Multiple uses of water

Artists: Jhun Jhun Jha and Hira Karn, Nepal

9 Reinventing irrigation

Coordinating lead author: Jean-Marc Faurès

Lead authors: Mark Svendsen and Hugh Turral

Contributing authors: Jeremy Berkoff, Madhusudan Bhattarai, Ana Maria Caliz, Salah Darghouth, Mohammed Rachid Doukkali, Mona El-Kady, Thierry Facon, M. Gopalakrishnan, David Groenfeldt, Chu Thai Hoanh, Intizar Hussain, Jean-Yves Jamin, Flemming Konradsen, Alejandro León, Ruth Meinzen-Dick, Kathleen Miller, Monirul Mirza, Claudia Ringler, Lisa Schipper, Aidan Senzanje, Girma Tadesse, Rebecca Tharme, Paul van Hofwegen, Robina Wahaj, Consuelo Varela-Ortega, Robert Yoder, and Gao Zhanyi

Overview

The conditions that led to large public investment in irrigation in the second half of the 20th century have changed radically, and today's circumstances demand substantial shifts in irrigation strategies. Irrigation has ensured an adequate global food supply and raised millions out of poverty, especially in Asia, thanks to massive investments. But a stable world food supply, declining population growth rates, continuing declines in the real price of food, and the rising importance of investment in other sectors diminish the need to maintain similar levels of irrigation investment today. The era of rapid expansion of public irrigation infrastructure is over.

For many developing countries investment in irrigation will continue to represent a substantial share of investment in agriculture, but the pattern of investment will change substantially from previous decades. New investment will focus much more on enhancing the productivity of existing systems through upgrading infrastructure and reforming management processes. Irrigation will need to adapt to serve an increasingly productive agriculture, and investments will be needed to adapt yesterday's systems to tomorrow's needs. Substantial productivity gains are possible across the spectrum of irrigated agriculture through modernization and better responses to market demand. These gains will be driven by the market and financial incentives that will lead to higher farm incomes.

Large surface irrigation systems will need to incorporate improvements in water control and delivery, automation and measurement, and training of staff to better respond to farmers' *needs*. Conjunctive use of canal water and groundwater will remain an attractive option to enhance flexibility and reliability in water service provision. Under pressure from other sectors, the irrigation sector will find it increasingly hard to secure public finance for irrigation and drainage infrastructure. This situation will increase the financial burden on local government and users and is likely to have severe consequences for the irrigation sector. Cost-recovery mechanisms that guarantee the sustainability of systems will become imperative. At the same time, private investment in irrigation will likely grow in response to new opportunities for agricultural production.

Irrigation and drainage will be more site-specific and much more closely linked with policies and plans in agriculture and other sectors

Irrigation and drainage will still expand on new land, but at a much slower pace. They will be more site-specific and much more closely linked with policies and plans in agriculture and other sectors. Irrigation will remain critical in supplying cheap, high-quality food, and its share of world food production will rise to more than 45% by 2030, from 40% today. Farmers around the world will increasingly integrate into a global market, which will dictate their choices and behavior. New market opportunities will emerge where suitable national policies, infrastructure, and institutions are in place. Countries will need to tailor irrigation investment more closely to the stage of national development, degree of integration into the world economy, availability of land and water resources, share of agriculture in the national economy, and comparative advantage in local, regional, and world markets.

In regions that rely heavily on agriculture irrigation is likely to remain important in rural poverty reduction strategies. But irrigation's contribution to poverty reduction remains contentious, with some experts arguing that there are more effective ways to address rural poverty. In these regions increasing productivity in agriculture is often the only way out of poverty, and new irrigation development can be a springboard for economic development. The type and scale of intervention will vary considerably from one region to another. In Sub-Saharan Africa the best option to enhance food security and reduce people's vulnerability to external shocks and climate variability is investment in both rainfed and irrigated agriculture, combined with programs to improve soil fertility; increase access to inputs, information, and markets; and strengthen local institutions. Public investment in bulk infrastructure will be required to support private initiatives, especially those in small-scale irrigation.

The changing demand for agricultural products and the increasing understanding of the impacts of climate change on agriculture and the water cycle will also influence future investment in irrigation and water control. Rapidly rising incomes and urbanization in many developing countries are shifting demand from staples to fruits or vegetables, which typically require irrigation technologies that improve reliability, raise yields, and improve product quality. But as the century unfolds, weather events will become more variable—extreme events will increase, rainfall distribution will change, and glaciers and mountain snowpacks will shrink. Investment will be required to respond to these changes; especially where average precipitation declines and shrinking glacial and snowpack storage reduces summer streamflows. Adaptation strategies will generally require more storage capacity and new operating rules for reservoirs, posing onerous tradeoffs between allocations for environmental and agricultural water.

As competition for water from other sectors intensifies, irrigation will increasingly be under pressure to release water for higher value uses. Increased water scarcity will be an incentive for irrigation to perform better. The number of regions where water availability limits food production is on the rise, and intersectoral competition for water will increase almost universally with urbanization and economic development. Environmental water allocations will steadily increase and present a much greater challenge to irrigation than will cities and industries, because the volumes at stake are likely to be larger. Transfers of water from irrigation to higher value uses will occur and require oversight to ensure that they are transparent and equitable. Water measurement, assessment, and accounting will likely grow in importance, and water rights will need to be formalized, especially to protect the interests of marginal and traditional water users. The use of water pricing as an economic tool for demand management remains low and is not a workable option in the prevailing economic conditions for most irrigation schemes.

Irrigation and drainage performance will increasingly be assessed against the full range of their benefits and costs, not only against commodity production. The overall performance of irrigation has been acceptable, as judged by the current stability in world food supply and continually declining real prices for food. But this global gain has come at considerable financial cost, and in many cases irrigation systems have failed to meet their performance targets. Some have failed completely. The success of irrigation has also often come at the environment's expense, degrading ecosystems and reducing water supplies to wetlands. It has also had mixed impacts on human health. Better nutrition and improved water availability for domestic needs have improved hygiene and reduced infections and diseases. But irrigation is also associated with higher prevalence of malaria, schistosomiasis, and other waterborne diseases.

The overall performance of irrigation has been acceptable but at considerable cost

Decentralized and more transparent governance will be important in irrigation and drainage water management, and the role of governments will change. The recent trend to devolve the responsibility for irrigation management and the associated costs to local institutions, with more direct involvement of farmers, is likely to intensify. The many possible outcomes will range from full farmer ownership and operation, to contracted professional management, to joint management by government and farmers. As governments withdraw from direct managerial functions they will need to develop compensating regulatory capacities to oversee service provision and to protect public interests. While control of system infrastructure will likely be devolved, bulk water supply infrastructure, because of its multiple functions and strategic value, will usually remain the responsibility of the state.

Irrigation: a key element in the 20th century's agricultural revolution

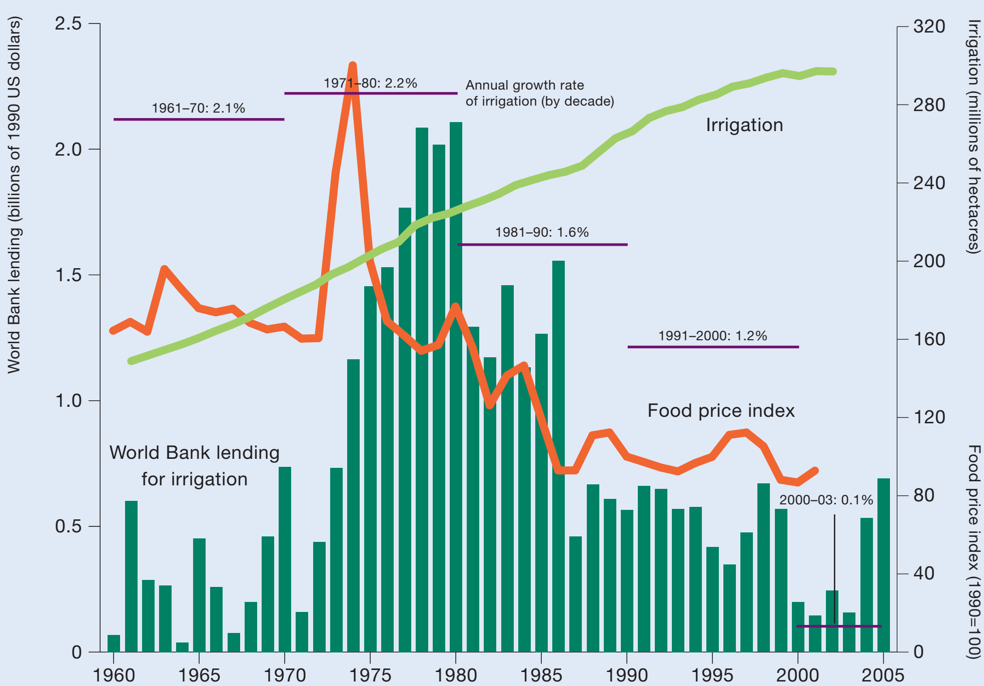
The last 50 years have seen massive investments in large-scale public surface irrigation infrastructure as part of a global effort to rapidly increase staple food production, ensure food self-sufficiency, and avoid devastating famine. Private and community-based investment in developing countries, particularly groundwater pumping, has grown rapidly since the 1980s, propelled by cheap drilling technology, rural electrification, and inexpensive small pumps.

Trends in irrigation development

Investment in irrigation accelerated rapidly in the 1960s and the 1970s, with area expansion in developing countries at 2.2% a year reaching 155 million hectares (ha) in 1982 (figure 9.1). Global irrigated area rose from 168 million ha in 1970 to 215 million ha over the same time frame (Carruthers, Rosegrant, and Seckler 1997). Rapid growth in irrigated area, together with other components of the green revolution package, such as improved crop varieties and substantial growth in fertilizer use, particularly in Asia, led to a steady increase in staple food production and a reduction of real world food prices. More recently, agricultural subsidizes in developed countries have helped keep food prices low (Rosegrant and others 2001).

The annual growth rate of irrigation development, particularly in large-scale public schemes, has decreased since the late 1970s due to several factors. The areas best suited to irrigation have already been developed, leading to increased construction costs for future

figure **9.1** | **Irrigation expanding, food prices falling**



Source: Based on World Bank and Food and Agriculture Organization data.

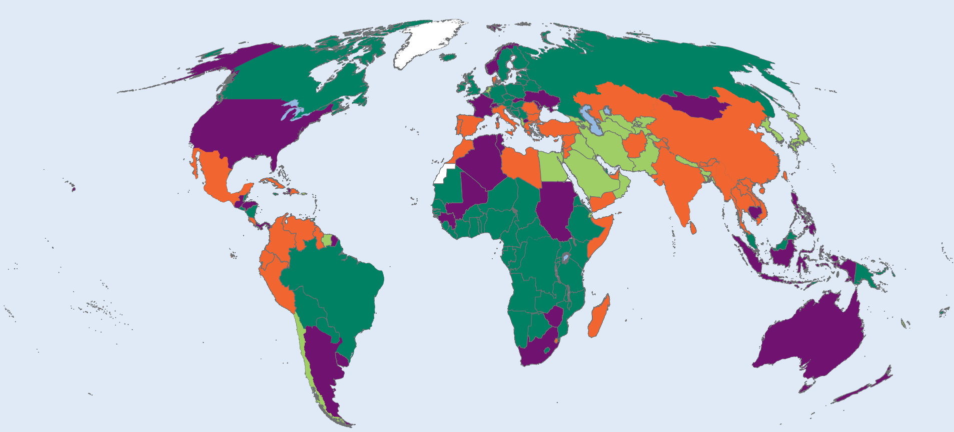
dams and related infrastructure, and prices of staple cereals have declined. Both of these factors have made irrigated agriculture progressively less economically attractive than in the past. The underperformance of large-scale irrigation (Chambers 1988) has also reduced donor interest (Merrey 1997). Concerns over negative social and environmental impacts, particularly the dislocation of residents in affected communities and the calls for increased in-stream flows for environmental purposes have received heavy publicity and discouraged lenders from investing in irrigation. More competition for water from other sectors has also reduced the scope for further development of irrigation. Declining cereal prices have slowed growth in input use and investment in crop research and irrigation infrastructure, with consequent effects on yield growth (Rosegrant and Svendsen 1993; Carruthers, Rosegrant, and Seckler 1997; Sanmuganathan 2000).

Irrigation is particularly crucial in sustaining agriculture across the "dry belt" that extends from the Middle East through Northern China to Central America and parts of the United States (map 9.1). Asia alone has over 60% of the world's irrigated land, both in semiarid and humid tropical conditions. By contrast, irrigation has remained limited in most of Sub-Saharan Africa, with a few large commercial schemes developed during the colonial period and a relatively modest small-scale irrigation subsector. The 1990s saw a substantial rise in private irrigated peri-urban agriculture in Sub-Saharan Africa in response to higher demand from growing cities for fresh fruits and vegetables (FAO 2005).

The advent of affordable drilling and pumping technologies in India and Pakistan in the mid-1980s led to rapid development of shallow tubewells and conjunctive use of

map **9.1** | **Irrigated areas as a share of cultivated area by country, 2003** (percent)

Less than 5% | 5%–15% | 15%–40% | More than 40% | No data | Inland water bodies



Source: FAO 2006a.

table 9.1 | **Irrigated land, total and as share of arable land, 1980, 1990, and 2002**

	Total irrigated area (thousands of hectares)			**As share of arable land** (percent)		
Region	**1980**	**1990**	**2002**	**1980**	**1990**	**2002**
World	*210,222*	*244,988*	*276,719*	*15.7*	*17.6*	*19.7*
Developed countries	*58,926*	*66,286*	*68,060*	*9.1*	*10.2*	*11.1*
Industrialized countries	37,355	39,935	43,669	9.9	10.5	11.9
Transition economies	21,571	26,351	24,391	7.9	9.8	10.0
Developing countries	*151,296*	*178,702*	*208,659*	*21.9*	*24.1*	*26.3*
Latin America and the Caribbean	13,811	16,794	18,622	10.8	12.5	12.6
Near East and North Africa	17,982	24,864	28,642	21.8	28.8	32.3
Sub-Saharan Africa	3,980	4,885	5,225	3.2	3.7	3.6
East & Southeast Asia	59,722	65,624	74,748	37.0	33.9	35.1
South Asia	55,798	66,529	81,408	28.6	33.9	41.7
Oceania, developing	3	6	14	0.7	1.2	2.4

Source: FAO 2004a.

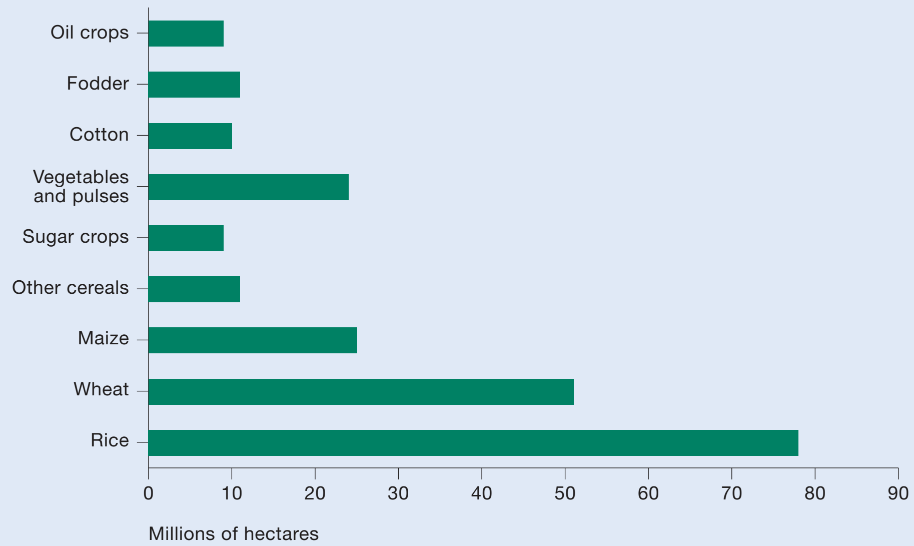
surface water and groundwater (Shah 1993; Palmer Jones and Mandal 1987). Direct control of farmers' water sources—either through groundwater pumping, drainage reuse, or direct pumping from canals and rivers—brought the flexibility and reliability in water delivery that most large-scale surface distribution systems did not offer. It also brought new challenges in managing irrigation schemes under conjunctive use, falling groundwater tables, and indirect subsidies though cheap or free electricity from public distribution systems (see chapter 10 on groundwater).

Official statistics indicate a total of 277 million ha of land under irrigation in 2002 worldwide (table 9.1; FAO 2006a), but the extent of land under irrigation is likely to be higher when unreported private investment in irrigation is taken into account. Irrigation covers 20% of all cultivated land and about 40% of agricultural production. In 1995, 38% of cereals grown in developing countries were on irrigated land, accounting for just under 60% of cereal production (Ringler and others 2003). Rainfed cereal yields averaged 1.5 metric tons per hectare in the developing world in 1995, but irrigated yields were 3.3 metric tons per hectare (Rosegrant, Cai, and Cline 2002). The difference in productivity between irrigated and rainfed agriculture varies widely, depending on the climate, combination of crops, and technologies. Typically, land productivity is two to four times higher in irrigated agriculture.

Moreover, cropping intensity is typically higher under irrigation, with up to three rice crops per year in parts of Southeast Asia and two crops per year in most of the Asian subcontinent. Figure 9.2 shows the distribution of crops under irrigation worldwide.

A diversity of systems

The term *irrigation system* covers a diversity of situations associated with a variety of crops, leading to multiple development and management strategies. There are fundamental figure **9.2** **Global distribution of crops under irrigation, 2000**



Source: Food and Agriculture Organization estimates based on data and information for 230 million hectares in 100 countries.

differences between public and privately managed schemes, between cash crop and food grain production, and between the humid tropics and arid areas. Irrigation plays different roles in different climatic contexts, supplying full, partial, or supplementary irrigation. To organize the discussion here, a simplified typology with five categories of irrigation systems is used, based principally on mode of governance (table 9.2 and appendix).

The analysis of irrigation systems and its implication in political terms must also take into account the economic environment. This typology is thus further refined by defining three stages of economic development of a particular region or country:

- Stage 1: Countries or regions within countries where agriculture accounts for a substantial share of the economy and employs a large proportion of the population (including most of Sub-Saharan Africa; Diao and others 2005).

table **9.2** **Typology of irrigation systems**

Type	Description
1	Large-scale public irrigation systems in dry areas, growing mostly staple crops.
2	Large-scale public paddy irrigation systems in humid areas.
3	Small- to medium-scale community-managed (and -built) systems.
4	Commercial privately managed systems, producing for local and export markets.
5	Farm-scale individually managed systems, producing for local markets, often around cities.

- Stage 2: Countries in transition to more market-based and industrial economies where the relative importance of agriculture is falling in economic terms but where a large part of the population still derives its livelihood from it (including most of Southeast Asia and the Middle East).
- Stage 3: Countries where agriculture contributes only a small share of the economy and further large-scale investment is unlikely (Republic of Korea, Malaysia, and Taiwan). The farming sector in these countries may follow divergent paths: from a competitive international market orientation (such as Australia or Brazil) to redefining the role of farmers as "guardians of the landscape," as in Europe, Japan, the Republic of Korea, and Taiwan (Hung and Shih 1994). In large countries all these outcomes can occur, and national policies must account for regional specificities.

> Private and informal irrigation is important in terms of both food production and food security

Trajectories of change within and between categories of irrigation farmers are shaped not only by agricultural policies but also by the capacity to ensure allocations of water in all three stages, by wider financial restrictions, and by local capacity to overcome pollution and environmental damage in countries moving through stages 2 and 3.

Past investment in irrigation

Irrigation has received most of the public agricultural investment in the developing world—and most of the public operating subsidies (Jones 1995). In the early 1980s irrigation investment peaked at 60% of total agricultural expenditures in the Philippines and more than 50% in Sri Lanka (Kikuchi and others 2002). In Viet Nam slightly more than half of public agricultural expenditures were still devoted to irrigation during the 1990s (Barker and others 2004). In most cases direct cost recovery has not fully covered either investment costs or operations and maintenance costs, making these investments subsidies to the agriculture sector. The investments have, however, helped balance the typically adverse agricultural terms of trade (agricultural price controls, taxes, and the like) also operating within the sector and eventually indirectly supported all food consumers.

Private investment (private entrepreneurs, commercial irrigation, farmers' investment in public irrigation) is significant (and in some places even larger than public investment) and generally growing. In parts of Latin America, where the private irrigation sector is most dynamic, 56% of irrigation is private (FAO 2000). Recognition and knowledge of farmer-managed and private irrigation, its importance, and its success are growing, and these forms of investment are likely to grow faster than public investment (Shah 2003). But government departments, having served primarily large public irrigation schemes, have rarely had the opportunity to learn from them and to provide them with the required support. Yet private and informal irrigation is important in terms of both food production and food security.

Economic benefits and costs of irrigation

Through increased productivity irrigation produces secondary benefits for the economy at all levels, including increased productivity of rural labor, promotion of local agro-enterprises, and stimulation of the agriculture sector as a whole. The overall multiplier effect on the economy has been estimated at 2.5–4 (Bhattharai, Barker, and Narayanamoorthy forthcoming; Lipton, Litchfield, and Faurès 2003; Huang and others 2006).

Under these conditions the multiplier effects are so broad that irrigation's impacts need to be viewed from the context of rural development rather than simply agricultural development. Road systems, education, health, and the entire way of life in rural areas are transformed by irrigation. Public investment in irrigation has been crucial in agricultural growth in many Asian countries: in Viet Nam it accounted for 28% of growth in overall agricultural output during the 1990s. Investments in agricultural research closely follows, accounting for 27% of total growth (Barker and others 2004).

Irrigation has historically had a large positive impact on poverty reduction (see chapter 4 on poverty) (Hussain 2005; Lipton and others 2003). At the same time, growing prosperity has highlighted the plight of those who have not benefited from irrigation. The largest positive impacts of irrigation on poverty and livelihoods, in both urban and rural areas, have been relatively cheap food for everyone and employment opportunities for the landless poor. Many recent studies agree that an increase in farm income from enhanced farm productivity creates an increase in demand for local nontradable goods and services, which offer labor opportunities to the poorest segments of the rural population (see chapter 4). The growth induced by increases in agricultural productivity that raise farm income does not worsen income distribution and therefore decreases the level of absolute poverty (Mellor 2002). Recent studies in India have found that irrigation and farmer's education level are the two main factors in improving agricultural productivity and alleviating rural poverty (Bhattarai and Narayanamoorthy 2003).

The largest positive impacts of irrigation on poverty and livelihoods have been relatively cheap food for everyone and employment opportunities for the landless poor

In addition to these large and far-reaching benefits there are many direct and indirect costs associated with irrigation. The budgetary costs are the easiest to document: irrigation-related development was the biggest budgetary item for some Asian countries in the 1980s. The environmental and social costs of irrigation are partly intrinsic to the nature of irrigation (for example, transformation of natural habitats) and partly due to choices about the type of agricultural practices that irrigation supports. Negative impacts can outweigh the positive ones, for example, when pollution, displacement of populations, increased inequity, reduced biodiversity, and waterborne diseases are not compensated for by substantial increases in productivity and well-being (Dougherty and Hall 1995; MEA 2005b). Important challenges for irrigation are to acknowledge, account for, and mitigate the unavoidable alterations of ecological systems while ensuring that negative impacts are minimized.

Beyond production: the multiple functions of irrigation

Economic assessments of irrigation projects are typically based on the internal rate of return, which compares the costs and benefits of irrigation development. But this approach does not capture the intangible benefits associated with irrigation (Tiffen 1987). In addition, multiple uses of irrigation water are also rarely taken into account (see chapter 4 on poverty). Irrigation development is usually associated with intensive agriculture and the forces of modernization, but it has a long history and in some places is closely linked to local culture and tradition, acting as a stable agroecosystem. As economies develop, the relationships among food production, food consumption, and food security become more complex.

Irrigation affects the material and the cultural life of society and the environment in four main ways: economic, social, environmental, and cultural (table 9.3). The impact in

table 9.3 **Impact of irrigation by type of system**

Impact	Large-scale public, dry zone	Large-scale public, paddy-based	Small- or medium-size community-managed	Private, commercial	Smallholder, individual
Economic					
Production	Low positive	Low positive	Low positive	High positive	High positive
Food security	High positive	High positive	High positive	Low positive	High positive
Rural employment	High positive	High positive	High positive	Low positive	High positive
Social					
Settlement strategies	Mixed	Mixed	High positive	None	None
Social capital	None	Low positive	High positive	None	None
Health	Mixed	Mixed	Mixed	Low negative	Mixed
Environmental					
Biological diversity	Mixed	Mixed	Mixed	Mixed	None
Soil and water conservation	Mixed	Mixed	Mixed	Mixed	None
Water quality	High negative	Mixed	Mixed	High negative	Low negative
Cultural					
Religious ceremonies	Low negative	None	Low positive	None	None
Landscape, aesthetics	Mixed	High positive	High positive	Low negative	None
Cultural heritage	Mixed	Mixed	High positive	None	None

Note: Mixed indicates a large variability of local situations.

each area varies with the type of irrigation system, and the magnitude (positive or negative) is subjective, but there is value in highlighting the complex and diverse roles of irrigation and in remembering that in many places, particularly Asia, the Near East, and South America, irrigation is embedded in the culture and history.

The next era of irrigation investments

The rapid expansion of irrigation in the 20th century is unlikely to be repeated because the economic justification for irrigation has changed with falling food prices and the overall adequacy of current food production levels. This section analyses the main factors that will influence future investments in irrigation and drainage.

The context has changed

While most major changes affecting public irrigation are progressive, the end of the cold war and acceleration of globalization have certainly intensified some of these trends (table 9.4). Population pressures are now easing. The world food system can now satisfy the needs of a slower growing population, and fears of food shortages and famines are receding in most places outside of Sub-Saharan Africa, though local shortages may intensify, leading to increased food trade (FAO 2003). Technology, including biotechnology, will table **9.4** Evolution of public irrigation since the 1960s

Context	1960s to 1980s	1990s to present
Goals: drivers	Food security	Livelihood, income
Resources: land, water, and labor	Abundant	Increased scarcity
Hydraulic development stages	Construction, utilization	Utilization, allocation
Dominant expertise	Hydraulic engineering, agronomy	Multidisciplinary, sociology, economics
Irrigation governance	Public	Mixed
Irrigation technology	Surface	Conjunctive use, pressurized
System management	Supply-driven	Farmer-oriented
Crops	Fixed, cereals and cotton	Diversified
Cropping intensity[a]	1–1.5	1.5–2.5
Value of water	Low	Increasing
Concern for environment	Low	Increasing

a. Average number of crops per year on area equipped for irrigation.
Source: Adapted from Barker and Molle 2004.

further enhance the productive capacity of agriculture and most crop yields will continue to increase. However, compared with the last two decades, the food supply may become tighter as a result of declining public expenditure on irrigation and agricultural research, leading to stagnation and increases in world food prices and to further degradation of the agricultural resource base.

Other changes will characterize the coming era as well. While food grain prices should continue to fall, perhaps eventually stabilizing at historically low levels, rising incomes will lead to shifts in food preferences, away from grains and toward fruits, vegetables, meat, and dairy products, all of which are higher value commodities and require more water and energy inputs. The population will continue to urbanize, and agriculture's share of GDP will fall in most countries. Finally, global climate change will disrupt existing cycles and patterns in various ways, including increased variability in precipitation (IPCC 2001) and reduced snowpack storage in mountains (Barnett, Adams, and Lettenmaier 2005).

Projections of developing country irrigation expansion by the Food and Agriculture Organization (FAO), International Food Policy Research Institute, and the International Water Management Institute predict much lower rates of expansion of irrigated land over the next 20–30 years (FAO 2003; Rosegrant, Cai, and Cline 2002; IWMI 2000). The FAO (2003) predicts an average increase of 0.6% a year between 1997/99 and 2030 in developing countries, compared with 1.6% a year from 1960 to 1990. Such projections are systematically lower than those given by most national irrigation departments, which generally rely more on past trends than on a careful analysis of demand for agricultural outputs. Nevertheless, irrigation's contribution to total agricultural production is expected to exceed 45% by 2030 as yields continue to increase and cropping patterns shift to higher value crops (FAO 2003). This means 12%–17% more water withdrawn for irrigation.

The situation will vary substantially from one region to another, and places where water is already stretched to the limit will see reductions in allocations for agriculture, a trend that will intensify as competition for water increases (Molle and Berkoff 2006).

Rationale for future investments in irrigation

This section considers investment in a broad sense, covering capital, institutional, and operational investments (box 9.1). There are five principal reasons to invest in irrigation over the next three to five decades.

> Irrigation's contribution to total agricultural production is expected to exceed 45% by 2030 as yields continue to increase and cropping patterns shift to higher value crops

First is to preserve and modernize the present stock of irrigation infrastructure. Continuing investment will be required to preserve the safety and improve the functionality of existing irrigation. Different elements have different lifetimes. Large dams may last hundreds of years with proper maintenance and attention to safety (unless rapid siltation reduces their lifespan), while pumps and other equipment may last only a decade.

Second, irrigation can be a path out of poverty for the rural poor. Where pockets of rural poverty exist within an irrigated agricultural context, intensification and shifts to higher value crops will create new employment opportunities, as will value-added post-harvest processing and water-dependent off-farm rural employment in handicrafts, livestock raising, and similar activities (Bakker and others 1999). Where rural poverty is widespread, other employment options are absent, and climate variability affects production (figure 9.3), as in parts of Sub-Saharan Africa, soil moisture control, along with complementary investments in rural infrastructure (such as roads and stronger local institutions), provides new farming opportunities. However, the extent to which irrigation contributes to poverty alleviation remains a contentious issue, with alternative vigorous arguments about ways to address rural poverty (Lipton, Litchfield, and Faurès 2003; Bhattarai and Narayanamoorthy 2003; Berkoff 2003).

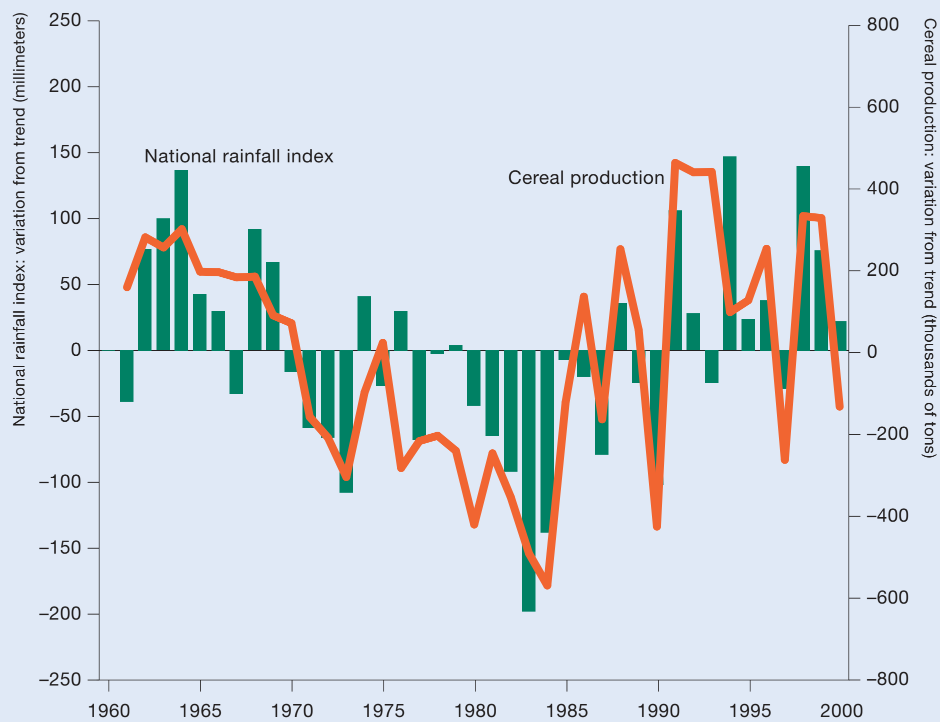
Third is to adapt to changing food preferences and changing social priorities. Most of the increased production of staple crops in the coming decades will come from intensification in existing irrigated areas, with higher yields per unit of water and land and higher cropping intensities. This implies investment in modernizing equipment and in

box 9.1 What do we mean by investment?

Investment in irrigation usually means public expenditure on new irrigation systems (capital investment). A broader definition is used here to include public investment in irrigation and drainage development, modernization, institutional reform, improved governance, capacity building, management improvement, creation of farmer organizations, and regulatory oversight, as well as farmers' investment in joint facilities, wells, and on-farm water storage and irrigation equipment.

Financing for major capital works has historically come from international development banks with varying levels of contribution from national budgets, as low-income countries typically lack sufficient resources to invest in large capital projects (Winpenny 2003) such as large dams. There has been significant experimentation with financing packages to attract private investment to developing countries through design, build, and operate contracts and franchises. But the niche for these instruments is limited, and expected financing levels have not been, and are unlikely to be, achieved.

figure **9.3** **Burkina Faso: rainfall and cereal production, 1960–2000**



Note: The national rainfall index is a measure of annual precipitation in the agricultural areas of a country (Gommes 1993). Both the national rainfall index and cereal production are presented here as the deviation from the long-term trend to better illustrate the impact of the interannual variation of precipitation on production.

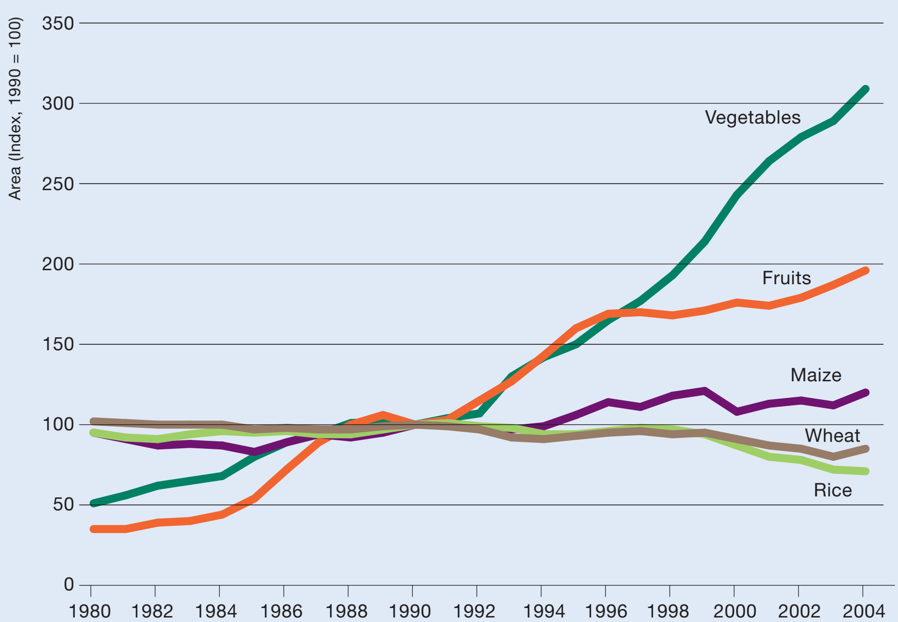
Source: Food and Agriculture Organization statistics.

improved water control. Irrigated basic food grain production will remain a priority in some countries. Rising incomes and growing urbanization in many developing countries are shifting demand from staple crops to fruits, vegetables, and "luxury" goods such as wine, as in China, for example (figure 9.4). These shifts are typically associated with investment in supply reliability and precision water application, but—more important for farmers—they also raise yields and improve product quality. Other shifts, such as increased meat and milk demand, also require increased grain production. Increased global trade also opens developed country markets to these commodities. Notably, these production shifts also require major investment in the entire post-harvest marketing chain.

Fourth, rapidly expanding urban populations and industrialization increase demand for both surface water and groundwater (Molle and Berkoff 2006). Changing social values that emphasize natural ecosystem protection will increase water allocations to the environment. In many cases these competing uses will take water directly away from agriculture, requiring compensating investment in new supplies or increased water productivity (see chapter 7 on water productivity). Reusing urban and industrial wastewater in agriculture will require new investment in water treatment and conveyance.

Fifth, investment will probably be needed to respond to climate change. Predictions by global climate models are gradually converging, and several characteristics now seem clear (IPCC 2001). Weather patterns will become more variable and will include more extreme events. The assured supply of water will decline and the need for additional storage, above or below ground, will increase to compensate. Rainfall distribution and volumes will change, and investment in groundwater and surface storage will be required in response. Finally, in several important locations high mountain snowfields serve as frozen reservoirs, releasing water gradually over the summer. The most notable example is the Himalayan Mountains, which source seven major rivers of East and South Asia. Climate change is shrinking these snowfields, reducing their storage capacity, and causing more precipitation to fall as rain, increasing spring flows and flooding while reducing summer flows (Barnett, Adams, and Lettenmaier 2005). With more than one-sixth of the Earth's population relying on glaciers and seasonal snow packs for their water supply, the consequences of these hydrological changes are likely to be severe.

figure **9.4** **Evolution of harvested area for major crop groups in China, 1980–2004**



Source: FAO 2006a.

The most vulnerable people are the poor, landless, and marginal farmers in rural areas dependent on isolated rainfed agricultural systems in humid, semiarid, and arid regions. Small changes in rainfall will result in big changes in river flows and soil moisture. The African continent has the largest number of countries that are already vulnerable to climate variability and extremes because of a lack of surface water and groundwater resources in the semiarid and arid regions. Further compensatory irrigation development will be necessary in these regions, to supplement both existing irrigation systems and rainfed systems. Necessary changes to fixed capital associated with irrigation may represent one of the largest costs associated with climate change adaptation and will present considerable challenges to the poorest farmers (Quiggin and Horowitz 1999).

While irrigated grain production will remain important, a variety of niche markets will emerge, creating opportunities for innovative entrepreneurial farmers where suitable national policies are in place

Types of investment

The environment in which irrigation investment decisions will be made is far more complex today than in the past: more stakeholders, more competing demands for water, and no single overwhelming driver for investment. Irrigation investment will thus be more carefully tailored to particular circumstances, reflecting stage of national development, market opportunities, degree of integration into the world economy, land and water availability, share of agriculture in the national economy, and comparative advantage in regional and world markets.

Farmers around the world will continue to integrate into a global market that will increasingly dictate their choices and behavior. While irrigated grain production will remain important, a variety of niche markets will emerge, creating opportunities for innovative entrepreneurial farmers where suitable national policies are in place. By contrast, smallholder farmers in Sub-Saharan Africa have few opportunities to take advantage of global markets. Water control investment could be an important part of rural development strategies in many Sub-Saharan countries, but it should be made in connection with policies that allow farmers to better serve local or regional markets (FAO 2006b).

Countries with a legacy of aging irrigation infrastructure will need to invest more in technical and managerial upgrading and less in new development, progressively improving the performance of irrigation in response to growing demand for more reliable water service. Investment in drainage will continue at relatively modest levels, although regional waterlogging and salinization problems resulting from past development will continue to require remediation. Thus there will be considerable tension arising from these financial needs compared with government's willingness and ability to finance them.

New development will still take place where enough land and water resources are available and where national priorities support it. It will be more site-specific and more closely linked with policies and plans in other sectors. Table 9.5 shows projections of expansion of irrigated land and investments in new development and rehabilitation between 1998 and 2030 based on unit costs provided by various lending agencies. Irrigation investment costs vary widely in developing countries, from less than $1,000 per hectare to as much as $20,000, averaging $3,500 in 2000 (Inocencio and others forthcoming; FAO data). Irrigation investment costs are generally much higher in Sub-Saharan Africa than in Asia, reflecting the challenging environment of the region, unfavorable geomorphological

table 9.5 Projections of capital investment needs in irrigation development and rehabilitation in 93 developing countries, 1998–2030

Region	Irrigated area (thousands of hectares)			Unit cost (US dollars per hectare)		Total cost (millions of US dollars)		
	1998	2030	Change (percent)	New	Rehabilitated	New	Rehabilitated	Total
East & South East Asia	71,500	85,300	19	2,900	700	40,000	46,400	86,500
Latin America & Caribbean	18,400	22,000	20	3,700	1,300	13,400	23,900	37,300
Near East & North Africa	26,400	33,100	25	6,000	2,000	40,100	52,800	92,900
South Asia	80,500	95,000	18	2,600	900	37,600	68,500	106,100
Sub-Saharan Africa	5,300	6,800	30	5,600	2,000	8,900	10,500	19,400
Total	202,000	242,200	20	3,500	1,000	140,100	202,000	342,100

Source: Based on FAO 2003 and Inocencio and others forthcoming.

conditions, higher infrastructure development costs, and differences in the scale of irrigation development projects. These factors seriously constrain attempts to develop irrigation in the region.

Priorities for investment by type of system

In large-scale public surface irrigation systems in dry areas most investment in existing systems should improve water control capability and supply predictability and increase transparency and accountability to the user. Areas with incomplete drainage and high water tables will probably see investment in completing these networks and associated salt disposal works to mitigate secondary soil salinization. Investment will typically involve a mix of technological and managerial upgrading.

In large-scale public surface irrigation systems in humid areas investment should enhance flexibility in the service of water in existing systems and the potential for operation to enhance the multifunctionality of the system. The level of flexibility needed in irrigation is subject to debate (Ankum 1996; FAO 1999a; Horst 1998; Perry and Narayanamurthy 1998). It will likely be determined case by case based on farmers' needs and cropping opportunities, local agricultural policies, and the availability of financial resources for investment. Flexible service will be increasingly important as off-season cropping expands, as in Viet Nam's Red River Delta (Malano, George, and Davidson 2004). It may be achieved through private investment in low-lift pumps or on-farm storage reservoirs, for example, or through public investment in intermediate in-system storage reservoirs. Investment in flexibility will also support new cultural practices for rice which may, for example, involve alternate wet and dry irrigation as opposed to continuous ponding (see chapter 14 on rice). Some countries in humid regions that did not participate in the construction boom of the 1960s and 1970s may continue to construct storage to enhance basin-level water control, including for irrigation, far into the 21st century.

Further dramatic private investment in groundwater irrigation and on-farm storage can be anticipated in large-scale surface irrigation systems (photo 9.1) in both dry and humid areas, as well as in very small (farm) systems. A major challenge in national investment strategies will be arriving at a balance of polices that allow equitable development (for instance, policies favoring cheap imported pumps and motors) but constrain overuse (for instance, by limiting or withholding energy subsidies for abstraction) (see chapter 10 on groundwater). Investment will be required to more effectively monitor and regulate such private development.

In areas of small- to medium-scale community-managed irrigation, mostly traditional subsistence schemes, complementary investments in roads, communications, and other supporting infrastructure that enhances information flows and market access usually offer high payoffs. Additional investment in new small-scale development is warranted in some circumstances, and incorporating small-scale irrigation development into comprehensive rural development programs may offer better chances of success and sustainability (Ward, Peacock, and Gamberelli 2006). These systems are also fertile ground for low-pressure irrigation technologies. Low-cost technologies, including small pumps, marketed through the private sector have rapidly expanded in several countries over the last decade (Shah and others 2000; Heierli and Polak 2000; Barker and Molle 2004).

For private commercial irrigation responding to local and export markets, water will become more of a commercial commodity than a common good

For private commercial irrigation responding to local and export markets, water will become more of a commercial commodity than a common good. Improving connectivity, in combination with well specified water rights, will allow regular water transactions among users and more extensive reuse of drainage and treated wastewater. Growers will likely continue to make major investments in on-farm water application technology to improve productivity and product quality. Governments and individuals would need to invest in measurement and control technology.

Photo by G. Bizzarri/FAO

Photo 9.1 Farmer pumping groundwater for irrigation table **9.6** **Focus for investment by type of irrigation system**

System type and category	Agriculture economy, large rural population	Transition	Industrial, market-based economy
Large-scale public irrigation systems in dry and humid areas			
Policy focus	Integrated rural development	Linking water and agriculture policies	Implementing integrated water resources management approach
Capital investment, water	Small and large dams, gravity irrigation development, drainage development, on-farm groundwater development		Upgrading irrigation and drainage infrastructure
Capital investment, other	Rural infrastructure, roads, markets, social and health infrastructure, electrification		Upgrading rural infrastructure
Regulation	Land tenure and water rights, stakeholder involvement in scheme management	Water rights, local institutions regulations, participatory irrigation management	Irrigation management transfer
Management	Increased reliability in system operation	Restructuring, improved accountability and transparency, improved system control and operations, enhanced flexibility of water service, enhancing system multifunctionality	
Capacity building	Training irrigation staff and farmers, water user association formation and strengthening		Strengthening of professional organizations, market information systems
Finance	Term finance, rural credit and micro-credit, grants	Term finance, agricultural savings and loans	Commercial financing
Technology	Land leveling, shallow wells, small-scale pumping technology, conjunctive use of surface water and groundwater		Automation, pressurized irrigation systems, water quality monitoring
Small- to medium-scale community-managed systems			
Policy focus	Integrated rural development	Linking water and agriculture policies	
Capital investment, water	Runoff river, weirs, diversion, local storage and small dams	Local storage and small dams, improved water distribution infastructure	
Capital investment, other	Rural infrastructure, roads, market access and information, social and health infrastructure, electrification		
Regulation	Water rights, including traditional water rights	Recognition and formalization of water rights and bulk water allocation	
Management	Conflict management, on-farm water management		
Capacity building	Training of extension staff, water user association formation and empowerment	Water user association monitoring and support, staff training	
Finance	Grants, targeted subsidies	Rural finance	
Technology	Small-scale microirrigation systems, tanks	Mechanized agriculture, deep tubewell drilling, pressurized irrigation systems	

table 9.6 Focus for investment by type of irrigation system (continued)

System type and category	Agriculture economy, large rural population	Transition	Industrial, market-based economy
Commercial privately managed systems			
Policy focus	Market chain; negotiating favorable trade policies		
Capital investment, water	Diversion dams, deep tubewells	Runoff recycleing, automation of water supply	Automation
Capital investment, other	Markets, communication and storage infrastructure, including for export		
Regulation	Bulk water allocation, water rights, tariffs		
Management	Irrigation scheduling, soil moisture monitoring		
Capacity building	Water quality monitoring		
Finance	Commercial finance		
Technology	Overhead irrigation, sprinkler and micro-irrigation technologies	Precision farming, pivots, lateral moves, microirrigation, fertigation	
Farm-scale individually managed systems for local markets			
Policy focus	Food safety, food security and nutrition policies		
Capital investment, water	Shallow well drilling, canals		
Capital investment, other	Market and infrastructure development	Rural electrification, energy pricing	Market and infrastructure development, wastewater treatment
Regulation	Tenure security, water rights, food safety control		Tenure security, food safety control, environmental control
Management	Wastewater reuse		
Capacity building	Training on on-farm water management and food and water quality control		
Finance	Micro-finance		
Technology	Low-cost, robust irrigation technology	Mechanized groundwater use	Water measurement and control, automation, low pressure irrigation

Note: *Term finance* refers to equity or medium- and long-term loan finance.

For individual smallholder irrigation responding to local markets, private investment in water application technology should be able to support improved output and product quality. Complementary public investment in governance and improved markets and infrastructure should strengthen this sector. Public intervention will also be needed in regulatory fields, including tenure security and specification and registration of equitable water rights, and in health-related monitoring and education. The link among smallholders, the private sector, and governments for the provision of services (technical advisory, finance, and marketing) needs to be better developed. Innovative approaches, such as the farmer field school, will be needed to compensate for the reduction of public extension services.

In nearly all situations significant investment will be required in training, particularly to manage the transition from construction to management orientation in irrigation systems. There will be a strong demand for well trained professionals at all levels of water management, with increasingly multidisciplinary perspectives and the acquisition of a learning culture (see chapter 5 on policies and institutions). Table 9.6 summarizes possible focuses for investment by type of irrigation system.

> Investment in irrigation has not always been driven by the need to increase food supply or to stabilize production; other hidden political agendas have also considerably influenced investment decisions

Adapting yesterday's systems to tomorrow's needs

The recent rapid development of irrigation has been the subject of many controversies, and experts disagree strongly on its overall performance. Rehabilitation, modernization, and a range of institutional reforms including irrigation management transfer and participatory irrigation management have been advocated over the last 20 years as ways to improve the delivery of water services, reduce recurrent costs, and boost productivity in large irrigation schemes. The results have been mixed, and it is important to understand the reasons behind the failures and successes to distinguish which options can be pursued, what can be further improved upon, and what innovations can replace them (see chapter 5 on policies and institutions).

Overall performance of public irrigation schemes

On average, the economic performance of public irrigation projects has been relatively good. About 67% of World Bank–financed irrigation projects from 1961 to 1987 were rated satisfactory by the Bank's Operations Evaluation Department, with an average internal rate of return of 15% (Jones 1995). Large investment projects tended to show higher returns than small ones, mainly because of economies of scale, but small-scale irrigation projects within them had lower costs and offered higher returns (Lipton, Litchfield, and Faurès 2003; Inocencio and others forthcoming).

This positive view is often contested, and there are numerous cases of poor performance, mostly relating to failure to meet design performance targets (ODI various years). In addition, there are several cases of significant failure of large-scale irrigation schemes for reasons varying from overcommitment of water resources to poor design and construction, to lack of market, labor, managerial skills, or financial resources for operations and maintenance. In Sub-Saharan Africa, for instance, about 18% of land under irrigation is not used (FAO 2005), and many Asian countries have large amounts of unused irrigable land.

Indeed, investment in irrigation has not always been driven by the need to increase food supply or to stabilize production. Other hidden political agendas have also considerably influenced investment decisions, with obvious implications for the systems' overall economic performance. Public funding aimed at benefiting a particular area for electoral purposes has influenced investment priorities, with politicians promising new irrigation schemes to villages even when such schemes are not feasible in technical or economic terms (Mollinga 1998; Reisner 1986). In other places large public irrigation schemes are being constructed to lay claim to transboundary water even when rivers are already overcommitted. Moreover, perverse incentives for lending institutions increase project budgets beyond requirements. Corruption and rent-seeking have also led to higher project costs and lower economic returns on irrigation investments in many cases (Wade 1982; Repetto 1986; Rinaudo 2002). Land tenure, where it favors absentee landlords, can also seriously constrain the development of productive irrigated agriculture (Hussain 2005).

Planning and design flaws are among the main causes of irrigation schemes' poor performance and often lead to nonfunctioning systems, unreliable water supplies, and excessive management complexity (Plusquellec 2002; Albinson and Perry 2002; Bos, Burton, and Molden 2005; IFAD and IWMI forthcoming). Possible future developments of irrigation technology are summarized in box 9.2.

box 9.2 | Technologies and irrigation in the future

Technological improvements will happen at all levels and affect all types of irrigation systems. Better technologies do not necessarily mean new, expensive, or sophisticated options, but ones that are appropriate to the agricultural needs and demands, the managerial capacity of system managers and farmers, and the financial and economic capacity needed to ensure proper operation and maintenance. We can expect better design and better matching of technologies, management, and institutional arrangements.

Technological innovation will occur in broadly two categories:

- At the irrigation system level: water level, flow control, and storage management within surface irrigation systems at all scales.
- On farm: storage, reuse, water lifting (manual and mechanical), and the adoption of precision application technologies such as overhead sprinkler and localized irrigation. As farms consolidate, particularly in larger more formal systems, increasing mechanization will require greater attention to land forming and farm layout. In Africa the emerging pattern of development and adoption of low-cost, microirrigation technologies will likely continue and strengthen (see chapter 4 on poverty).

Many of the technologies already exist, particularly the hardware. Considerable change can be expected on the soft technology side as electronics, communication systems, computers, and instrumentation become cheaper, more reliable, more accessible, and more available throughout the developing world. Automation for monitoring and control (including supervisory control and data acquisition in formal canal systems) and measurement (of groundwater levels, canal discharges, and even on-farm and water-course deliveries) will become more widespread. Over time this technology will be adopted in smaller informal systems and in groundwater irrigation, as well as more quickly by more commercially oriented growers at all scales.

Satisfying real-time demand more quickly and improving flexibility in formal canal systems will be achieved largely by further expansion of conjunctive use of groundwater and assisted by better canal management, mostly likely through intermediate service options such as "arranged demand." Software for managing lower system level demands will become more commonplace.

Some irrigation systems may continue with simple infrastructure and management systems, provided that they are well understood and appropriate to cropping patterns and user needs. Islands of minimal technology development in irrigation are also likely, especially where water remains abundant. There will be increasing interest in affordable technologies of all types (Keller and Keller 2003), well adapted to private investments.

Engineering designs sometimes do not match the management capacities of agency staff, water user associations, or farmers (Murray-Rust and Snellen 1993). Even simply structured large-scale irrigation systems with proportional division of flows through branching networks of canals (typically in Asia) require well trained professional managers and operators to achieve acceptable levels of performance in water delivery service (Horst 1998).

Many attempts to privatize water services have failed, and the extent to which such a model should be widely promoted remains highly controversial

Institutional reforms and prospects for future water management

The last 15–20 years have seen the development of institutional reforms for public irrigation management in more than 50 countries (FAO 1997; FAO 1999b; Johnson, Svendsen, and Gonzalez 2004), with a focus on withdrawing government from management and devolving responsibilities from centralized bureaucratic management to lower levels, including water user associations. Positive outcomes have been reported in Armenia, Australia, China, Colombia, Malaysia, Mexico, Peru, and Turkey, where reforms have improved maintenance standards of irrigation infrastructure. In most cases the transfer of costs from government to farmers improved maintenance, equity, yields, and income, thus at least partially fulfilling the purpose of the reforms. But the nature and degree of success is contested (Rap, Wester, and Pérez-Prado 2004; Vermillion 1997; Shah 2003), and there are many cases of wholesale nonperformance in irrigation management transfer.

In the context of irrigation management transfer, public-private partnership and the scope for professional "third-parties" between farmers and government are receiving increasing attention (Tardieu and others 2005). In Chile, China, Iran, and Viet Nam experiments are being conducted where farmers contract private or semiprivate companies to provide irrigation services. In China legally established water user associations establish operating franchises with public water bureaus.

But many attempts to privatize water services have failed (Qian 1994), and the extent to which such a model should be widely promoted remains highly controversial. To be viable, private water services must be based on reliable and measurable provision of service and include a reliable source of funding. Also needed are adequate regulations and dispute settlement mechanisms and training for water user associations and local service providers. Of particular concern are the difficulties in assessing operation and maintenance costs and ensuring that private managers do not delay rehabilitation and maintenance to show reduced management costs. The transfer of responsibilities for collecting water taxes from government to local institutions also presents challenges in financial accountability.

Sectoral reforms in irrigation management cannot succeed in a vacuum and depend heavily on broader reforms in governance and transparency at the national level and on agricultural policies (see chapter 5 on policies and institutions). The necessary legal reforms have often not happened or have been enacted only on paper and thus fail to give a solid and practical underpinning to irrigation management reforms. The main conditions for success and reasons for failure of institutional reforms are presented in table 9.7.

Another reason for failure often lies in the emphasis on water by irrigation departments. Poor performance of irrigated agriculture may be the result of non-water-related constraints, in which case irrigation management reforms will attract little attention from

table 9.7	Main conditions for success and reasons for failure of institutional reforms
Conditions for success	**Reasons for failure**
▪ Strong political backing. ▪ A clear role for the different stakeholders. ▪ Support for the empowerment of institutions at all levels (including water user associations and local governments). ▪ The autonomy of the water user associations. ▪ The legal framework needed to accommodate the proposed changes in authority. ▪ Capacity building of the people governing the transferred system. ▪ Functioning infrastructure. ▪ Success in recovering operation and maintenance costs.	▪ Lack of political support. ▪ Resistance of public agencies and water users. ▪ Insufficient resources. ▪ Poor water quality. ▪ Lack of proper involvement of water users. ▪ Transfer of dilapidated or badly designed infrastructure that is dysfunctional and needs major improvement.

Source: FAO forthcoming

farmers. The broad sociotechnical environment of irrigation is summarized in figure 9.5 to illustrate the importance of matching technology and institutional development in a specific context. Reality is inevitably far more complex, and the intention of the figure is to show key issues that need to be addressed to achieve good irrigation system performance rather than to offer a prescription with neat cause and effect links. Underlying this set of links are the incentives, vested interests, and communication pathways that are more intangible and hard to include in a simple diagram.

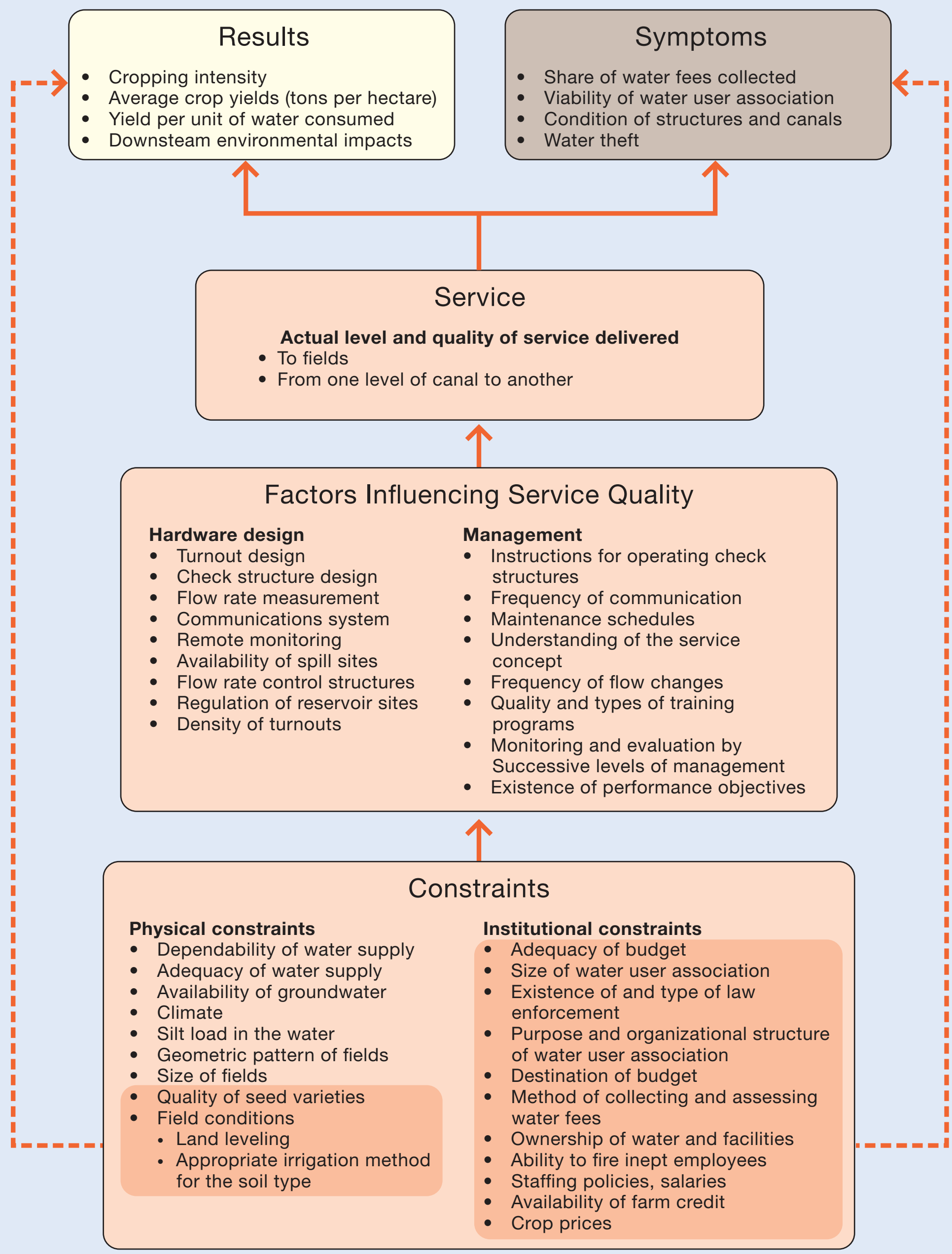
The historical bias toward infrastructure investment to the neglect of training, capacity building (for farmers and for irrigation service providers), and institutional strengthening interventions is one cause of poor irrigation performance. But training, personnel policies, and salaries are still major problems in many countries (see chapter 5 on policies and institutions). A more balanced approach should characterize future interventions as the synergies are recognized and the cost effectiveness of an approach balancing soft and hard investment is demonstrated.

Most reforms have been based on the assumption that greater user participation will result in improved responsiveness and performance and that users will be increasingly interested in the management of their irrigation service as the state retreats from providing and financing its provision. However, much has to be learned about how to do this effectively in practice without resorting to simplistic and prescriptive "magic bullets" that have been prevalent over the last 15–20 years.

Cost recovery, water charging, and sustainability

Cost recovery and associated water charges have been the subject of intense debate and controversy (Molle and Berkoff forthcoming). As financial resources become scarcer, the issue is becoming critical and will have a major impact on the sector in the near future. Evidence confirms that most governments in developing countries already face a serious funding crisis with broad consequences for rural services, including irrigation. Funding for housing, infrastructure, education, and social services in urban centers competes with

figure 9.5 **Factors affecting the performance of irrigation schemes**



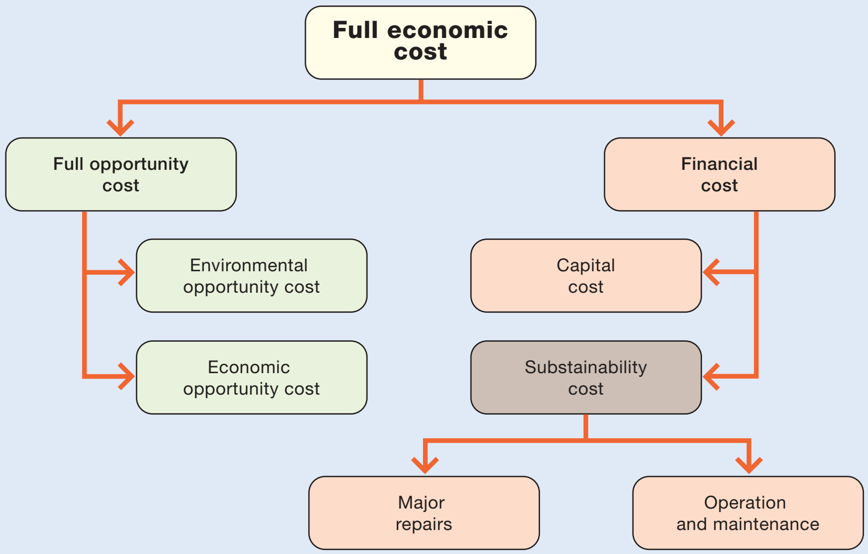
Source: FAO 1999a.

requirements in rural areas. Given these conditions, a drastic reduction of government funding can be expected for irrigation programs in many countries. The irrigation landscape will undoubtedly change in response to this pressure, but in ways that are hard to predict, ranging from gradual disuse and disbandment to dynamic self-financing.

The current school of thought in the water sector is well illustrated by the Global Water Partnership (GWP 2000): full cost recovery should be the goal for all water uses. However, assessment of the full cost of water is often out of reach (figure 9.6), and the Global Water Partnership also argues that while all efforts need to be made to estimate costs in order to ensure rational allocation and management decisions, these costs should not necessarily be charged to the user (GWP 2000). In irrigation the relevant question therefore is how users (through water charges) and taxpayers (through subsidies) should share the costs associated with irrigation (ICID 2004).

In addition to a thorough understanding of the costs associated with irrigation, information on economywide benefits of irrigation is critical to efficiently allocate irrigation cost across sectors. Indeed, in many cases society as a whole gets a much larger share of irrigation benefits through induced and indirect benefits than a typical irrigated farmer gets through increased crop productivity (Mellor 2002). This is evidenced by the high multiplier of investment in irrigation—between 2.5 and 4 in India (Bhattarai, Barker, and Narayanamoorthy forthcoming)—a factor to consider in setting cost-recovery policies for irrigation.

figure **9.6** **Components of costs associated with irrigation**



Source: Adapted from ICID 2004; Rogers, Bhatia, and Huber 1998; FAO 2004b.

Contention usually focuses on whether and what to charge: service, operation, and maintenance only, or those plus the full cost of capital investment, either in the past or as future replacement annuity. The answer varies widely according to the role irrigation plays in the country's economy: while some advanced economies may seek full cost recovery from irrigation, others may consider subsidies in irrigation as part of wider rural development strategies. In both cases the concept of sustainable cost recovery (see figure 9.6), which is gaining increasing attention, remains valid and deserves decisionmakers' attention: ensuring the sustainability of existing irrigation infrastructure requires that operation, maintenance, administrative, and renewal costs be adequately covered.

> Users often enjoy the benefits of water use while passing on the environmental and social costs to others, leading to problems of equity, groundwater mining, pollution of drainage water, poor health of farm workers, and contamination of consumer products

Programs aimed at increasing cost recovery will not be accepted by farmers if they result in an overall reduction in benefits. Any substantial increase in cost recovery should be discussed and agreed on with representatives of farmers as part of an overall package of management reform, linking increased charges with guarantees of improved water service (Murray-Rust, and Snellen 1993). Under such conditions a progressive rise in water charges, corresponding to increased accountability and transparency on the part of service providers and progressive transfer of authority to users, matched by increased profitability of irrigated agriculture, is a sensible option for reducing public funding in irrigation. The fact that farmers bear the full financial cost of irrigation under private irrigation shows that irrigation systems are economically viable in some settings. Irrigation service provision in large public systems will increasingly need to incorporate accountability systems based on explicit or implicit contracts and financial arrangements (Huppert and others 2001).

Modes of charging for water service vary widely and must be adapted to the level of development of the irrigation scheme. While volumetric water charging may epitomize the service-payment concept and allow for possible demand management (Malano and Hofwegen 1999), the transaction costs associated with volumetric measurement are rarely justified. Semivolumetric measurement methods, or area-based water charges, which are often added to other land taxes, may be appropriate as long as transparency and equity are guaranteed.

In addition to the controversy over cost-recovery levels, considerable confusion prevails in the public debates on the distinction between water charges (aimed at covering all or part of the costs associated with irrigation) and water pricing (FAO 2004b). The issue of pricing as a demand management tool for irrigation is discussed later, but evidence suggests that in most cases the incremental leap that would be required to reach levels of water charges that would affect demand would be politically unmanageable in the prevailing economic conditions of most irrigation schemes (Molle and Berkoff forthcoming).

The changing role of government

With the general decline in construction of new systems and the increasing shift of management responsibilities to users, the role of public irrigation agencies is rapidly changing. Past activities involving planning and designing systems, contracting for and supervising civil works, and delivering water to farms will be less important than in the past. New responsibilities will include resource allocation, bulk water delivery, basin-level management, sector regulation, and the achievement of global social and environmental goals such as the Millennium Development Goals (see chapter 5 on policies and institutions).

Regulation and oversight

Because water is generally regarded as a public good, the state has a duty to sustain its availability and quality. Users often enjoy the benefits of water use while passing on environmental and social costs to others, leading to problems of equity, groundwater mining, pollution of drainage water, poor health of farm workers, and contamination of consumer products. The state should play an important role in regulating these externalities. Moreover, water will increasingly become a commodity, quantified and governed by agreements among users and between public authorities and users. Governments will play important roles in sanctioning and regulating these agreements.

Most governments will need to modify their water-related agencies to carry out these new responsibilities. There will be a tendency to separate regulatory agencies from water management and supply agencies to avoid conflicts of interest. Private or client-controlled organizations are likely to be responsible for water supply to users in an increasing number of cases. Adjudication mechanisms will be needed to resolve disputes among parties over water allocation, quality, and use. These mechanisms may be a part of the national legal system or a separate set of institutions that rely more on mediation and consensus. In all cases, institutional development should be shaped by context and the existing laws, regulations, and approaches to water rights and priorities.

Assessing and collecting fees and taxes have been a key role for many public agencies in the past. With the devolution of irrigation system management, financing structures will need to change as well to allow sufficient funds to sustain operations to those who actually run them: therefore, there will be increasingly complicated cost-recovery mechanisms in large irrigation systems involving local service charges as well as bulk water supply costs.

Governments will continue to play the role of water wholesaler by operating or contracting to private service providers large and strategic facilities such as dams (in particular multipurpose dams) and major irrigation infrastructure such as main canals and pumping stations.

The problems of the private irrigation sector are more directly related to questions of equity and environmental sustainability, including mining of groundwater, land subsidence, pollution, and health for farm workers, consumers, and other water users downstream. These issues require public intervention, and regulatory frameworks are needed for equitable and secured use of land and water resources. Public interventions are also likely to be sought to stimulate the private sector through marketing policies and targeted investment in bulk infrastructure and to enable private sector provision of farm-level water technology.

> **Changing demand patterns for water will require not only investing in appropriate infrastructure but also reallocating water among competing uses, either administratively or through market mechanisms established and regulated by the government**

Resources allocation and management

Changing demand patterns for water will require reallocating water among competing uses as well as investing in appropriate infrastructure. This may be done either administratively or through market mechanisms established and regulated by the government. In both cases, great strides are required in quantifying water supplies, water deliveries, and uses. Without quantification, neither more careful allocation nor reallocation is possible.

Integrated management of water resources at the basin level will be an important task involving government, users, and other stakeholders. Although dedicated river basin management agencies are often proposed as a key solution, well orchestrated institutional development between existing agencies can be as effective (Turral 1998). Basin management entities will often be cross-sectoral and multidisciplinary, with a governing body that includes representatives from agriculture, municipal authorities, industry, and the environment, along with significant civil society representation (consumers and producers).

Governments will need to improve conflict management skills and mechanisms to deal with increasing competition for water. Transboundary water management will become more important with growing water scarcity, and governments will need dialogue and negotiation on transboundary water allocation.

> Where agriculture contributes significantly to GDP and employs many people, irrigation can ensure pro-poor growth and fuel nonagricultural growth

Sustaining growth and reducing poverty in rural areas

While macroeconomic conditions are changing, there are still many settings in which irrigation is an important element of poverty reduction strategies: areas of slow rates of rural outmigration; high prevalence of unemployed and underemployed labor; and high dependence on agriculture for livelihoods (photo 9.2). Poverty reduction and rural employment strategies may justify investments in agriculture-dependent areas that cannot be justified in direct economic terms.


Photo by G. Bizzarri/FAO

Photo 9.2 Water tank for irrigation on a small Andean farm

Where agriculture contributes significantly to GDP and employs many people, irrigation can ensure pro-poor growth and fuel nonagricultural growth. Farmers with higher incomes tend to spend a high proportion locally, a stimulus to local employment. But where irrigation is controlled by large-scale absentee farmers who have consumption patterns intensive in capital and imports, the local impact on rural poverty reduction is much lower. In very low-income societies without a well developed rural economy, as in much of Sub-Saharan Africa, the multiplier from agricultural growth to the nonfarm sector is much weaker (Mellor 2002).

Investments in irrigation and related interventions for agricultural development are, under certain conditions, preferred means of creating jobs and reducing rural poverty (Dhawan 1988; Mellor 1999, 2002; Hussain 2005). Equity and security of rights to land and irrigation resources matter for larger poverty impacts. Where the distribution of land and water is equitable, irrigation has larger poverty-reducing impacts (Brabben and others 2004; Hussain 2005).

Designs and investment in irrigation improvement that allow for multiple uses of water are also good for poverty reduction. Often the use of water for domestic water supply, irrigation, and other farm and nonfarm enterprises may have higher benefits than separate investments. Many recent studies have highlighted the significant benefits and contributions to livelihoods from these multiple uses, especially for poor households (Van Koppen, Moriarty, and Boelee 2006).

Water-application technologies and improved production practices offer promise. Some technologies are scale-neutral and may even self-select the poor (treadle pumps, labor-intensive agricultural activities). Some can be redesigned to better serve the poor (microirrigation technologies). Others, such as resource-conservation technologies, can be made available to the poor through efficient institutional arrangements or efficient rental markets for the machinery. The benefits of these technologies to the poor can be enhanced through initial targeted subsidy schemes, targeted training opportunities, private participation in the input-supply chain, quick payback technologies, and strengthened public research systems.

One aspect of poverty alleviation and equity that has been hotly debated, but with little progress, is women's access to and use of water and the benefits this brings (Boelens and Zwarteveen 2002). There are well documented cases of women being disenfranchised by poorly targeted irrigation development, mainly in Africa (Van Koppen 2000) but also in Asia (Udas and Zwarteveen 2005). Better targeting of female farmers is likely to increase agricultural productivity and growth (see chapter 5 on policies and institutions). There has also been a progressive feminization of agriculture due to urban and seasonal migration (Buechler 2004): women represent 54% of the agricultural and related labor force in Sub-Saharan Africa and 65% in Southern Asia, and their role in agriculture is likely to grow (photo 9.3). But the design, operation, and management of systems have rarely accommodated such changes (Vera 2005). Some simple gender-related questions for irrigation management suggest where to direct practical efforts for better services to female farmers (box 9.3) (Bruins and Heijmans 1993; Meinzen-Dick and Zwarteveen 1998; Van Koppen 2002).

One aspect of poverty alleviation and equity that has been hotly debated, but with little progress, is women's access to and use of water and the benefits this brings

In many countries women may be responsible for domestic and livestock water use and for irrigation of garden plots that make a vital contribution to the variety and nutritional quality of diets (FAO 1999a). If these needs are not explicitly understood, there may be too much bias toward field crop irrigation at the expense of household needs, especially when the volumes required are small but have relatively high value (Meinzen-Dick and van der Hoek 2001).

Photo by J. Boethling/FAO

Photo 9.3 A group of female farmers planting rice seedlings by hand

box 9.3 | Gender and irrigation—issues that matter

Some specific questions to better target irrigation service to women are:

- Do women have recognized access to land and water?
- Are women represented in formal water user associations?
- How are women's needs expressed and communicated?
- Is it safe for women to irrigate at night?
- Do irrigation schedules accommodate women's needs for flexibility?
- How can structures be improved so that women can easily operate them?
- Are irrigated plots close to households?
- Do women have the same access to credit and inputs as men?
- Are separate financial mechanisms required?
- Are household nutritional needs being met by the chosen cropping pattern?
- Is the importance of backyard gardening recognized and adequately promoted?

Managing the impacts of irrigation on health and the environment

Irrigation's health and environmental impacts are closely linked. For health, the negative impacts of irrigation development can be mitigated through better design and operation of new and existing systems, especially through multiple uses of irrigation water. For the environment, the impacts of irrigation can be positive but they more usually are negative (Goldsmith and Hildyard 1992; Dougherty and Hall 1995; Petermann 1996). Better identification and understanding of the externalities related to irrigation during design or redesign and management of irrigation systems can enhance the positive impacts and mitigate the negative ones (Bolton 1992).

> Potentially the greatest negative health impact of intensified agriculture at a global scale is from pesticide use. Integrated pest and plant fertility management can reduce the negative impacts of agrochemicals in irrigated systems

Health impacts of irrigation

A potentially negative impact of irrigation on human health is the increased incidence of vectorborne diseases, such as malaria and schistosomiasis, with the expansion of suitable habitat for the disease-transmitting organisms. While irrigation systems may significantly increase the number of malaria mosquito vectors in an area, that does not necessarily result in a greater incidence of malaria, especially when the introduction of an irrigation system leads to higher income, better access to health care, improved housing, and greater use of mosquito nets. Vulnerable community members not benefiting from the irrigation development may, however, face an increased malaria burden, and in certain cases the introduction of irrigation has been found to prolong the malaria transmission season.

Upgrading irrigation can improve health. Water management strategies, such as alternate wet and dry irrigation, and water-saving irrigation technologies reduce sites for the breeding of intermediary host snails of schistosomiasis and insect vectors of diseases. Clever modernization of irrigation infrastructure to minimize standing water can do the same. Institutional reforms, such as creating water user associations or improving extension services, can facilitate multiple uses and bridge the divide between agricultural and health departments (Bakker and others 1999).

In Africa irrigation development is associated with the spread of schistosomiasis and the intensification of human infections (McCartney and others 2005). Medical and engineering options exist to deal with the problem. Irrigation water management and weed control (including maintenance of drains and canals and night storage dams) can reduce the burden of schistosomiasis, in both large- and small-scale irrigation systems.

Irrigation water is an important potential source of domestic water supplies, but satisfying both needs often poses management problems. Access to irrigation water close to homesteads can have significant health benefits, especially in the reduction of hygiene-related diarrheal or skin and eye diseases (van der Hoek, Feenstra, and Konradsen 2002). Water-saving strategies and the increasing use of low-quality water for irrigation in situations where people are fully dependent on canal water for most domestic purposes can have negative health impacts. High water tables may severely limit the options for safe sanitation, and therefore drainage in waterlogged areas will have positive results.

Potentially the greatest negative health impact of intensified agriculture at a global scale is from pesticide use. Banning the use of the most toxic pesticides would be the first priority in preventing poisoning episodes (Eddleston and others 2002). Inappropriate pest management policies in developing countries increasingly hamper their exports of goods to Organisation for Economic Co-operation and Development markets because of high pesticide residues. Integrated pest and plant fertility management can considerably reduce the negative impacts of agrochemicals in irrigated systems.

Irrigation can also create or enhance wetland ecosystems, generating habitats to support biodiversity conservation and ecosystem services

Environmental impacts of irrigation

Policies and practices associated with irrigated agriculture continue to be a major driver of change in both terrestrial and aquatic ecosystems, exerting a wide range of largely detrimental impacts globally. The impacts, ranging from local and subtle to long distance and severe, have adverse effects on human well-being through reductions in ecosystem services and resilience (MEA 2005a,b).

Many of irrigation's negative environmental effects arise from withdrawal, storage, and diversion from natural aquatic ecosystems and the resultant changes to the natural pattern and timing of hydrological flows (Rosenberg, McCully, and Pringle 2000; also see chapter 6 on ecosystems). Rivers have in many instances become disconnected from their floodplains and from downstream estuaries and wetlands—with, in some instances, total and irreversible wetland loss (MEA 2005b). The routes and systems of infrastructure for water transfer and storage have also led to the introduction and proliferation of invasive species, such as aquatic weeds, in both water management systems and natural wetlands.

Wetland water quality has deteriorated in all regions, particularly in areas under high-intensity irrigation (MEA 2005b). Nutrient loading—primarily from fertilizers (nitrogen and phosphorus) applied to irrigated (and rainfed) areas—is one of the most important drivers of ecosystem change, resulting in eutrophication, hypoxia, and algal blooms. Total pesticide use is still increasing, and though many of the more persistent chemicals used in irrigated agriculture are being phased out and replaced by ones with less environmental impact, this is not necessarily so in developing countries.

The extent to which irrigation induces waterlogging and salinization is imperfectly known but estimated at 10% of the total irrigated area worldwide. In large river basins in arid regions the picture is much more severe, with salinity buildups in drainage water and the consequent salinization of the land and rivers (Smedema and Shiati 2002). Salinization causes the loss of natural vegetation, reduces crop yields, and leaves drinking water unfit for human and animal consumption. Drainage is systematically neglected until salinity problems are manifest, because of the additional capital cost it incurs. If drainage is constructed early, the likelihood of accumulating salts is much lower and the loads disposed in natural streams and rivers are smaller. Adapting farming systems through the use of salt-tolerant varieties may provide short-term respite for producers but is likely to increase the negative environmental impacts in the long run.

Irrigation can also create or enhance wetland ecosystems, generating habitats to support biodiversity conservation and ecosystem services. This is particularly so where irrigation-based agroecosystems have developed over centuries and function as wetlands

(Wiseman, Taylor, and Zingstra 2003; Fernando, Göltenboth, and Margraf 2005; photo 9.4). There is a school of thought that argues for the positive biodiversity impacts of water management and irrigation systems in their own right, as for waterbirds in rice systems in Asia (Galbraith, Amerasinghe, and Huber-Lee 2005). In several instances, however, the biodiversity of irrigated systems is of less ecological and socioeconomic value than that of the natural system it replaced (see chapter 6 on ecosystems).

Another positive impact of irrigation is the higher agricultural productivity through which irrigation has contained some of the expansion of rainfed agricultural areas into forested or marginal lands (Carruthers 1996).

> The scope for water conservation strategies that free water from agriculture to satisfy the requirements of other sectors is limited

Developing countries with significant irrigation have paid relatively little attention to safeguarding flows for the environment, but this is changing rapidly, with more countries embedding environmental flow principles in policy and legislation (for example, the South African National Water Act and the Mekong Agreement) and undertaking local assessments of environmental water needs in basins (Tharme 2003). The scope and expertise now exist to reallocate water in major rivers to restore downstream ecosystems, including highly productive riverine floodplains. Water management techniques can create substantial flexibility in how infrastructure is operated, opening possibilities to restore lost ecological functions and processes. In particular, changing the operating rules for dams can improve environmental performance while allowing continuing provision of water, power, and flood control.

A growing range of ecoagriculture strategies can be applied in irrigation systems to prevent or mitigate habitat fragmentation—for example, through corridors of natural or seminatural vegetation to enhance connectivity for biodiversity conservation (Molden and others 2004). Systems need to accommodate the multiple uses of water, including environmental uses, by understanding their role and importance.

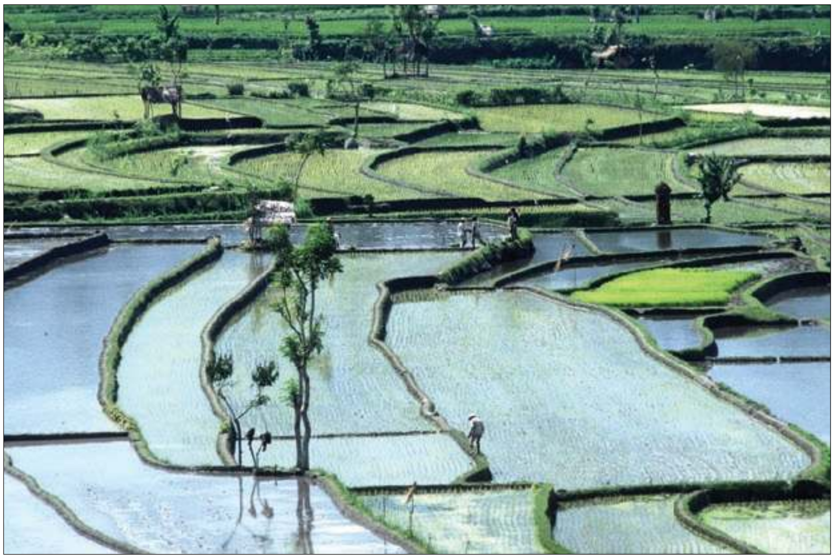


Photo by R. Raidutti/FAO

Photo 9.4 Rice terraces in Indonesia

Adapting to sectoral competition

In the growing political and economic tussles over access to water, agriculture is perceived as the low-value residual user. Experience shows that water conservation in agriculture does not drive transfers of water from agriculture to other sectors. Transfers occur in a variety of ways—including land and water purchase, appropriation by default as cities expand into peri-urban irrigated areas, competitive development, and water conservation investment in return for "saved" water. This mostly ad hoc set of mechanisms will lead to a framework of rules and practices that will gradually regularize the process. Under conditions of increasing competition the stakes are high for all current and prospective water users, and governments bear responsibility to ensure a level playing field for these processes to play out.

The scope for water conservation strategies that free water from agriculture to satisfy the requirements of other sectors is rather limited. Focusing on water conservation alone is certainly not sufficient to sustain agricultural production while releasing the water for environmental, urban, and other uses. Rather, a strategy that provides farmers with the means to increase their productivity within the broader context of agricultural modernization is more likely to succeed (Kijne, Molden, and Barker 2003).

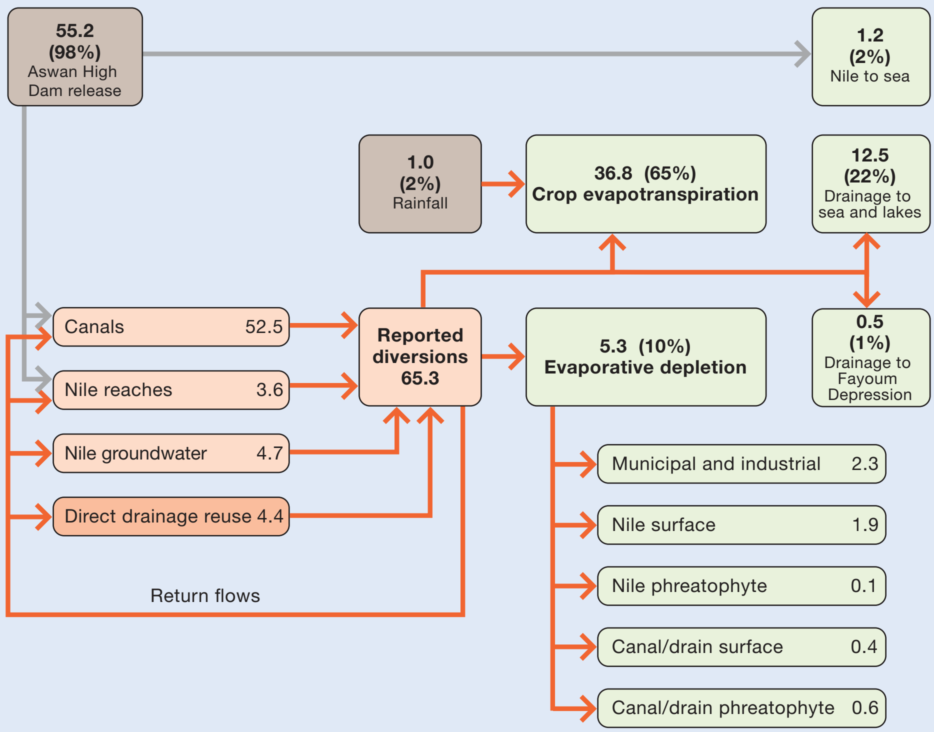
In countries where water rights exist and are separate from land rights, markets can theoretically lead to efficient reallocation of water among sectors. In practice, water trading has so far reallocated only small volumes of the resource

Water saving and water-use efficiency in irrigation

The concept of water-use efficiency (the ratio between effective water consumption by crops and water abstracted from its source for irrigation) is subject to controversy and misinterpretation. Developed initially for use in the design of physical structures of water storage and conveyance in irrigation systems (Israelsen 1932), the concept was later interpreted as a measure of irrigation inefficiency and waste: because only 30%–50% of the water withdrawn from its source is actually transpired by crops in a typical irrigation system, many conclude that substantial gains in water volumes can be obtained by increasing water-use efficiency in irrigation.

However, most investments aiming primarily at increasing water-use efficiency (in particular through canal lining) result in little real water savings, especially when there is little degradation in water quality. Large surface irrigation systems circulate massive volumes of water through canals and drains. Because a substantial portion of these flows is recaptured downstream, water-saving technologies on farms upstream may make only minor contributions to savings considered on a larger scale, such as at the irrigation system or river basin level (Seckler, Molden, and Sakthivadivel 2003). This is most evident where irrigation efficiencies are low in a fully allocated basin, such as the Yellow River in China, and there is little outflow to the sea (see chapter 16 on river basins).

For the Nile River in Egypt conveyance and field application efficiencies are low, but about 75%–87% of the water withdrawn from the Nile is ultimately evaporated by irrigation (figure 9.7; Abu Zeid and Seckler 1992; Molden, el Kady, and Zhu 1998). In some situations reducing percolation from irrigated fields can lower groundwater tables and reduce the water available to crops from below, while increasing the cost of figure **9.7** **Nile water balance in Egypt, 1993–94 (cubic kilometers per year)**



Note: Values may not sum to totals because of rounding.

Source: Adapted from Molden, el Kady, and Zhu 1998.

pumping for reuse downstream. So when planning programs to conserve water in irrigated agriculture, it is vital to have a full understanding of the regional hydrology to avoid expensive solutions that simply move water from one location to another within the irrigation system.

Nevertheless, the concept of water-use efficiency is site-, scale- and purpose-specific (Lankford 2006). Efficiencies matter locally, in terms of irrigation design, for satisfactory operation and monitoring of existing systems (Bos, Burton, and Molden 2005), equitable access to water within the irrigation schemes, energy saving, and control of waterlogging and salinization (see chapter 7 on water productivity).

Tools for demand management in irrigation

Many economists argue that the low prices paid for irrigation water are a disincentive to efficient use and that improved water pricing policies could save water and increase productivity. But there are almost no examples of pricing as a primary mechanism for efficiency gains in irrigation (see chapter 5 on policies and institutions).

There are two reasons for this. First, water pricing must be based on measured deliveries. In the vast majority of irrigation schemes, delivered volumes of water are not measured, making volumetric water pricing impossible, and measuring them would involve huge investments. It is now more widely recognized that the applicability of volumetric water pricing to individual farms is limited to a small subset of technologically and managerially advanced irrigation schemes. Second, the water charges currently levied in most irrigation schemes have rarely reached even a fraction of that needed to constrain demand (Perry, Rock, and Seckler 1997). In these systems the political consequences of increasing water charges to the point that the demand elasticity becomes significant can be expected to be severe and constraining.

In countries where water rights exist and are separate from land rights, markets can theoretically lead to efficient reallocation of water among sectors. In practice, water trading has so far reallocated only small volumes of the resource (less than 1% a year of permanent entitlements in Australia and the western United States) (Turral and others 2005). It is unlikely that water markets will affect irrigation water use and reallocation in most countries of Asia or Sub-Saharan Africa in the coming 20–30 years because of the time lag in the development of suitable water rights and allocation frameworks and the marginal nature of markets once established. A major challenge in formalizing water rights is to include traditional (often small) systems and to avoid disenfranchising established small-scale water users (Bruns and Meinzen-Dick 2000; Bruns, Ringler, and Meinzen-Dick 2005). Water markets will also need to adopt more comprehensive water valuation approaches that encompass the broad range of benefits and costs of water management in agriculture—and that include payment for environmental services.

In the future the magnitude of environmental reallocations and their impact on agriculture will be greater than incremental demands rising from cities and industry

In the interim, consultative and participatory arrangements for water allocation will be required. Consultation is a key process in water allocation—along with data collection, analysis, and promulgation, and negotiation—to find optimal sharing of benefits. The challenge over the next 20 years is to develop cost-effective arrangements for doing this and erect a functional framework of facilitating laws, treaties, and regulations. Since the water allocation process is inherently political, effective representation is crucial. A major challenge for the coming decades is to develop strong and effective representative voices on behalf of those stakeholders now underrepresented, including small-scale farmers, women, and the environment (Ostrom, Schroeder, and Wynne 1993; Blomquist 1992).

Governments will have to be proactive in managing the growing competition for water, by establishing effective water rights systems, setting out targeted policies on conservation, and implementing appropriate land-use restrictions to facilitate equitable transfers from irrigation to other sectors. In the case of environmental demands, some public recognition of its value is necessary prior to any reallocation. The degree of recognition and the magnitude of the unmet environmental need for additional water varies considerably from country to country. In the future the magnitude of environmental reallocations and their impact on agriculture will be greater than incremental demands rising from cities and industry, as is already the case in many higher income countries such as Australia and the United States, since environmental uses are essentially consumptive.

Appendix: Typology of irrigation systems

The following typology of irrigation systems is based primarily on mode of governance.

- *Large-scale public irrigation systems in dry areas, growing staple crops.* They include most of the large public schemes of Northern China, the dry part of the Indo-Gangetic Plain, Central Asia, Sudan, the Middle East, the Nepalese Terai, and Mexico. These schemes are mostly run by public management agencies and for the last 10–15 years have been the focus of irrigation management transfer programs. In these schemes water delivery services are typically rather inflexible and inequities between the head and tail ends of the schemes are marked. In response to poor service, farmers typically seek to improve the reliability of supply by stealing water, pumping from drains, or using shallow groundwater in conjunction with canal water. These schemes were built with the purpose of providing large numbers of people with either full or partial irrigation to stabilize and augment staple food production and were usually not expected to pay their own operating expenses. Today, they face the challenge of economic and financial viability, and of the technical and managerial upgrading that would allow them to respond to the new needs of their farmers.
- *Large-scale public paddy irrigation systems in humid areas.* These irrigation systems were progressively developed to produce paddy rice and have in most cases gone through a process of accretionary development, leading progressively to increased water control and increased cropping intensity. Typical of this type of systems are the large terrace systems of Southeast Asia or the tank and delta systems of East and South India and Sri Lanka. While they face similar challenges for viability and upgrading as do the dry area systems, they also have unique features and properties related to their high rainfall environment and paddy cultivation.
- *Small- to medium-scale community-managed (and -built) systems.* Such systems are found across the world in Afghanistan, Indonesia, Nepal, the Philippines, the Andes Mountains, the Atlas Mountains, Sub-Saharan Africa, and highland areas in general. While this category covers a wide range of situations, it is characterized by the small size of the systems, private or community investment, and management. Public sector involvement focuses on rehabilitation, consolidation, or improvement. These systems form the basis of the economies of their communities and typically show a large variety of cropping patterns.
- *Commercial privately managed systems, producing for local and export markets.* These systems do not represent a large share of irrigated areas worldwide but can be important locally. They can be found in Latin America (Argentina, Brazil, Chile, northern Mexico), Morocco, Turkey, and industrialized countries. They are governed by cultivators, employ paid staff, often use advanced technologies, and are responsive to local and international market opportunities. Sugar production is a special case of commercial irrigation, where management of irrigation and cultivation is often combined in a single entity.
- *Farm-scale individually managed systems, producing for local markets, often around cities.* These systems develop around cities to take advantage of local markets for high-value

crops like fruits and vegetables. They are highly dynamic and volatile, face land tenure problems as cities grow, and are often characterized by large short-term returns on investment. They rely on groundwater or wastewater and often face environmental and health related problems, for both consumers and field workers.

Reviewers

Chapter review editor: Linden Vincent.
Chapter reviewers: Charles Abernethy, Ger Bergkamp, Belgin Cakmak, Evan Christen, Bert Clemmens, Biksham Gujja, Hammond Murray-Rust, Ursula Oswald Spring, Shaheen Khan Qabooliya, Jorge Ramirez Vallerjo, Ranjith Ratnayake, Juan Sagardoy, R. Sakthivadivel, Jose Trava, Pranita Udas, and Xiaoliu Yang.

References

Abu Zeid, M., and D. Seckler, eds. 1992. "Roundtable on Egyptian Water Policy." Conference Proceedings. Ministry of Public Works and Water Resources, Water Research Centre, Cairo, and Winrock International, Arlington, Va.
Aerts, J., and P. Droogers, eds. 2004. *Climate Change in Contrasting River Basins: Adaptation Strategies for Water, Food and Environment.* Oxfordshire, UK and Cambridge, Mass.: CABI Publishing.
Albinson, B., and C.J. Perry. 2002. "Fundamentals of Smallholder Irrigation: The Structured System Concept." Research Report 58. International Water Management Institute, Columumbo.
Ankum, P. 1996. "Selection of Operation Methods in Canal Irrigation Delivery Systems." In *Irrigation Scheduling: From Theory to Practice.* Water Reports 8. Proceedings of the International Commission on Irrigation and Drainage and Food and Agriculture Organization Workshop on Irrigation Scheduling, 12–13 September, Rome.
Bakker, M., R. Barker, R.S. Meinzen-Dick, and F. Konransen, eds. 1999. *Multiple Uses of Water in Irrigated Areas: A Case Study from Sri Lanka.* SWIM Report 8. Colombo: International Water Management Institute.
Barker, R., and F. Molle. 2004. *Evolution of Irrigation in South and Southeast Asia.* Comprehensive Assessment Research Report 5. Colombo: International Water Management Institute.
Barker, R., C. Ringler, N.M. Tien, and M.W. Rosegrant. 2004. *Macro Policies and Investment Priorities for Irrigated Agriculture in Viet Nam.* Comprehensive Assessment Research Report 6. Colombo: International Water Management Institute.
Barnett, T.P., J.C. Adams, and D.P. Lettenmaier. 2005. "Potential Impacts of a Warming Climate on Water Availability in Snow-Dominated Regions." *Nature* 438 (7066): 303–09.
Berkoff, J. 2003. "Prospects for Irrigated Agriculture: Has the International Consensus Got It Right?" Alternative Water Forum, May 1–2, Bradford, UK.
Bhattarai, M., and A. Narayanamoorthy. 2003. "Impact of Irrigation on Rural Poverty in India: An Aggregate Panel-Data Analysis." *Water Policy* 5 (5–6): 443–58.
Bhattarai M., R. Barker, and A. Narayanamoorthy. Forthcoming. "Who Benefits from Irrigation Development in India? Implication of Irrigation Multipliers for Irrigation Financing." *Irrigation and Drainage.*
Blomquist, W. 1992. *Dividing the Waters: Governing Groundwater in Southern California.* San Francisco, Calif.: ICS Press.
Boelee, E., and H. Laamrani. 2004. "Environmental Control of Schistosomiasis through Community Participation in a Moroccan Oasis." *Tropical Medicine and International Health* 9 (9): 997–1004.
Boelens, R., and M. Zwarteveen. 2002. "Gender Dimensions of Water Control in Andean Irrigation." In R. Boelens and P. Hoogendam, eds., *Water Rights and Empowerment.* Assen, Netherlands: Van Gorcum.
Bolton, P. 1992. "Environmental and Health Aspects of Irrigation." OD/P 116. Hydraulics Research, Wallingford, UK.
Bos, M.G, M.A. Burton, and D.J. Molden. 2005. *Irrigation and Drainage Performance Assessment: Practical Guidelines.* Wallingford, UK: CABI Publishing.
Brabben, T., C. Angood, J. Skutch, and L. Smith. 2004. *Irrigation can Sustain Rural Livelihoods: Evidence from Bangladesh and Nepal.* Wallingford, UK: HR Wallingford.
Brohan, P., J. Kennedy, I. Harris, S.F.B. Tett, and P.D. Jones. Forthcoming. "Uncertainty Estimates in Regional and Global Observed Temperature Changes: A New Dataset from 1850." *Journal of Geophysical Research.*
Bruins, B., and A. Heijmans. 1993. "Gender Biases in Irrigation Projects: Gender Considerations in the Rehabilitation of Bauraha Irrigation System in the District of Dang." SNV Nepal, Kathmandu.
Bruns, B.R., and R. Meinzen-Dick, eds. 2000. *Negotiating Water Rights.* London: Intermediate Technology Press.

Bruns, B.R., C. Ringler, and R.S. Meinzen-Dick, eds. 2005. *Water Rights Reform: Lessons for Institutional Design.* Washington, D.C.: International Food Policy Research Institute.
Buechler, S. 2004. "Women at the Helm of Irrigated Agriculture in Mexico: The Other Side of Male Migration." In V. Bennett, S. Dávila-Poblete, and M. Nieves Rico, eds., *Swimming Against the Current: Gender and Water in Latin America.* Pittsburgh, Pa.: Pittsburgh University Press.
Carruthers, I. 1996. "Economics of Irrigation." In L. Pereira, R. Feddes, J. Gilley, and B. Lesaffre, eds., *Sustainability of Irrigated Agriculture.* Dordrecht, Netherlands: Kluwer Academic.
Carruthers, I., M.W. Rosegrant, and D. Seckler. 1997. "Irrigation and Food Security in the 21st Century." *Irrigation and Drainage Systems* 11: 83–101.
Chambers, R. 1988. *Managing Canal Irrigation: Practical Analysis from South Asia.* New York: Cambridge University Press.
de Fraiture, C. 2005. *Assessment of Potential of Food Supply and Demand Using the Watersim Model.* Columbo: International Water Management Institute.
Dhawan, B.D. 1988. *Irrigation in India's Agricultural Development: Productivity, Stability, Equity.* New Delhi: Sage Publications.
Diao, X., and A. Nin Pratt with M. Gautam, J. Keough, J. Chamberlin, L. You, D. Puetz, D. Resnick, and B. Yu. 2005 "Growth Options and Poverty Reduction in Ethiopia: A Spatial, Economywide Model Analysis for 2004–15." DSGD Discussion Paper 20. International Food Policy Research Institute, Washington, D.C.
Dougherty, T.C., and A.W. Hall. 1995. "Environmental Impact Assessment of Irrigation and Drainage Projects." Irrigation and Drainage Paper 53. Food and Agriculture Organization, Rome.
Eddleston, M., L. Karalliedde, N. Buckley, R. Fernando, G. Hutchinson, G. Isbister, F. Konradsen, D. Murray, J.C. Piola, N. Senanayake, R. Sheriff, S. Singh, S.B. Siwach, and L. Smit. 2002. "Pesticide Poisoning in the Developing World: A Minimum Pesticides List." *Lancet* 12 (360): 1163–67.
FAO (Food and Agriculture Organization). 1997. "Modernization of Irrigation Schemes: Past Experiences and Future Options." FAO Technical Paper 12. Rome.
———. 1999a. "Modern Water Control and Management Practices in Irrigation: Impact on Performance." FAO Water Report 19. International Program for Technology and Research in Irrigation and Drainage, Rome.
———. 1999b. "Transfer of Irrigation Management Services. Guidelines." FAO Irrigation and Drainage Paper 58. Rome.
———. 2000. *Irrigation in Latin America and the Caribbean in Figures.* Rome.
———. 2003. *World Agriculture towards 2015/2030: An FAO Perspective.* Rome and London: Food and Agriculture Organization and Earthscan Publishers.
———. 2004a. *Compendium of Food and Agriculture Indicators.* Rome.
———. 2004b. *Water Charging in Irrigated Agriculture: An Analysis of International Experience.* FAO Water Report 28. Rome.
———. 2005. *Irrigation in Africa in Figures. Aquastat Survey—2005.* FAO Water Report 29. Rome.
———. 2006a. FAOSTAT database. [http://faostat.fao.org/].
———. 2006b. "Demand for Products of Irrigated Agriculture in Sub-Saharan Africa." FAO Water Report 31. Rome.
———. Forthcoming. "Irrigation Management Transfer: Worldwide Efforts and Results." Rome.
Fernando, C.H., F. Göltenboth, and J. Margraf, eds. 2005. *Aquatic Ecology of Rice Fields: A Global Perspective.* Ontario, Canada: Volumes Publishing.
Galbraith, H., P. Amerasinghe, and A. Huber-Lee. 2005. *The Effects of Agricultural Irrigation on Wetland Ecosystems in Developing Countries: A Literature Review.* CA Discussion Paper 1. Comprehensive Assessment Secretariat, Colombo.
Gerrards, J. 1994. "Irrigation Service Fees (ISF) in Indonesia: Towards Irrigation Co-Management with Water Users Associations through Contributions, Voice, Accountability, Discipline, and Plain Hard Work." Proceedings of the International Conference on Irrigation Management Transfer, 20–24 September, Wuhan, China. International Irrigation Management Institute, Colombo.
Goldsmith, E., and N. Hildyard. 1992. *The Social and Environmental Effects of Large Dams. Volume III: A Review of the Literature.* Bodmin, UK: Wadebridge Ecological Centre.
Gommes, René. 1993. "Current Climate and Population Constraint on Agriculture." In H. Kaiser and T.E. Drennen, eds., *Agricultural Dimension of Global Climatic Change.* Delray Beach, Fla.: St. Lucie Press.
Grey, D., and C. Sadoff. 2005. "Water Resources, Growth and Development." A Working Paper for discussion at the UN Commission on Sustainable Development, Panel of Finance Ministers. World Bank, Washington, D.C.
GWP (Global Water Partnership). 2000. "Integrated Water Resources Management." TAC Background Paper 4. Technical Advisory Committee, Stockholm.
Heierli, U., and P. Polak. 2000. "Poverty Alleviation as Business: The Market Creation Approach to Development." Swiss Agency for Development and Cooperation, Bern.

Horst, L. 1998. *The Dilemmas of Water Division, Considerations and Criteria for Irrigation System Design.* Colombo: International Water Management Institute.
Huang, Qiuqiong, S. Rozelle, B. Lohmar, Jikun Huang, and Jinxia Wang. 2006. "Irrigation, Agricultural Performance and Poverty Reduction in China." *Food Policy* 31 (1): 30–52.
Hung, Tun Yueh, and C. Shih. 1994. "Development and Outlook for Irrigation Water Management in Taiwan." Proceedings of the International Conference on Irrigation Management Transfer, 20–24 September, Wuhan, China. International Irrigation Management Institute, Colombo.
Huppert, Walter, Mark Svendsen, and Douglas L. Vermillion with Birgitta Wolff, Martin Burton, Paul van Hofwegen, Ruth Meinzen-Dick, Waltina Scheumann, and Klaus Urban. 2001. *Governing Maintenance Provision in Irrigation: A Guide to Institutionally Viable Maintenance Strategies.* Eschborn, Germany: GTZ.
Hussain, I. 2005. *Pro-poor Intervention Strategies in Irrigated Agriculture in Asia. Poverty in Irrigated Agriculture: Issues, Lessons, Options and Guidelines.* Asian Development Bank and International Water Management Institute, Colombo.
ICID (International Commission on Irrigation and Drainage). 2004. "Irrigation and Drainage Services: Some Principles and Issues towards Sustainability." ICID Position Paper. New Delhi.
IFAD (International Fund for Agricultural Development). 2001. *Rural Poverty Report 2001: The Challenge of Ending Rural Poverty.* New York: Oxford University Press.
IFAD (International Fund for Agricultural Development) and IWMI (International Water Management Institute). Forthcoming. "Study on Agricultural Water Development and Poverty Reduction in Eastern and Southern Africa." Rome and Colombo.
Inocencio, A., D. Merrey, M. Tonasaki, A. Maruyama, I. de Jong, and M. Kikuchi. Forthcoming. "Costs and Performance of Irrigation Projects: A Comparison of Sub-Saharan Africa and Other Developing Countries." IWMI Research Report. International Water Management Institute, Colombo.
IPCC (Intergovernmental Panel on Climate Change). 2001. *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press.
[HYPERLINK "http://www.grida.no/climate/ipcc_tar/wg1/index.htm"
www.grida.no/climate/ipcc_tar/wg1/index.htm].
IPTRID (International Program for Technology and Research in Irrigation and Drainage). 1999. *Poverty Reduction and Irrigated Agriculture.* Issues Paper 1. Rome.
Israelsen, O.W. 1932. *Irrigation Principles and Practices,* 1st ed. New York: John Wiley and Sons.
IWMI (International Water Management Institute). 2000. *World Water Supply and Demand.* Colombo.
Johnson, S., III, M. Svendsen, and F. Gonzalez. 2004. *Institutional Reform Options in the Irrigation Sector.* Agriculture and Rural Development Discussion Paper 5. World Bank, Washington, D.C.
Jones, W.I. 1995. *The World Bank and Irrigation.* Operations Evaluation Study. World Bank, Washington, D.C.
Keller, J., and A.A. Keller. 2003. "Affordable Drip Irrigation Systems for Small Farms in Developing Countries." Proceedings of the Irrigation Association Annual Meeting, 18–20 November, San Diego, Calif.
Kendy, Eloise, D.J. Molden, T.S. Steenhuis, and C.M. Liu. 2003. *Policies Drain the North China Plain: Agricultural Policy and Groundwater Depletion in Luancheng County, 1949–2000.* Research Report 71. International Water Management Institute, Colombo.
Kijne, J.W., D. Molden, and R. Barker, eds. 2003. *Water Productivity in Agriculture: Limits and Opportunities for Improvement.* Comprehensive Assessment of Water Management in Agriculture Series, No. 1. Wallingford, UK: CABI Publishing.
Kikuchi, M., R. Barker, P. Weligamage, and M. Samad. 2002. *Irrigation Sector in Sri Lanka: Recent Investment Trends and the Development Path Ahead.* Research Report 62. International Water Management Institute, Colombo.
Lankford, B. 2006. "Localising Irrigation Efficiency." *Irrigation and Drainage* 55: 1–18.
Lipton, M., J. Litchfield, and Jean-Marc Faurès. 2003. "The Effects of Irrigation on Poverty: A Framework for Analysis." *Water Policy* 5 (5): 413–27.
Lipton, M., Julie Litchfield, Rachel Blackman, Darshini De Zoysa, Lubina Qureshy, and Hugh Waddington. 2003. *Preliminary Review of the Impact of Irrigation on Poverty.* AGL/MISC/34/2003. Rome: Food and Agriculture Organization.
Loeve, R., L. Hong, B. Dong, G. Mao, C.D. Chen, D. Dawe, and R. Barker. 2004. "Long Term Trends in Intersectoral Water Allocation and Crop Water Productivity in Zhanghe and Kaifeng, China." *Paddy and Water Environment* 2 (4): 237–45.
Malano, H., and P.V. Hofwegen. 1999. *Management of Irrigation and Drainage Systems: A Service Approach.* IHE Monograph 3. Rotterdam: A.A. Balkema.

Malano, H.M., B.A. George and B. Davidson, eds. 2004. "A Framework for Improving the Management of Irrigations Schemes in Vietnam." Australian Centre for International Agricultural Research, Canberra.

McCartney, M., Boelee, E., Cofie, O., F. Amerasinghe, and C. Mutero. 2005. "Agricultural Water Development in Sub-Saharan Africa: Planning and Management to Improve the Benefits and Reduce the Environmental and Health Costs." Final Report (Health). Investments in Agricultural Water Management in Sub-Saharan Africa: Diagnosis of Trends and Opportunities Project. International Water Management Institute, Colombo.

MEA (Millennium Ecosystem Assessment). 2005a. *Ecosystems and Human Well-being: Biodiversity Synthesis.* Washington D.C. : World Resources Institute,

———. 2005b. *Ecosystem and Human Well-being: Wetlands and Water Synthesis.* Washington D.C.: World Resources Institute.

Meinzen-Dick, Ruth, and Wim van der Hoek. 2001. "Multiple Uses of Water in Irrigated Areas." *Irrigation and Drainage Systems* 15 (2): 93–98.

Meinzen-Dick, R., and Margreet Zwarteveen. 1998. "Gendered Participation in Water Management: Issues and Illustrations from Water Users' Associations in South Asia." *Agriculture and Human Values* 15 (4): 337–45.

Mellor, John W. 1999. "Faster More Equitable Growth—The Relation Between Growth in Agriculture and Poverty Reduction." Paper prepared for United States Agency for International Development, Bureau for Global Programs, Center for Economic Growth and Agricultural Development, Division of Agriculture and Food Security. Abt Associates Inc., Cambridge, Mass.

———. 2002. "Irrigation, Agriculture and Poverty Reduction: General Relationships and Specific Needs." In I. Hussain and E. Biltonen, eds., *Managing Water for the Poor: Proceedings of the Regional Workshop on Pro-Poor Intervention Strategies in Irrigated Agriculture in Asia, Bangladesh, China, India, Indonesia, Pakistan and Vietnam.* Colombo: International Water Management Institute.

Merrey, D.J. 1997. *Expanding the Frontiers of Irrigation Management Research: Results of Research and Development at the International Irrigation Management Institute 1984–1995.* Colombo: International Water Management Institute.

Molden, D.J., M. el Kady, and Z. Zhu. 1998. "Use and Productivity of Egypt's Nile Water." In J.I. Burns and S.S. Anderson, eds., *Contemporary Challenges for Irrigation and Drainage: Proceedings from the USCID 14th Technical Conference on Irrigation, Drainage and Flood Control, Phoenix, Arizona, June 3-6, 1998.* Denver, Colo.: U.S. Committee on Irrigation and Drainage.

Molden, D., R. Tharme, I. Abdullaev, and R. Puskur. 2004. "Water, Food, Livelihoods and Environment: Maintaining Biodiversity in Irrigated Landscapes." Proceedings of the International Ecoagriculture Conference, 27 September–1 October, Nairobi.

Molle, F., and J. Berkoff. 2006. "Cities versus Agriculture: Revisiting Intersectoral Water Transfers, Potential Gains, and Conflicts." Comprehensive Assessment of Water Management in Agriculture Research Report 10. International Water Management Institute, Colombo.

Molle, F., and J. Berkoff., eds. Forthcoming. *Irrigation Water Pricing Policy in Context: Exploring the Gap between Theory and Practice.* Colombo: CABI Publishing and International Water Management Institute.

Mollinga, P. 1998. "On the Waterfront; Water Distribution, Technology and Agrarian Change in a South Indian Canal Irrigation System." PhD diss., Wageningen Agricultural University, Netherlands.

Murray-Rust, D.H., and W.B. Snellen. 1993. *Irrigation System Performance Assessment and Diagnosis.* Colombo: International Irrigation Management Institute.

ODI (Oversees Development Institute). Various years. Irrigation Management Network Papers. Overseas Development Institute, London.

Ostrom, E., L. Schroeder, and S.G. Wynne. 1993. *Institutional Incentives and Sustainable Development: Infrastructure Policies in Perspective.* Boulder, Colo.: Westview Press.

Palmer Jones, R.W., and M.A.S. Mandal. 1987. *Irrigation Groups in Bangladesh.* Irrigation Management Network Paper 87/2c. Overseas Development Institute, London.

Peel, M. C, Thomas A. McMahon, and Brian L. Finlayson. 2004. "Continental Differences in the Variability of Annual Runoff – Update and Reassessment." *Journal of Hydrology* 295 (1–4): 185–97.

Peel, M.C., Thomas A. McMahon, and Geoffrey G.S. Pegram. 2004. "Global Analysis of Runs of Annual Precipitation and Runoff Equal to or Below the Median: Run Magnitude and Severity." *International Journal of Climatology* 25 (5): 549–68.

Peel, M.C., T.A. McMahon, B.L. Finlayson, and F.G.R. Watson. 2001. "Identification and Explanation of Continental Differences in the Variability of Annual Runoff." *Journal of Hydrology* 250 (1–4): 224–40.

Perry, C.J., and S.G. Narayanamurthy. 1998. *Farmer Response to Rationed and Uncertain Irrigation Supplies.* IWMI Research Report 24. International Water Management Institute, Colombo.

Perry, C.J., Michael Rock, and D. Seckler. 1997. *Water as an Economic Good: A Solution or a Problem?* IWMI Research Report 14. International Water Management Institute, Colombo.

Petermann, T. 1996. *Environmental Appraisals for Agricultural and Irrigated Land Development.* Zschortau, Germany: German Foundation for International Development and Food and Agriculture Development Centre.

Plusquellec, Hervé. 2002. *How Design, Management and Policy Affect the Performances of Irrigation Projects.* Food and Agriculture Organization, Regional Office for Asia and the Pacific, Bangkok.

Qian, Zhengying. 1994. *Water Resources Development in China.* Beijing: China Water and Power Press.

Quiggin, John, and John K. Horowitz. 1999. "The Impact of Global Warming on Agriculture: A Ricardian Analysis: Comment." *American Economic Review* 89 (4): 1044–45.

Rap, E., P. Wester, and L.N. Pérez-Prado. 2004. "The Politics of Creating Commitment: Irrigation Reforms and the Reconstitution of the Hydraulic Bureaucracy in Mexico." In P. Mollinga and A. Bolding, eds., *The Politics of Irrigation Reform: Contested Policy Formulation and Implementation in Asia, Africa, and Latin America.* Hans, UK: Ashgate.

Reisner, M. 1986. *Cadillac Desert: The American West and its Disappearing Water.* London: Secker and Warburg.

Repetto, R. 1986. *Skimming the Water: Rent-seeking and the Performance of Public Irrigation Systems.* Research Report 4. World Resources Institute, Washington, D.C.

Revenga, C., and Y. Kura. 2003. *Status and Trends of Biodiversity of Inland Water Ecosystems.* Technical Series 11. Secretariat of the Convention on Biological Diversity, Montreal, Canada.

Rinaudo, J.D. 2002. "Corruption and Allocation of Water: The Case of Public Irrigation in Pakistan." *Water Policy* 4 (2002): 405–22.

Ringler, C., M. Rosegrant, X. Cai, and S. Cline. 2003. "Auswirkungen der zunehmenden Wasserverknappung auf die globale und regionale Nahrungsmittelproduktion." *Zeitschrift für angewandte Umweltforschung (ZAU)* 15/16 (3–5): 604–19.

Rogers, P., R. Bhatia, and A. Huber. 1998. *Water as a Social and Economic Good: How to Put the Principle into Practice.* Technical Advisory Committee Working Papers 2. Stockholm: Global Water Partnership.

Rosegrant, Mark W., and Mark Svendsen. 1993. "Asian Food Production in the 1990s: Irrigation Investment and Management Policy." *Food Policy* 18 (2): 13–32.

Rosegrant, M.W., X. Cai, and S. Cline. 2002. *World Water and Food to 2025: Dealing with Scarcity.* Washington, D.C.: International Food Policy Research Institute and International Water Management Institute.

Rosegrant, M.W., M.S. Paisner, S. Meijer, and J. Witcover. 2001. *Global Food Projections to 2020: Emerging Trends and Alternative Futures.* Washington, D.C.: International Food Policy Research Institute.

Rosenberg, D.M., P. McCully, and C.M. Pringle. 2000. "Global-scale Environmental Effects of Hydrological Alterations: Introduction." *BioScience* 50 (9): 746–51.

Sanmuganathan, K. 2000. *Assessment of Irrigation Options.* WCD Thematic Review Options Assessment IV.2. World Commission on Dams, Cape Town. [www.dams.org/docs/kbase/thematic/drafts/tr42_finaldraft.pdf].

Seckler, D., D. Molden, and R. Sakthivadivel. 2003. "The Concept of Efficiency in Water-resources Management and Policy." In J.W. Kijne, R. Barker, and D. Molden, eds., *Water Productivity in Agriculture: Limits and Opportunities for Improvement.* Wallingford, UK: CABI Publishing.

Shah, T. 1993. *Groundwater Markets and Irrigation Development: Political Economy and Practical Policy.* Mumbai: Oxford University Press.

———. 2003. "Governing the Groundwater Economy: Comparative Analysis of National Institutions and Policies in South Asia, China and Mexico." *Water Perspectives* 1 (1): 2–27.

Shah, T., M. Alam, D. Kumar, R.K. Nagar, and M. Singh. 2000. *Pedaling out of Poverty: Social Impacts of a Manual Irrigation Technology in South Asia.* IWMI Research Report 45. International Water Management Institute, Colombo.

Shah, T., B. Van Koppen, D. Merrey, M. de Lange, and M. Samad. 2002. *Institutional Alternatives in African Smallholder Irrigation: Lessons from International Experience with Irrigation Management Transfer.* IWMI Research Report 60. Colombo: International Water Management Institute.

Smedema, L.K., and K. Shiati. 2002. "Irrigation and Salinity: A Perspective Review of the Salinity Hazards of Irrigation Development in the Arid Zone." *Irrigation and Drainage Systems* 16 (2): 161–74.

Tardieu, H., B. Prefol, A. Vidal, and S. Darghouth. 2005. "Public Private Partnerships in Irrigation and Drainage: Need for a Professional Third Party between Farmers and Governments." Draft paper prepared for the World Bank, 8th International Seminar on Participatory Irrigation Management, 9–13 May, Tarbes, France.

Tharme, R.E. 2003. "A Global Perspective on Environmental Flow Assessment: Emerging Trends in the Development and Application of Environmental Flow Methodologies for Rivers." *River Research and Applications* 19 (5–6): 397–441.

Thenkabail, P.S., C.M. Biradar, H. Turral, and M. Schull. Forthcoming. *A Global Irrigated Area Map (GIAM) at the End of the Last Millennium using Multi-sensor, Time-series Satellite Sensor Data.* Research Report. International Water Management Institute, Colombo.

Tiffen, M. 1987. "Dethroning the Internal Rate of Return: The Evidence from Irrigation Projects." Development Policy Review 5 (4): 361–77.

Turral, H.N. 1998. *Hydro Logic? Reform in Water Resources Management in Developed Countries with Major Agricultural Water Use: Lessons for Developing Nations.* ODI Research Study. Overseas Development Institute, London.

Turral, H.N., T. Etchells, H.M.M. Malano, H.A. Wijedasa, P. Taylor, T.A.M. McMahon, and N. Austin. 2005. "Water Trading at the Margin: The Evolution of Water Markets in the Murray-Darling Basin." *Water Resources Research* 41 (7): W07011.1–W07011.8, doi:10.1029/2004WR003463.

Udas, P.B., and M. Zwarteveen. 2005. "Prescribing Gender Equity? The Case of Tukucha Nala Irrigation System, Central Nepal." In D. Roth, R. Boelens, and M. Zwarteveen, eds., *Liquid Relations: Contested Water Rights and Legal Complexity.* Piscataway, N.J.: Rutgers University Press.

UK Met Office. 2006. Global Temperatures. [www.met-office.gov.uk/research/hadleycentre/obsdata/globaltemperature.html].

Van der Hoek, W., S.G. Feenstra, and F. Konradsen. 2002. "Availability of Irrigation Water for Domestic Use in Pakistan: Its Impact on Prevalence of Diarrhoea and Nutritional Status of Children." *Journal of Health, Population and Nutrition* 20 (1): 77–84.

Van der Hoek, W., R. Sakthivadivel, M. Renshaw, J.B. Silver, M.H. Birley, and F. Konradsen. 2001. *Alternate Wet/Dry Irrigation in Rice Cultivation: A Practical Way to Save Water and Control Malaria and Japanese Encephalitis?* IWMI Research Report 47. International Water Management Institute, Colombo.

Van Koppen, B. 2000. "Discussion Note: Policy Issues and Options for Gender-balanced Irrigation Development." Proceedings of the 6th International Microirrigation Congress, October 22–27, Cape Town.

Van Koppen, B. 2002. *A Gender Performance Indicator for Irrigation: Concepts, Tools and Applications.* IWMI Research Report 59. International Water Management Institute, Colombo.

Van Koppen, B., P. Moriarty, and E. Boelee. 2006. *Multiple-use Water Services to Advance the Millennium Development Goals.* Research Report 98. International Water Management Institute, Colombo.

Vera, J. 2005. "Irrigation Management, the Participatory Approach and Equity in an Andea Community." In V. Bennett, S. Davila-Poblete, and M. Nieves Rico, eds., *Opposing Currents: The Politics of Water and Gender in Latin America.* Pittsburgh, Pa.: University of Pittsburgh Press.

Vermillion, D.L. 1997. *Impacts of Irrigation Management Transfer: A Review of the Evidence.* IWMI Research Report 11. International Water Management Institute, Colombo.

Wade, R. 1982. "The System of Administrative and Political Corruption: Canal Irrigation in South India." *Journal of Development Studies* 18 (3): 287–328.

Ward, C., A. Peacock, and G. Gamberelli. 2006. "Investment in Agricultural Water for Poverty Reduction and Economic Growth in Sub-Saharan Africa." Synthesis Report. African Development Bank, World Bank, International Fund for Agricultural Development, and Food and Agriculture Organization Consultative Group.

WCD (World Commission on Dams). 2000. *Dams and Development: A New Framework for Decision Making.* London: Earthscan Publications Ltd.

Winpenny, J. 2003. *Financing Water for All.* Report of the World Panel on Financing Water Infrastructure, chaired by Michel Camdessus. Kyoto: World Water Council, 3rd World Water Forum, and Global Water Partnership.

Wiseman, R., D. Taylor, and H. Zingstra, eds. 2003. *Wetlands and Agriculture. Proceedings of the Workshop on Agriculture, Wetlands, and Water Resources. 17th Global Biodiversity Forum, Valencia, Spain, November 2002.* New Delhi: National Institute of Ecology and International Scientific Publications.