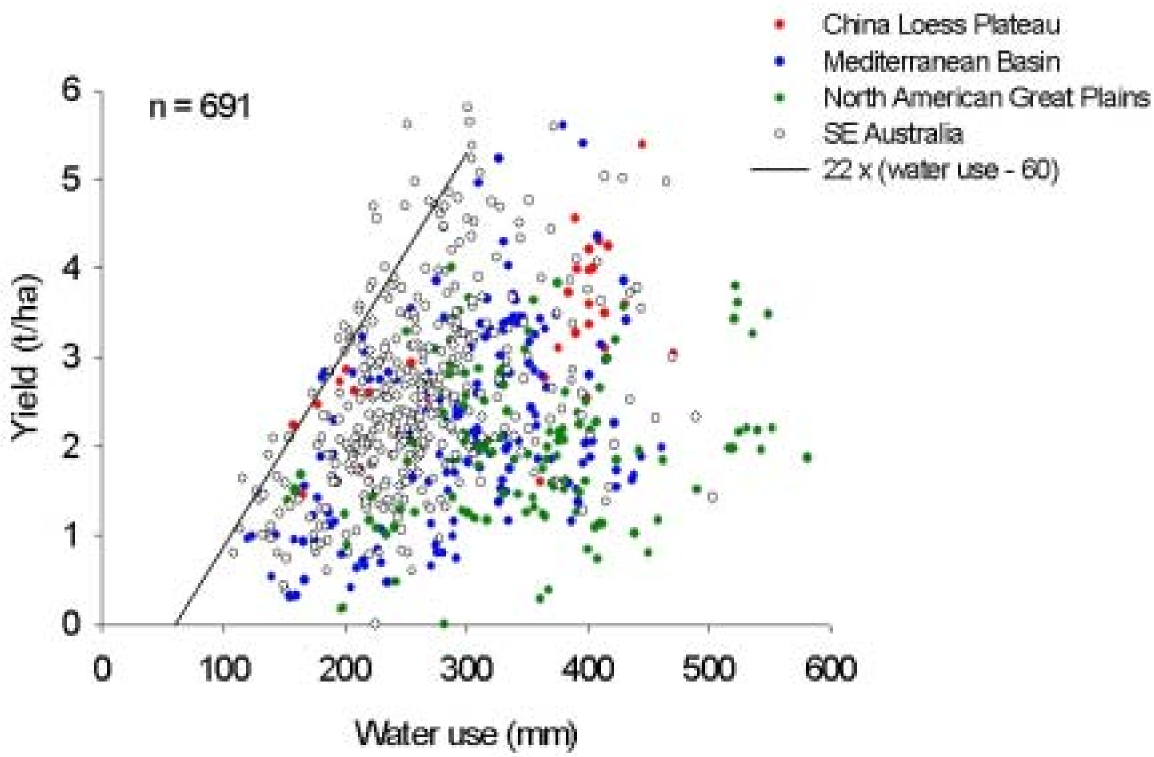


Figure 2. Yield of wheat as function of the amount of water evaporated and transpired (Source: Sadras and Angus, 2006)

Table 3. Units and their values for indicators of agricultural water productivity.

Indicator of agricultural WP	Units	Indicator value	
		Bhakra	Chishtain
Cropped area	10^3 ha	2945.0	103.8
Wheat yield	ton/ha	2.3	1.4
Rice yield	ton/ha	3.0	2.1
SGVP	US$/ha	782.7	413.3
Wheat yield per unit Et	kg/m^3	1.1	0.6
SGVP per gross inflow	SGVP/Gross inflow	0.12	0.06
SGVP per available water for irrigation	SGVP/AW irrigation	0.15	0.06
SGVP per process consumption	SGVP/ETa	0.17	0.07

- Select units for investigation, where sufficient water supply data exists
- Estimate gross irrigation inflows

3. Obtain and spatially interpolate rainfall data. Using secondary data, determine typical values of effective rainfall (that retained in the root zone or as surface storage in the case of rice)

4. Obtain canal flow data and determine seasonal surface water supply. Where flow data are not generally available at lower levels of the distribution network, it is possible to develop and apply disaggregation techniques to estimate the net local supplies from canal head flows (Ahmad and Bastiaansen, 2003)
5. Survey groundwater pump locations, capacities and average operating hours to determine groundwater supplies.
    - Where necessary, apply more advanced procedures to estimate net groundwater contribution (see PhD thesis by Ahmad, 2002), using remote sensing and soil-plant-water models.
6. Estimate Et_a using SEBAL for each crop season (Droogers and Kite, 2001). Disaggregate Et_a by cropping system.
7. Calculate land productivity (LP) in terms of GVP and gross margin.
8. Calculate water productivities (WP), with respect to total supply and Et_a:
    - Physical production (kg)
    - Gross value (SGVP)
    - Gross margin
9. Identify innovative water use practices where WP is low but LP is high and vice versa.
10. Calculate water productivity at larger scales of irrigation system and basin, using the depleted and process fractions of water supply (Molden *et al.*, 2001)
11. Determine system and basin average WP across all agricultural uses.

Livestock systems

Peden *et al.* (2002, Figure 3) illustrates the complexity of accounting for water use in livestock systems in Africa.

Multiple benefits of livestock systems include meat, milk, hide/wool, draught power, and drought protection. These benefits will be realized within complex farming system at different times (e.g. draught power is required for ploughing; the sale of animals to help buffer incomes is expected to occur only occasionally) and space (animals are moved large distances between grazing and between grazing, fattening areas and markets). Evaluating the transferred benefits within such systems is consequently difficult, and would require an estimate of net gain for the area for which water consumption is estimated.

Consumption of water occurs both directly through stock watering or making downstream water non-utilizable through pollution and indirectly through the production of feed as crop, sown pasture or as rangeland. In rainfed farming systems, grain is only one output of value to the farmer – others include green fodder and dry fodder (straw and stubble). In pastoral systems, the value of green biomass is optimal at a certain stage of growth and it is common to convert estimates of green and dry biomass into estimates of digestible dry matter (DDM). It may be possible to combine estimates of grain, green fodder and straw according to DDM basis, such that total production is expressed as:

$$\text{Production (kgDDM)} = \text{Grain (kgDDM)} + \text{Green fodder (kgDDM)} + \text{Dry fodder (kgDDM)}$$

Hill and Donald (2003) present a commercialized method of using satellite remote-sensing to quantify digestible pasture feed over large areas.

It may be necessary to estimate marginal value to evaluate WP fully, since it is uncertain whether the water consumed by pasture would be more productive if used elsewhere? Certainly the low stocking densities of rangeland will present low benefit per m^3 Et. The marginal value of pasture or rangeland vegetation is realized only when the feed resource is accessed by animals. Peden *et al.* (2002) examine options for alternative routes of water in livestock systems.

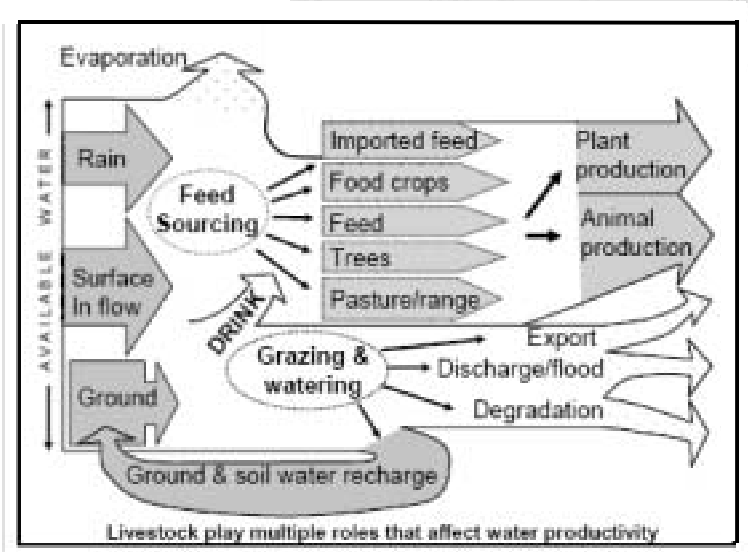


Figure 3. Framework for improving water productivity of livestock (From Peden *et al*., 2002

Fish production systems

There are few accurate assessments of the economic value of fisheries for most parts of Africa, Asia and Latin America (LARS2, 2003; Neiland, 2003). Furthermore, the special contribution of fisheries to food security and livelihoods is poorly represented in official statistics.

Valuation of benefits from fisheries

Methods to evaluate the full range of benefits from fisheries and aquatic resources are summarized by Bené and Neiland (2003) according to the following categories. These are specifically intended to address the complex issues associated with changes to fisheries and aquatic resources:

1. Conventional economic analysis
    - Economic efficiency analysis. Seeks actions which maximize social welfare in comparison with costs.
    - Total economic value. Acknowledges use and non-use values (see Figure 4).
2. Economic impact analysis: Assesses effect on specific variables
3. Socio-economic analysis: Distributional analysis of winners and losers from changes
4. Livelihood analysis: Broader analysis of multiple attributes that support sustainable livelihoods

Demand for water by fisheries

Baran *et al.* (2001) related fish catches to water levels in the Tonle Sap river in the Mekong basin, calculating a loss of between 2500 and 5000 t of 'Dai' fish catch for each drop of 1 m in the average October levels of the river. The assessment of the denominator (water required to achieve a given outcome) for fisheries and aquatic resources is more complex than consumptive uses by crops, not least because – given the complex life cycles of both fish and their feed - several years' measurement are required to determine the actual requirement. Welcomme (2001), working in the Niger, concluded that at least 14 years are required to evaluate the impact of low flows on fish stocks. See Dugan *et al* (2005) for more details.

Several issues are relevant to the demand for water by fisheries:

- River fisheries require substantial non-consumptive volumes of water to provide suitable environments for growth and breeding.

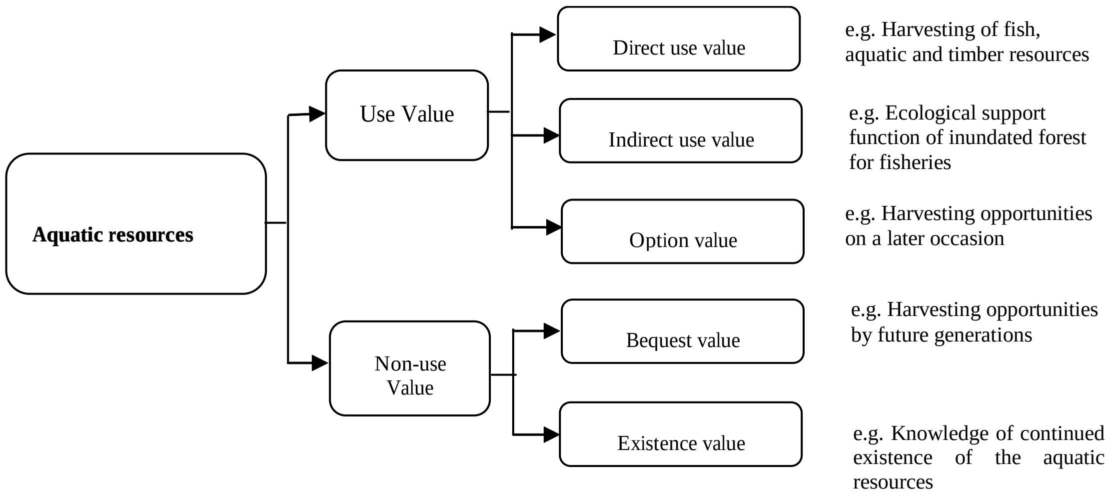


Figure 4. Total economic value and valuation methods (from Barbier *et al.*, 1997)

- There are opportunities for dual-use of irrigation infrastructure for fisheries (integrated agriculture-aquaculture - IAA), which can provide substantial supplements to both incomes and food security (Renwick, 2001).
- Development of rice-fish culture can significantly increase income and soil fertility in deep flooded paddy rice, without increasing water consumption. However, these gains have to be offset against increased cost of buying more water, especially if it is priced at its real cost to encourage more efficient water use.

Direct consumption of water by aquaculture occurs through evaporation and seepage. The former can be estimated from data of pan evaporation over the time required to produce a given weight of fish. For example, Brummett (2002) showed that integrated aquaculture in Malawi produced up to 264g/m^2 of footprint, approximating to evaporative consumption of between 0.2 and 0.7 m^3 of water for a 100 day production cycle (1.3 to 0.38 kg/m^3). This figure needs to be evaluated in relation to the price of fish products, which are normally readily available for traded products, and other costs of production that can be quite high. Impacts of intensive aquaculture on downstream water quality should also be considered.

Tree systems

Benefits from tree-based systems include both timber and non-timber products. Timber products are evaluated as m^3/ha, or $/ha. Non-timber forest products comprise a wide array of animal and plant products, often of particular value to the poorest people that live in or on the margin of forests. Like fish resources, these tend to be under-valued by conventional economic analyses. It is possible that evaluation techniques similar to those used for fisheries could be used.

With respect to consumptive water use, a huge literature exists of forest hydrology, including some more recent evaluations that question the hydrologic benefits routinely attributed to forests (see Bruijnzeel *et al.*, 2006, Mulligan and Burke, 2005). Space does not permit review of the methods of evaluating the scale of positive and negative hydrologic effects of forests.

Multi-scale estimation of WP

We envisage WP will be estimated at three scales[1]:

[1] Given the complexity of this subject, we propose it as the first of a series of technical papers to be developed during the life of the Basin Focal Projects of the Water and Food Challenge Program.

- Whole basin estimation of WP: Coarse-resolution estimation of WP using readily-available productivity data at national scale or administrative district level. Whole-basin estimates of well-being derived from agriculture may be approximated from readily available data of crop production, rural population, the extent to which basic needs are met, the proportion of the population engaged in agriculture, etc., and compared with water consumption using Molden's (1997) water accounting methods. While useful for broad scale estimation, this will not provide the detailed insight necessary for further analysis.
- Small-area estimation of WP: Detailed estimation of WP is envisaged from small case study areas, where these exist. These will produce high-resolution crop, fisheries and livestock productivity/income data, which can be combined with detailed estimates of water balance. Such studies will provide valuable detailed insight into variations of WP within farming systems, and of the hazards and limitations that constrain increases in WP. Where reasonable, these estimates could be used to represent the WP of farming systems.
- Aggregated estimates of partial WP: Having estimated partial WP for contrasting disaggregated agricultural systems, it is necessary to consider how to estimate WP for aggregated farming systems at the sub-basin level or, to provide a detailed picture over whole basin or sub-basins. The following approaches are offered for consideration:
- Classification into sub-units: Sub-divide the area into *n* parcels of *i* classes, defined according to land use, agroclimatic zone or other classification. Aggregate individual estimates of WP for *n* land uses in a single measure for a larger area as "($WP_i.A_i$). This approach may work well for small or moderate areas, for which reasonably secure estimates exist of each WP. For larger areas, the approach is likely to prove difficult because:
- Many areas are likely to have missing data;
- Different land uses may use contrasting valuation systems;
- Estimation in some land uses will be seriously affected by seasonal variation and
- Spatial resolution will vary between different land uses, hence apparently equivalent land units will contain different degrees of uncertainty.
- 'Hot-spot' approach: Broad estimates of WP are offered, for regional comparison, supplemented by more detailed information about specific areas known to be of particular interest.
- An integrated approach, whereby coarse-resolution estimates of WP are used as a 'background' for overlays of more detailed estimates, resolved according to known variations of land use, agro-ecological zone, terrain position, erosion intensity or other factor that has a known (if approximate) association with WP. Coarse resolution and detailed estimates of WP may be combined using a probabilistic Bayesian Network approach (see Lacave and Diez, 2000).

References

Ahmad, M.D. 2002. Estimation of net groundwater use in irrigated river basins using geo-information techniques: A case study in Rechna Doab, Pakistan. Ph.D. Thesis, Wageningen University, the Netherlands. http://www.gcw.nl/dissertations/3334/dis3334.pdf.

Ahmad, M.D. and Bastiaanssen, W.G.M. 2003. Retrieving soil moisture storage in the unsaturated zone from satellite imagery and bi-annual phreatic surface fluctuations. *Irrigation and Drainage Systems* 17:141-161.

Ahmad, M.D., Bastiaanssen, W.G.M. and Feddes, R.A.. 2005. A new technique to estimate net groundwater use across large irrigated areas by combining remote sensing and water balance approaches, Rechna Doab, Pakistan. *Hydrogeology Journal* 13:653-664

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements.* FAO Irrigation and Drainage Paper 56. FAO, Rome. ISBN 92-5-104219-5

Baran, E., van Zalinge, N. and Bun, N. P. 2001. *Analysis of the Cambodian Bagnet ("Dai") fishery data*. ICLARM, Penang, Malaysia, Mekong River Commission Secretariat and Department of Fisheries, Phnom Penh, Cambodia.

Barbier, E. B., Acreman, M. C. and Knowler, D. 1997. *Economic valuation of wetlands: a guide for policy makers and planners*. Ramsar Convention Bureau, Gland, Switzerland. ISBN 2-940073-21-X

Béné, C. and Neiland, A. E. 2003. Contribution of inland fisheries to rural livelihoods in Africa: Empirical evidence from the Lake Chad Basin areas. In: Welcomme, R. and Petr, T. (eds.) *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries, Volume II*. pp. 67-77. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. RAP Publication 2004/17.

Bouman, B. 2006. A systems approach to the analysis of crop water productivity. *Agricultural Systems.* In review.

Bruijnzeel, L.A., Burkard, R., Carvajal, A., Frumau, A., Köhler, L., Mulligan, M., Schellekens, J., Schmid, S. and Tobón, C. 2006. DfID Project R7991 Final Technical Report. 31 January 2006.

Brummett, R., 2002. Realizing the potential of integrated aquaculture: Evidence from Malawi. In: Uphoff, N. (ed.) *Agro-ecological Innovations—Increasing Food Production with Participatory Development.* Earthscan Publications, Sterling, Virginia, pp. 115–124.

Davis, J. 2003. *Choosing a Method for Poverty Mapping*. FAO, Rome. ISBN 92-5-104920-3. URL: ftp://ftp.fao.org/docrep/fao/005/y4597e/y4597e00.pdf.

Dawes, W. and Hatton, T.J. 1993. TOPOG-IRM. 1. Model Description. CSIRO Technical Memorandum 93/5. CSIRO, Australia.

Díaz Nieto, J., Cook, S., Jones, P. and Skees, J. 2006. Developing a method of site-specific drought insurance for bean farmers in Honduras. *Research Journal on Microfinance and Development* (In press)

Droogers, P. and Kite, G., 2001. *Estimating Water Productivity at Different Spatial Scales using Simulation Modeling*. Research Report 53. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Dugan, P., Dey, M.M. and Sugunan, V.V. 2005. Fisheries and water productivity in tropical river basins: Enhancing food security and livelihoods by managing water for fish. *Agricultural Water Management.* In press.

Falkenmark, M. and Rockström, J. 2004. *Balancing Water For Humans And Nature: A New Approach In Ecohydrology.* Earthscan, London, UK.

Farber, S.C., Costanza, R. and Wilson, M.A. 2002. Economic and ecological concepts for valuing ecosystem services. *Ecological Economics* 41:375–392

Groenfeldt, D. 2003. The future of indigenous values: Cultural relativism in the face of economic development. *Futures* 35:917-929.

Hameed, T. and O'Neill, R. 2005. River Management Decision Modelling In Iqqm. Presented at MODSIM 2005 Conference, Brisbane. URL: http://www.mssanz.org.au/ modsim05/papers/hameed.pdf

Hill, M.J. and Donald, G.E. 2003. Estimating spatio-temporal patterns of agricultural productivity in fragmented landscapes using AVHRR NDVI time series. *Remote Sensing Environment* 84:367-384.

Hill, H. and Tollefeson, L. 1996. Institutional questions and social challenges. In: Pereira, L.S., Feddes, R.A., Gilley, J.R. and Lesaffre, B. (eds.) *Sustainability of Irrigated Agriculture.* pp. 47-59. NATO ASI Series. Kluwer, Dordrecht.

Hoogenboom, G., Jones, J.W., Porter, C.H., Wilkens, P.W., Boote, K.J., Batchelor, W.D., Hunt, L.A. and Tsuji, G.Y. (eds.) 2003. *Decision Support System for Agrotechnology Transfer Version 4.0. Volume 1: Overview.* University of Hawaii, Honolulu.

Hussain, I., Turral, H., Molden, D. and Mobin-ud-Din, A. 2005. Measuring and enhancing the value of agricultural water in irrigated river basins. *Irrigation Science Journal* (Submitted.)

Jones, P.G., Thornton, P.K., Díaz, W., Wilkens, P.W. and Jones, A.L. (2002). MarkSim: a computer tool that generates simulated weather data for crop modeling and risk Assessment: Version 1. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia.

Kjine, J.W., Barker, R. and Molden, D. (eds.) 2003. *Water Productivity in Agriculture.* CABI, Wallingford.

Kozanayi, W. 2002. The Use of Informal Institutions and Social Networks to Access and Manage Water Resources in a Semi-Arid Area in Zimbabwe. URL: http://www.ictp.trieste.it/~eee/files/WP2%20%20Kozanayi.pdf

Lacave, C., and Diez, F. J. 2000. *A Review of Explanation Methods for Bayesian Networks.* Technical Report IA-2000-01, Dept. Inteligencia Artificial, UNAD, Madrid.

LARS2. 2003. Summary conclusions. In: tatement and recommended actions. In: Welcomme, R. and Petr, T. (eds.) *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries, Volume I*. pp. VII-X. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. RAP Publication 2004/16.

Linacre, E.T. 1977. A simple formula for estimating evaporation rate in various climates, using temperature data alone. *Agricultural Meteorology* 18:409-424.

Maxwell, S. 1999. *The Meaning and Measurement of Poverty*. ODI Poverty Briefing, ODI, UK. URL: http://www.odi.org.uk/publications/briefing/pov3.html

Molden, D. 1997. *Accounting for Water Use and Productivity*. SWIM Paper 1. System-Wide Initiative for Water Management. International Water Management Institute (IWMI), Colombo.

Molden, D., Sakthivadivel, R. and Habib, Z. 2001. *Basin-Level Use and Productivity of Water: Examples from South Asia*. IWMI Research Report 49. International Water Management Institute (IWMI), Colombo.

Mulligan, M. and Burke, S. 2005. *Global Cloud Forests and Environmental Change in a Hydrological Context*. DfID FRP Project ZF0216.

Murray-Rust, H. and Salemi, H.R. 2002. *Water Resources Development and Water Utilization in the Zayandeh Rud Basin, Iran*. -IAERI-IWMI Research Report.

Neiland, A. (ed.) 2003. *Valuation of tropical river fisheries: A global review*. Report for the WorldFish Center, Penang, Malaysia.

Oweis, T., and Hachum, A. 2003. Improving water productivity in the dry areas of West Asia and North Africa. In: Kijne, W.J., Barker, R. and Molden, D. (eds.) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. pp. 179-197. CABI, Wallingford.

Peden, D., Tadesse, G. and Mammo, M. 2002. Improving the Water Productivity of Livestock: An Opportunity for Poverty Reduction. URL: http://www.ilri.org/publications/cdrom/integratedwater/iwmi/Documents/Papers/Don.htm. Accessed 18 May, 2006.

Pracilio, G., Asseng, S., Cook, S.E., Hodgson, G., Wong, M.T.F., Adams, M. and Hatton, T. J. 2001. Estimating spatially variable deep drainage across a central-eastern wheatbelt catchment, Western Australia. *Australian Journal of Agricultural Research* 54:789–802.

Renwick, M.E. 2001. *Valuing Water in Irrigated Agriculture and Reservoir Fisheries: A Multi-use Irrigation System in Sri Lanka*. Research Report 51, International Water Management Institute (IWMI), Colombo, Sri Lanka.

Rockström, J., Barron, J. and Fox, P. 2003. Water productivity in rainfed agriculture: Challenges and opportunities for smallholders farmers in drought-prone tropical ecosystems. In: Kjine, J.W., Barker, R. and Molden, D. (eds.) *Water Productivity in Agriculture*. pp. 145-162. CABI, Wallingford.

Rockström, J., Gordon, L., Folke, C., Falkenmark, M. and Engwall, M. 1999. Linkages among water vapor flows, food production, and terrestrial ecosystem services. *Conservation Ecology* 3:5. [online] URL: http://www.consecol.org/vol3/iss2/art5/

Sadras, V.O. and Angus, J.F. 2006. Benchmarking water use efficiency of rainfed wheat in dry environments. Australian Journal of Agricultural Research 57(8) (In press).

Sakthivadivel, R., Fraiture, C.D., Molden, D. J., Perry, C. and Kloezen, W. 1999. Indicators of land and water productivity in irrigated agriculture. *International Journal of Water Resources Development* 15:161-179.

Smakthin, V., Revenga, C. and Doll, P. 2004. Taking into account environmental water requirements. In: *Global-Scale Water Resources Assessments. Comprehensive Assessment Research Report 2*. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Stoorvogel, J., Antle, J. and Crissman, C. 2004. Tradeoff analysis in the northern Andes to study the dynamics in agricultural land use. *Journal of Environmental Management* 72:23–33.

Turner, K., Georgiou, S., Clark, R., Brouwer, R. and Burke, J. 2004. *Economic Valuation of Water Resources in Agriculture: From the Sectoral to a Functional Perspective of Natural Resource Management*. FAO Water Reports - 27. ISBN: 9251051909.

Welcomme, R.L. 2001. *Inland Fisheries: Ecology and Management*. Fishing News Books. Blackwell Science, Oxford, UK.

Wolf, A.T., Yoffe, S.B and Giordano, M. 2003. International waters: identifying basins at risk. Water Policy 5: 29–60