Global Water Shortages and the Challenge Facing Mexico

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\textbf{ABSTRACT} Numerous countries are facing a severe water shortage for food production, drinking water and industry, with profound impacts on the world’s poor and the potential for global conflicts. This article traces the past 30 years’ trends in irrigation and water productivity and projects global water supply and demand for the next 30 years, including estimates for Mexico. Options to address water shortages are discussed, including developing additional water resources, improving the management and productivity of already developed water resources and increasing food imports. In the short run, problems associated with water scarcity in many regions will become more severe. But with appropriate policies and institutions, the world’s water resources can be managed to meet the needs of a much larger population.

Introduction

Until recently most people believed that we would always have enough water to grow food, to drink and to support industry. As we begin the next millennium, however, many countries are entering an era of severe water shortage. Water scarcity could have a profound impact on the world’s poorest people and lead to global conflicts.

This article begins with a discussion of the development of irrigated agriculture and increase in water productivity over the past 30 years, the era of the so-called green revolution in agriculture. This is followed by a projection of global water supply and demand for the next 30 years—1995 to 2025—including estimates for water supply and demand in Mexico. The next two sections of the article discuss options for dealing with water shortages: developing additional water resources, improving the management and productivity of already developed water resources, or increasing food imports. The specific challenges facing Mexico are discussed. The article concludes that in the short run for many regions of the world problems associated with water scarcity will become more severe. However, there are sufficient water resources to meet the future needs of a much larger global population if appropriate policies, institutional reforms and management practices are adopted.

Growth in Irrigation and Water Productivity over the Past Three Decades

Over the past 30 years increases in food production have been achieved largely
by expanding irrigated area and increasing crop yields. New crop varieties were developed with shorter growth duration and greater yield response to fertilizer that performed well under irrigated conditions. Higher yields were achieved per hectare and per unit of water consumed. The expansion of reservoirs and of tubewell irrigation increased the area irrigated by over 70% (Table 1). Much of this expansion occurred in the season of high solar energy (the dry season) with high crop yield response to fertilizer. The higher food grain production resulting from this complementary relationship between varietal improvements, increased use of fertilizer and expanded irrigation came to be known as the green revolution. Food grain prices fell to 50% of their level in the 1960s and 1970s and have remained low and stable for the past 15 years (Figure 1).

The expansion of irrigation was achieved initially through the construction of dams and reservoirs. Of the more than 40,000 large dams, all but 5000 have been built since 1950 (McCully, 1996). In Mexico, the era of large dam construction (1930s to 1960s) coincided with increasing federal government involvement in irrigation that had previously been developed at a local level using local resources. Over time, however, the area irrigated by groundwater has increased in importance around the world. More reliable water delivery and declining extraction costs due to advances in technology and in many instances government subsidies for power and pump installation have encouraged private investment in tubewells. For example, in India and China, which account for 40% of the world’s irrigation, the area irrigated by groundwater rose from about 25% in the 1960s to well over 50% in the 1990s. This has led to the overexploitation of groundwater resources in the semi-arid regions where water tables have been falling at an alarming rate—often 1 to 3 m a year. These regions include
### Table 1. Irrigated area of the world: 1965 and 1995

<table>
<thead>
<tr>
<th>Region</th>
<th>Arable land ('000 ha)</th>
<th>Irrigated area ('000 ha)</th>
<th>Growth in irrigated area 1965-95 as % area in 1965</th>
<th>Irrigated area as a % of:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>1 277 457</td>
<td>1 376 872</td>
<td>149 923</td>
<td>260 576</td>
<td>74</td>
</tr>
<tr>
<td>Asia</td>
<td>461 263</td>
<td>499 787</td>
<td>102 695</td>
<td>180 658</td>
<td>76</td>
</tr>
<tr>
<td>North &amp; Central America</td>
<td>250 339</td>
<td>261 338</td>
<td>19 474</td>
<td>30 219</td>
<td>55</td>
</tr>
<tr>
<td>Europe</td>
<td>319 939</td>
<td>297 055</td>
<td>13 768</td>
<td>24 944</td>
<td>81</td>
</tr>
<tr>
<td>Africa</td>
<td>143 927</td>
<td>173 539</td>
<td>7 722</td>
<td>12 242</td>
<td>59</td>
</tr>
<tr>
<td>South</td>
<td>40 020</td>
<td>50 950</td>
<td>4 911</td>
<td>9 696</td>
<td>97</td>
</tr>
<tr>
<td>America</td>
<td>61 968</td>
<td>94 202</td>
<td>1 329</td>
<td>2 751</td>
<td>107</td>
</tr>
</tbody>
</table>

*Source: FAOSTAT database.*
some of the world’s major breadbaskets such as the Punjab and the North China Plain. Mexico has followed a similar pattern of rapid increases in groundwater extractions, for both agriculture and a burgeoning urban sector. Of a total of 600 aquifers identified nationwide, the number in overdraft rose dramatically from 35 (6%) in 1975 to 100 (17%) in 1999 (World Bank and CNA, 1999), with water tables falling as much as 2–5 m a year.

The world’s attention has been focused on the environmental degradation and dislocation associated with large dams. Meanwhile, hidden from view beneath our very feet a worldwide explosion in the use of pumps for irrigation, domestic and industrial use is degrading our water resources. The point has been reached in some areas where the overexploitation of groundwater poses a major threat to the environment, health and food security. The annual overdraft is estimated to be 200 BCM or approximately 7% of worldwide annual primary water diversions for irrigation (Postel, 1999).

**Projecting Supply and Demand for Water: 1995–2025**

The International Water Management Institute (IWMI) has launched a long-term programme to improve our understanding of water problems and to guide irrigation development and related food security efforts as we move into the next century. This section presents a synthesis of research conducted by the IWMI over the past four years to gain a better understanding of the magnitude of the water problem and the options open to countries in dealing with water shortages. The focus is on irrigation, which accounts for two-thirds of fresh water consumed globally, more than 80% in the developing countries and 83% in Mexico. The section draws heavily from two key documents: *World Water Demand and Supply, 1990 to 2025: Scenarios and Issues* (Seckler et al., 1998) and *World Water Supply and Demand: 1995 to 2025* (prepared as a part of the World Water Vision for Food and Rural Development presented at the World Water Forum in The Hague in March 2000). Since the first report on scenarios of water supply and demand for 2025 (Seckler et al., 1998) the analysis and data have been refined through the development of PODIUM, a *Policy Interactive Dialogue Model*. To our knowledge, PODIUM is the first model that attempts to project future supply and demand for food incorporating the supply and demand for water as a specific constraint.

The PODIUM model is designed to explore the technical, social and economic aspects of alternative scenarios projecting supply and demand for food and water in 2025. A major objective is to assist national governments in assessing various options for water resource development and management as they plan for the future. Figure 2 shows a global summary of the results of a *base scenario* for 125 countries representing 96% of the world’s population in 2025. For the same *base scenario* Table 2 presents a more detailed assessment of water supply and demand for 45 countries representing 83% of the world’s population in 2025. Separate projections are included for China, India and Mexico. The *base scenario* reflects a fairly optimistic assessment of the ability of countries to achieve higher food productivity developed water resource.

Making projections is hazardous, particularly when the data on which projections are based are of highly questionable validity as is certainly the case with regard to water supplies and demand. We have been unable, for example, to obtain any estimates of environmental water demand. This fact not withstand-
Table 2. Water supply and demand: 1995 estimates with projections to 2025

<table>
<thead>
<tr>
<th>Country</th>
<th>Number in group</th>
<th>Population</th>
<th>2025 Average of UN low &amp; medium</th>
<th>Domestic &amp; industrial use 2025 total</th>
<th>Primary irrigation supply 2025</th>
<th>Indicators 2025 primary water supply</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>% increase from 1995</td>
<td>% increase from 1995</td>
<td>% increase from 1995</td>
<td>% increase of UWR</td>
</tr>
<tr>
<td>All countries</td>
<td>45</td>
<td>4716</td>
<td>28</td>
<td>67</td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td>Group I</td>
<td>11</td>
<td>399</td>
<td>65</td>
<td>109</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Group II</td>
<td>14</td>
<td>934</td>
<td>46</td>
<td>146</td>
<td>50</td>
<td>64</td>
</tr>
<tr>
<td>Group III</td>
<td>18</td>
<td>1229</td>
<td>8</td>
<td>11</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>China</td>
<td>1</td>
<td>1221</td>
<td>18</td>
<td>303</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>India</td>
<td>1</td>
<td>934</td>
<td>36</td>
<td>376</td>
<td>18</td>
<td>40</td>
</tr>
<tr>
<td>Mexico</td>
<td>1</td>
<td>91</td>
<td>84</td>
<td>132</td>
<td>22*</td>
<td>45*</td>
</tr>
</tbody>
</table>

Notes: Group I: physical water-scarce countries; Group II: economic water-scarce countries; Group III: no water-scarce countries.

* Mexico projections of percentage increases in primary irrigation supply and primary water supply are from 1990, not 1995 as for the other countries or groups.

ing, the projections help to call attention to problems that if not addressed can have (and in fact in some locations are already having) serious social consequences. For example, the 1960s studies projecting food gaps and rising food prices never came to pass because appropriate investments were made and actions taken to prevent this. The projection exercises have also called attention to the weakness of the global data and the need for more reliable data at the national level.

Figure 2. Projected water scarcity in 2025. Note: The cross-hatched lines indicate countries that will import more than 10% of their cereal consumption in 2025.
As shown in Figure 2, 125 countries have been grouped into three basic categories of water scarcity:

- **Group I** (black) represents countries that face physical water scarcity in 2025. This means that, even with the highest feasible efficiency of water use, these countries do not have sufficient water resources to meet their agricultural, domestic, industrial and environmental needs in 2025. Indeed, many of these countries cannot even meet their present needs. The only options available for these countries are to invest in expensive desalination plants and/or reduce the amount of water used in agriculture, transfer it to the other sectors and import more food.

- **Group II** (grey) represents countries that face economic water scarcity in 2025. These countries have sufficient water resources to meet 2025 needs but will have to increase water supplies through additional storage, conveyance and regulation systems by 25% or more over 1995 levels to meet their 2025 needs. Many of these countries face severe financial and development capacity problems in meeting their water needs.

- **Group III** (white) consists of countries that have no physical water scarcity and that will need to develop less than 25% more water supplies to meet their 2025 needs. In most cases, this will not pose a substantial problem for them. In fact, several countries in this group could actually decrease their 2025 water supplies from 1995 levels because of increased water productivity.

- The crosshatched countries on this map are countries that are projected to import over 10% of their total cereal consumption in 2025.

A projected 2.7 billion people, including one-third of the populations of India and China, will live in regions that will experience severe water scarcity within the first quarter of the next century. Water shortages could lead to conflicts in the Middle East and North Africa but are likely to impact most severely on the poorest segments of the population in South Asia and sub-Saharan Africa where incidents of poverty are already high. However, the shortage of water will be pervasive, extending well beyond the semi-arid regions (depicted in black) and affecting even populations in well-watered areas. Expanding demand for water is draining some of the world’s major rivers, leaving them dry throughout most of the year including, we project, the Yellow River in China, the Cauvery and Ponnaiyar in South India, the Colorado and Rio Bravo in the southwestern US and Mexico and the Lerma in Mexico.

Table 2 summarizes for 45 countries the growth in population and in domestic and industrial demand for water. Despite the assumed improvements in management and significant increases in the productivity of the developed water resource through better water management, an estimated 17% increase in developed water resources will be required to meet food demand and 22% to meet demands of the total economy. For Group I countries (black), the potential for further development is almost completely lacking and for Group III countries (white) it is scarcely needed. The bulk of the development of new irrigated areas is projected to occur in Group II countries (grey) and in China and India. Group I countries will import most of their future cereal requirements. Many of the orange and some of the blue countries will also import in excess of 10% of their cereal requirements.

At the country level Mexico is endowed with sufficient water resources to cover its actual and future needs. According to the IWMI base scenario for the
year 2025, primary diversions to agriculture, industry and domestic demands will amount to 104 km$^3$; that is, less than half of the country’s potentially utilizable water resources. But the country average masks substantial differences among states. The spatial distribution of rainfall and water resources in Mexico is extremely uneven. Some 50% of the country’s runoff occurs in 20% of the territory in the Southeast. The North accounts for 30% of the territory but receives only 4% of the runoff.

Population and economic activities—and consequent water demands—are concentrated in the dry parts with little concerted planning effort to reconcile demand for water with supply. The arid and semi-arid areas account for 76% of the population, 90% of the irrigated area and 70% of the industries but only receive 20% of the precipitation (SEMARNAP, 1996). Problems related to over-exploitation of groundwater such as declining groundwater tables, pollution and salt intrusion occur primarily in the North, Northwest and the Mexico Valley. Despite significant pressure from water users and the general public to resolve these growing problems, the Comisión Nacional del Agua (CNA) has not addressed them systematically.

Figure 3 presents a state-level analysis of projected water scarcity in Mexico in 2025. The Group I states (black), which will face physical water scarcity, are concentrated in the North and centre of the country and account for 54% of the population. These are also the states where intensive irrigated agriculture is located (Sinaloa, Sonora, Guanajuato, Coahuila and Tamaulipas). Group II states (grey) are located in the Southeast (with the exception of San Luis Potosí, which appears to have relatively more water owing to the Huasteca region). Water is available in Chiapas, Tabasco, Campeche, Yucatán and Quintana Roo; however, the rate at which water resources development will need to increase to meet future demands places them in the economic scarcity condition.

Finally, Group III states (white) are projected to face little or no water scarcity in 2025 for several reasons, principally because there is relatively little irrigation
development to push demand. It should be noted, however, that poor water resource availability in states like Durango and Zacatecas may have prevented irrigation development in the first place. The remaining states in this group appear to have little or no projected scarcity, in part because of Mexico’s geography—the rivers that flow off the central plateau and collect additional runoff on their way to the Pacific Ocean or the Gulf of Mexico are ill-suited to irrigation development because the coastal plains are relatively narrow.

Major Paths for Increasing the Utilization and Productivity of Irrigation Water

There are three paths to generating more agricultural output per unit of country or state-level utilisable water:

- develop and consume more of the world’s utilisable water resource—expand irrigated area through development of irrigation infrastructure and storage facilities;
- consume more of the developed water resource for beneficial purposes—through recycling or other changes in basin- or system-level water management;
- produce more output per unit of developed water resource consumed—through crop varietal improvement, improved agronomic practices and/or improved water management.

The growing scarcity and competition for water will dramatically change the way we value and utilize water and the way we mobilize and manage water resources. Each country or state will have to assess its own situation given its particular set of resources and domestic demand for food. Should irrigated area be expanded and if so how? To what extent can we improve the productivity of already-developed water resources? How much should we rely on food imports? These are the questions that must be addressed by national policy makers as they plan for the future. The PODIUM model allows policy makers and planners in each country to run scenarios based on different assumptions about food demand, food supply and water availability for irrigated agriculture. They can assess the potential for increasing the utilization and productivity of irrigation water and estimate percentage of cereal grain demand that can be met with domestic resources.

IWMI studies designed to identify the potential for saving water and increasing water productivity typically start with water balance or water accounting. That is to say an assessment is made at basins, systems and farm level of water flows, water utilization for various purposes and the unutilized portion of the water. An analysis of water balance also is needed ex post to assess whether alternative interventions have resulted in an increase in water for beneficial consumptive purposes and an increase in water productivity. Having said this, it should be noted how few water-balance studies are conducted. For example, IWMI was recently asked to review a Project Completion Report of a number of World Bank investments in one of the world’s major irrigation countries (Perry, 1999). These investments were largely aimed at improving the ‘efficiency’ of irrigation systems by lining canals, better water control structures, improved water management and so on. The investment cost totalled about US$500 million and none of the associated documents included any form of water balance. Thus we do not know how much, if any, real water was saved by these investments.
Poor water quality has prevented economic development in this group of countries, as has Mexico's poor water management, an additional major problem in Mexico well-suited to an irrigation project.

Irrigating with Salted Water

Part of country water is called "salty," and it needs to be managed differently from freshwater. Water is salted—expand the definition of "water" and storage facilities. Similarly, many uses—such as irrigation—may require water management systems different from those of freshwater.

Irrigation

While traditional irrigation practices can reduce conveyance losses, they often result in a reduction in groundwater recharge, thus "robbing Peter to pay Paul."

An example of a water balance assessment is given in Table 3 for three very different systems: the Bhakra in north-west India, Kirindi Oya in southern Sri Lanka and the Lerma-Chapala in Mexico. In the Bhakra system 75% of the water inflow is consumed by the crop. By contrast, in the Lerma-Chapala 26% and Kirindi Oya only 20% of the water is consumed by the crop with significantly higher percentages consumed by trees, forests and home gardens. In both the Asian systems, there are some outflows to the sea, which with proper water management could be captured to increase crop production. The Bhakra is typical of many irrigation systems in semi-arid regions, while Kirindi Oya is typical of many in monsoon Asia. Particularly in the monsoon regions, the design of irrigation systems fails to take into account the very substantial demand and beneficial use of water for purposes other than crop production, including environmental demands. The result, as in the case of Kirindi Oya, may be an overestimation of the area that can be irrigated. The Lerma-Chapala data are particularly significant in that they demonstrate a 7.4% overcommitment of available water resulting from inadequate enforcement of existing water-allocation agreements. This overdraft clearly comes at the cost of the basin's aquifers and refers back to the earlier observation that aquifer overdraft may tend to disguise the urgency of water shortage.

In the remainder of this section we discuss in turn the three options listed above, providing examples from IWMI's own research of the potential for better water resource management and increased productivity per unit of water consumed.

Expanding Irrigated Area

The base scenario (Table 2) suggests that even with significant gains in water-use efficiency there will still be a need to develop a significant amount of new storage facilities whether through large dams and reservoirs, small reservoirs, or underground storage. Keller et al. (2000) outline the pros and cons of various storage strategies: groundwater storage, small surface water reservoirs, large dam reservoirs. However, the potential for expansion remains limited for a number of reasons. First, many rivers such as the Yellow in China, the Colorado in the US, the Cauvery in India, the Rio Bravo and Rio Lerma in

<table>
<thead>
<tr>
<th></th>
<th>Bhakra (India) 1995-96</th>
<th>Kirindi Oya (Sri Lanka) 1996</th>
<th>Lerma-Chapala (Mexico) 1950-79 average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net inflow (MCM)</td>
<td>17 684</td>
<td>475</td>
<td>35 470</td>
</tr>
<tr>
<td>Consumed by crops (%)</td>
<td>75.3</td>
<td>20.0</td>
<td>26.4</td>
</tr>
<tr>
<td>Consumed by forest, trees and home garden (%)</td>
<td>0</td>
<td>38.7</td>
<td>75.3</td>
</tr>
<tr>
<td>Evaporated in water bodies and falls (%)</td>
<td>2.1</td>
<td>11.1</td>
<td>4.2</td>
</tr>
<tr>
<td>Committed outflow to environment/downstream (%)</td>
<td>12.3</td>
<td>10.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Uncommitted outflow (%)</td>
<td>10.3</td>
<td>20.2</td>
<td>0</td>
</tr>
<tr>
<td>Change in storage (%)</td>
<td>0</td>
<td>0</td>
<td>-7.4</td>
</tr>
</tbody>
</table>

Source: Molden et al. (forthcoming) and Consejo Consultivo (1991).
Mexico are closed. That is to say the water resources in these rivers have been fully exploited and very little drains into the sea or other sinks. Additional water use by one party means reduced use by another party. Second, the cost of irrigation system development has been rising and the price of food grain has fallen resulting in unfavourable benefit–cost ratios for investment in irrigation infrastructure. Finally, environmental concerns have discouraged investment in irrigation, particularly among the international development banks. Biswas (1999) suggests that the Sardar Sarovar (Narmada Dam) in India became the World Bank’s ‘Vietnam’ in terms of support to water projects in the 1990s.

In the development of water resources, the complementary relationship between surface water and groundwater systems often is not well understood. With water tables falling, recharging groundwater has become a major concern. Chambers (1988), writing on canal irrigation in India, suggests that a major and perhaps the main beneficial effect of canal irrigation is to distribute water through the command area allowing it to seep and so provide water for groundwater irrigation. Paddy fields and small reservoirs can serve as ‘percolation tanks’ for groundwater recharge. IWMI studies in Mexico (Scott & Garcés-Restrepo, forthcoming) have clearly demonstrated the linkage between ‘leaky’ canals and ‘inefficient’ surface water irrigation on the one hand and aquifer recharge on the other.

Improving Water Management at System and Basin Level

A common perception is that irrigation wastes enormous quantities of water. If we could just be more efficient in the management of water for irrigation, there would be adequate water for irrigation and for other use. We believe that there are potentials for water saving and increasing water productivity through better management. However, the classical measure of irrigation efficiency is a misleading indicator of systems performance.

Typically countries such as India report an irrigation efficiency of 40%. This is based on the amount of water diverted from a source such as a river, aquifer or reservoir and delivered to the field through various channels to meet the water needs of the crop. Much of this water is ‘lost’ through seepage and percolation and runoff in conveyance and at the field plot level. But in most instances a significant portion of this drainage (the amount of the water diverted and conveyed to the field, but not used for evapotranspiration) is used elsewhere—perhaps in the next farmer’s field, perhaps through a return flow, or through groundwater extraction further down the basin. In short, one person’s drainage may be another person’s water supply. Thus, the potential for saving water through better management is not as great as the traditional measures of irrigation efficiency would lead us to believe. This fact notwithstanding, there are significant opportunities for improving basin- and system-level water management as illustrated below.

Policies, institutions and incentives. The growing scarcity of water, accompanied in many areas by closing water basins and rapid groundwater depletion, dictates the need for new policies, institutions and incentives. Institutional reforms will require the establishment of water resources bureaux or departments to coordinate the use of all the water resources in the basin, both ground- and surface water and to allocate water equitability among competing sectors—irrigation,
industry, domestic, hydropower and environment. For the past two decades the emphasis in institutional reform has been on the devolution of responsibility for operation and maintenance (O&M) in government-operated systems to local user groups. Mexico has been in the forefront of O&M transfer to users, although the CNA still firmly (and legally) controls water sources and their allocation. At the present time, O&M responsibility for over 95% of the area in public systems has been transferred to water-user associations at the local (secondary level) and the main canal responsibility is being transferred to groups or associations. This fact notwithstanding, government responsibility for managing and regulating water resources at basin or higher levels will increase as water becomes more scarce and will call for new management skills.

There are those who believe that the management of our water resources should be largely in the private sector and water resource development should be charged at its full cost, both to achieve economic efficiency and to induce institutional change. In some sectors this may be appropriate. However, the role of water—as a basic need, a merit good and a social, economic, financial and environmental resource—makes the selection of an appropriate set of prices exceptionally difficult (Perry et al., 1997). In irrigation, water resource management is subject not only to public sector failure but also to private sector or ‘market failure’. Technically, water recycling results in massive external benefits and costs that violate the optimizing conditions of a free-market systems. The intensity of external effects in water use is perhaps greater than in any other sector of the economy. Policy reforms should call for a more realistic pricing of water in its various uses while recognizing that water is both a public and private good and a necessity of life. Policies and regulatory responsibilities should include, for example, the safety of dams, flood control, water-quality regulation and enforcement and regulation of groundwater development (Perry, 1999).

Recycling. IWMJ’s research in Kirindi Oya provides an example of the potential impact of recycling. Through water balance studies (Table 3), it was determined that the cropping intensity could be increased and the area irrigated expanded to include the entire designed command area. This was accomplished by installing simple water-recycling structures in the drainage system (Renault, 1999). Through recycling plus better supply management 6000 poor farm families have seen their lives improve over the past two years.

Irrigation using wastewater, including urban sewage, is a common example of recycling that is gaining recognition around the world. In Mexico, for example, the entire 100 000 ha Mezquital valley irrigation system depends on Mexico City’s wastewater as its primary source of water. Nationwide, an estimated 250 000 ha of land are irrigated with wastewater, providing considerable water and nutrient benefits to farmers, while at the same time exposing both farmers and consumers to increased health and environmental risks. The CNA position for many years was that irrigation using Mexico City’s raw sewage water had no health or environmental costs, despite scientific evidence to the contrary (Cortés et al., 1996; Mendoza et al., 1996).

Reliable and responsive delivery. At Mahi Kadam in Gujarat, India, changes in the way water is delivered increased water productivity by 100% (Sakthiivadivel & Gulati, 1997). In China, farmers have tank ponds close to their fields where water
can be stored and accessed when needed. But in most developing country irrigation systems, water releases tend to be correlated with rainfall. Reliable and timely delivery is the exception, not the rule. Many farmers, frustrated by unreliable water deliveries, have opted to install tubewells. Crop yields under tubewell irrigation have been significantly higher. As noted earlier, today in India and China well over half of the irrigated area is served by wells. A number of other micro-irrigation technologies such as sprinkler and trickle irrigation have been developed that improve reliability and precision in irrigation delivery. Modifications in design to lower cost should make these technologies more widely available to developing country farmers in the future.

Large surface-water irrigation systems in Mexico often do not allow sufficient operational control to supply water on demand, even though water releases in general do correlate with periods of crop demand. Most of the country's high-value vegetable production for export is irrigated using wells. A number of cost-share programmes exist to promote the adoption of improved irrigation technologies, nominally with the objective of improving irrigation efficiency (notwithstanding our earlier observations on real water losses). Farmers who have benefited from these programmes have clearly admitted to us that the real effect is simply to expand their irrigated area, which in fact will increase water lost to evapotranspiration and result in even greater aquifer overdraft.

**Improving Water Management at Farm Level**

It is difficult to separate a discussion of improved farm-level water management from that of system or basin level. Likewise it is difficult to separate a discussion of improved farm-level water management from other improvements in farm-level agronomic practices. All three are closely linked. In the absence of reliable water deliveries, for example, farmers often opt to sink tubewells. Where water deliveries are reliable, farmers have different options. Reliable water can influence the choice of crop, amount of fertilizer applied and a host of other agronomic practices. Some of these decisions such as choice of planting date, method of land preparation, method of stand establishment (transplanted or direct seeded) can influence the amount of water that is lost through evaporation, runoff, or seepage and percolation. Then there are direct measures to either save and store water or use water more productively, such as raising the height of bunds to store rainwater in paddy fields or applying water to a crop only at critical periods. Finally, it should be remembered that increases in water productivity over the past three decades have come principally through the introduction of higher yielding varieties. That is to say, higher yield per hectare results in higher yield per cubic metre of water.

**Irrigated versus Rain-fed Agriculture**

Scientists disagree as to the relative contribution of growth in rain-fed versus irrigated agriculture for meeting future food needs. The total cultivated area of the world is about 1 billion ha, of which only about one-third is irrigated—the same percentage as found in Mexico where 30% of the total agricultural area of 21 million ha is served by irrigation infrastructure. Thus, a 10% increase in productivity of rain-fed agriculture would have twice the impact of a similar
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increase in irrigated agricultural productivity. In sub-Saharan Africa, however, only 5% of the area is irrigated.

Scientists have shown that a number of water harvesting and supplemental irrigation techniques hold great promise for increasing crop yields in water-scarce areas. But the adoption by farmers has been extremely limited, as the risk and costs have outweighed the benefits (Oweis et al., 1999). The answer seems to lie in providing lower cost technologies. In South Asia and Africa very low cost bucket-and-drip sets are becoming increasingly popular with farmers. In areas where shallow groundwater is plentiful, thousands of poor farmers in Bangladesh have used low-cost treadle pumps to supply water for crops for their own food security and additional income (Shah et al., 1999). Percolation tanks, used in India, provide another mechanism for capturing and storing water-shallow water tables to be pumped up when needed. We do not as yet know the potential of these technologies, the mechanisms for promoting large-scale uptake, or the impact on basin-level water balance.

International Trade and Comparative Advantage

As countries develop, agriculture as a portion of the total GDP shrinks although in absolute terms agriculture may continue to grow. The developed economies have chosen to subsidize agriculture. This has been a major factor in maintaining low world food prices but has reduced exports from developing to developed countries. The labour force in agriculture also shrinks during the course of economic growth, but the productivity of agriculture globally has continued to grow. Today 5% of the world’s farmers produce half of the world’s food (Carruthers & Morrison, 1994).

Figure 2 projects that most of the countries in Group I and II (black and grey) zones of physical and economic water scarcity will be importing 10% or more of their cereal grain needs. Allan (1998) has coined the valuable term ‘trade in virtual water’ to show how international trade can help alleviate water scarcity and other problems in many countries. Countries with plentiful water should export water-intensive crops, such as rice, to water-scarce countries. This is a natural application of the principle of comparative advantage in international trade. It happens historically with rice, which has been exported from the major river deltas, Vietnam, Thailand and Myanmar, where water is plentiful and labour has been cheap. Wheat is exported from Canada, the USA and Europe where it can be grown in cool seasons, with low water requirements. In the mid-1990s approximately 100 million tons of wheat exports reflected a ‘water trade’ of at least 100 km annually (Allan, 1998). Maize is exported from the USA largely because it can be grown without irrigation owing to the exceptionally favourable agroclimatic conditions of the ‘corn belt’. Figure 4 shows the trend in per capita exports of wheat and maize to Asia, Africa and Latin America. In Asia, because of substantial gains in food grain production, the trend has levelled off since 1980. But in Africa and more recently in Latin America there has been a steady rise. This principle also pertains to trade within countries. Egypt could save nearly 10% of its scarce water supplies, for example, by replacing sugar-cane production in the very hot south with cool season sugar beet production in the north.

In Mexico, while growth in production of cereal grains has stagnated, the volume of exports of irrigated high-valued crops continues to grow. Over the
last 30 years vegetable and fruit exports increased more than tenfold while at the same time cereal imports are growing. Mexican farmers increasingly focus on high-value crops such as fruit and vegetables that consume relatively little water at the expense of low-value and water thirsty crops such as cereals. Figure 5 shows that during the last five years the value of exports was 1 to 1.5 billion dollars higher than the value of cereal imports. To produce the fruit and vegetable exports, only 1 km$^3$ of water was evaporated by crops, while the production of imported cereals would have taken six times as much. The numbers clearly show the gain in both monetary and water terms of Mexico’s de facto virtual water conservation.

Food imports are essential where countries cannot grow enough food because of water or other constraints, as in many countries of the Middle East and sub-Saharan Africa. This is also true for some countries in Southeast Asia, like Malaysia, where the expanding industrial-service sectors are creating severe labour resource constraints in agriculture. In some countries in sub-Saharan Africa, the cost of inland transportation makes it better to feed coastal cities through imports than through domestic production—at least in the near term, until the rural infrastructure can be created.

A major problem with trade, of course, is that food imports must be paid for in foreign exchange, earned from exports or by grants and loans. This fact is somewhat hidden by large amounts of donor assistance in hard currency and historically heavily subsidized exports from the USA and Europe. In the theory of comparative advantage, every country should be able to export enough to cover imports. But in practice, this does not happen. Many of the most needy
regions of the world.

Figure 5. Value and ‘virtual water’ of cereal imports and vegetable/fruit exports in Mexico: 1961–97. Note: US dollars and ‘virtual water’, assuming water productivity of 1.2 kg/m³ crop evapotranspiration for cereals and 4 kg/m³ for fruit and vegetables.

countries, such as those of sub-Saharan Africa, do not have sufficient exports to pay for imports.

Challenges for Mexico

The opportunities for further irrigation development in Mexico are limited, although there may be scope for additional agricultural production in the more
humid, tropical south-east of the country that would be based on specialty crops (such as tropical fruits) grown under rainfed conditions or supplemental irrigation.

With the expected growth in urban population (and by extension, urban poverty), Mexico has established legal priority for domestic, potable water above all other uses. While this appears to be an appropriate measure, there is in fact little enforcement of existing agreements for inter-sectoral water allocation, resulting in rampant overexploitation of water resources (particularly groundwater) and little or no concern for environmental quality. The CNA does not have feasible water quality management, monitoring or evaluation programmes for the country despite rapid industrialization and the ensuing deterioration of water quality. The implications of urban wastewater reuse and peri-urban agriculture resulting from these trends have yet to be understood. For instance, what sorts of investments will be required to handle this water as a resource rather than as waste? What treatment processes are most suitable to preserve some of the nutrient value of wastewater? Finally, what are the environmental and health consequences of this inevitable reuse assuming appropriate investments and safeguards are established? The CNA must seriously consider these and related questions.

Mexico faces a complex set of external and internal factors and challenges that will determine the nature of future water scarcity. It is clear that with a common border and increasingly interdependent economic ties with its northern neighbour, Mexico has the opportunity to benefit from advances and gaps in US agriculture and water management. These include low and falling prices for basic agricultural commodities, particularly grains, and increased profitability of specialty markets for vegetables and fruits. These trends may act in concert to mitigate the severity of water shortages in Mexico, but must be seized on proactively by decision makers in Mexico, particularly the CNA.

Internally, Mexico has revised the legal and institutional contexts that could allow for reforms in its water sector; these processes are being observed carefully throughout the region and the world at large. Nevertheless, initiatives for real reform based on broader public and administrative participation in water management have been opposed by the CNA whose position is that participation processes must mature (Scott et al., 1998). This strident opposition is in fact sanctioned by the 1992 Law of the Nation’s Water (Ley de Aguas Nacionales) that identifies the CNA as the arbiter of who may and who may not participate in water-management decision making.

Despite the fact that as a country Mexico faces economic water scarcity, over half the population will face physical or absolute water scarcity in 2025. With a rapidly growing urban population and increasing industrial share of overall economic growth, it may seem to appear that agriculture will be the ‘sacrificial lamb’. Nevertheless, the social equity and migration implications—both within and past Mexico’s borders—make this option undesirable. The country’s limited but critical water resources must be managed responsibly to address the long-term goals listed above. Today’s policy decisions on how to guide water resources and agricultural development, through investments in infrastructure, management capacity and the energy sector, will significantly influence and may be able to alleviate the projected water-scarcity situation. This scenario poses serious challenges for the water sector in Mexico, particularly the CNA.
Conclusion

Today we are faced with a paradox. There appear to be sufficient global fresh water supplies to meet the needs of a much larger global population (Allan, 1998). In fact, it has been suggested by Biswas (1999) that as water prices increase there will be more investment in groundwater exploration to increase supply. Meanwhile, many parts of the world, Mexico, are already facing severe water scarcity and deteriorating water quality. Projections of future supply and demand suggest that the number of people affected is expected to increase sharply.

The World Water Forum held in The Hague in March 2000, the annual Stockholm Water Symposium and a host of other activities under the sponsorship of the World Water Council, the Global Water Partnership and the International Rice Commission of Irrigation and Drainage have done much to bring the growing water problem to the attention of the public. This fact not withstanding, there appear to be major obstacles in the short run to achieving increased productivity in water resources and the development of new water supplies.

The potential for further expansion of irrigated area is limited. Costs of new surface irrigation construction have risen to two to three times their previous level. This, coupled with the growing concerns of environmentalists, has discouraged further investments in large dam construction. Although the area irrigated by groundwater has been expanding, overexploitation and an associated decline in water quality have been occurring particularly in the semi-arid regions of the world including northern Mexico.

Institutional and policy reforms are needed to improve the management and increase the productivity of already developed water resources. Entrenched bureaucracies are major barriers to such reforms. Furthermore, there is as yet inadequate research to indicate the most profitable alternatives for saving water and increasing water productivity in agriculture.

Finally, owing to the sharp decline in world food grain prices, investments in cereal crop research have declined. Crop-yield growth (a major source of growth in water productivity over the past 30 years) has slowed. Today we are faced with a Catch 22. It does not pay to invest in improvements in crop production and management or water resources at today's low prices. But because of the long gestation period, the failure to invest could exacerbate the problem of water scarcity and threaten food security.

Severe droughts and sharply rising food prices spurred national governments and international agencies to address the ‘food crisis’ of the 1960s and 1970s. The projected shortages in food grain production were averted. The projected water shortages can also be averted. But perhaps it will require a shock such as occurred in the 1960s and 1970s to awaken policy makers and the public at large to take the necessary actions. Meanwhile, in many regions of the world, water scarcity will continue to shake the well-being, particularly of the poorest members of society.

Note

1. The International Commission on Large Dams defines a ‘large dam’ as one measuring 15 meters or more from foundation to crest.
References


