Producing more food with less water in a changing world: assessment of water productivity in 10 major river basins

Xueliang Cai \(^a\), David Molden \(^b\), Mohammed Mainuddin \(^c\), Bharat Sharma \(^d\), Mobin-ud-Din Ahmad \(^c\) & Poolad Karimi \(^b\)

\(^a\) International Water Management Institute, Southern African Office, Pretoria, South Africa
\(^b\) International Water Management Institute, Colombo, Sri Lanka
\(^c\) Commonwealth Scientific and Research Organization (CSIRO) Land and Water, Canberra, Australia
\(^d\) International Water Management Institute, New Delhi, India

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International Water Management Institute, Southern African Office, Pretoria, South Africa; International Water Management Institute, Colombo, Sri Lanka; Commonwealth Scientific and Research Organization (CSIRO) Land and Water, Canberra, Australia; International Water Management Institute, New Delhi, India

This article summarizes the results of water productivity assessment in 10 river basins across Asia, Africa and South America, representing a range of agro-climatic and socio-economic conditions. Intensive farming in the Asian basins gives much greater agricultural outputs and higher water productivity. Largely subsistence agriculture in Africa has significantly lower water productivity. There is very high intra-basin variability, which is attributed mainly to lack of inputs, and poor water and crop management. Closing gaps between “bright spots” and the poorly performing areas are the major tasks for better food security and improved livelihoods, which have to be balanced with environmental sustainability.

Keywords: agriculture; basins; food security; livelihood; water productivity

Introduction

The concept of water productivity

The world is under great pressure to feed nine billion people by 2050. Total evapotranspiration (ET) from global agricultural land could double in the next 50 years if trends in food consumption and current practices of production continue (de Fraiture et al. 2007). With increasing demand from non-agricultural sectors and the uncertainties in water management brought about by climate change, the agricultural sector in many areas will get less water in the future (Bakkes et al. 2009). Together, the increasing demand for water for food production and the limits of the availability of water resources suggest that agriculture must produce more food with less water, that is, make more productive use of water resources (Cai and Sharma 2010).

Water productivity (WP) measures how the system converts water, together with other resources, into goods and services. It is defined as the ratio of net benefits from crop, forestry, fishery, livestock and other mixed agricultural systems to the amount of water used in the production process (Molden et al. 2010). The benefits can be measured with various terms including physical mass (kilogram), economic value (monetary) and nutritional value (calorie). The water input, denominator in the WP equation, also has a set of choices depending on the purpose of the examination and the availability of data. For
example, irrigation diversion, gross/net inflow, evapotranspiration and precipitation can all be used to calculate WP indicators. These variations give WP assessment flexibility and robustness as a tool to measure efficiency of water use.

WP indicators enable performance assessment and comparison for better water management, which is driven by water scarcity and increasing food demand (Cook et al. 2006, Ahmad et al. 2009a). Different WP indicators enable different stakeholders to examine water-use performance according to their specific interests. For example, WP as expressed in kg/m$^3$ of irrigation diversion might be of interest to an irrigation manager, while WP in US$\text{/m}^3$ of ET is more interesting to a basin development agency that is concerned with overall water consumption and the outputs generated. A water resources planner might look at the difference between kg/m$^3$ irrigation diversion and kg/m$^3$ ET to assess how well irrigation water is managed (Molden et al. 2007). With increasing problems of water scarcity, the food and other manufacturing industries have also started measuring the water required to produce a unit of output, which is termed “water footprint”, for example, water footprints of milk, coffee or palm oil production (Hoekstra et al. 2009).

The WP indicators need to be used with caution, however, especially when making cross-system comparisons. The WP concept is more relevant in water-scarce regions where increased production is constrained by water. WP values are affected by many factors including natural and management conditions. They are better understood in conjunction with specific system settings, for example, whether it is a water-abundant or water-scarce area; whether WP is constrained by yield or water use; whether it is an irrigated or a rain-fed system. WP is scale dependent, which is related to specific geographic extents as well as the types of farming systems involved. The interpretations are thus restricted by the boundary conditions. As WP has variable forms, the user needs to make sure to use the same form when making intra- (or inter-) system comparisons.

**Assessment of basin water productivity: the implications for livelihood, food security and sustainable development**

Holistic understanding of water management needs to examine issues at large scales such as a whole river basin. Agricultural water management has been traditionally organized around farming and irrigation systems. Hydrological processes are often more complex because of extensive interactions between water, ecosystems and people. Control and use of water upstream often impacts downstream users. In water-rich basins the impact might be in terms of water quality alone, while in water-scarce basins both quality and quantity might be affected. Full water accounting is required for integrated water management within the confines of the natural basin boundary (Turner et al. 2009).

Basin WP has important implications for regional food security and livelihoods, especially in places where there is poverty and crop production is low. Improved WP means more food, more income, less vulnerability to risks, and possibly less water used. Improving WP may leave more water for other sectors to produce more, which in turn contributes to regional development. Africa withdraws less than 4% of its renewable water resources for agriculture (Hanjra and Gichuki 2008). Lack of inputs such as land preparation (energy), seeds, fertilizer, pesticides and irrigation water limit the opportunity to increase productivity. Increasing water productivity through higher yields and improved water use helps to enhance crop production, generate and stabilize income, boost employment, reduce consumer prices and reduce costs. Mixed agricultural systems that include crops, livestock and fisheries help to distribute risks and maximize benefits from limited water resources (Ahmad et al. 2009b, Mainuddin and Kirby 2009). Cash crops are efficient
in reducing poor communities’ vulnerability to natural disasters such as droughts (Mertz et al. 2005).

The importance of livestock and fisheries is often underestimated. At the global level, livestock is responsible for around 20% of agricultural water ET (de Fraiture et al. 2007). With the changing diet of a wealthier population, consumption of milk, meat and fish is projected to double by 2050. Both livestock and fish can be part of integrated water management systems, with less additional water required for fish and more land management for livestock.

Gains in WP need to be balanced with environmental sustainability. Environmental degradation has emerged as a severe problem in several of the world’s largest river basins such as the Yellow and the Indus-Ganges (Singh and Sontakke 2002, Economy 2004). Non-point pollution from agriculture is a major threat to the health of rivers (Carpenter et al. 1998), and over-exploitation of limited water resources, especially groundwater, is another (Rodell et al. 2009). Wetlands have been diminishing at a fast pace, and so have forests. Sustainable development needs to take account of the environmental consequences of the exploitation of basins’ water resources. In cases where the volume of water is obviously insufficient, actions need to be taken to balance agricultural gains and environmental sustainability (Molden et al. 2010).

**The water productivity assessment across river basins**

Assessment of WP is a key procedure to link basin social and physical settings, water management and agricultural production. As part of the Basin Focal Projects (BFP) of the Challenge Program on Water and Food (CPWF), assessments of WP were carried out in 10 river basins with different physical and social settings: the Yellow River in China, the Mekong in Southeast Asia, the Indus-Ganges in South Asia, the Karkheh in Iran, the Nile in eastern Africa, the Limpopo in southern Africa, the Niger and the Volta in western Africa, the São Francisco and a collection of basins in the Andes in South America.

The 10 river basins are at different development stages and have distinct differences in their social and physical settings. They are located on three continents in regions ranging from humid to semi-arid. The contribution of agriculture to gross domestic product (GDP) varies from 6.5% in the Limpopo to more than 50% in the Mekong, Nile, and Niger (Figure 1), and involves 23% to more than 90% of the basin population. The percentage rural poverty also varies widely, from 11% in the Yellow River to more than 70% in the Niger. The three Asian basins have the highest total and percentage rural population, closely followed by the African basins, but both are much lower in the Andes and the São Francisco. The contributions of agriculture to GDP and the incidence of poverty in the African basins are significantly higher than in other basins. Although the rural population in South American basins is relatively low, rural poverty is high. It is noteworthy that there is high variability in some transboundary basins where the characteristics of one country may skew the basin average.

Irrigation development is diverse in the 10 basins. The Indus-Ganges, with mean rainfall of 1250 mm, has by far the highest percentage of irrigated area (78%), followed by the Yellow with 45%. The São Francisco and the Volta have the lowest ratios of about 6% and 1% respectively. Maize is the dominant crop in commercial cultivation in most basins except the Indus-Ganges, the Mekong and the Niger. Wheat and rice are the dominant crops in the Yellow, Mekong, Indus-Ganges, Nile and Karkheh. The Niger, however, is dominated by millet and sorghum and the São Francisco by maize, beans and rice. Among these major crops rice usually requires heavy irrigation. Wheat is also intensively irrigated in the Yellow and the Indus-Ganges. Maize in Africa and South America is mostly rainfed.
The objectives of this paper are to examine the methodologies used in the assessments; to give an indication of water productivity across different locations of the world, and to draw inferences about the underlying reasons.

**Methodology overview**

There were various approaches, combining a range of datasets, used to assess WP, because the 10 basins have diverse social and physical settings with different levels of data availability. Crops dominate agricultural production and are the biggest water consumer, so we gave them more attention in WP assessment. In some basins, where livestock and fisheries are important contributors, we also included them. The basic equation to calculate WP is (Molden 1997):

\[
WP = \frac{Output \ derived \ from \ water \ use}{Water \ input}
\]  

(1)

The numerator, and particularly the denominator, were determined using various methodologies such as field experiments, (agro-) hydrological modelling, spreadsheet calculations and remote sensing. Datasets come from sources such as field monitoring, household surveys, official statistics, weather stations, remote-sensing imagery and literature review. We combined the datasets to make assessments of WP at various scales from the field, through sub-catchments, to the basin.

**Crop water productivity**

An important prerequisite to assess crop WP at the basin scale is to understand the cropping pattern/distribution, which is usually complex and dynamic. Land-use/land-cover (LULC) maps based on remote sensing provide pixel-level information on the distribution of agriculture. They help identify the distribution of crops and subsequently estimate crop production and water consumption (ET). Global-, regional-, and national-level LULC products were used to assess WP. These include GlobCover from the European Space
Agency (http://ionia1.esrin.esa.int/) in the Nile, moderate resolution imaging spectroradiometer (MODIS) continuous vegetation fields (www.landcover.org/data/vcf/) in the Andes, the global irrigated area map (GIAM) (http://www.iwmigiam.org) in the Indus-Ganges, and the South Africa national farmland boundaries in the Limpopo. Crop types are rarely distinguishable in large-scale LULC maps. However, a crop-dominance map, based on GIAM products and other LULC maps, was produced for crop-specific analysis (Cai and Sharma 2010).

There are a number of ways to assess crop production, the numerator in the WP equation. Gross value production (GVP) of crops was frequently used in the BFP basins to calculate the outputs of all crops. GVP was calculated by summing local market value of the different crops and converting them into US dollars for a constant year, which enabled comparisons across basins (Molden et al. 2003). Crop production was also converted into energy (calories) in the Volta Basin. Statistical data of cultivation and production for major crops, which differentiate well the spatial variation within basins, are usually available at the district level. Remote sensing is an effective technique to monitor crop condition and yield accumulation. Vegetation dry matter production was mapped in the Andes basins based on a time series from the Système Probatoire d’Observation de la Terre vegetation sensor (SPOT-VGT) data. The spatial and temporal distribution was then analysed against land-use maps to examine crop and pasture production. A method combining remote sensing and census data was developed to estimate yields of major crops at pixel level in the Indus-Ganges basins (Cai and Sharma 2010). This method maximizes the utilization of existing data from different sources, eases the often-seen gap between census and remote sensing, and produces pixel-based yield maps to depict the natural distribution of crop yields regardless of administrative boundaries.

There was a range of denominators used to assess WP in the BFP basins: potential ET, actual ET, rainfall, evapotranspirable water, irrigation diversion and gross inflow. Potential ET is the maximum water requirement, which can be calculated from the weather data that are available in every basin. Calculation of actual ET across large scales is more challenging but enables estimates of real agricultural water use. Water consumption was estimated using hydrological models: for example, water balance for the whole of the Nile and the Indus-Ganges was computed with water evaluation and planning (WEAP) system. Estimates of ET were provided by two-dimensional modelling, for example, the decision-support system for agrotechnology transfer (DSSAT) crop simulation in the Volta and a soil water balance model in the Mekong.

Remote sensing provides spatially explicit maps of ET, which avoids the complex hydrological processes on the ground. Several basins adopted remote sensing approaches to estimate ET including the surface-energy balance system (SEBS) in the Karkheh (Muthuwatta et al. 2010), the surface-energy balance algorithm for land (SEBAL) in the Nile (Mohamed et al. 2004) and the upper Indus basin (Ahmad et al. 2009a), and a simplified surface-energy balance (SSEB) model in the Indus-Ganges (Cai and Sharma 2010) and the Limpopo. While all three models are based on the principle of land-surface energy balance, SEBS and SEBAL derive most of the parameters from satellite imagery and require few ground data inputs. In contrast, SSEB combines ground-measured weather data and land-surface temperature measured by satellite. The grid-based maps allow analysis of water consumption across different spatial scales and patterns of land use.

Livestock

WP of livestock is the market value of meat, milk, eggs and other items, divided by water used to raise and maintain the animals. Previous estimates have shown that 1 kg of animal
products requires 1 to 20 m³ water (Molden et al. 2007). The water directly consumed by animals is tiny compared with the water required to produce their feed, which varies according to management practices and types of feed (for example, grassland or crop residues). Current assessments in the 10 basins focused more on production analysis using statistical data. In the Karkheh Basin, however, ET estimated from remote sensing for grazing land, including pasture and crop residues, were used to estimate water use (Ahmad et al. 2009b). A more rigorous approach was developed in the Nile Basin where animal production was linked to the quantity of feed and then to water required to produce it. While there were still a number of assumptions in the parameterization of these two approaches that need to be validated, they present new methods to examine livestock water consumption and productivity.

**Fisheries**

Fisheries, including capture fish and aquaculture, are also mostly reported based on analysis of production. In the Nile Basin, water balance of aquaculture ponds was monitored in the field and the impacts of dams and water quality on capture fish production assessed (Alemayehu et al. 2008). It was assumed that evaporation losses estimate the water used to produce fish, which, however, reflects only the climatic conditions but does not reflect the fish-farming practices. In the Niger Basin, the catch of capture fish is directly related to the amount of water available in river channels. In the inland delta area, fish production increases by 27.8 t for each increase of 1 m³/s in river flow. Case studies in the Gorai sub-basin (Bangladesh) of the Ganges collected primary data on water productivity in terms of weight, economic value, and drivers for different capture and aquaculture systems (Mustafa et al. 2010).

**Discussions on methodology**

The various techniques described above were used in the 10 river basins, giving WP with different numerators and divisors. Estimates of WP with same terms are directly comparable, for example, kg/m³ for major crops or GVP/m³ for all crops. Obviously, results are not comparable when the terms used are different. For example, kg/ET will give different results than kg/applied water. The term ET as the denominator has inherent strength at the basin scale because the hydrological processes are especially complex at large scale. The ability to assess ET (crop water consumption) directly allows the assessment of actual water use versus water inputs in different conditions of water availability.

Remote sensing has proved to be a promising approach in assessing WP. It provides information of actual water consumption while avoiding the complex ground hydrological processes. It enables analysis at sub-catchment level and down to the level of individual pixels, which is often more informative than arbitrary administrative levels. Maps based on this level of analysis enables assessment of the magnitude and variations in WP to pinpoint hot and bright spots, which can then be linked to factor analysis and assessment of potential performance. A major challenge is to produce maps of dynamic crop rotation, which are essential for explicit estimates of production and water use.

Remote sensing can readily be integrated with hydrological modelling, which simulates the processes of water flows on the ground, to assess agricultural WP. This process-based analysis provides better opportunities to study the nexus between water, interventions and the responses of the production system (for example, Roost et al. 2008, Kim et al.
The approach differs from monitoring by remote sensing alone, which only measures results (for example, yield and ET). Spatially explicit maps from remote sensing, when combined with the results of hydrological modelling at fine temporal resolution, strengthen the analysis. A further step is to use hydro-economic modelling, which allows comprehensive analysis of food security and income generation to support strategic decisions.

Assessment of WP for crops is relatively well developed compared with WP of livestock and fisheries, for which both the concept and methods need further development and validation. Livestock and fisheries are important contributors to food security and livelihood in rural communities (Béné and Friend 2009, Descheemaeker et al. 2009), yet there are still large gaps in identifying the water they consume. The difficulty comes from accounting the water required to produce feed, which comes from grazing land, crop residues and commercial grain-based products. Commercial feed also requires consideration of the trade in virtual water, which might go beyond the basin boundary. Water consumption by fisheries is even more complicated. The yield of capture fisheries is related to the volume of water in the watercourses (see above), but losses to evaporation occur regardless of the fish catch. Evaporation from single-purpose aquaculture pond can be treated as water consumed, as for crops. Water lost to seepage and percolation is likely to be available for further use downstream, so that evaporation is the appropriate measure of water use. In addition, however, and analogous to livestock, the water used to produce the fish feed also needs to be considered. Multiple-purpose fish ponds (for example, a rice–fish system) are more difficult since their operation is very flexible and their water use is highly dynamic. They are, however, important to the livelihoods of local communities hence should be included in overall agricultural WP assessment.

This discussion of methodology demonstrates the need to develop a standard framework to assess WP at the basin scale. In the absence of such a framework, it is difficult to compare results across sites, although agro-hydrological modelling together with remote sensing can help. The extension of agricultural WP to include livestock, fisheries, probably also agro-forestry, as well as other relevant outputs needs further development.

**Water productivity and its importance in the BFP basins**

**Agricultural productivity, water use and water productivity**

Yields of the major crops (maize, wheat and rice) vary both across and within basins (Figure 2). All three crops in the Yellow River basin have relatively high yields, although not the highest for maize and rice. The yields for the Nile in Egypt are very high for all three crops, although low yields elsewhere reduce the Nile’s overall figures. The Indus-Ganges basins are the most populous and have the most intensive cultivation, but have relatively low yields overall for both rice and wheat, which are the major sources of food and income.

There is large intra-basin variability in all the basins. The average yield of maize in the Limpopo is 3.6 t/ha. While the irrigated commercial farms yield as high as 9 t/ha, the large area of subsistence farms, which are threatened by frequent droughts and crop failure, yields less than 2 t/ha. The Indian states of Punjab and Haryana, the “bright spots” in the Indus-Ganges basins, yield more than double elsewhere. The highest yields of rice among all BFP basins are in the Nile Basin, because of the very high yields in the delta in Egypt. Elsewhere in the basin, including most of Ethiopia and Sudan, yields are very low. There is similar variability in the Mekong Basin, where yields are high in the delta, but low in Cambodia and northeast Thailand.
WP values in terms of GVP divided by ET are available for some of the basins, and vary widely between them (Table 1). For each m\(^3\) water consumed, irrigated crops in the Karkheh generate US$0.22, the Indus-Ganges US$0.13, while the Mekong only US$0.012–0.059. Crop yields in the Karkheh are high, which accounts for the high crop WP. The Indus-Ganges basins also stand out with relatively high WP in spite of moderate yields, which contrasts with the Mekong Basin with higher yields but much lower WP. Both basins have more than 1200 mm/year rainfall, slightly higher in the Mekong. However, the cropping intensity in the Indus-Ganges is much higher so that there is a high demand for water for irrigation. Farmers are therefore under pressure to increase water-use efficiency. Crop diversification in the Indus-Ganges also contributes significantly to high WP. Cash crops such as millet, sugarcane and pulses greatly increase the economic returns to irrigation, and reduce the risks imposed by climate extremes such as floods and droughts (Sharma et al. 2010).

Several basins calculated WP in terms of ET for maize, rice and wheat separately so that we can compare the performance of the production systems of these major food staples. WP of maize is highest in the Yellow River (0.97 kg/m\(^3\)), followed by the Mekong (0.58 kg/m\(^3\)). Maize is the single dominant crop in the Limpopo but WP is very low at 0.14 kg/m\(^3\). For wheat, ET used in the Limpopo Basin is the yearly total while for other basins it is only for the wheat-growing season. However, even when we correct ET for the crop growth period in the Limpopo, which has pronounced seasonality, WP is still considerably lower than in the Yellow River. The difference is explained by the difference in yields of the mostly irrigated, high-yielding Yellow River compared with the rainfed, low-yielding Limpopo. The WP of wheat in the Yellow Basin is 48% higher than that of the Indus-Ganges, although wheat is a major crop in both basins. WP of rice showed less variation. The Indus-Ganges lead all the basins with 0.74 kg/m\(^3\), closely followed by the Yellow River (0.50 kg/m\(^3\)), the Mekong (0.43 kg/m\(^3\)) and the Nile (0.14–0.67 kg/m\(^3\)). Rice is an important component of regional food security in the Indus-Ganges and the Mekong and the areas of rice cultivation are much bigger than in any other basins.

Yields and WP of irrigated crops were compared with rainfed crops in some basins. As expected, irrigated crops yield much higher than rainfed crops in all cases, although WP showed different trends. In the Yellow River yields of maize were 3.7 and 3.0 t/ha.
Table 1. Water consumption and water productivity of the 10 BFP basins. Combined data for the latest years.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Water source</th>
<th>Cropland area</th>
<th>Precipitation</th>
<th>ETa</th>
<th>ETp</th>
<th>Crop productivity</th>
<th>Yields</th>
<th>As ET</th>
<th>Crop WP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>million ha</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>Crop types</td>
<td>t/ha</td>
<td>kg/m³</td>
<td>USS/m³</td>
</tr>
<tr>
<td>Yellow River</td>
<td>irrigated</td>
<td>7.5</td>
<td>452</td>
<td></td>
<td></td>
<td>wheat/maize/soybean/rice</td>
<td>3.7/5.3/</td>
<td>1.39/0.97/</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>irrigated</td>
<td>11.22</td>
<td>1254</td>
<td>416/299</td>
<td>610</td>
<td>rice/wheat</td>
<td>2.6/2.65/</td>
<td>0.74/0.94/</td>
<td>0.131</td>
</tr>
<tr>
<td>Mekong</td>
<td>irrigated</td>
<td>3.28</td>
<td>1516</td>
<td>657</td>
<td>1457</td>
<td>maize/soybean</td>
<td>3.0/1.4/</td>
<td>1.09/0.41/</td>
<td>–</td>
</tr>
<tr>
<td>Indus-Ganges</td>
<td>irrigated</td>
<td>11.22</td>
<td>1254</td>
<td>416/299</td>
<td>610</td>
<td>rice/wheat</td>
<td>2.6/2.65/</td>
<td>0.74/0.94/</td>
<td>0.131</td>
</tr>
<tr>
<td>Karkheh</td>
<td>irrigated</td>
<td>0.45</td>
<td>358</td>
<td>323</td>
<td></td>
<td>wheat/barley/maize</td>
<td>3.3/2.6/</td>
<td>7.4/ –</td>
<td>–</td>
</tr>
<tr>
<td>Nile</td>
<td>irrigated</td>
<td>5.5</td>
<td>563</td>
<td>554</td>
<td></td>
<td>maize/rice/wheat</td>
<td>8.9/5.6/</td>
<td>6.5/</td>
<td>–</td>
</tr>
<tr>
<td>Limpopo</td>
<td>irrigated</td>
<td>0.244</td>
<td>530</td>
<td>779b</td>
<td>1676</td>
<td>maize</td>
<td>3.6/</td>
<td>0.14</td>
<td>0.012</td>
</tr>
<tr>
<td>Niger</td>
<td>irrigated</td>
<td>0.075</td>
<td></td>
<td></td>
<td></td>
<td>rice</td>
<td>0.14–0.67/</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Volta</td>
<td>irrigated</td>
<td>0.036</td>
<td></td>
<td></td>
<td></td>
<td>millet, sorghum</td>
<td>1.0</td>
<td>0.1</td>
<td>–</td>
</tr>
<tr>
<td>São Francisco</td>
<td>irrigated</td>
<td>0.355</td>
<td></td>
<td></td>
<td></td>
<td>maize/sorghum/millet</td>
<td>1.3/1/0.9</td>
<td>0.15/0.1/0.08</td>
<td>–</td>
</tr>
<tr>
<td>Andes</td>
<td>irrigated</td>
<td>3.09</td>
<td>1835</td>
<td></td>
<td></td>
<td>banana/mango/coconut/grape</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>irrigated</td>
<td>10.88</td>
<td></td>
<td></td>
<td></td>
<td>maize/beans</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>irrigated</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>potato/maize/pasture</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Notes: a Actual ET of growth periods of major crops unless specified; b Actual ET of a calendar year; c It is assumed the three major crops in the Egypt are fully irrigated and elsewhere are rainfed.
irrigated and rainfed respectively. In contrast, WP of irrigated maize is 0.97 kg/m³ compared to rainfed 1.09 kg/m³. Patterns in the Karkheh were different. Both the yields and WP of rainfed crops are lower than irrigated crops, which suggest that there may be several factors contributing to water productivity. In assessing WP performance, WP values have to be considered in relation to the specific basin setting and comparisons can only be made between the same settings.

There was wide spatial variability of crop WP within each of the basins. The coefficient of variation (CV) of WP for maize, rice and wheat in the four Asian basins varied mostly from 0.3 to 0.5, with the extreme high of 0.7 for wheat in the Indus-Ganges and extreme low of 0.16 for rice in the Mekong. Higher CVs indicate higher levels of heterogeneity in the basin, suggesting greater chances to close the gap between the good and the poor performers. Figure 3 illustrates the magnitude and variations of crop WP in the Nile and Indus-Ganges basins. WP in the Indus-Ganges is greater than that of the Nile whose narrower range of WP lies within the broader variation of the Indus-Ganges. The intra-basin variability is also clearly demonstrated in the two pixel-based WP maps. There are bright spots in the upstream of the Indus and the delta of the Nile with average high WP of US$/m³ 0.19 and 0.20 respectively, which are 1.5 and 4.8 times of basin averages respectively. Understanding the reasons for these differences would both assess the potential for improvement and identify priority interventions in low-performing areas. We discuss this aspect in later in the paper.

Analysis of time-series data on crop production, water consumption and WP shows the temporal evolution of agricultural systems. Where time-series data were available, physical WP generally increased, though at different rates. Figure 4 shows the trend of ET, yield and WP of rice in the lower Mekong Basin 1995–2003. Yields have gradually increased while ET has decreased. As a result, WP for ET has increased 20% from 0.344 kg/m³ to 0.431 kg/m³. WP of rice in US$/m³, however, has declined significantly over this period. Markets have played an important role here. The farm gate price of rice has decreased from US$166/t in 1995 to US$126/t in 2003 (FAOSTATS,
ET, yield and water productivity of rice in the lower Mekong Basin. The data were normalized to 2003 values.

http://faostat.fao.org/site/570/default.aspx), with even greater inter-season fluctuations within this period. This means that the farmers’ gain from improved crop and water management has been offset by the market. In Bangladesh, WP of kharif (wet season) rice has always been lower than that of the rabi (dry season) rice. This is possibly due to the faster pace of adoption and deeper penetration of the high-yielding variety (HYV) technology and groundwater irrigation during the rabi season.

The importance of livestock and fishery production systems

Livestock and fisheries are important sources of farmers’ food production and income in the BFP basins. When we add data for livestock and fisheries to crops, the agricultural production changes dramatically. Figure 5 shows the time trend 1999–2004 of GVP of crops, livestock and aquaculture in Cambodia and Vietnam in the Mekong (Kirby et al. 2009). There are no reliable figures for capture fish except in 2000. Even without capture fish, livestock and aquaculture fisheries contributed 24–34% to the overall agricultural GVP in the basin in 2003/04. The rapid development of aquaculture ensured substantial improvement

Figure 5. The gross value production of crops, livestock, and aquaculture in: (a) Cambodia; and (b) Vietnam in the Mekong Basin. The dot indicates the addition of GVP of capture fish. Data were only available for 2000. Source: Kirby et al. (2009).
in agricultural production, especially in Vietnam where crop production remained static.
Results were similar in the Karkheh Basin, where livestock made a major contribution to WP (Ahmad et al. 2009b).

Contribution of WP to food security and livelihood

The contribution of agriculture to GDP ranges from 7% to 55% across the 10 basins. This contribution supports one billion people living in rural areas, which account for 72% of the total population of the 10 basins. More than 300 million people live below poverty lines as defined by the United Nations or the respective countries. The poor are overwhelmingly dependent on agriculture for their livelihoods.

Improved agricultural water productivity could significantly contribute to food security and livelihoods (Cook et al. 2009) of rural and city dwellers. Improved agricultural WP is possible through either increased production or reduced water use. When production is increased, either through higher yields or diversified crops, food security increases, and most likely the increment will be converted into higher income. Figure 6 illustrates the relation between revenue from land and crop WP of lime fruit at Buriti Vermelho, in the São Francisco Basin in Brazil. Higher WP is positively linked to higher income generated by the crop. When water is saved, the cost of its diversion, that is, labour, electricity and water fee, are reduced. The saved water will also contribute to downstream users for more agricultural production, recreation, or city uses, which overall contributes to regional development and livelihoods of all people in the basin.

Irrigation helps assure higher yields and water productivity. The Yellow, the Indus-Ganges, and the Karkheh basins are better equipped with irrigation and drainage facilities, farm machinery, plant breeding, pesticide control and other technologies than most other BFP basins. Consequently, production of agriculture is reliably sustained at higher levels. In contrast, the predominantly rainfed agriculture of the African basins is most vulnerable to droughts. With the exception of the large commercial farms in the South African part of the Limpopo, crop failure due to drought is common. Small-scale supplementary irrigation has been successful in the Indus-Ganges, Nile, Volta, Niger and Limpopo basins. The technology uses minimum water to help crops survive short dry spells and hence increase both crop production and water productivity (Sharma et al. 2010). Poor farmers with access to the technology are better protected from the hazard of drought.

![Figure 6](image)

Figure 6. The relation between land revenue and WP of lime fruit in Buriti Vermelho, São Francisco Basin.
Livestock and fisheries are also important components of food security and livelihoods. We have described their contribution to agricultural production in the Mekong Basin above. In the riparian countries of the Limpopo (South Africa, Mozambique, Botswana and Zimbabwe) livestock contributes 45% of agricultural production. In the lower reaches of the Ganges, Bangladesh produces 2.6 Mt of fish annually, which contributes 21% of the country’s total agricultural production. It provides more than 60% of the population’s intake of animal protein and is the second most important sector in export earnings. It employs 12.5 million people, most of whom are rural poor, and thereby makes a substantial contribution to poverty reduction. Livestock and fisheries offer more livelihood opportunities for the poorest farmers who have limited land or poor access to water and other inputs.

Towards improved water productivity for people’s livelihoods

Causes of variations and threats to water productivity

Land and water productivity varies widely both across and within basins. The Asian basins, Yellow, Mekong, Indus-Ganges and Karkheh have more productive farming systems than those in Africa and South America. There are many causes for the variation, some of which we discuss in this section, together with some of the threats to sustainable agriculture.

The level of socio-economic development has a big impact on agriculture. Hanjra and Gichuki (2008) suggested that, in most cases, the higher the contribution of agriculture to GDP the higher the incidence of poverty. In turn, this limits farmers’ capacity to increase inputs to agriculture, improve WP, and cope with climate extremes such as droughts and floods. The contribution of agriculture to GDP is slightly lower in Asia and highest in the Nile, Volta and Niger. The African basins mostly rely on rainfed agriculture with poor infrastructure, low inputs of fertilizer and irrigation, and consequently low crop yields and low crop WP. But the Limpopo and the Andes basins, which have the lowest contribution of agriculture to GDP, also have low agricultural and water productivity. The reason is that South Africa skews the mean because it is a relatively well-developed country with severe inequity of highly developed commercial agriculture juxtaposed with a large number of poor subsistence farmers. The latter, together with poor smallholders from other Limpopo countries are most vulnerable to the droughts that occur frequently.

Water stress is a determining factor for all basins. Water stress occurs either due to physical scarcity, poor access, floods or waterlogging. Water for crop production is a concern in most areas including the extremely water-scarce basins of the Yellow, the Limpopo and the Indus. Water scarcity has worsened over years and the trend will continue due to the competitive demand from the rapidly expanding cities. Access to water is another constraint. The basins in Africa and South America are not the driest, but overall they do have the poorest access to water. Lack of appropriate storage and diversion infrastructure exposes farmland to droughts. At the other end of the scale, waterlogging affects the Mekong, and downstream parts of the Ganges, Limpopo and the Andes basins. Waterlogging is largely due to shallow groundwater or excess rainfall, whose effects can be reduced by suitable drainage infrastructure and appropriate management of irrigation water.

Improved seed varieties, traction energy, fertilizers, pesticides and soil management are critical inputs for large areas of low productivity. Land degradation is often another serious problem. Tanner and Sinclair (1983) concluded that, where actual yields are less than 40–50% of the potential, the effects of non-water factors are more pronounced. Combined management of soil, water, plants and pests is required to overcome these limits and give yield increases (de Wit 1992, Deborah et al. 2010).
Often site-specific technologies are required to achieve better outputs from land and water. For example, maize in the downstream parts of the Limpopo often suffers from waterlogging, indicating a need for improved drainage. It might also be practical however, to change cropping patterns to include more tolerant crops. Rice is an important crop in Ningxia Province, upstream in the Yellow Basin. However, the increasing demand on water reallocation from downstream provinces has put pressure on farmers to reduce rice cultivation by 30% or more. In the Indian state of Punjab, rice irrigated with groundwater cannot by law be transplanted until the monsoon starts, avoiding high evaporation losses in the hot weather that precedes the monsoon. Monocrops are popular in the Indus-Ganges Plain for the convenience of supplying irrigation water and operation of farm machinery. In most other areas, however, crop diversification is important to improve overall land and water productivity and reduce risks. For example, the smallholder farmers in the Lao PDR have increased production of various upland crops while production of rice has remained static.

Access to well-functioning markets is central to determining the overall value of agricultural production and net returns to farmers. Although agriculture is often subsidized, markets often are not accessible to many farmers. Subsistence farmers in the Limpopo Basin are often obliged to sell their produce to big farmers, who have the resources and bargaining power to send it to distant markets (Rosemary and Johann 2009). In the Gazeira in Sudan, cotton is a mandatory crop financed and marketed by the government. It is increasingly grown at a loss as production falls because of the lack of incentives to the tenant farmers (Abdel Karim and Kirschke 2009). Price fluctuations have strong impacts on the value of agricultural crops regardless level of crop yields. For example, maize yields are similar in the riparian countries of the Limpopo Basin, but local market prices are widely different in each causing huge differences in GVP and consequently the returns to land and water. Figure 4, discussed above, shows that increases in crop yield and WP in the Mekong basin were totally offset by falls in the market price of rice. On the other hand, the minimum support price (MSP) of wheat and rice by the government of India provides good remuneration to the farmers but discourages them from diversifying into crops with lower water requirement (Joshi 2005).

Although there have been continuous efforts to enhance the efficiency of agricultural systems, new threats are emerging, among which environmental degradation and climate change are the two major concerns. As agriculture develops it almost certainly has negative impacts on the environment (Bakkes et al. 2009). But the externalities can be managed to different degrees. Agriculture withdraws and consumes water that could be otherwise beneficial to other users including the environment (Molden et al. 2010). In closed basins, where there is competitive demand for water, the environment is often the loser. Environmental flows, which are the minimum flows required to maintain the health of rivers, are often ignored (Smakhtin and Anputhas 2006). The Yellow River ceased to reach the sea in the 1990s. This is no longer the case, but the pressure of high demand for water keeps increasing. Although the national south-to-north water transfer project will deliver a good amount of water to the basin, it does not consider environment flows due to the very high cost of diversion. The Indus is another closed basin where both surface water and groundwater are over exploited, causing drastic declines in groundwater table, which threatens sustainability of the agricultural systems that depend on it. In these cases the broadly defined WP, including industry outputs, are increasing but at the expense of agricultural sustainability, which supports multi-billion rural populations.

For the limited quantity of water left in river channels and aquifers, water quality often becomes a major concern. A survey in the Yellow River in 2007 found that 33.8% of the river system registered worse than level V for water quality, which is classified as not
suitable for drinking, aquaculture, industry, or even agriculture (YRCC 2007). The Andes basins, due to their steep slopes, suffer from soil erosion in the upstream areas, which imposes another kind of water scarcity downstream due to loss of quality. In the Mekong Basin, water quality issues are more often confined to water-poor areas, for example, water pollution in the Tonle Sap, quality of groundwater in Northeast Thailand, and water salinization and acidification in the delta area of Vietnam (Kirby et al. 2009). In the lower parts of the Ganges Basin (West Bengal, Bangladesh), arsenic contamination of groundwater is widespread and is linked to its over-exploitation. Degradation of water quality is mainly caused by effluent from cities and rural households, but also from agriculture itself. Non-point-source pollution from agriculture is a major threat to water quality in areas of intensive irrigation, where it is often accompanied by high fertilizer inputs (FAO 1996). The severely degraded water quality that results threatens water supplies and consequently, water productivity.

Climate change is projected to have various impacts on agricultural production systems. In spite of forecasts that total rainfall may increase in some regions, the water available to agriculture will likely fall if water storage, diversion infrastructure, and management remain at their current levels (Backlund et al. 2008). More extreme climatic events, such as shorter and more intense rainy seasons and longer and more intense dry seasons will make agriculture, especially rainfed agriculture, more vulnerable, and hence reduce agricultural WP. The faster snow melt caused by increased temperature will increase flows in the river channels in the short term but in the longer term flows will change their seasonality as rain replaces snow in the headwaters. The glaciers of the Tibetan plateau and surrounding mountains that border South and East Asia will be significantly affected by global warming. The changes in this region could affect billions of people in the East, Southeast, South and Central Asia, many of whom depend on river diversion for irrigated agriculture.

Sea level rises will adversely affect the deltas, causing greater risks of floods and salt-water intrusion. It is estimated in the Mekong Basin more than one million people are expected to be affected by 2050 (Nicholls et al. 2007). Climate change will also have negative impacts on crop yields on a global scale as a result of shorter growth periods and lower soil moisture caused by increased temperatures and more uneven distribution of rainfall (Wheeler et al. 2000, Lobell and Field 2007). Crop water-use efficiency will decrease both because of lower yields as well as increasing evaporation from bare soil (Xiao et al. 2009). Figure 7 illustrates the sensitivity of runoff to climate change together with land-use change in the Andes basins, with the most sensitive regions indicated by the red circles. Although it is forecast that climate change will have an impact on agriculture and water management, more detailed studies on the effects of changed rainfall and particularly the impacts on runoff are required. Assessments of the impact of climate change on agriculture and agricultural water productivity is especially needed.

The rapid expansion of cities is also a potential threat to agriculture by diverting resources away from the agricultural sector. Cities are much more powerful in negotiating water reallocation (Molle and Berkoff 2009). They convert surrounding farmlands, which are usually favourable for cultivation with high agricultural productivity, into factories, settlements and roads. Cities also attract large numbers of rural youth. A survey in the Yellow River basin revealed that the average age of household heads increased from 42.7 years in 2004 to 50 years old in 2008, and women in the labour force increased from 62% to 78% respectively (Song et al. 2009). The rural areas are likely to face shortage of experienced male labour in the near future, which will potentially lead to poorer land and water management.
Figure 7. Sensitivity of the Andes to land use and climate change: What will happen by 2050 as we continue to push? (a) runoff sensitivity to tree cover change (% change in runoff per % change in tree cover); (b) runoff sensitivity to precipitation change (% change in runoff per % change in precipitation); (c) runoff sensitivity to temperature change (% change in runoff per % change in precipitation). Red circles indicate areas of particularly high sensitivity. Source: Mulligan et al. (2010).

**Potential for improvement**

We can look at the potential for improvement of water productivity in two steps: firstly through the comparison of “bright spots” and “hot spots” to identify visible yield gaps, and secondly through site-specific assessment of the biophysical potential. The second step involves local analysis based on solar radiation and soil of the region to explore water-fertilizer applications in conjunction with crop genetic innovations. This approach was successful in achieving the green revolution and still remains a major strategy to achieve the world’s long-term goal of food security. While agriculture in most of the developing world is still at a low level of management, however, the first approach provides a greater chance for improved agriculture performance in near future.

As described above, there is large variation in WP across basins as well as within basins. Crop WP from remote sensing at the pixel level provides explicit description of both the magnitude and the variation. The levels of WP for rice and wheat in the Indus-Ganges Basin are plotted in Figure 8. The CVs, 0.44 for rice and 0.70 for wheat, are much higher than those for the world (Zwart and Bastiaanssen 2004). This is because remote sensing captures every pixel in a basin, including extreme spots. The CV of wheat is much higher than that of rice, meaning water management of wheat is more diverse compared with rice. This is because there is little rainfall during the wheat-growing season and hence the crop depends on irrigation. Improving the irrigation management of wheat is probably the most urgent and easiest way to improve basin WP.

The potentials of rice and wheat are different, both in terms of magnitude and areas of focus. Water productivity generally increases with increasing yield (Figure 9). The “bright
Figure 8. The histogram distribution of WP values for rice and wheat.

Figure 9. Relations between (a) water productivity and yield and (b) yield and evapotranspiration of rice in the Indus-Ganges basins. Adapted from Cai and Sharma (2010).

The “bright spot” of the Indian Punjab clearly stands out in both plots (circled). The yields of the Punjab are so high that the slope of yield against ET changes from $S_3$ to $S_4$. The largest scope for improvement of rice in the region will be firstly to improve the low yield and low WP areas to match those that provide the $S_2$ trend. That is, to maintain yields with less consumption of water. The final target would be to increase the yield levels of all areas to “bright spot” values, during which the water consumption too will increase.

Such well-performing “bright spots” with higher crop yields, higher gross value of production and higher water productivity exist in every basin, for example, the Delta in the Nile and the centre-pivot irrigated commercial farms in the Limpopo. There are local constraints to prevent large areas from achieving the same, but clearly there is large scope for improvement.

**Implications for interventions**

Increasing agricultural WP can contribute to better food security and enhanced livelihoods, but requires addressing a number of institutional and technical issues amongst which is the need to avoid environmental degradation (Molden et al. 2010).

Bright spots identify sites where farm yields most nearly match the biophysical potential through a range of interventions, which may not be directly replicable but are indicative
of success. There are sites in every basin that have high yields, and often high WP. Molden et al. (2010) and Cai and Sharma (2010) conclude that further increasing yields and WP in these areas will be a long and gradual process, including innovations in plant breeding. A more pressing priority will be to increase the yields and WP of the large under-performing areas through tailored interventions.

Improving WP through better water management is central to the solutions for improved productivity. In rainfed systems, it is often the poor distribution of rainfall rather than the total precipitation that limits productivity (Sharma et al. 2010). On-farm conservative farming practices can reduce non-beneficial evaporation and increase soil water content. In irrigated systems, Molden et al. (2010) suggested that the general perception about the potential to save water is commonly overstated. This is especially true at the basin scale, where irrigation return flows are reused (Ahmad et al. 2007). Reliable, low-cost irrigation would enable more poor farmers to improve their productivity. Appropriate drainage systems can have major impacts on downstream lowland areas. Enhancing the level of water management together with management of soil, pests and diseases together could significantly improve WP of many agricultural systems.

Strategies to manage water better, together with other production resources, are different in different regions. In water-scarce situations, improving WP is critical to produce more food with less water. In water-rich areas, improvement of water productivity is not necessarily the target. Rather, it will be to produce as much as possible from limited land resources.

Agricultural sustainability is a key element to be maintained in the process of improving agricultural and water productivity. Over-exploitation of surface and ground water, as often seen in the Asian basins, leaves little water or low quality water for environment flows. These issues are often ignored by local stakeholders and few basins have the institutional capacity to deal with it (Giordano 2003). Localized institutions for sub-watersheds and basins covering broader social issues have to be established, which introduce tradeoffs between agriculture and the environment and include incentives and compensations.

Conclusions

Agricultural WP is a key indicator to link basin water resources and agricultural outputs, which sets a useful baseline for efficient agricultural water management. A holistic overview of agricultural production systems at the basin level can help to identify the issues that are relevant for informed policy making. Agricultural WP is important to regional food security as well as to farmers’ livelihoods. Increasing WP needs to consider the economic costs of doing so. While bright spots illustrate the potential for improvement, it might not be feasible to achieve same level of WP elsewhere in a cost-efficient way. Small-scale interventions, such as supplemental irrigation, are relatively easy to adopt with less investment, and could significantly improve agricultural WP.

The potential to save water is not as big as many think, but there is significant scope to improve WP. Different farming systems have different priorities in different locations. Markets play a key role in converting agricultural production to income. We note, however, the need to balance WP and environment.

The concept of WP has gone through various stages of development, and recently has been expanded to the basin context and to cover broad systems of agricultural production. However, methodology development is still a major issue for large-scale assessment of whole basins. Current assessment relies overwhelmingly on statistical data, which are variable in quality, the spatial scale is often poor and does not correspondent to hydrological
boundaries. Remote sensing is a powerful tool to estimate both crop production and consumptive water use. Basin-scale hydrological modelling also helps to study the processes of water cycling and to examine existing interventions. Combining the two provides greater opportunities to capture images of WP as well as understanding processes on the ground. WP for livestock and fisheries needs major development of both concepts and methodology. The key issue is to measure the actual water use, which can then guide potential interventions.

References


