Meeting Water Needs for Food and Environmental Security

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Abstract

Dried-up and polluted rivers, damaged ecosystems, and poor people without adequate access to water are a few of the most obvious symptoms of what is rapidly becoming a *global* water crisis. Fueling the crisis are increasing competition for water and water scarcity driven by population growth and additional demands for water by agriculture, cities and industries. IWMI Water Scarcity Studies show that if current trends continue, large areas of the world will face physical water scarcity—a condition where there is not enough water to meet all agricultural, domestic, industrial and environmental needs. Much of the developing world is already suffering from what we call economic water scarcity—where a lack of human and/or financial resources constrains the ability to tap the water needed to meet human needs. But there are actions we can take now to resolve the crisis. The objective of this paper is to define the nature and extent of the crisis, and how improvements in agricultural water use are a key part of the solution.

The amount of additional irrigation needed in the future is at the heart of the debate on water for food and environmental security. Additional irrigation may help ensure food security, but often at high environmental and financial costs. Increasing the productivity of water in agriculture is an attractive option. By producing more food with less water, water can be made available to other environmental and urban uses. Our research has shown that by increasing productivity of irrigated water by 60% and rainfed agriculture by 30% over the next 25 years, it is possible to produce enough food globally, while reducing irrigation withdrawals. Increasing productivity of water to these levels will require several simultaneous agricultural improvements in the fields of crop breeding, soil and nutrient management, policies and institutions, co-managing water for agriculture and the environment, water management in irrigation, and innovative poverty-focused approaches.

Introduction: The Global Water Crisis

The Green Revolution — based on modern, high-yielding plant varieties, requiring high inputs of fertilizer and water — has led to increases in world food production at a pace that outstripped population growth. Food prices have declined markedly. Increased water use in irrigated agriculture has benefited farmers[2] and

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[2] A review by the World Bank of 585 irrigation projects found an average economic internal rate of return (IRR) of 15%, substantially above the assumed opportunity costs of capital (World Bank, 1994). Many irrigation projects, particularly in Africa, under-performed however, or had major social and environmental external costs. This has led to strongly held differences of opinion concerning the benefits and costs of irrigated agriculture.

the poor[3] alike. But increased water and chemical use that fueled the Green Revolution has contributed to environmental degradation, and threatened the resource base upon which we depend for food and livelihoods.

In spite of increases in agricultural production and lower food prices, the task of providing food security to all is incomplete. In 1997, 790 million people in developing countries remained food-insecure, with 60 % living in South Asia and sub-Saharan Africa. In sub-Saharan Africa, the number of food-insecure people has risen from 125 to 186 million people over the last period from 1980 to 1997 (FAO, 1999), much of this in regions of economic water scarcity where resources constraints limit the development of water resources.

We are all quite aware of issues of dried-up and polluted rivers, of endangered aquatic species, of accumulation of agricultural chemicals in natural ecosystems. Worldwide, 20 - 35% of freshwater fish are vulnerable, endangered or extinct; 20% of insects have aquatic larval stages; and 57% of freshwater dolphins are endangered (Cosgrove and Rijsberman, 2000). Rapidly growing cities, burgeoning industries, and rising use of chemicals in agriculture have undermined the quality of many rivers, lakes, aquifers, and natural ecosystems. Groundwater, the preferred source of drinking water, is extremely difficult to clean.

The objective of the paper is to describe problems arising from water scarcity, then to forward solutions. Many of the solutions are found in the way water is developed and managed in agriculture.

Stages of development – emerging scarcity within river basins

To understand different types of scarcity, let us consider the development of water basins over time. The water resources of a basin enter by rain or by trans-basin diversions. An important distinction and conceptual advance was forwarded by Falkenmark (2000) who separated water into blue and green water. Blue water contributes to river runoff, while green water would evaporate before reaching rivers. Agriculture is dependent on both blue and green water.

Renewable water resources represent a physical upper limit to the volume of water entering a basin (Fig. 1). The actual *available water* for human use at any time in the course of river basin development is a function of the existing infrastructure. Initially, before much human influence, river water flowed freely to the sea. Then with increasing human activity, small structures were built to meet water needs for drinking and food. Each new structure tapping blue water adds to the available supply, yielding the stair step pattern as shown in Fig. 1. Replacing natural vegetation with agricultural cropland makes an additional amount of rainwater available for human use ("green" water, if this water would not have otherwise entered into the cycle of renewable water resources).

As demand increases and more water is made available, more water is depleted. More land is put into agriculture; more irrigation water is diverted, and demand for urban and industrial water increases. Eventually, the amount of depleted water approaches that of available water, and a new structure may be required. In a highly developed basin, depletion approaches the potentially available supplies. The potentially available water represents the maximum water that can be made available, unless more water is brought in through a trans-basin diversion.

[3] There is no consensus on the poverty alleviation impacts of irrigation. Recent research led by IRRI, for instance, concluded for 6 villages in Madhya Pradesh, India, that incidence, depth and severity of poverty were substantially lower in the villages where there was irrigation – compared to rainfed villages (Janaiah *et al.*, 2000). Similar research in Myanmar concluded that recent expansion of irrigation infrastructure in the 1990s has not increased household income, due to farmers' inability to cope with the economic and technical demands of the new rice-based technologies (Garcia *et al.*, 2000). The acrimonious debate on dam development has convinced many that water resources development threatens livelihoods. A recent article on the Mekong in Newsweek, for instance, was titled "Strangling the Mekong: A spate of dam building has stopped up Southeast Asia's mighty river and may threaten the livelihood of millions who lie along its banks" (Newsweek, March 19, 2001).

In increasingly more cases, water depletion even exceeds the potentially available resource — in the long run, a non-sustainable situation. For example, in many areas of the world (Postel, 1999), there are severe problems with groundwater levels falling. In other areas, water is so intensively used that flows are reduced to a point where pollutants and salts cannot be washed out of the basin. In other cases we mine into what should be our natural reserves by removing excess amounts of natural vegetation, or removing water from wetlands.

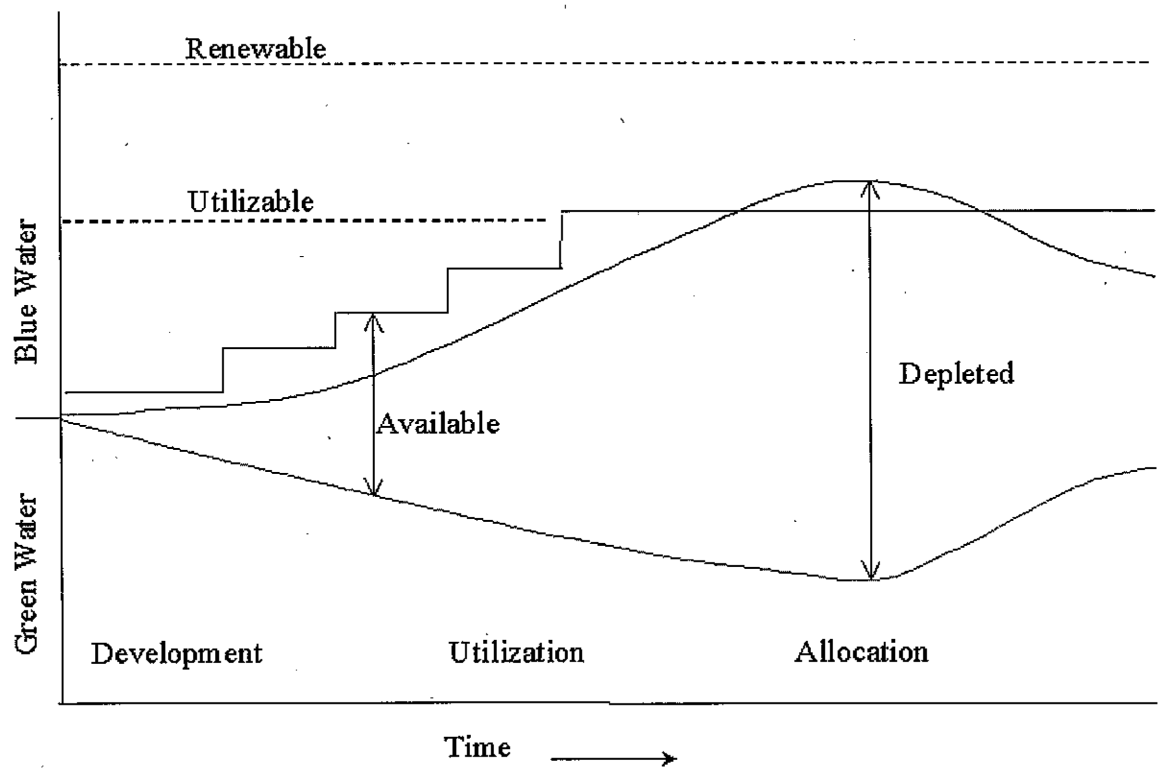

Fig. 1 Phases of river basin development

Figure 1 graphically illustrates three important phases of river basin development implicit in the above discussion (Molden *et al.*, 2001).

1 *Development* In this phase the amount of naturally occurring water is not a constraint. Rather, expansion in demand drives the construction of new infrastructure and expansion of agricultural land.

2 *Utilization* Significant construction has taken place, and the goal now becomes to make the most out of these facilities. Water savings and improved management of water deliveries are important objectives. Early at this stage, inter-sectoral competition is minimal. Institutions are primarily concerned with sectoral issues such as managing irrigation water, or managing drinking water supplies.

3 *Allocation* When depletion approaches the potential available water, there is limited scope for further development. An important means of adding value to water resources use is to reallocate water from lower to "higher value" uses. Managing demand becomes increasingly critical.

In many basins in the allocation phase, depletion by human uses exceeds what is environmentally desirable, and often what is environmentally sustainable. The situation is out of balance and cannot be sustained. In such stressed areas, basin water depletion will inevitably fall to minimally sustainable levels. Whether basins will suffer a painful collapse, as in the ancient irrigation areas of Mesopotamia that were destroyed by salinization, or return to a more acceptable state, is a major water management issue of our times.

Concerns of scarcity, water pollution, and poverty differ during differing phases of development. These concerns may exist at all times, but their importance or emphasis changes over time as illustrated in Table 1.

Table 1 Various concerns at different phases of river basin development (Molden *et al.*, 2001)

Development	Utilization	Allocation
Construction	Improving O&M services	Shifting to higher value uses
Managing supply distribution	Investing in and improving O&M	Managing demand
Economic water scarcity	Localized water scarcity	Physical water scarcity
Low value of water	Increasing value of water	High value of water
Fewer water conflicts	Within-system conflicts	Between-system conflicts
Large structures	Modernization/rehabilitation	Measurement, regulating
Utilizing groundwater	Conjunctive management	Regulating groundwater
Diluting pollution	Emerging pollution/salinity	Cleaning up pollution
Including/excluding poor in development of facilities	Including poor in O&M decision making	Poor people lose access to water

Eventually, with growing demand, the physical supply of water becomes limiting. When water depletion approaches available supplies, there are two typical responses. If there is more water remaining for development (available water is less than potentially available water), exploitation through more infrastructure development is physically possible. Later, after the easiest locations have been exploited, or as concerns about social and environmental impacts increase, infrastructure development becomes more costly. Finally, during the allocation phase, the amount of water resources is the constraining factor. Different kinds of infrastructure development prevail during the allocation phase: measurement and regulation structures to control water become more important; rehabilitation and modernization efforts are common; there may be scope for trans-basin diversions.

Over time, the value of water increases. When water is plentiful, water has a low value, but as the basin closes, the value of water rises dramatically. This leads to a shift from concern about developing the supply of low-value water to a phase where managing demand prevails. When low-value water is plentiful, conflicts can be mitigated with more supplies. As supplies become limiting, the potential for conflict increases.

Scarcity takes on different characteristics in each phase of development. During the development phase, scarcity is felt because there is no way to tap water. Scarcity is a reality for many people in Africa who do not have access to water at times because they do not have cost-effective technologies to access water. Water may be very close by, either underground or in rivers, but there may be formidable economic or institutional barriers that deny access. In the utilization phase, the technology may be present, but when it is poorly managed, people feel water scarcity. During the allocation phase, the absolute supply of the physical water resource causes scarcity – a situation called physical scarcity (IWMI, 2000).

These different types of water scarcity have important implications for poverty. During the development phase, an important consideration is to identify the beneficiaries. Will infrastructure benefit poor people? Will more powerful people capture the benefits? The problems change during the utilization phase. Even though conveyance structures exist, management may not meet the needs of the poor. During the allocation phase, water is reallocated amongst sectors and people. When water moves away from agriculture to cities and industries, will the poor and less powerful be able to maintain their right or access to water? Will poor people be able to capture the economic gains when water moves to higher valued uses?

Similarly, environmental concerns change over time. During the development phase, huge changes in nature can take place. Hydraulic infrastructure alters natural flow regimes and the landscape changes with growth in agricultural areas and cities. During the utilization phase, water use and depletion intensify, further removing water that has environmental functions. A common "solution" to scarcity is to tap into natural reserves of ecological significance for more water, resulting in damaged wetlands, or loss of biodiversity in ecosystems generally. During the early phases of development, dilution can be sufficient to solve pollution problems. During the allocation phase, dilution is not an option, because there simply is not enough water. Clean-up at the source becomes increasingly critical.

With land and water development, we give ourselves the ability to control more water resources. During the development phase, we remove water from nature. In the allocation phase, people are in a position to allocate supplies to nature - nature along with cities, agriculture, and industry becomes a competitive user of water. In many developed countries, we find a desire to allocate more water to nature. In California, in the year 1995, urban uses accounted for 11% of water use, agriculture for 42.5%, while environmental reservations accounted for 46.5% of water (Svendsen, 2001). In Australia, the New South Wales government recently reduced allocations to irrigation by 10%, so that allocations to the environment could be increased (Hatton MacDonald and Young, 2001).

A global picture

IWMI's water scarcity studies produced a global picture of water scarcity (Fig. 2). Physically, water-scarce areas are those that do not have sufficient water resources to meet agricultural, domestic and environmental needs by the year 2025. Most of the basins in these areas are in the allocation phase, many of them reaching levels of unsustainable use. Another important picture emerges with those areas with economic water scarcity, a condition where there is enough water resources to meet projected 2025 demands, but where heavy investments are required to increase supplies. Most sub-Saharan African countries face an "economic" scarcity of water – they will find it very difficult to raise sufficient resources to construct the water infrastructure needed to meet demands in the next few decades (IWMI, 2000). These are also areas of significant malnutrition.

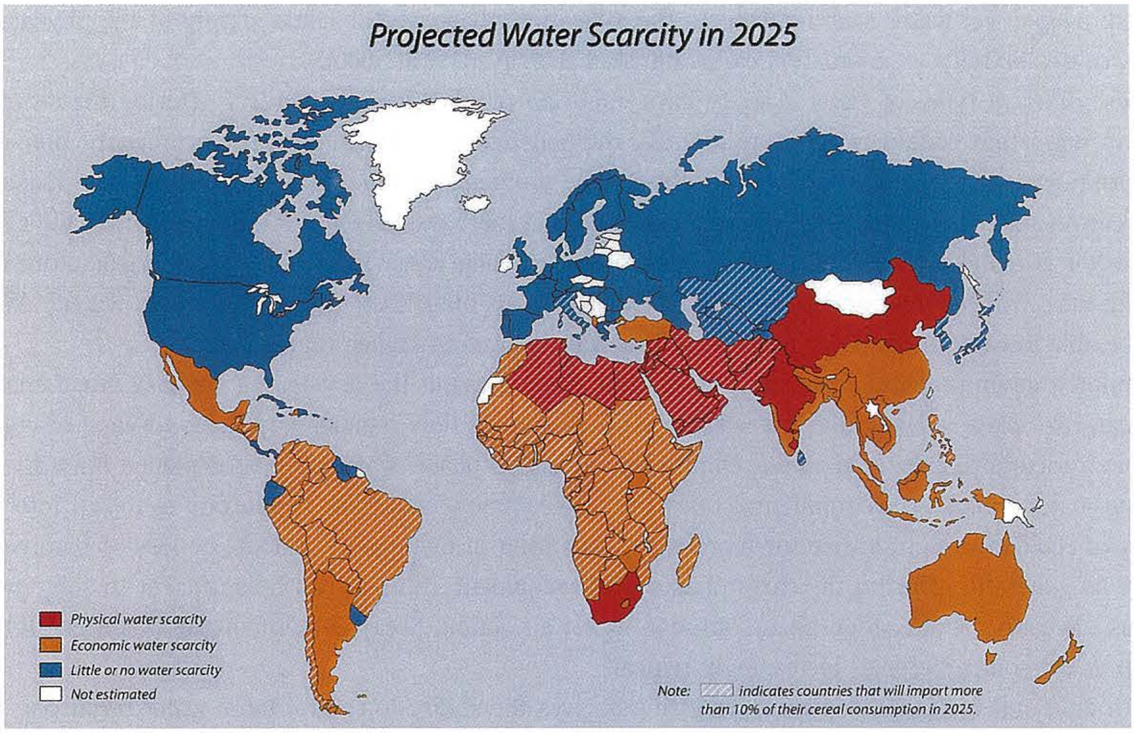

Fig. 2 Projected water scarcity in 2025 under a base scenario

By its nature, producing food requires a lot of water. To produce one kilogram of grain requires about one thousand liters[4] of crop evapotranspiration. However, one kilogram of meat requires much more water to produce - depending on how much feed is given. In California for example, about 13,500 liters of water are used to produce one kilogram of beef. Renault and Wallender (2000) estimate that a typical diet of a person from USA requires about 5,400 liters water in the form of evapotranspiration. On the other hand a vegetarian diet with approximately the same nutritional value is responsible for the consumption of 2,600 liters of water per day. Compared to the 2 to 5 liters of water we need to drink daily, and 20 to 50 liters needed for bathing and other personal needs, the 2,000 to 5,000 liters of water to produce food dominate the water for human needs equation.

It is often stated that irrigation uses 70% of all water withdrawn, and in some countries this number reaches 90%[5]. In fact, irrigation withdrawals are on the order of 2,500 km^3, which accounts for approximately 6% of the world's renewable resources. The other 94% of the renewable resources are used to support crop cultivation and terrestrial, aquatic and coastal ecosystems. Seen from another perspective, IWMI estimates that of evaporation from earth surfaces, lands supporting crop-based agriculture evaporate 20% — about 15% of which is from lands supporting rainfed agriculture and 5% by irrigated lands[6]. Certainly, we think that

[4] There is a wide range in the estimated amount of kg/m^3 of evapotranspiration, from about 0.5 to 1.5 - this reflects differences in the definition of crop per drop in agriculture.

[5] From 1900 to 1995, withdrawals for human use have increased from 600 km^3/year to 3,800 km^3/yr. Agricultural withdrawals are on the order of 2,500 km^3/year - in many developing countries this is over 90% of all water withdrawn for human uses. From another perspective, of the 100,000 km^3 per year reaching the earth's surface, only 40% or 40,000 km^3 are considered renewable water resources because they contribute to river runoffs and groundwater storage. Of this amount, some 10% or 3,800 km^3 is diverted from its natural courses, of which 2,500 km^3, 7% is withdrawn for irrigation (based on Shiklomonov, 1999).

[6] This preliminary estimate by IWMI was done by overlaying The World Water and Climate Atlas (*www.iwmi.org*) grids on the USGS land cover (Eidenshink and Faundeen, 1994) data set.

managing water in agriculture should not exclusively focus on improving the efficiency of the 2,500 km^3 diverted to irrigation, but must include the improvement of the productivity of the 16,000 km^3 used in rainfed agriculture as well.

Solutions

The solution to problems of food and environmental security lie mostly in agriculture, because of the magnitude of water consumption by agriculture. The first and foremost solution is to focus on increasing the productivity of water in agriculture. This must be done in a manner that recognizes and enhances the value of the multiple uses of water affected by water use. These are necessary, but not sufficient conditions to ensure food security. Special attention must be given to the poor who lack access to water, or the means to be most productive with their resource use.

Increasing the productivity of water

With water as an increasingly scarce resource, it is appropriate to shift our focus from production per unit land – yield, to productivity of water. Productivity of water in its broadest sense refers to the value obtained from the use of water, by agriculture, drinking water and industry, livestock fish, as well as other goods and services provided by ecosystems. In agriculture, productivity of water refers to obtaining more crop per drop, the subject of this symposium.

A common perception is that increasing efficiency in agriculture is the solution to the water crisis. Technically defined, efficiency tells us how much diverted water reaches the crops, and how much is wasted "down the drain". Unfortunately, this is a widespread misperception as I will illustrate. The real "wastage" comes from not being as highly productive as possible with the water that is currently consumed (not wasted down the drain) in agriculture.

The Chistian Irrigated area is located in Pakistan's Punjab with a landscape heavily dominated by agriculture. To get an idea of how efficiently water was used, IWMI performed a water accounting exercise (Molden *et al.*, 2001). During the 1993/94 agricultural year, 740 million cubic meters (MCM) of water entered the area[7] from irrigation deliveries, rain and groundwater. Human use, dominated by crop agriculture, consumed 90% of the supplies, evidently quite efficient.

From this larger, basin perspective, farmers are very effective in converting water into crop production. But, groundwater was mined during the year, and in this area very little water was available for environmental purposes such as flushing salts, or for ecosystem sustenance. Farmers as a group are, if anything, too efficient! Certainly increasing the efficiency, and leaving even less for other uses, is not recommended.

While efficiency is very high, productivity is very low. Wheat yields are on the order of only 2 tons per hectare, while rice yields are on the order of 1.4 tons per hectare. In terms of kilograms and dollars per cubic meter, water productivity is on the low end of the spectrum compared to other systems worldwide[8]. For wheat, water productivity is on the order of 0.6 kg/m^3 compared to a range of about 0.5 go 1.5 kg/m^3.

[7] 504 MCM from irrigation diversions, 143 MCM as rain, and 73 MCM as net groundwater abstraction. Crop evapotranspiration was 595 MCM, while evaporation from cities was about 50 MCM.

[8] For wheat this converts to 0.6 kg/m^3 of water. We have found a range of water productivity of wheat from 0.6 to about 1.5 kg/m^3 worldwide. The gross value of production for the rice-wheat cropping system per cubic meter of evapotranspiration is on the order of US$ 0.07, at the low end of the spectrum (Sakthivadivel *et al.*, 1999). For 40 systems, IWMI calculated a range of water productivity from $US 0.05 to about 0.80 per cubic meter.

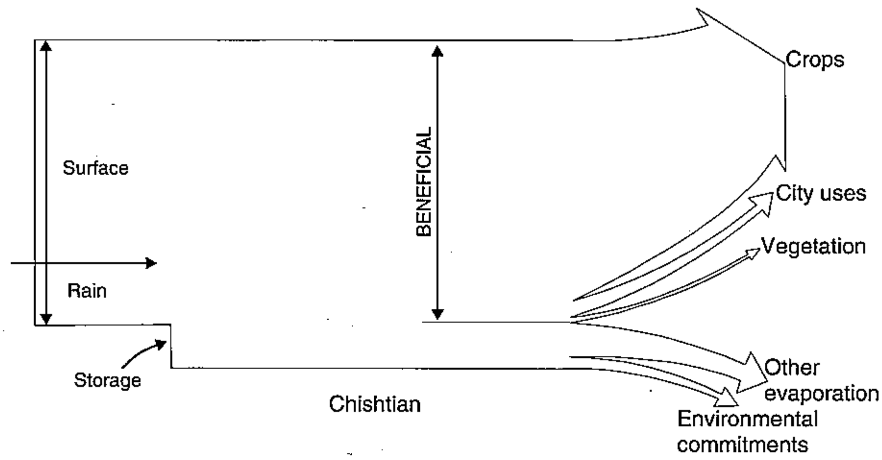

Fig. 3 Water accounting for the Chistian sub-division, Pakistan

Where water is limiting, there is a clear need to shift from an exclusive focus on productivity of land resources, yield in tons per hectare, to a view that focuses on productivity of water resources, tons per cubic meter, and in a broad sense, overall benefits derived from water used.

Why is getting more crop per drop so important? The answer is simple - growing more food with less water alleviates scarcity, contributes to achieving food security, and puts less strain on nature.

In many areas, potential productivity is not realized and this is in part due to poor irrigation management. Considering the productivity of water in more than 40 irrigation systems worldwide, Sakthivadivel *et al.* (1999) demonstrated a 10-fold difference in the gross value of output per unit of water consumed by evapotranspiration (Fig. 4). Some of this difference is due to the price of grain versus high-valued crops, and certainly not all agriculture can be devoted to high-valued crops. But even among grain-producing areas, the differences are large.

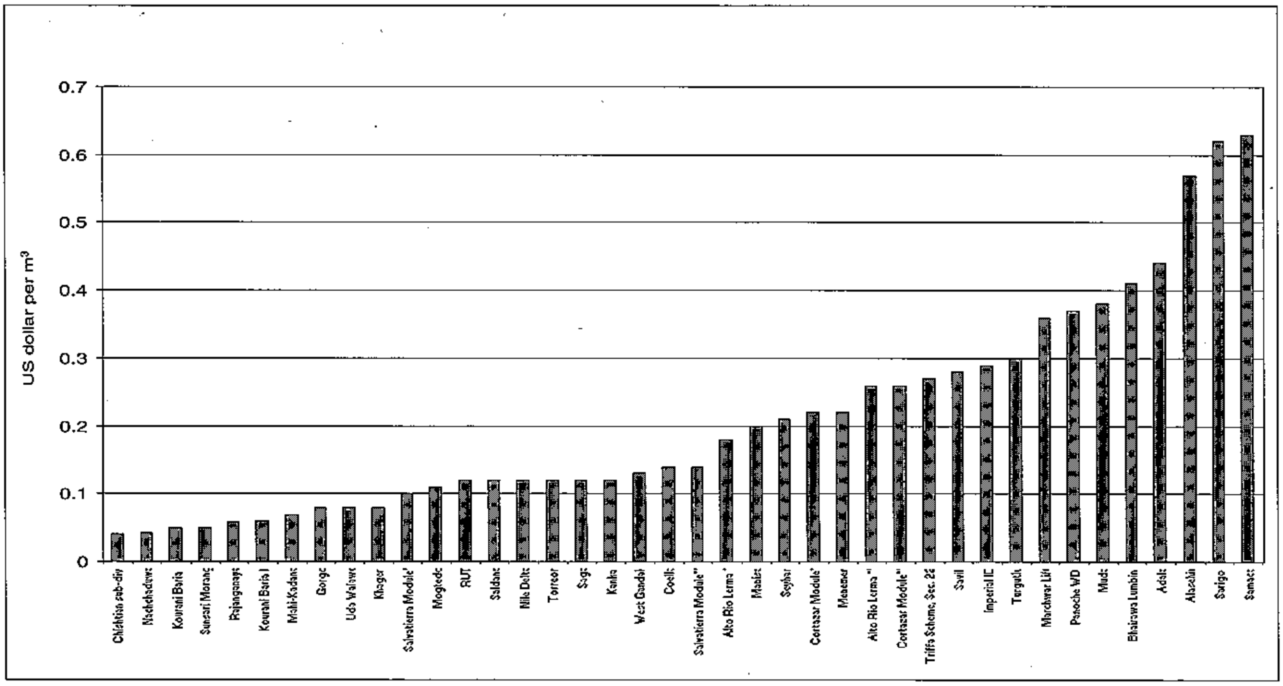

Fig. 4 Water productivity values in terms of standardized gross value of output per unit of evapotranspiration (Sakthivadivel, 1999)

In many places, real water savings[9] is an important mechanism to increase the productivity of water. In China, and many other places of the world, water is moving out of agriculture. The Zhanghe reservoir, situated in the Yangtze River basin, was constructed primarily for irrigated agriculture. Over time reservoir water also met increasing demands from higher valued urban and industrial water uses. Water managers — farmers, irrigation service providers, and water resource managers - were able to shift water out of agriculture to meet these other needs (Fig. 5). Production levels remained stable over the time period in spite of this massive shift of water out of agriculture (Table 2). The increase in water productivity can only partly be explained by yield growth which nearly doubled over a thirty- year period. This is compared to a near trebling of water productivity attributed to the Zhanghe supply. Growing more rice with less water — improving the productivity of water — was made possible through on-farm water-saving irrigation practices, ample recycling through the melons-on-the-vine system of reservoirs, pricing water, and strong institutions to back these approaches (Hong *et al.*, 2001).

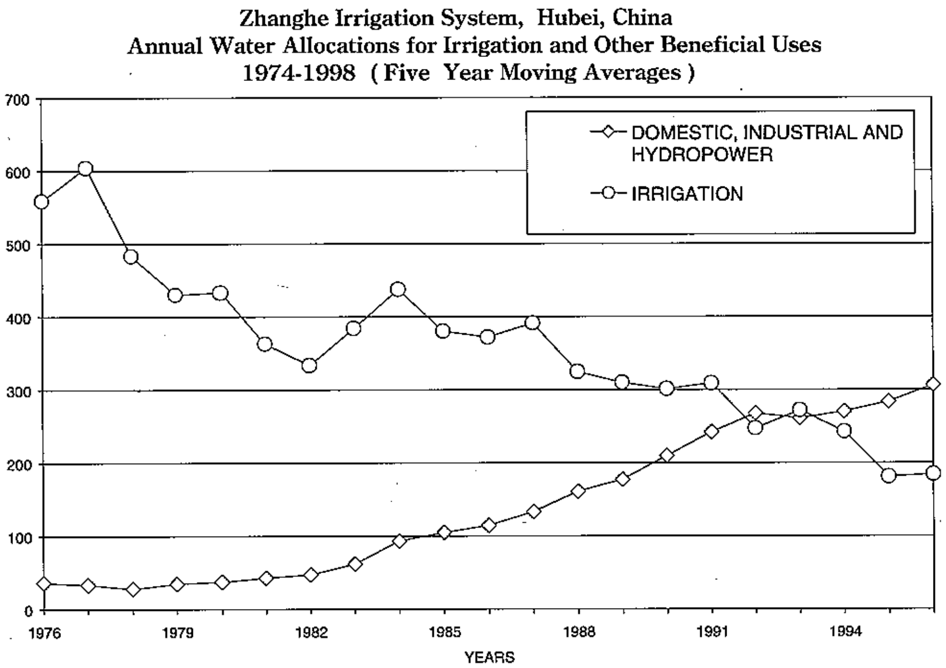

Fig. 5 Annual deliveries to irrigation and other uses in Zhanghe Irrigation District, China

Table 2 Changes in land and water productivity in Zhanghe irrigation district 1966-1998

Period	Annual irrigated area (10^3 ha)	Rice crop production (10^3 tons)	Rice yield (T/ha)	Rice water productivity (kg/m^3 water supply)
1966-78	139	561	4.04	0.65
1979-88	135	905	6.72	1.17
1989-98	118	920	7.80	2.24

[9] The term "real" water savings refers to saving water in agriculture so that water can be shifted to another use or for more agriculture. This is in contrast to "paper" water savings where the flow paths of water are changed, but no water is freed up for additional uses. See Seckler, 1996 for a discussion.

Managing for multiple uses

Water use in agriculture, and especially irrigation water serves the needs of many uses – including fisheries, livestock, bathing, small-scale industry and enhanced ecosystem services (Bakker *et al.*, eds. 1999). Understanding these multiple uses and their interaction requires new ways to consider water and natural resources management.

Especially in areas of high water stress, a water action taken in one part of a basin, may have negative impact in another part of the basin. Capturing and using "losses" in irrigation may indeed leave less water to fisheries, to people, and to wetlands. Plus, each drop of basin water can serve several purposes – for fisheries, for drinking water, and for ecosystem services. For example, IWMI studies in Sri Lanka have indicated that lining canals in an effort to improve efficiency may cause problems for drinking water and health. A further example is the capture fisheries in Cambodia's Mekong that are at risk from upstream developments along the Mekong. A shift in institutional focus is required to manage water for its multiple uses. Understanding the tradeoffs, making sure that our actions improve overall basin water use, is an area that requires much more attention. The broad definition of productivity of water, its values in various uses, provides a basis of analysis of our action.

Focus on poverty alleviation and household food security

A simple focus on increasing overall productivity can increase food production to assure global, national or regional food security – but does not guarantee food security at the household level. That is a matter of access and distribution. Fortunately, we are learning how to target small farmers and alleviate poverty while increasing productivity. For example, more than 1.3 million treadle pumps have been sold in Bangladesh alone (Shah *et al.*, 2000). The technology has reached a substantial number of rural poor in Bangladesh and irrigates about 600,000 ha of farmland and has raised the annual net household income by US$100 on the average. There is considerable activity in promising low-cost drip irrigation technologies and water harvesting that offer hope in increasing access to water, water productivity, and income for the poor.

Unanswered questions

One of the pressing questions related to food and environmental security is "how much irrigation is needed in the future?" The agricultural community sees continued growth of irrigation as an imperative to achieve the goals adopted by the international community to reduce hunger and poverty. Under a base scenario that included optimistic assumptions on productivity growth and efficiency, IWMI estimated that 29% more irrigated land will be required by the year 2025, and because of gains in productivity and more efficient water use, the increase in diversions to agriculture would be 17%. FAO and Shiklomanov had comparable results[10].

Citing similar international commitments to maintain and improve environmental quality and biodiversity, many in the environmental community see it as imperative that water withdrawn for agriculture is reduced, not increased. Irrigation development has impaired the ability of many ecosystems to provide valuable goods and services, including flood protection, water purification, and provision of food and fiber. It is argued that not enough attention is given to alternative, but more sustainable means of production. Taken from the

[10] FAO (2000) estimated a 34% increase in irrigated area, and a 12% increase in irrigation diversions, and similarly Shiklomanov (1999) projected a 27% increase in irrigated diversions.

perspective of sustainable use, Alcamo *et al.* (2000) projected an 8% decrease in the amount of water that should be diverted to irrigation. The difference between the 17% increase and *8% decrease* is on the order of 625 km^3 of water — close to the 750 km^3 of water that is presently used globally for urban and industrial use[11].

Clearly, there is a gap in thinking between the environmental and agricultural communities on future water development. The Global Dialogue on Water, Food, and Environment was recently launched in August 2001 to clear the gap.

Reducing water withdrawn by agriculture contributes by freeing up more water for nature, for drinking, and industrial uses. Can this be done and still provide food security and improved rural livelihoods. Here are the results of a global calculation using the IWMI's Podium Model[12]. In this scenario[13], there is a moderate expansion of 3% of the harvested area, and 10% of irrigated area. But we have actually required withdrawals by irrigation to decrease by about 10%. The only way that enough food can be grown is by increases in water productivity on rainfed and irrigated land. For the period of 2000 to 2025, we have estimated that an annual growth rate of about 1.8% or roughly a 60% increase for the period, on irrigated land, and 1.0%, or a 30% increase on rainfed land in water productivity would be required (see Table 3)[14]. This marked change in water productivity from business as usual scenarios is the challenge.

Table 3 Water productivity and yield growth rates for a scenario meeting goals of food and environmental security

	Irrigated	Rainfed
Recent annual growth rates (%) in yield	1.0%	0.5%
Business as usual scenarios		
- Growth in yield	1.0%	0.5%
- Growth in water productivity	0.6%	0.5%
- Growth in water productivity (25 years)	20%	15%
Food and environmental security scenario		
- Growth in yield	1.3%	1.0%
- Growth in water productivity	1.8%	1.2%
- Growth in water productivity (25 years)	60%	30%

Is such an increase feasible? Increases on rainfed land can be achieved by several means: improved varieties, better nutrient management, improved soil-water management practices, and by introducing supplemental irrigation to fill in the water gaps. It is estimated that in arid areas, 50% of rainfall evaporates back to the atmosphere without contributing to crop productivity[15]. Capturing this water before it evaporates,

[11] To get an idea of the magnitude, Egypt's High Aswan Dam releases annually about 55 km^3, so the difference is equivalent to more than 10 High Aswan Dams annual supply of water. Put in other terms, this is more than the 500 km^3 projected to be used for domestic water supply worldwide in 2025.

[12] http://www.iwmi.org

[13] Population grows as per the UN Medium population growth forecast to 7.8 million, and the calorie level is assumed to increase from a present per capita value of 2,700 to 3,000.

[14] For irrigation, water productivity was calculated as kg per cubic meter of water withdrawn. On irrigated land, we calculated the growth in terms of kg per unit of evapotranspiration.

[15] See Rockstrom, 1999 for a discussion.

through improved crop properties such as fast-growing roots, or improved tillage practices seems to offer potential. Drought-tolerant crops, while not necessarily lifting the yield ceiling, can improve water productivity. And supplying a small amount of water at a time of stress can greatly contribute to productivity.

It is not up to us as a research community to decide how much more irrigation water will be needed, rather it is up to society to choose. What we can do is provide more options than are available today.

Conclusions

Symptoms of a global water crisis are degraded and depleted land and water resources, loss of biodiversity, and malnutrition due to lack of access to water as a means of food production. Fueling the crisis are growing demands leading to increased scarcity and competition. Increasing water use by both irrigated and rainfed agriculture fuels the additional demand for water. Therefore, a large part of the solution to the crisis is to be found in how water is managed in agriculture. A focus on increasing the productivity of water in agriculture is required. Obtaining more production per unit of water will make available more water for other uses including environmental uses and relieve scarcity and competition. In a broad sense, this means increasing the value obtained from each drop of water consumed. To do this will require the combined and concerted efforts of crop breeders, agronomists, ecologists, water management specialists, institutional and policy experts combined with water users, managers, and policy makers.

Solving the water crisis will depend on how we develop and manage water in agriculture. Getting the solution right will result in food security, reducing poverty, and enhancing ecosystem services. We cannot afford to get it wrong.

Acknowledgement

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References

1) Alcamo, J., Henrichs, T. and Rosch, T. (2000): World Water in 2025: Global Modeling and Scenario Analysis. In Rijsberman (ed.), World Water Scenarios Analyses, Earthscan Publications, London.
2) Bakker, M., Barker, R., Meinzen-Dick, R. and Konradsen, F. eds. (1999): Multiple uses of water in irrigated areas: A case study from Sri Lanka. SWIM Paper 8. Colombo, Sri Lanka: International Water Management Institute.
3) Cosgrove, W. J. and Rijsberman, F. R. (2000): World Water Vision: Making Water Everybody's Business. Earthscan Publications, London.
4) Eidenshink, J. C. and Faundeen, J. L. (1994): The 1 km AVHRR global land data set-first stages in implementation. International Journal of Remote Sensing. 15(17), 3343-3462.
5) Falkenmark, M. (2000): Competing freshwater and ecological services in the river basin perspective: An expanded conceptual framework. Water International 25(2), 172-177.
6) FAO (1999): The State of Food Insecurity in the World 1999. Rome, Italy.
7) FAO (2000): FAOSTAT Agriculture database, www.fao.org, FAO: Rome.
8) FAO (2000): Agriculture: Towards 2015-30 - Technical interim report. Rome, Italy: FAO.

9) Garcia, Y. T., Garcia, A. G., Oo, M. and Hossain, M. (2000): Income distribution and poverty in irrigated and rainfed ecosystems: The Myanmar case. Economic and Political Weekly, December 30, 4670-4676.
10) Hatton MacDonald, D. and Young, M. (2001): Institutional arrangements in the Murray Darling River Basin. In Abernethy, C. L. (ed.), Intersectoral Management of River Basins: Proceedings of an international workshop on "Integrated Water Management in Water-Stressed River Basins in Developing Countries: Strategies for Poverty Alleviation and Agricultural Growth," Loskop Dam, South Africa, 16-21 October 2000. Sri Lanka: International Water Management Institute (IWMI) and German Foundation for International Development (DSE).
11) Hong, L., Li, Y. H., Deng, L., Chen, C. D., Dawe, D. and Barker, R. (2001): Analysis of changes in water allocations and crop production in the Zhanghe Irrigation System and District - 1966 to 1998. In International Workshop on Water Saving Irrigation for Paddy Rice, 23-25 March 2001, Wuhan, China. Wuhan, China: China Rural Water and Hydropower. pp.4-18.
12) IWMI (2000): World Water Supply and Demand in 2025, document prepared for the World Water Vision, forthcoming in Rijsberman (ed.), World Water Scenarios Analyses, Earthscan Publications, London.
13) IWMI (2000): World Water and Climate Atlas. http://www.iwmi/atlas/atlas.htm
14) Janiah, A., Bose, M. L. and Agarwal, A. G. (2000): Income distribution and poverty in irrigated and rainfed ecosystems: Village studies in Chhattishgarh. Economic and Political Weekly, December 30, 4664-4669.
15) Molden, D., Sakthivadivel, R. and Samad, M. (2001): Accounting for changes in water use and the need for institutional adaptation. In Abernethy, C. L. (ed.). Intersectoral Management of River Basins: Proceedings of an international workshop on "Integrated Water Management in Water-Stressed River Basins in Developing Countries: Strategies for Poverty Alleviation and Agricultural Growth," Loskop Dam, South Africa, 16-21 October 2000. Sri Lanka: International Water Management Institute (IWMI) and German Foundation for International Development (DSE).
16) Molden, D., Sakthivadivel, R. and Habib, Z. (2001): Basin Use and Productivity of Water: Examples from South Asia. Research Report 49, International Water Management Institute, Colombo, Sri Lanka.
17) Postel and Sandra (1999): Pillar of sand: Can the irrigation miracle last? New York, NY, USA: W. W. Norton & Company. xvi, 313p. (Worldwatch book).
18) Renault, D. and Wallender, W. W. (2000): Nutritional water productivity and diets.. Agricultural Water Management 45 (2000), 275-296.
19) Rockstrom (1999): On-farm green water estimates as a tool for increased food production in water scarce regions. Physics and Chemistry of the Earth, Part B, Hydrology, Oceans and Atmosphere. 24(4), 375-384.
20) Sakthivadivel, R., de Fraiture, C., Molden, D. J., Perry, C. and Kloesen, W. (1999): Indicators of Land and Water Productivity in Irrigated Agriculture. Water Resources Development, 15(1&2) 161-179.
21) Seckler, D. (1996): The new era of water resources management: From "dry" to "wet" water savings. Research Report No. 1. Colombo, Sri Lanka: International Irrigation Management Institute.
22) Shah, T. Alam, M., Kumar, D., Nagar, R. K. and Singh, M. (2000): Pedalling out of poverty: Social impact of a manual irrigation technology in South Asia. Research Report 45. Colombo, Sri Lanka: International Water Management Institute.
23) Shiklomanov, L. A. (1999): World Water Resources: An Appraisal for the 21st Century. IHP Report. UNESCO, Paris.
24) Svendsen (2001): Basin management in a mature closed basin: The case of California's Central Valley. In Abernethy, C. L. (ed.). Intersectoral management of river basins: Proceedings of an international workshop on "Integrated Water Management in Water-Stressed River Basins in Developing Countries: Strategies for Poverty Alleviation and Agricultural Growth," Loskop Dam, South Africa, 16-21 October 2000. Sri Lanka: International Water Management Institute (IWMI) and German Foundation for

International Development (DSE).
25) World Bank (1994): World Development Report 1994. World Bank, Washington, DC, USA.