10 World Water Productivity: Current Situation and Future Options

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Abstract

Water productivity is generally defined as crop yield per cubic metre of water consumption, including 'green' water (effective rainfall) for rain-fed areas and both 'green' water and 'blue' water (diverted water from water systems) for irrigated areas. Water productivity defined as above varies from region to region and from field to field, depending on many factors, such as crop patterns and climate patterns (if rainfall fits crop growth), irrigation technology and field water management, land and infrastructure, and input, including labour, fertilizer and machinery. In this chapter, we analyse water productivity at the global and regional levels through a holistic modelling framework, IMPACT-WATER, an integrated water and food model developed at the International Food Policy Research Institute (IFPRI). Scenario analysis is undertaken to explore the impact of technology and management improvement and investment on water productivity and to search for potentials in improving food security through enhancing water productivity. It is found that the water productivity of rice ranged from 0.15 to 0.60 kg m^{-3}, while that of other cereals ranged from 0.2 to 2.4 kg m^{-3} in 1995. From 1995 to 2025, water productivity will increase. The global average water productivity of rice and other cereals will increase from 0.39 kg m^{-3} to 0.52 kg m^{-3} and from 0.67 kg m^{-3} to 1.01 kg m^{-3}, respectively. Both the increase in crop yield and improvement in basin efficiency contribute to the increase in water productivity, but the major contribution comes from increase in the crop yield. Moreover, water productivity of irrigated crops, although higher than that of rain-fed crops in developing countries, is lower in developed countries.

Introduction

Producing enough food and generating adequate income in the developing world to better feed the poor and reduce the number of those suffering will be a great challenge. This challenge is likely to intensify, with a global population that is projected to increase to 7.8 billion in 2025, putting even greater pressure on world food security, especially in developing countries, where more than 80% of the population increase is expected to occur. Irrigated agriculture has been an important contributor to the expansion of national and world food supplies since the 1960s and is expected to play a major role in feeding the growing world population. However, irrigation accounts for about 72% of global and 90% of developing-country water withdrawals; and water availability for irrigation may have to be reduced in many regions in favour of

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rapidly increasing non-agricultural water uses in industry and households, as well as for environmental purposes. With growing irrigation-water demand and increasing competition across water-using sectors, the world now faces a challenge to produce more food with less water. This goal will be realistic only if appropriate strategies are found for water savings and for more efficient water uses in agriculture.

One important strategy is to increase the productivity of water (Molden, 1997; Molden *et al.*, 2001). Water productivity (WP) is defined as the physical or economic output per unit of water application. In this chapter, using a holistic water–food model, IMPACT-WATER, developed at the International Food Policy Research Institute (IFPRI), we assess the value of WP at both the regional and the global scale in a base year (1995), and project productivity to 2025 under plausible assumptions on food demand and supply and water demand and supply. Food production and consumption are examined simultaneously. The purpose of this chapter is to show how much increase of WP should be achieved between 1995 and 2025 in order to meet demand, and how the increase can be achieved.

Methodology, Data and Assumptions

WP is defined as crop yield per cubic metre of water consumption (WC), including ‘green’ water (effective rainfall) for rain-fed areas and both ‘green’ water and ‘blue’ water (diverted water from water systems) for irrigated areas. WC includes beneficial water consumption (BWC) and non-beneficial water consumption (NBWC). BWC directly contributes to crop growth at the river-basin scale, and NBWC includes distribution and conveyance losses to evaporation and sinks, which are not economically reusable. BWC is characterized by water-use efficiency in agriculture. We use effective efficiency at the river-basin scale (Keller *et al.*, 1996) to represent water-use efficiency, which is the ratio of BWC to WC (in the following it is called basin efficiency, BE, and P is crop production):

$$\mathrm{WP\ (kg\ m^{-3})} = \frac{\mathrm{P\ (kg)}}{\mathrm{WC\ (m^3)}} \tag{10.1}$$

$$\mathrm{WC} = \mathrm{BWC} + \mathrm{NBWC} = \frac{\mathrm{BWC}}{\mathrm{BE}} \tag{10.2}$$

WP defined as above varies from region to region and from field to field, depending on many factors, such as crop patterns, climate patterns (if rainfall fits crop growth), irrigation technology and field water management, land and infrastructure, and input, including labour, fertilizer and machinery. WP can be increased by either increasing crop yield (i.e. increasing the numerator in Equation 10.1 through other inputs while maintaining a constant water-use level) or reducing WC and maintaining the yield level (i.e. decreasing the denominator), or by both. In this chapter, we compute crop yield and WC through IMPACT-WATER, a modelling framework developed at IFPRI, and then compute WP as crop yield (kg) per cubic metre of WC.

IMPACT-WATER combines an extension of IFPRI’s International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) to include water in the agricultural supply functions with a newly developed water simulation model (WSM). IMPACT simulates food demand, supply and trade in the global scope (for a detailed description, see Rosegrant *et al.*, 2001a). Crop area and yield are functions of BWC for crop growth under the condition of crop evapotranspiration requirement, as well as of investment in crop and input prices in agricultural research.

$$P = A \times Y \tag{10.3}$$

$$A = A\,(\mathrm{BWC}|\mathrm{ETC},\ \text{crop prices, irrigation investment}) \tag{10.4}$$

$$Y = Y\,(\mathrm{BWC}|\mathrm{ETC},\ \text{crop prices, input prices, agricultural research investment}) \tag{10.5}$$

where A is the crop harvested area, Y is the crop yield and ETC is the crop evapotranspiration requirement.

Beneficial crop WC depends on effective water availability, including effective rainfall and effective irrigation-water supply.

Effective rainfall is calculated based on total rainfall, crop evapotranspiration requirement and soil characteristics (USDA, 1967). Effective irrigation-water supply is simulated by WSM, taking into account total renewable water, non-agricultural water demand, water-supply infrastructure and economic and environmental policies at the basin, country or regional levels (Fig. 10.1). A detailed description of effective irrigation-water supply within the model can be found in Rosegrant and Cai (2001).

IMPACT-WATER allows an exploration of the relationships between water availability and food production at various spatial scales, from river basins, countries or regions to the global level, over a 30-year time horizon (e.g. 1995–2025). Water availability is treated as a stochastic variable with observable probability distributions, in order to examine the impact of droughts on food supply, demand and prices. China, India and the USA, which together account for about 60% of global grain production, have been disaggregated into several basins. Other countries and regions are aggregated in 33 spatial units. In each unit, eight food crops are considered in detail: rice, wheat, maize, other coarse grains, soybean, potato, sweet potato, and cassava and other roots and tubers. Irrigation requirements for all other crops are also projected.

The starting-point for the analysis is a baseline scenario that incorporates our best estimates of the policy, investment, technological and behavioural parameters driving the food and water sectors. On the food side, total cereal demand is projected to grow by 758 million t between 1995 and 2025, of which 84% of the projected increase will be in developing countries. Expansion in area will contribute very little to future production growth, with a total increase in cereal crop area of only 54 million ha by 2021–2025, from 688 million ha in 1995. The slow growth in crop area places the burden of meeting future cereal demand on growth in crop yield. Although yield growth will vary considerably by commodity and country, in the aggregate and in most countries it will continue to slow down. The global growth rate of yield for all cereals is expected to decline from 1.5% year^{-1} during 1982–1995 to 1.0% year^{-1} during 1995–2020; and, in developing countries, average growth of crop yield will decline from 1.9% year^{-1} to 1.2% year^{-1}.

In the water component, the model utilizes hydrological data (precipitation, evapotranspiration and runoff) that re-create the hydrological regime of 1961–1991 (Alcamo, 2000). Non-irrigation water uses, including domestic, industrial and livestock water uses, are projected to grow rapidly. Total non-irrigation water consumption in the world is projected to increase from 370 km^3 in 1995 to 620 km^3 in 2025, an increase of 68%. The largest increase of about 85% is

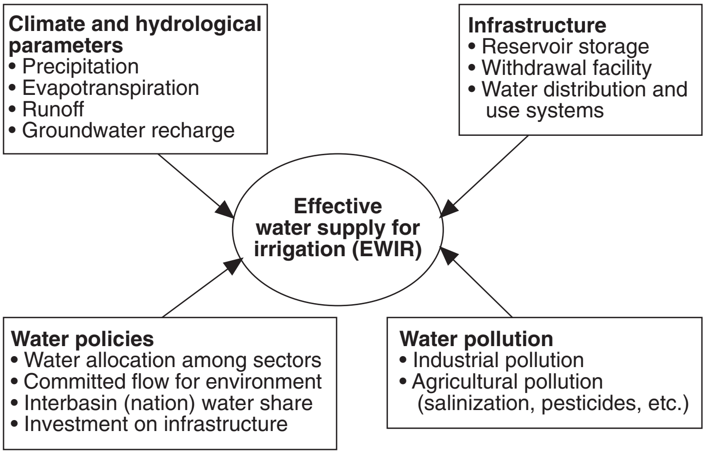


Fig. 10.1. Processes involved in simulating effective water supply for irrigation.

projected for developing countries. Moreover, in-stream and environmental water demand is accounted as committed flow that is unavailable for other uses, and ranges from 15% to 50% of the runoff, depending on runoff availability and relative demands of the in-stream uses in different basins. Irrigation-water demand is estimated and projected, based on crop evapotranspiration and effective rainfall (estimated on a monthly basis), irrigated area and water-use efficiency. Globally, irrigated harvested area for cereals is estimated to be 21 million ha in 1995, and growth is projected to be slow, with a total increase of 24 million ha for irrigated cereals by 2025. The global potential irrigation-water demand is 1758 billion m^3 in 1995 and 1992 billion m^3 in 2021–2025, increasing by 13.4%. The developing world is projected to have much higher growth in potential irrigation-water demand than the developed world between 1995 and 2021–2025, with potential consumptive demand in the developing world rising from 1445 billion m^3 in 1995 to 1673 billion m^3 (average) in 2021–2025, or 15.8%. However, as will be seen below, the effective increase in consumptive use of water for irrigation worldwide is only 3.9%, considerably lower than the growth in potential demand, due to constraints in water supply.

We assume moderate increases in water-withdrawal capacity, reservoir storage and water-management efficiency, based on estimates of current investment plans and the pace of water-management reform. The water outcomes are briefly summarized below:

- *Total maximum allowed water withdrawals.* The total global water withdrawals were 3722 km^3 in 1995, representing 7.8% of global renewable water resources. Water withdrawals for the base year 1995 are estimated as 2795 km^3 in developing countries and 926 km^3 in developed countries. Groundwater pumping in 1995 is up from 817 km^3 (21.9% of total water withdrawals). Total global water withdrawals are projected to increase to 23% between 1995 and 2025. Projected withdrawals increase by 28% in developing countries. Global consumptive use of water will increase by 16%, and the vast majority of the increase will be in developing countries, where consumptive use across all sectors will increase by 18%.
- *Reservoir storage.* The total global reservoir storage for irrigation and water supply is estimated at 3428 km^3 in 1995 (47% of total reservoir storage for all purposes), and is projected to reach 4118 km^3 by 2025, representing a net increase of 690 km^3 over the next 25 years.
- *Effective rainfall use.* It is assumed that effective rainfall use for rain-fed crops will increase by 3–5% in the baseline scenario, due to improvements in water harvesting and on-farm water management and varietal improvement that shifts crop growth periods to better utilize rainfall. This is approximately the equivalent of increasing crop evapotranspiration by 150 km^3.
- *BE.* The average BE for the base year 1995 is assessed at 0.56 globally (0.53 in developing countries and 0.64 in developed countries). Relatively large increases in BE are assumed under the baseline scenario for developed and developing countries where renewable water-supply infrastructure is highly developed (e.g. India, China, and west Asia and North Africa (WANA)). For other regions, such as in sub-Saharan Africa and South-East Asia, where water supply facilities are still fairly underdeveloped, only smaller increases in BE are projected. Based on the above assumptions, the average BE is projected to reach 0.61 worldwide, 0.59 in developing countries and 0.69 in developed countries by 2025. On a global basis, with the improvement in water-use efficiency in the baseline scenario, the global WC demand is 8% lower by 2025 relative to what it would be if effective efficiency remained constant.

Results

Although WP as defined above can be calculated for each of the crops in each spatial unit considered in IMPACT-WATER, without loss of generality, this chapter will focus on the results for rice and total cereals except for rice, mostly at an aggregated spatial scale, i.e. the developing world and the developed world, with some results shown at the region or basin level too. Results from two alternative scenarios are also presented, showing the impact of water-use efficiency and environmental water conservation.

Water productivity in 1995

Figure 10.2 shows a global map of WP of irrigated rice and Fig. 10.3 a similar map of total irrigated cereals excluding rice. The basic elements of these maps are the 36 countries and aggregated regions used in IMPACT (Rosegrant *et al.*, 2001a). Since rice usually consumes more water than other crops, the WP of rice is significantly lower than that of other cereals. Figures 10.2 and 10.3 show that the WP of rice ranges from 0.15 to 0.60 kg m^{-3}, while that of other cereals ranges from 0.2 to 2.4 kg m^{-3}. For both rice and other cereals, WP in sub-Saharan Africa is the lowest in the world. The WP of rice is 0.10–0.25 kg m^{-3} in this region, with an average yield of 1.4 t ha^{-1} and WC ha^{-1} is close to 9500 m^3. For other cereals in sub-Saharan Africa, the average yield is 2.4 t ha^{-1}, the WC is 7700 m^3 ha^{-1} and the average WP is 0.3 kg m^{-3} (ranging from 0.1 to 0.6 kg m^{-3}). Among developing countries, China and some South-East Asian countries have a higher WP of rice, ranging from 0.4 to 0.6 kg m^{-3}; however, the average of the developed world, 0.47 kg m^{-3} (yield, 4.7 t ha^{-1}; WC 10,000 m^3 ha^{-1}), is higher than the 0.39 kg m^{-3} of the developing world (yield, 3.3 t ha^{-1}; WC 8600 m^3). For other cereals, WP is lower than 0.4 kg m^{-3} in south Asia, central Asia, northern and central sub-Saharan Africa; it is 1.0–1.7 kg m^{-3} in China, the USA and Brazil; and 1.7–2.4 kg m^{-3} in Western European countries. The average WP of other cereals in the developed world is 1.0 kg m^{-3} (yield, 4.4 t ha^{-1}; WC 4500 m^3 ha^{-1}); in the developing world it is 0.56 kg m^{-3} (yield, 3.2 t ha^{-1}; WC, 5600 m^3 ha^{-1}).

It should be noted that, because of the level of aggregation, the values shown on these maps do not show the variation of WP within individual countries. Within

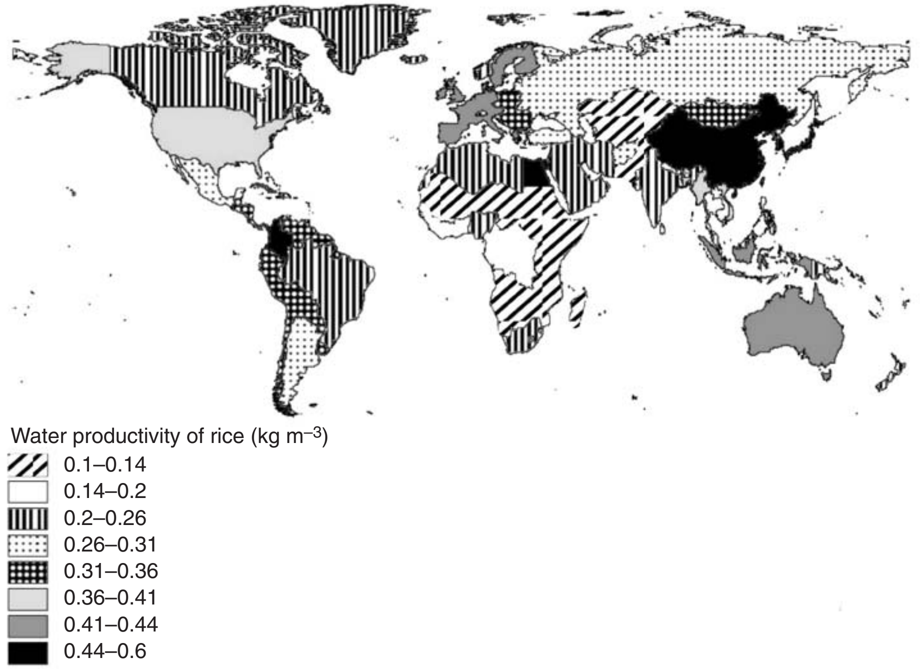


Fig. 10.2. Water productivity of rice in 1995.

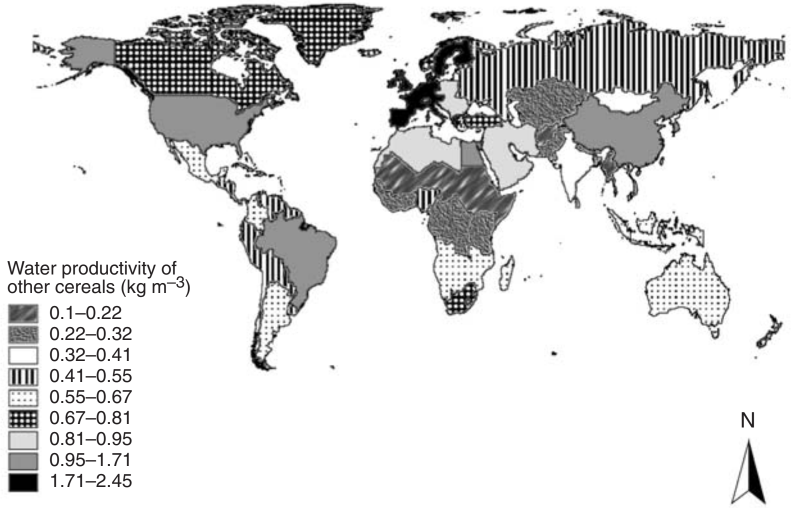


Fig. 10.3. Water productivity of total cereals, excluding rice, in 1995.

some large countries, WP varies significantly. Figure 10.4 shows the WP of total cereal excluding rice in major river basins in China, India and the USA. In China, WP for non-rice cereals ranges from 0.4 to 1.4 kg m^{-3}, with higher WP in the Yangtze River basin and north-east China (the Song-Liao river basin). Crop yields in these areas are relatively higher and water availability is relatively less restricted. However, in India, where non-rice cereal productivity ranges from 0.2 to 0.7 kg m^{-3}, higher WP occurs in northern India (0.4–0.7 kg m^{-3}), where crop yield is higher but water availability is more restricted than in other areas. In the USA, WP ranges from 0.9 to 1.9 kg m^{-3}, with higher values in the north than in the south and the highest in the north-western regions.

Changes in water productivity between 1995 and 2025

IMPACT-WATER simulates crop production and water use from 1995 to 2025, based on which WP year by year is calculated during the period. Figure 10.5 shows a projection of WP of irrigated rice in developing countries, developed countries and the world, from 1995 to 2025, and Fig. 10.6 shows the curves for other cereals. First, we can see that WPs vary from year to year due to variability in climate, which shows that the latter affects water availability and then WP. Secondly, based on our assumption on area and yield growth and on water supply enhancement, WPs are going to increase significantly between 1995 and 2025. For example, WP of other cereals will increase from 1.0 to 1.4 kg m^{-3} in developed countries, from 0.6 to 1.0 kg m^{-3} in developing countries and from 0.7 to 1.1 kg m^{-3} in the world. Figures 10.7 and 10.8 further compare WPs in several regions between 1995 and the average of 2021–2025, for rice and other cereals, respectively.

What is the major reason for the increase in WP from 1995 to 2025, the increase in yield or improvement in water efficiency that decreases WC per hectare? Figure 10.9 compares crop yield and WC for rice between 1995 and the average of 2021–2025. Figure 10.10 shows the same comparisons for other cereals. As can be seen, crop yield increases and WC per hectare decreases, except for a slight increase in WC for other cereals in sub-Saharan Africa. WC per hectare depends on the change of total consumption and the change of crop area. IMPACT-WATER projects a relatively small increase in irrigated cereal crop area, only 24 million ha or 10% from 1995 to 2025 for total irrigated cereals in the world. On the other hand, total realized

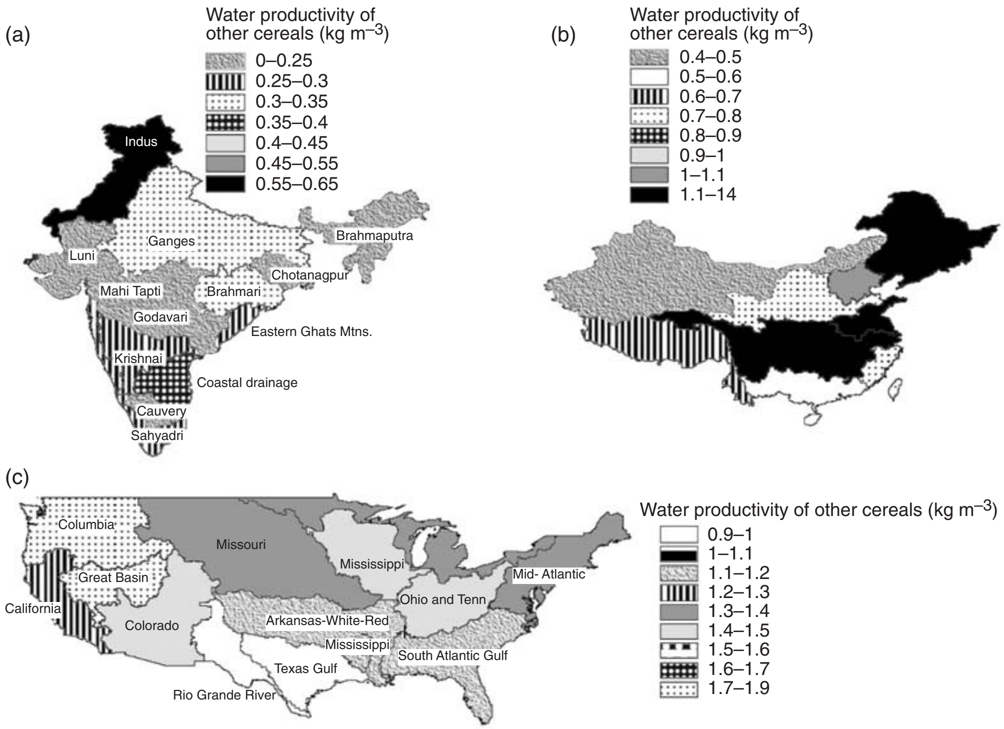


Fig. 10.4. Water productivity of total cereals, excluding rice, in 1995 in river basins in (a) India, (b) China and (c) the USA.

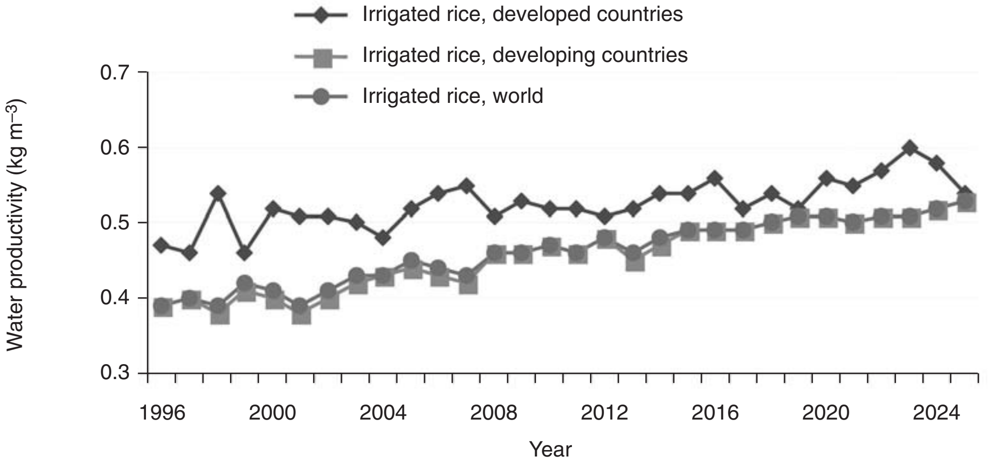


Fig. 10.5. Water productivity of irrigated rice.

crop WC is further determined by the change of water-withdrawal capacity, BE, the change of rainfall harvest and the change of the crop consumption requirements, as well as the amount of water taken by the non-irrigation sectors. Under the baseline scenario, total

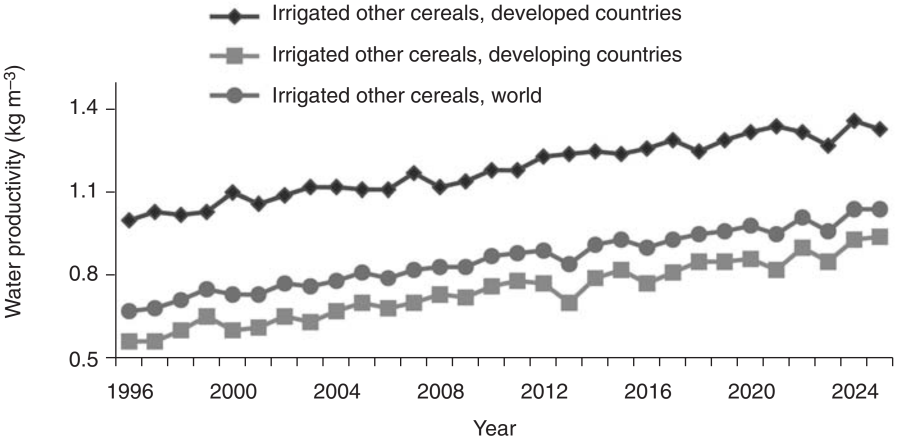


Fig. 10.6. Water productivity of irrigated other cereals.

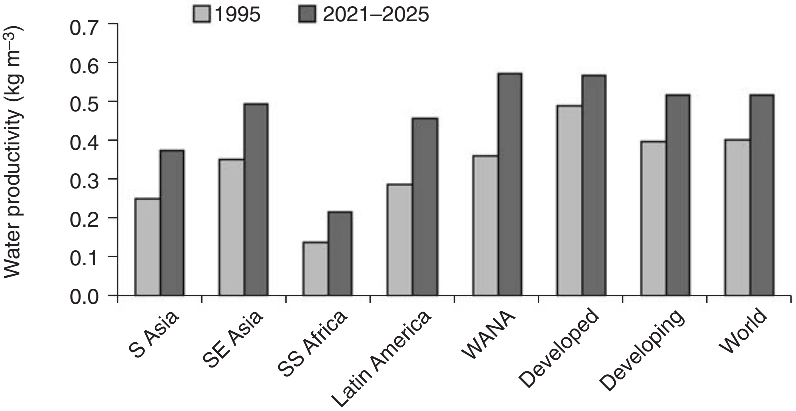


Fig. 10.7. Water productivity of rice in several regions in 1995 and 2021–2025. SS, Sub-Saharan.

global water withdrawals are projected to increase by 23% from 1995 to 2025, with the increase mainly used for non-irrigation sectors (increasing by 62% worldwide from 1995 to 2025). These will increase the total consumption. However, WC can be reduced, because the projected increase in effective river-basin water-use efficiency will decrease the crop consumption demand. All of these factors result in a 3.9% increase in consumptive use of water for irrigation worldwide. Overall, as can be seen in Figs 10.9 and 10.10, the change of WC per hectare is small compared with the change of crop yield. The increase in WP mainly results from the increase in crop yield.

What about the WP of rain-fed crops? Is it comparable to the WP of irrigated crops? Figures 10.11 and 10.12 show WP of rice and other cereals, respectively, from 1996 to 2025 in developing countries. WP for irrigated crops is higher than that of rain-fed crops, at a level of 0.15–0.2 kg m^{-3} for rice and 0.1–0.4 kg m^{-3} for other cereals. The difference becomes larger from 1996 to 2025, due to the higher rate of increase in irrigated yield and the increase in water-use efficiency over time. However, WP of irrigated crops is not higher than that of rain-fed crops everywhere in the world. This can be seen from Figs 10.13 and 10.14, which show the WP of rice and other cereals, respectively, from

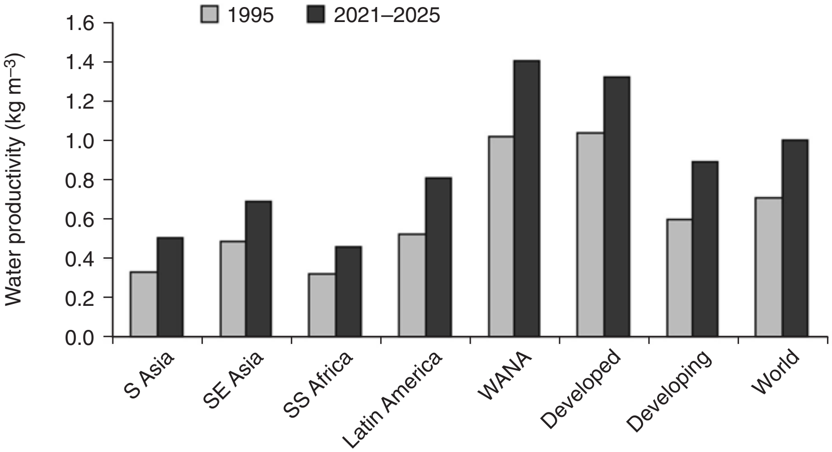


Fig. 10.8. Water productivity of other cereals in several regions in 1995 and 2021–2025. SS, Sub-Saharan.

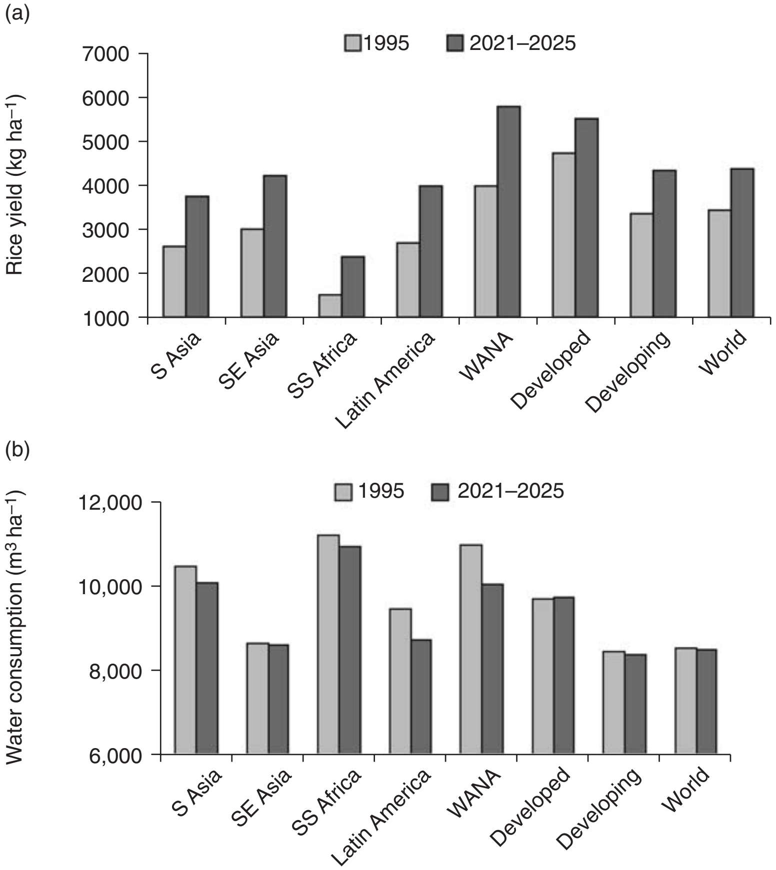
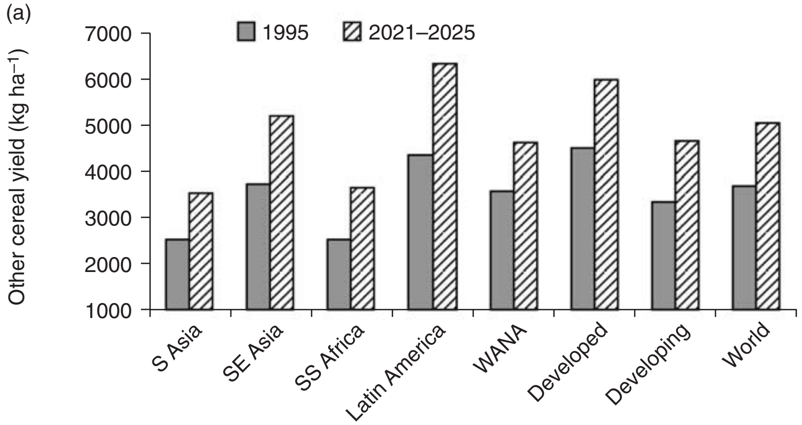


Fig. 10.9. Crop yield (a) and water consumption per hectare (b) of rice in several regions in 1995 and 2021–2025. SS, Sub-Saharan.



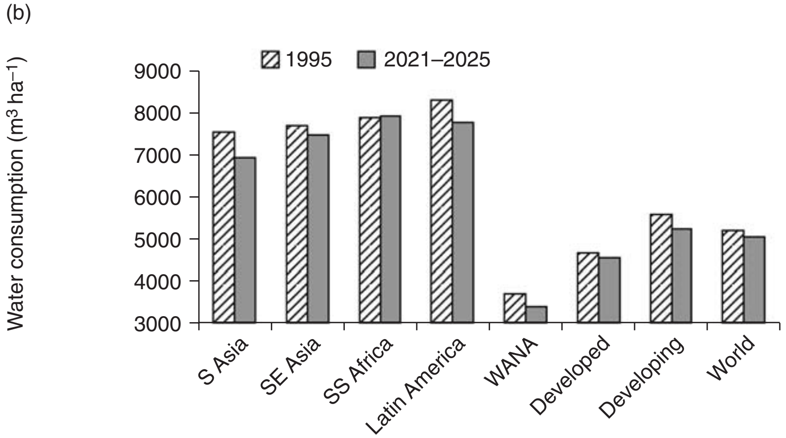


Fig. 10.10. Crop yield (a) and water consumption per hectare (b) of other cereals in several regions in 1995 and 2021–2025. SS, Sub-Saharan.

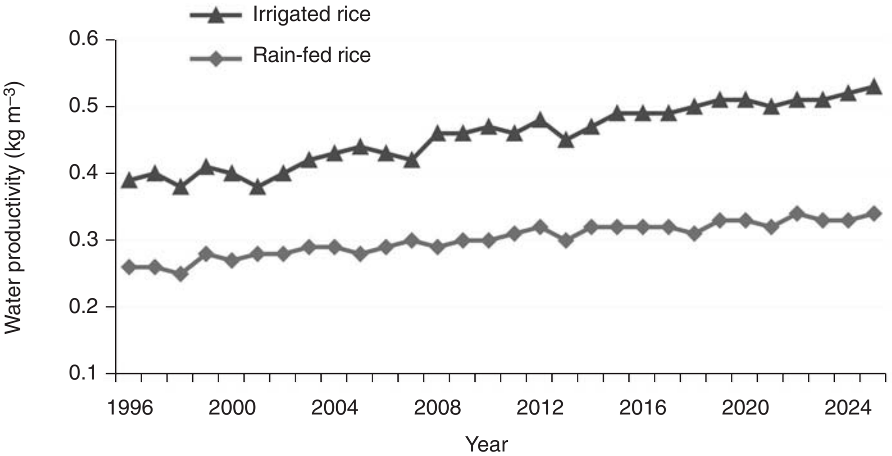


Fig. 10.11. Water productivity of irrigated and rain-fed rice in developing countries.

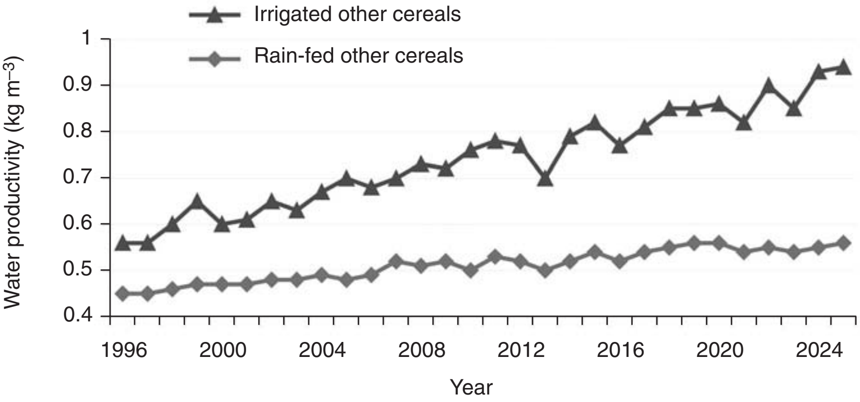


Fig. 10.12. Water productivity of irrigated and rain-fed other cereals in developing countries.

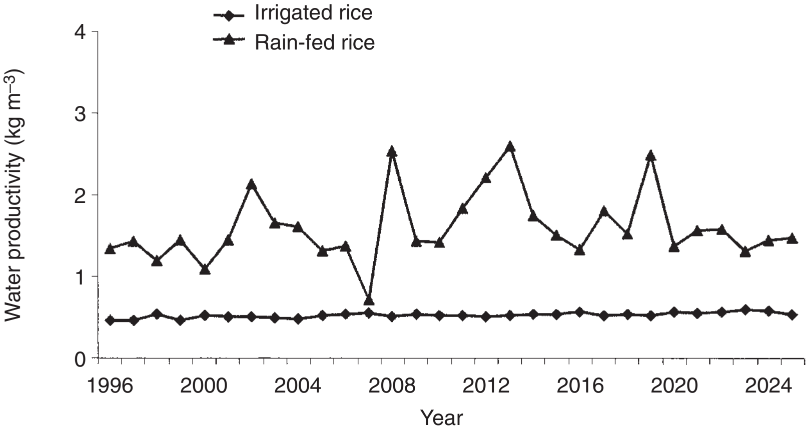


Fig. 10.13. Water productivity of irrigated and rain-fed rice in developed countries.

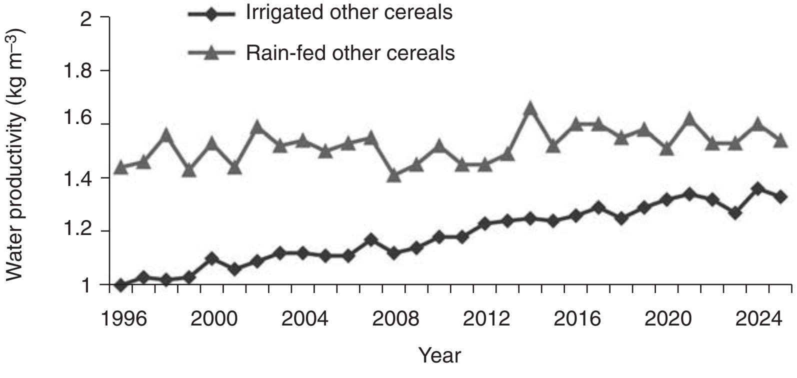


Fig. 10.14. Water productivity of irrigated and rain-fed other cereals in developed countries.

1996 to 2025 in developed countries. The curve of irrigated crops is below the curve of rain-fed crops. This indicates the relatively favourable rainfall conditions for crop growth and high rain-fed crop yields associated with infrastructure and other inputs to rain-fed crops in developed countries, compared with those in developing countries.

Alternative Scenarios

For irrigated crops, water-use efficiency is a key factor in WP. In one scenario, we assume higher basin efficiency (HBE) around the world in the next 25 years, and assess the impact of this on WP. An alternative scenario is defined, based on the increasing concern for environmental reservation of water in the world. This scenario tests the possibility of maintaining the baseline food outputs with larger improvement in effective agricultural water-use efficiency (the same as assumed in the first scenario), but with lower water withdrawal (HBE-LW) so that more water is left for environmental purposes. Assumptions under the two alternatives and the baseline are illustrated in Table 10.1, showing BE, water withdrawal and irrigation consumption under the three scenarios. The two alternative scenarios have HBE and lower water withdrawal and irrigation consumption in both developed and developing countries in 2021–2025. For example, compared with the baseline, HBE-LW results in 443 km^3 or 13% lower withdrawal in developing countries, and 94 km^3 or 7% lower withdrawal in developed countries; and 231 km^3 or 19% less irrigation consumption in developing countries, and 47 km^3 or 17% less irrigation consumption in developed countries.

Table 10.2 compares the WP of rice and other cereals under the three scenarios. Compared with the baseline, higher WPs result from the two alternative scenarios. The highest WP occurs under HBE-LW, which implies that, with HBE, restricting water withdrawals even more will lead to still higher WP. Water use per hectare decreases correspondingly under HBE, and HBE-LW. For example, compared with the baseline, water use per hectare of other cereals is reduced by 4% and 10% under HBE and HBE-LW, respectively, in developing countries, and 6% and 12% under HBE and HBE-LW, respectively, in developed countries. For developing countries, Figs 10.15 and 10.16 show water productivity of rice and other cereals, respectively, during 1996–2025 under the three scenarios. Figures 10.17 and 10.18 show water consumption per hectare of rice and other cereals, respectively, during 1996–2025 under the three scenarios. These curves show that the difference between the baseline and the alternative scenarios contin-

Table 10.1. Estimated and projected values of basin efficiency, water withdrawal and irrigation consumptive use.

		Projected, 2021–2025 average		
	Estimated 1995	Baseline	High basin efficiency	High basin efficiency and low withdrawal
Basin efficiency (%)				
Developing countries	0.54	0.59	0.77	0.77
Developed countries	0.64	0.69	0.81	0.81
Water withdrawal (km^3)				
Developing countries	2764	3486	3347	3043
Developed countries	1144	1277	1228	1183
Irrigation consumptive use (km^3)				
Developing countries	1162	1214	1135	983
Developed countries	268	274	250	227

Table 10.2. Estimated and projected values of water productivity and water use for rice and other cereals.

		Projected, 2021–2025 average		
	Estimated 1995	Baseline	High basin efficiency	High basin efficiency and low withdrawal
Rice				
Water productivity (kg m^{-3})				
Developing countries	0.39	0.53	0.56	0.58
Developed countries	0.47	0.57	0.61	0.63
Water use ha^{-1} (m^3 ha^{-1})				
Developing countries	8,580	8,445	8,040	7,510
Developed countries	10,200	9,730	9,100	8,710
Other cereals				
Water productivity (kg m^{-3})				
Developing countries	0.56	0.94	1.01	1.03
Developed countries	1.00	1.32	1.45	1.5
Water use ha^{-1} (m^3 ha^{-1})				
Developing countries	5,720	5,260	5,040	4,760
Developed countries	4,430	4,530	4,275	3,980

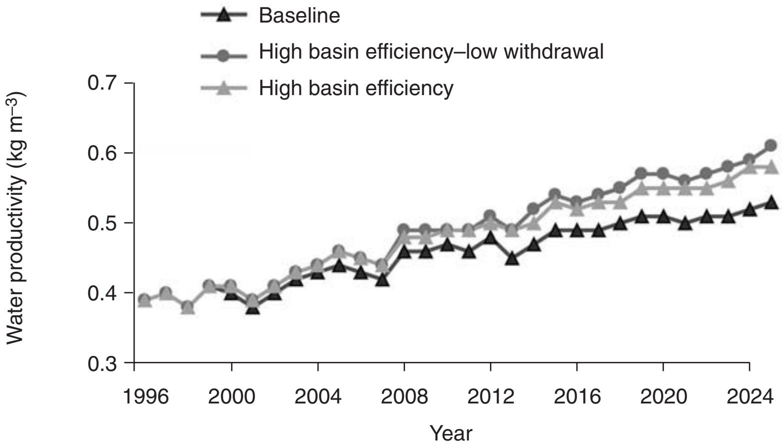


Fig. 10.15. Water productivity of rice under three scenarios.

ues to grow with time, corresponding to higher growth rate of BE and lower growth rate of water withdrawal.

HBE results in significantly higher crop yields and irrigation production during 2021–2025 than in the baseline scenario (except for rice yield in developed countries), which reduces the world price of rice by 15% for rice and 12% for other cereals, and reduces imports of cereals for developing countries from 235 to 213 million tons (Table 10.4). It should be noted that rice yield in developed countries under HBE declines slightly due to less economic incentives (crop prices), since lower prices tend to reduce crop yield. This effect for rice yield in developed countries is stronger than the impact of higher basin efficiency. As designed, HBE-LW compensates for the effect of lower water withdrawal by using larger improvements in BE, so that the baseline food production and demand balance will be maintained and the results come out as expected. Crop yield and production and crop prices under HBE-LW are close to those under

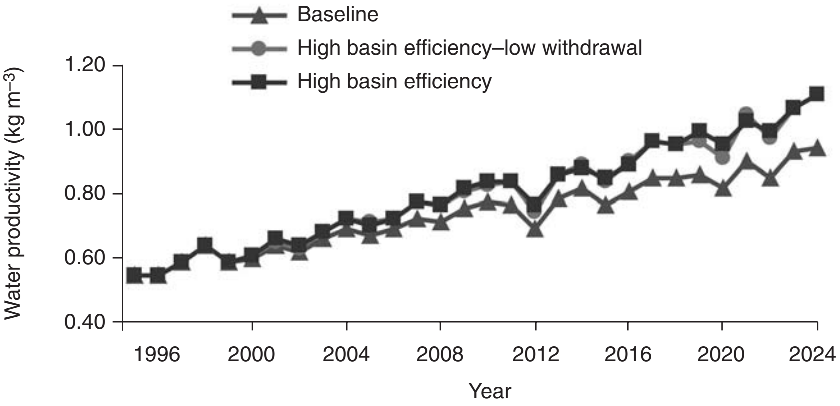


Fig. 10.16. Water productivity of other cereals under three scenarios.

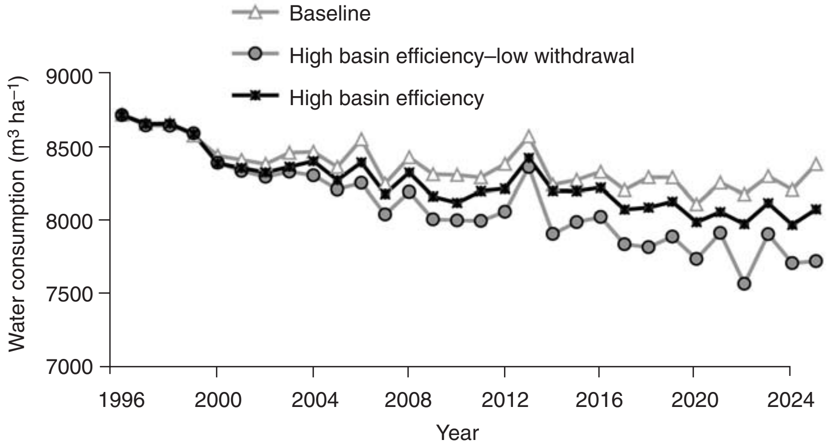


Fig. 10.17. Water consumed per hectare of irrigated rice under three scenarios.

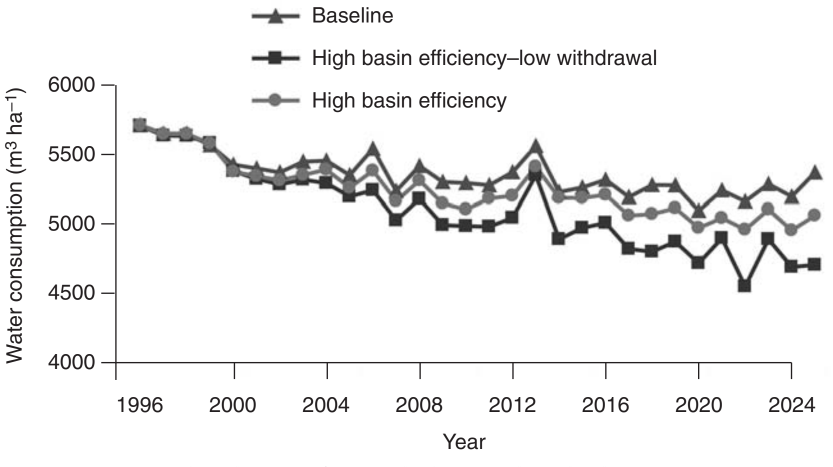


Fig. 10.18. Water consumed per hectare of irrigated other cereals under three scenarios.

Table 10.3. Estimated and projected values of rice and other cereal yields, and irrigated cereal production.

		Projected, 2021–2025 average		
	Estimated 1995	Baseline	High basin efficiency	High basin efficiency and low withdrawal
Rice				
Crop yield (kg ha^{-1})				
Developing countries	3310	4330	4530	4360
Developed countries	4790	5520	5505	5455
Other cereals				
Crop yield (kg ha^{-1})				
Developing countries	3185	4670	5165	4835
Developed countries	4410	6000	6180	5980
Irrigated cereal production (million t)				
Developing countries	557	867	938	880
Developed countries	186	269	274	267

Table 10.4. Estimated and projected world price of rice and other cereals, and developing-country cereal imports.

		Projected, 2021–2025 average		
	Estimated 1995	Baseline	High basin efficiency	High basin efficiency and low withdrawal
World price (US\$ t^{-1})				
Rice	285	236	201	239
Other cereals	114	108	95	110
Cereal imports (million t) by developing countries	107	235	213	220

the baseline scenario. A small switch occurs between developed and developing countries: crop yields under HBE-LW are slightly lower than those under the baseline scenario in developed countries, while the opposite is true in the developing countries. This results in slightly lower cereal import to developing countries, as shown in Table 10.4. The reason behind the switch is a relatively more restrictive water-withdrawal condition for developed countries than for developing countries under the baseline scenario. Thus, the further restriction of water-withdrawal under HBE-LW results in a larger effect on irrigated crop production in developed countries.

Conclusions

WP is defined as crop yield per unit of WC (kg m^{-3}) and is computed through an integrated water and food modelling framework, IMPACT-WATER, for individual crops in each spatial unit (individual or aggregated basins) in the global scope during a period of 30 years (1995–2025). It was found that WP of rice ranged from 0.15 to 0.60 kg m^{-3}, while that of other cereals ranged from 0.2 to 2.4 kg m^{-3} in 1995. WP is relatively low in sub-Saharan Africa and high in developed countries. China and South-East Asian countries have higher WP for rice than other countries, mainly because of higher crop yields. WP will increase from 1995 to 2025: the global average WP of rice will increase from 0.39 kg m^{-3} to 0.52 kg m^{-3}, and the global average WP of other cereals will increase from 0.67 to 1.01 kg m^{-3}. Both the increase in crop yield and reduction in WC through improvement in BE contribute to the increase in WP, but the major contribution comes from the increase in crop yield. Therefore, investments in agricultural infrastructure and agricultural research might have higher pay-offs than investments in new irrigation, in order to increase WP and ensure food security in the next 25 years (see also Fan *et al.*, 1999). This conclusion is based on our assumption that water supply is becoming more and more restricted due to source availability and environmental and financial constraints. However, as shown by the HBE alternative, large improvements in BE would significantly increase WP and reduce water-withdrawal constraints (alternative scenario HBE-LW). The technical and financial feasibility for greatly improving BE needs more research (Cai *et al.*, 2001).

We also find that WP of irrigated crops is higher than that of rain-fed crops in developing countries, but lower in developed countries. This shows that, in developing countries, irrigated agriculture is more efficient in resource utilization and food production than rain-fed agriculture; but this also points to the untapped potential to increase WP of rain-fed crops through research and infrastructural investment (Rosegrant *et al.*, 2001b).

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