



**Water Resources and Environment**  
**Technical Note E.2**

**Irrigation and Drainage:  
Rehabilitation**

**Series Editors**  
**Richard Davis**  
**Rafik Hirji**

# WATER RESOURCES AND ENVIRONMENT

TECHNICAL NOTE E.2

## *Irrigation and Drainage: Rehabilitation*

SERIES EDITORS  
RICHARD DAVIS, RAFIK HIRJI



The World Bank  
Washington, D.C.



# Water Resources and Environment Technical Notes

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## FOREWORD

The environmentally sustainable development and management of water resources is a critical and complex issue for both rich and poor countries. It is technically challenging and often entails difficult trade-offs among social, economic, and political considerations. Typically, the environment is treated as a marginal issue when it is actually key to sustainable water management.

According to the World Bank's recently approved Water Resources Sector Strategy, "the environment is a special 'water-using sector' in that most environmental concerns are a central part of overall water resources management, and not just a part of a distinct water-using sector" (World Bank 2005: 28). Being integral to overall water resources management, the environment is "voiceless" when other water using sectors have distinct voices. As a consequence, representatives of these other water using sectors need to be fully aware of the importance of environmental aspects of water resources management for the development of their sectoral interests.

For us in the World Bank, water resources management—including the development of surface and groundwater resources for urban, rural, agriculture, energy, mining, and industrial uses, as well as the protection of surface and groundwater sources, pollution control, watershed management, control of water weeds, and restoration of degraded ecosystems such as lakes and wetlands—is an important element of our lending, supporting one of the essential building blocks for sustaining livelihoods and for social and economic development in general. Prior to 1993, environmental considerations of such investments were addressed reactively and primarily through the Bank's safeguard policies. The 1993 Water Resources Management Policy Paper broadened the development focus to include the protection and management of water resources in an environmentally sustainable, socially acceptable, and economically efficient manner as an emerging

priority in Bank lending. Many lessons have been learned, and these have contributed to changing attitudes and practices in World Bank operations.

Water resources management is also a critical development issue because of its many links to poverty reduction, including health, agricultural productivity, industrial and energy development, and sustainable growth in downstream communities. But strategies to reduce poverty should not lead to further degradation of water resources or ecological services. Finding a balance between these objectives is an important aspect of the Bank's interest in sustainable development. The 2001 Environment Strategy underscores the linkages among water resources management, environmental sustainability, and poverty, and shows how the 2003 Water Resources Sector Strategy's call for using water as a vehicle for increasing growth and reducing poverty can be carried out in a socially and environmentally responsible manner.

Over the past few decades, many nations have been subjected to the ravages of either droughts or floods. Unsustainable land and water use practices have contributed to the degradation of the water resources base and are undermining the primary investments in water supply, energy and irrigation infrastructure, often also contributing to loss of biodiversity. In response, new policy and institutional reforms are being developed to ensure responsible and sustainable practices are put in place, and new predictive and forecasting techniques are being developed that can help to reduce the impacts and manage the consequences of such events. The Environment and Water Resources Sector Strategies make it clear that water must be treated as a resource that spans multiple uses in a river basin, particularly to maintain sufficient flows of sufficient quality at the appropriate times to offset upstream abstraction and pollution and sustain the downstream social, ecological, and hydrological functions of watersheds and wetlands.

With the support of the Government of the Netherlands, the Environment Department has prepared an initial series of Water Resources and Environment Technical Notes to improve the knowledge base about applying environmental management principles to water resources management. The Technical Note series supports the implementation of the World Bank 1993 Water Resources Management Policy, 2001 Environment Strategy, and 2003 Water Resources Sector Strategy, as well as the implementation of the Bank's safeguard policies. The Notes are also consistent with the Millennium Development Goal objectives related to environmental sustainability of water resources.

The Notes are intended for use by those without specific training in water resources management such as technical specialists, policymakers and managers working on water sector related investments within the Bank; practitioners from bilateral, multilateral, and nongovernmental organizations; and public and private sector specialists interested in environmentally sustainable water resources management. These people may have been trained as environmental, municipal, water resources, irrigation, power, or mining engineers; or as economists, lawyers, sociologists, natural resources specialists, urban planners, environmental planners, or ecologists.

The Notes are in eight categories: environmental issues and lessons; institutional and regulatory issues; environmental flow assessment; water quality management; irrigation and drainage; water conservation (demand management); waterbody management; and selected topics. The series may be expanded in the future to include other relevant categories or topics. Not all topics will be of interest to all specialists. Some will find the review of past environmental practices in the water sector useful for learning and improving their performance; others may find their suggestions for further, more detailed information to be valuable; while still others will find them useful as a reference on emerging topics such as environmental flow assessment, environmental regulations for private water utilities, inter-basin water transfers and climate variability and climate change. The latter topics are likely to be of increasing importance as the World Bank implements its environment and water resources sector strategies and supports the next generation of water resources and environmental policy and institutional reforms.

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## INTRODUCTION

Irrigated agriculture provides about 40 percent of the world's food resources from 18 percent of the world's cultivated land. A recent analysis<sup>1</sup> shows that 4,000 km<sup>3</sup> of the 9,000 km<sup>3</sup> of readily available freshwater runoff is already used for human consumption. Compared to other water uses, irrigation is a high volume, low quality, low cost use accounting globally for 70 percent of the world's water usage. Given this existing pressure on the world's water resources, it is unlikely that many major new sources of water will be developed for irrigation use.

Most of the world's major irrigation districts were developed more than 30 years ago. Many are now in need of rehabilitation because of either failing infrastructure, excessive leakiness, or poor management. Even small improvements in water usage rates (more crop per drop) can result in significant water savings, which can be used for other purposes including the production of more food. Furthermore, their environmental performance is often unacceptable by modern standards. For example, waterlogging and salinization are common on-farm problems, impediments to fish migration, agrochemical pollution, and loss of wetlands are common off-farm problems. In Central Asia, the rehabilitation of failing irrigation systems is essential for the sustenance of the population. It will require a massive investment beyond the resources of any single institution.



Long, crested weir regulator, Majalgaon, India

The World Bank's recently published Rural Development Strategy notes that future investment priorities for agricultural water use will focus on improving the productivity of existing systems. This will not only defer the need for investment in new sources of water, but will also help protect natural resources and the environment by maintaining natural stream flows. The Strategy also points out that irrigation and drainage development and improvements will need to be planned and executed as part of integrated watershed/catchment systems.

This Technical Note is one of three dealing with irrigation and drainage (I&D) issues. Technical Note E.1 focuses on environmental aspects of irrigation and drainage development. Technical Note F.2 discusses issues, concepts, techniques and methods of water conservation in irrigation schemes. This Note focuses on irrigation and drainage rehabilitation issues. It provides information on the planned and actual performance of irrigation and drainage systems and explains why rehabilitation is so often needed. It briefly presents relevant environmental issues and associated terminology. Finally, the Note presents guidelines for strategic environmental assessments of irrigation and drainage projects and drainage rehabilitation projects.

assessments of irrigation and drainage projects and drainage rehabilitation projects.

<sup>1</sup> "Water Resources 2000-2001. People and Ecosystem: The Fraying Web of Life." Washington D.C.: UNDP, UNEP, World Bank, Water Resources Institute.

## SUSTAINABLE IRRIGATION AND DRAINAGE SYSTEMS

### ACTUAL VS. EXPECTED PERFORMANCE

Rehabilitation of irrigation and drainage systems should aim to correct the causes, not just the symptoms, that lead to degraded system performance or environmental problems. Inefficient water use, for example, may reduce the number of hectares that can be irrigated or cause soils to become waterlogged. The causes of low water-use efficiency could include an operation and maintenance budget that is inadequate or improper water pricing.

### LESSONS FROM BANK EXPERIENCE

In 1989, the Operations Evaluation Division (OED) of the World Bank reviewed 21 Bank projects that were approved between 1961 and 1978 and completed between 1970 and 1986.<sup>2</sup> The projects were considered typical of those supported by the Bank in the 1960s and 70s. While all had yielded important long-term economic benefits, their general economic performance was less than expected at the time of project completion. The generally lower than expected cost recovery was attributable to the poor performance of the irrigation systems—both physical aspects and operational aspects. Thus, the physical infrastructure had deteriorated markedly, partly because of poor construction and partly because of poor maintenance. The rigid operation of water delivery, often according to a fixed schedule, meant that farmers could not optimize their use of water and much water was wasted. Although the projects had environmental benefits, more than half also had negative environmental effects, including waterlogging and salinization, as a result of poor drainage. Most of the projects were unlikely to be viable in the long-term without rehabilitation to both physical infrastructure and changes to operational procedures.

Similarly, a 1990 evaluation of water-use efficiency in 10 internationally funded irrigation systems found that actual performance of irrigation schemes var-

ied considerably. Actual efficiencies varied from 48 to 92 percent of the design efficiency.

Although both studies were based on samples, they typify the status of I&D systems in many parts of the world. The economic and environmental consequences of these inefficiencies affect many economic sectors. For example, low water-use efficiency causes either lost agricultural production (because water is not available for agriculture elsewhere in the project area or because water-logging and salinity depresses yields) or problems with activities such as fishing upstream or navigation downstream. Similarly, overuse of water causes excess leaching of nutrients and chemicals, erosion of surface soils with attached fertilizers or pesticides, and reductions in environmentally important flows. This increases the cost of agricultural production, reduces the quality of water for human uses downstream, and damages downstream aquatic habitats (see Note C.1).

In spite of I&D systems performing at less than their design expectations, a major 1995 OED study of 208 Bank-funded irrigation projects<sup>3</sup> found that two thirds had been rated satisfactory (84 percent satisfactory if weighted by area). Over 16 million farm families benefited directly from these projects, and many millions more benefited indirectly.

The message from these reviews is that, although Bank investments in irrigation have successfully benefited millions of people, there is a considerable need to rehabilitate old projects (including ones not funded by the World Bank) because of poor construction, inadequate maintenance, poor operational procedures, lack of adequate drainage, and institutional deficiencies. The need for rehabilitating de-

<sup>2</sup> OED, 1991. Annual review of project performance audit results. Operations Evaluation Department. Washington DC: World Bank.

<sup>3</sup> Jones, W. I. (1995).

teriorating I & D infrastructure and reforming institutions is probably most apparent in Central Asia, where little has been spent on maintenance since the end of the Soviet era and where many communities are dependent on irrigated agriculture. All Bank-funded investments in rehabilitation will be carried out in accordance with the Bank's sector strategies and safeguard policies, so that the resulting I&D schemes are environmentally and socially sustainable in the long term.

## REASONS FOR UNDER-PERFORMING IRRIGATION AND DRAINAGE SYSTEMS

The common performance and environmental problems that have plagued large-scale irrigation and drainage systems are discussed in the documents listed at the end of this Note. These problems typically have social and political aspects as well as technical aspects, so managers need to consider non-technical issues even when the technical issues are apparent.

*Inappropriate policy objectives.* Investments in I&D systems are made in the pursuit of social objectives. For example, deliberate policies to build simple and cheap I&D systems as rapidly as possible have been adopted in the pursuit of food security or to support migration (e.g. California). The OED study cited above included such inappropriate policy objectives among the core reasons for underperformance of many of the I&D systems it surveyed.

This problem is by no means limited to infrastructure investments in the developing world. A 1998 World Bank report<sup>4</sup> noted that the “objectives of closer settlement in rural Australia had a great influence on the development of irrigation. Unfortunately the lack of financial discipline inherent in these policies left a legacy of irrigation enterprises of low profitability, small farms, financially unviable irrigation authorities, ageing irrigation infrastructure, a large public debt, and environmental degradation through salinity and waterlogging.”

*Unrealistic or culturally unsuitable designs.* Designs that entail operation and maintenance practices that are not within local capacity are numerous. Usually this fault can only be corrected realistically at the design stage; task managers need to assess all designs carefully for the realism of their operational implications. In assessing the Maneungteung Irrigation Project in Indonesia, a 1994 World Bank report<sup>5</sup> observed that the “system calls for a bi-weekly assessment of demand for every tertiary block, and a readjustment of every gate in the system to meet the changed water distribution plan. This requires a very intensive data collection program and an efficient and effective information management system. Because it is carried out in an environment of unpredictable water availability, it becomes almost impossible to achieve, even if there were a huge increase in the number and skills of field staff.” In this case, an effective rehabilitation project would need to focus on re-design to make operational procedures much simpler, rather than on increasing local capacity to operate the system as it was initially (and inappropriately) designed.

Another common problem is the inclusion of technologies—such as control gates in subsidiary distribution channels—where there is a lack of capacity to enforce proper operation of these devices. Consequently, such devices are widely misused to benefit locally powerful irrigators.

*Inadequate management capacity for operation and maintenance (O&M).* In other instances, system design is realistic and appropriate for the country, but management capacity is inadequate to operate and maintain the system effectively. The term “inadequate management capacity” covers a very broad category of causes. Some of the more common capacity issues, discussed in more detail in the documents cited in the Further Information section, are:

- **Insufficient training of O&M staff.** This includes not just an understanding of how to op-

<sup>4</sup> Langford, K. J. , C.L. Forster, D.M.Malcolm (1998).

<sup>5</sup> Murray-Rust, D. H., and W.B. Snellen (1991), in a draft paper cited by Plusquellec et.al. (1994).



erate the system under a variety of conditions, but the importance of systematic preventative maintenance plans.<sup>6</sup> Maintenance costs (including losses to users when the system is “down”) are highest when maintenance is only performed after system components break down.

- **Insufficient training of accounting and financial staff.** It is difficult to operate more efficiently or avoid environmental problems based on past experience when staff members do not know how to analyze the information.
- **Inadequate accounting and financial practices, even when staff members are well trained.** For example, depreciation based on historical costs, although commonly used to account for capital consumption, does not provide financial reserves to replace capital assets when they are worn out. In some cases, this depreciation practice, even if well implemented, will eventually undermine system operation.
- **Inappropriate pay and career pathways for employees.** This includes not only inadequate pay or opportunities for advancement for junior staff, but also excessive pay and patronage or years-of-service systems of promotion for more senior staff. Poorly motivated staff have little incentive to collect fees and may be more susceptible to corruption. The result is that many water users do not pay for their water, reducing the income that should be used for maintenance.
- **Insufficient experience with new management strategies or tools.** Although not always a cause of O&M failure, there is increasing demand for management staff to apply new techniques when they have no background or training in these topics. Experience in developed countries shows that some of these management skills cannot be taught but must be obtained through experience.

*Conflicting incentives.* Management rules or behaviors can create incentives that diminish system performance or create environmental problems. A common example occurs when water delivery is erratic. This creates an incentive for upstream water users to take as much water as they can, reducing or eliminating water for downstream water users. This, in turn, creates an incentive for down-



Photo by Walter Ochs, World Bank

Irrigation ditch and turnout, near Manisa, Turkey

stream water users to withhold payment for system operation and maintenance, which can make water delivery even more erratic or infrequent. As a result, downstream users sometimes shift to uncontrolled groundwater abstraction, causing depletion of aquifers.

Conflicting incentives can also occur between project beneficiaries and other groups. For example,

<sup>6</sup> The 1989 OED study cited previously concluded that poor construction standards, insufficient funding, and lack of systematic maintenance plans were the main reasons for poor maintenance.

drainage systems that dispose of irrigation water in a way that damages downstream water quality (see Note D.1) may create an incentive for irrigators to neglect maintenance of drains so that they discharge less water as an informal way of responding to complaints from downstream relatives or neighbors. If this happens, the irrigators will be rewarded socially by fewer complaints, but they will be affected eventually by reduced yields and increased waterlogging if they continue to irrigate without adequate drainage. Thus, environmental problems can result from conflicting incentives implicit in the system design and the O&M procedures.

*Input subsidies or output controls.* There is an extensive literature on the environmental and operational problems that have resulted from subsidized water pricing or from controls over production. Water-use efficiency, for example, is much lower in cases where recipients of irrigation water are charged by size of the area irrigated rather than by the volume of water used because the land area is fixed, and so there is no incentive to use less water. Waterlogging, excess use of fertilizer and pesticides, degraded water quality, aquatic habitat degradation downstream, and other environmental and performance problems have been documented to result from these pricing practices.

Pricing schemes that distort water use are widespread. A 1995 World Bank review<sup>7</sup> found that area-based pricing exists in 9 of the 11 developing countries and 2 of the 5 developed countries studied.<sup>8</sup> The review also found that 15 of the 16 countries—including all five developed countries—do not have rates that fully recover the cost of providing irrigation water.

Subsidies for agricultural inputs have also contributed to extensive water pollution and soil degradation, most notably in the agricultural areas of the transition economies of the former Soviet Union. Output controls, such as specification of crop type, used in India and other countries to maintain self-sufficiency in staples, will also contribute to environmental and performance problems when irrigators have to forgo other crops that are better suited to local conditions and market prices.

*Priority given to irrigation over drainage.* A political emphasis on the development of irrigation systems, with drainage issues being either neglected entirely or postponed, has in a number of cases caused environmental damage and consequent reduction in agricultural performance. Neglect of agricultural drainage does not usually cause performance or environmental problems in the short term, but it is probably the most significant cause of these problems in the long term. A World Bank study<sup>9</sup> examined 186 I&D projects from 1983 to 1991. Of these, 125 were irrigation alone, 16 were drainage alone, and 45 were both irrigation and drainage.

In particular, soil degradation from salinity has undermined the initial agricultural gains from irrigation. Although the data are old (1985 to 1992), the above study reported that areas with irrigation-induced salinity, expressed as a percentage of total irrigated area, amounted to 11 percent in India, 21 percent in Pakistan, 10 percent in Mexico, 23 percent in China, 48 percent in Turkmenistan, 24 percent in Uzbekistan, 17 percent in Kazakhstan, and 28 percent in the United States. Studies in India, Mexico, and Turkey found yield losses of 30 to 56 percent due to irrigation-induced salinity, and associated reductions in net income to farmers of 35 to 97 percent. These figures do not apply to all cases of soil degradation, but they show that the drainage component of irrigation systems is closely linked to both environmental impact and economic performance. Irrigation system rehabilitation projects must address all soil or water degradation problems to make the overall schemes sufficiently sustainable to avoid future rehabilitation.

<sup>7</sup> Tsur, Y., and A. Dinar (1995).

<sup>8</sup> Only volumetric rates are used in the other five countries. Volumetric rates are combined with area-based rates in two of the nine developing countries and one of the two developed countries with area-based rates.

<sup>9</sup> Umali, D. L., (1995).



## STRATEGIC ENVIRONMENTAL ISSUES FOR I&D REHABILITATION

Environmental assessments (EA) of I&D projects, including rehabilitation projects, must address numerous potential impacts. These are listed in the World Bank’s 1991 Environmental Assessment Sourcebook and its updates. The documents in the Further Information section provide more technical information. Table 1 lists some additional impacts that can arise with I&D rehabilitation projects.

Some potential environmental impacts are strategic. That is, if recognized early in the project cycle, they can lead to alterations in the project plan or conceptual design. Thus, lining irrigation canals when they are being rehabilitated may initially seem prohibitively expensive. However, if more drains will eventually be required to prevent waterlogging due to seepage, then a system design that includes lined canals may be economically and environmentally superior (see Note F.2).

Depending on local circumstances and the history of the I&D facilities that are to be rehabilitated, the environmental and production issues that are “stra-

tegic” will differ between projects. As emphasized previously, identification of possible environmental problems is not enough. The underlying causes of these problems need to be identified and corrected.

### ON-SITE AND OFF-SITE IMPACTS

On-site impacts on irrigated or drained land include soil erosion and other damage to soils in irrigation areas; off-site impacts include downstream pollution or deposits of eroded soil. The distinction is important because on-site impacts are borne by the party that benefits from irrigation or drainage, while off-site impacts are borne by others, sometimes including downstream beneficiaries of irrigation or drainage. In a perfect world, farmers would weigh the cost of on-site impacts against the benefits of irrigation and drainage, and decide how much on-site damage to accept. However, farmers may adopt a short time horizon and may not possess full knowledge about these impacts, so their decisions may not be optimal. Thus, strategic solutions to on-site

**TABLE 1.**  
**SOME ENVIRONMENTAL IMPACTS SPECIFIC TO REHABILITATION PROJECTS**

Potential Impact	On- or Off-Site	Possible Strategic Actions
Leached elements from disposed, dredged sediments	Off-site	If testing confirms this possibility, seek to incorporate dredge spoils within engineering embankments or other less exposed locations.
Loss of habitat within heavily silted or vegetated canals	On-site	Construct similar habitat outside the canals using dredged materials.
Loss of habitat supported by leaking irrigation facilities	On- or off-site	Assess the economic value of this habitat and, if feasible, convince beneficiaries to pay for irrigation water or drainage flows to sustain the habitat.
Reduced fish spawning or survival due to inability to pass formerly leaky control gates or structures	On- or off-site	Install fish ladders or other facilities to support fish migration, paid for by beneficiaries.
Human health impacts from restoring flows from canals that are being (informally) used for sewage disposal	Primarily off-site (downstream)	Perhaps allow continue informal use if modeling indicates health risks are minimal. If risks are significant, include sewage disposal as part of the project.

impacts often involve education and technical assistance to farmers, so they have information on the long-term consequences of their decisions.

Off-site impacts, on the other hand, exemplify negative<sup>10</sup> environmental externalities. Inexpensive pollutant disposal is beneficial to the creator of pollution, but harmful to the downstream recipients. Unless the polluter pays the recipients for the costs they face—or, under some circumstances, the recipients pay the polluter to reduce pollution—the optimal level of pollution will be exceeded. Strategic solutions to off-site impacts often involve getting the affected groups to agree on how to share the benefits and costs of the new project, and to mediate the disputes that will inevitably arise as the remediated I&D system is constructed, operated, and maintained.

## WATER QUANTITY AND QUALITY

The same water quantity and quality issues that are considered when an I&D project is being developed are also relevant when an existing scheme is being rehabilitated. Thus, the effect of changes in water flow on both upstream and downstream communities and environments should be assessed as part of an EA. These would include effects on livelihoods (fishing, recession agriculture, fiber, small-scale irrigation, etc) as well as effects on environmental processes, particularly those that communities depend on. Changes in flow that trigger fish breeding, alter habitat, or maintain wetlands and floodplains are examples of such environmental processes. Generally, rehabilitation will lead to greater water use efficiency, so there will be opportunities to mitigate these adverse effects, including effects from when the I&D scheme was constructed, using the “saved” water.

I&D rehabilitation will commonly lead to reduced water losses from both canals and on-farm distribution and application systems. These reductions can affect communities and habitat within the I&D area that have become dependent on this source of water. Thus, it is common for villages that have developed within the I&D area to obtain their water

from surface ponds or groundwater systems that are fed by these leakages. Rehabilitation may also eliminate habitat that was originally created by the I&D system itself, but is now scarce and valuable because most natural habitat of that type has been destroyed. The Santa Clara Valley Water District in northern California, for example, is required to remove sediment and vegetation from one side only of flood control channels in order to maintain in-channel habitat because rare species of birds may now be dependent on this habitat. This concern typically arises with rehabilitation of unlined I&D canals and I&D canals or control structures where adjacent wetlands have developed because of continual leakage.

More direct habitat loss can occur during rehabilitation. Examples include wetlands that are drained for agriculture as a result of water-use improvements, land flooded by new or expanded reservoirs, and floodplains that are no longer flooded because they are protected by levees. Less obvious on-site habitat loss may also be important. For example, a declining water table—caused by either reductions in recharge because of leakage control measures or groundwater being used for supplementary irrigation—may cause deep-rooted trees and shrubs to die.

Development of new or improved drainage systems as part of rehabilitation will almost always lead to beneficial on-site effects (see below) but may lead to either beneficial or detrimental downstream effects. For example, the rehabilitation can lead to an increase in the discharge of nutrients and pesticides if modern irrigation techniques and improved crop varieties are introduced. On the other hand, it can lead to a reduction in the discharge of these pollutants if on-farm water conservation techniques are

<sup>10</sup> Positive environmental externalities also occur, but less frequently. For example, irrigation system rehabilitation can reduce the incidence of water-related diseases (e.g., malaria transmitted by mosquitoes). For people outside the service area that is rehabilitated, a positive environmental health externality exists.

introduced that reduce leaching and surface runoff (see Note F.2). Again, rehabilitation can lead to longer growing seasons, greater abstractions of water during the dry season, reduced dry season river flows and detrimental impacts on downstream environments. Each rehabilitation project will have to be assessed on its merits, and a decision made that takes account of not just the benefits of the rehabilitation to the farmers in the I&D area but also the downstream benefits and costs.

## SALINIZATION

Salinization is one of the most common and most costly environmental consequences of inadequate drainage in irrigation areas. It occurs either because irrigation water contains dissolved solids (many of which are salts) and evaporation from fields leaves behind a salt burden, or because excessive applications of water cause the watertable to rise, bringing old salt deposits to the surface. If the surface soils already contain a high salt concentration from one of these causes, then a small excess of irrigation water (the leaching fraction) needs to be applied to gradually wash the salt to either deeper groundwater or to drainage systems (where it may cause other environmental problems). If the salt is brought to the surface by rising groundwater tables, then irrigation water needs to be applied carefully to pre-

vent excess deep percolation, thereby lowering the watertables and conserving surface water supplies.

Salinity buildup will reduce the yield of crops that are sensitive to the particular salts that accumulate. Changing to less sensitive crops will reduce this problem, temporarily. An imbalance between salt ions, most notably an excess of sodium in comparison with calcium and magnesium, can degrade soil structure (see Note E.1). For example, clay particles in soil may swell or form a crust when wetted, reducing or preventing water infiltration, or they may clump, reducing air penetration and water holding capacity.

## OTHER SOIL DEGRADATION ISSUES

Acidification refers to the process of increasing soil acidity, either due to irrigation with acidic water or drainage of lands that contain high concentrations of unoxidized organic matter. The first cause is not common, and can be avoided through monitoring of irrigation water quality, lime addition, or other means of buffering soil against excess acidity. The second cause is more widespread and more serious. Swamps and mangrove forests often accumulate unoxidized organic matter as stagnant or brackish water is depleted of oxygen by decomposition of organic matter. Drainage can expose

organic matter, which then oxidizes, releasing more organic acids that are in turn degraded by bacteria. Acid-sulphate soils are an extreme example of a drainage-induced acidification problem (see Note E.1), where the pH can drop to 3.

Waterlogging occurs when near-surface soils become saturated due to either a rise in the water table or water becoming trapped near the surface due to an impermeable sub-soil layer. Waterlogging can cause fields and nearby lands to flood easily. It makes access to fields



Salinized soils, China

Photo by Hervé Plusqueliec, World Bank

(other than rice paddy) more difficult, and prevents air from penetrating soil pore spaces. Lack of air in soil leads in turn to the death of many species of worms and other soil organisms that aerate the soil and make nutrients available to crop species.

Soil erosion, borne either by wind or water, is relatively common, leading to nutrient loss as well as

depleting the topsoil. Less topsoil may not be a problem initially, but can eventually make rooting difficult for plants and make them more susceptible to being uprooted by wind or water. Wind-borne erosion is less common, but can be quite severe if the soil structure has been degraded by other factors such as salinization.

## LESSONS FROM EXPERIENCE

The following guidelines summarize lessons from past successes and mistakes. They are not a blueprint or checklist, but provide signposts towards successful I&D rehabilitation.

### CONSIDER PROJECT IMPACTS AT THE REGIONAL SCALE

The World Bank has endorsed integrated water resources management since its 1995 Water Resources Management Policy. Water and salt balance calculations are a relatively simple way to introduce integrated management issues into the comparison of conceptual alternatives for a rehabilitation project. This has been done successfully in the Indus Basin of Pakistan through a series of salt balances. In Australia's Murray-Darling Basin, a recently released salinity audit (Box 1) demonstrates how such analysis can guide regional investments in salt reduction, so that project investments are part of a regional least-cost strategy to achieve environmental objectives. That is, the amount of salt control required from each I&D rehabilitation project partially depends on the regional salt balance and partially on regional economic and environmental priorities. In the case of the Murray-Darling Basin, this region-wide analysis has been followed up with rules for water allocation and management that take account of the needs of all water users.

Similarly, the targets for water-use efficiency depend on alternative uses for water in the region, including instream uses both upstream and downstream of the project site. Comprehensive water

resources planning that is being introduced in Tamil Nadu and Orissa, India, includes I&D system rehabilitation and exemplifies this type of approach. This type of planning led to cancellation of the formerly proposed Gumti 2 Flood Control and Irrigation project in India because the economic loss of (non-commercial) fish traditionally caught on the floodplain was estimated to be greater than the flood control benefits of the project. This example shows how I&D system rehabilitation may be economically justified on agricultural grounds alone, but cannot be justified from a multisectoral, regional perspective.

### ADDRESS DRAINAGE ISSUES THOROUGHLY FROM THE OUTSET

When drainage is left until a later stage of development, it is critical to have a firm commitment to particular drainage facilities from the outset. As the selenium problem in the Kesterson ponds (see Note E.1) demonstrated, failure to realistically specify when, how, and at whose expense drainage facilities would be installed led to serious environmental problems. In most cases, failure to provide irrigation drainage will eventually lead to significant economic losses, so detailed planning and financial guarantees should be sought for drainage facilities early in I&D rehabilitation planning. Although irrigation systems that were initially constructed without drainage can be rehabilitated in some cases (Box 2), experience has shown that such facilities tend to become political priorities only after significant damage has occurred.



### Box 1. THE MURRAY-DARLING BASIN SALINITY AUDIT

The irrigation and drainage management program of the Murray-Darling Basin in Australia is among the most advanced I&D management programs in the world. By the late 1980s, 96,000 hectares of irrigated land in the basin were showing visible signs of salinization, and it was estimated that areas affected by high water tables would increase from 560,000 hectares in 1985 to 870,000 hectares in 2015. Estimates of basin-wide impacts of salinity and water table rise range from \$600 million to \$1 billion per year over the coming century. These findings prompted development of a salinity and drainage strategy, including regional cooperation among five state governments, the Australian federal government, and many communities within the basin. The basin-wide strategy achieved impressive gains by the late 1990s. For example, at a key downstream monitoring location, salt concentrations exceeding the target level of 800 electrical conductivity units (ECU) declined from 42 percent to 8 percent of the time. Projections, however, suggested that salt concentrations will rise over the next 100 years, and these gains could be lost within perhaps 20 years.

These projections were examined in much greater detail through an audit of all salt sources in the basin completed in late 1999. The audit produced numerous important findings, of which three were clearly relevant to setting priorities for environmental investments within the basin. First, salinity trends were more severe than previously anticipated. The annual movement of salt in the basin landscape was estimated to double in the next 100 years. Secondly, salinization of non-irrigated, dryland farming areas is significant (around 300,000 hectares in 1995), and salt from dryland farming areas is anticipated to contribute 60 percent of the salt load in the lower Murray River in future decades as irrigation loads are controlled. This has significant implications for the long-term benefits of continuing investments in I&D rehabilitation. Thirdly, significant salt loads are created from drainage of naturally occurring, saline groundwater that can often be prevented or reduced at relatively low cost.

The salinity audit demonstrates the value and feasibility of basin-wide analysis of significant environmental problems. The limitation that the increasing salt load from dryland salinity imposed on further I&D rehabilitation had not been previously recognized, and this result significantly affected decisions at the I&D project level. Admittedly, it is difficult to integrate project planning with basin-wide planning, especially when data and financial resources are more limited than in Australia. But less-complicated evaluations of strategic considerations at the basin level are valuable for putting I&D investments into a larger context.

Source: The Murray-Darling Basin Commission. 1999. *The Salinity Audit of the Murray-Darling Basins*. Canberra Australia: The Murray-Darling Basin Commission.

## ENSURE THE PARTICIPATION OF STAKEHOLDERS

Promoting the participation of water users in the management of irrigation systems has greatly improved the performance of I&D systems in many countries, including Turkey, India, the Phillipines, and Mexico. Examples of the types of performance improvements that have been achieved by participatory irrigation management (PIM) are provided in Box 3.

One of PIM's objectives is to replace the vicious cycle of low irrigation system performance—leading to low farmer support and lower performance—with a greater sense of ownership, leading to improved system performance and greater participation and

support, which increases performance over time. However, it is clear that improved collection of fees and charges only results in improved system performance if the irrigation system has financial independence from government.<sup>11</sup> Otherwise, the fees end up in consolidated government revenue and are not used within the irrigation area. Because the cost of on-site environmental impacts is borne by water users, PIM also has the potential to reduce on-site environmental impacts such as waterlogging and salinization. However, there is little evidence of this happening at present.

Off-site environmental impacts are unlikely to be reduced by PIM, unless those who are harmed by

<sup>11</sup> Jones, W. I. (1995).



**Box 2.****SALINITY REVERSAL: THE EXPERIENCE IN EGYPT AND PAKISTAN**

In general, it is economically and environmentally better to prevent salinization through well-designed drainage systems than to have to reverse it once it has occurred. However, it can be reversed in many cases, as experience in Egypt and Pakistan demonstrates.

By 1970, about 60 percent of all cultivated land in Egypt was classified as moderately to severely affected by salinity and waterlogging, with crop yields below the national average. Only about 7 percent of irrigated land was unaffected by these problems. As a result, large-scale drainage works were introduced in the 1970s. By June 1990, some 1.43 million hectares had been provided with drainage systems (out of 2.95 million hectares of total arable land). The installation of the drainage systems reduced soil salinity and increased yields. After drainage was installed, soil salinity declined by a factor of 2 to 5 in newly drained areas, wheat yields increased from 1 to 2.4 metric tons per hectare, and maize yields increased from 2.4 to 3.6 metric tons per hectare.

Pakistan irrigates about 14 million hectares of land—one of the largest irrigation systems in the world. Unlined irrigation canals, inefficient irrigation practices, and the absence of drainage have all contributed to extensive waterlogging and salinity problems. The Water and Power Development Authority initiated a program of salinity control and reclamation projects (SCARPs) in 1958. By the late 1980s, about 3.7 million hectares were serviced by SCARPs. Deep tubewells were used to assist drainage. In areas with saline groundwater, they promote deep drainage. In areas with fresh groundwater, they permit supplemental irrigation with groundwater, lowering the water table and reducing the demand for irrigation from surface waters. Despite numerous obstacles and setbacks, an average of 80,000 hectares of affected lands have been brought back into production every year due to improved drainage.

Source: Umali, D. L. (1993).

**Box 3.****PERFORMANCE IMPROVEMENTS FROM PARTICIPATORY IRRIGATION MANAGEMENT**

Involving irrigation water users and other stakeholders in management of I&D systems often greatly improves system performance. For example, irrigators in New Zealand were able to reduce costs by nearly 66 percent due to increased efficiency of operation, lower overhead costs than government management, reduction in overly elaborate engineering design and specifications, and the greater personal responsibility irrigators take for maintaining the systems they themselves own.

Similarly, in Chile, government management of 60,000 hectares of irrigated land on the Rio Dugullin involved 5 engineers, 8 to 10 technicians, 15 to 20 trucks, and 5 bulldozers, compared to 1 engineer, 2 technicians, 1 secretary, and 2 trucks under farmer management in the same area. Greater knowledge of user needs and responsibility for meeting (and paying for) one's needs create incentives for cost-effectiveness that often do not exist under other types of management. Increased performance, and the closer link between O&M expenditures and those who pay for them, was also reported to increase the willingness-to-pay of irrigation water users in this Chilean example.

In Senegal, poor service reliability under agency management resulted in a low collection rate of irrigation fees. Electricity was subsidized and agency staff usually turned pumps on and left them on, resulting in overpumping and frequent system breakdowns. Farmers' fees increased by a factor of two to four when water users took over the system and paid for full electricity consumption, along with maintenance and a fund for pump replacement. Water users were willing to pay these higher fees because service reliability increased and was now largely within their control.

Source: Subramanian, A. et al (1997).

off-site impacts are included in the water user group. Participatory management by water users alone might greatly improve system performance and reduce on-site environmental impacts, while ignoring or even increasing off-site impacts. A strategic

EA should assess whether significant off-site impacts exist now or might exist after rehabilitation, and whether those who are affected by these impacts can participate in irrigation management in a way that will encourage tradeoffs to occur between

those causing and those facing these impacts. Even though experience shows the benefits from the participation of water user groups in water allocation and management, institutions such as government departments still need to be involved. They possess legal authority and financial resources that are essential for effective management.

## INCREASE THE ROLE OF THE PRIVATE SECTOR

Many irrigation systems include privately owned components. For example, Egyptian irrigation canals are usually lower than the fields that are irrigated. Each farmer or group of farmers owns the pumps that lift water from canal to field. Although there is a trend toward privatization of the public portion of irrigation systems, there has been less (but nonetheless substantial) attention to involving the private sector in investments that complement operation of the public system.

In Bangladesh, institutional changes that made it possible for farmers to purchase and install tubewells and low-lift pumps led to a substantial increase in the number of tubewells. This helped to control waterlogging from an irrigation-induced rising water table and reduced the amount of irrigation water required from surface water sources. Widespread private investment that complements public investment is only possible when credit is widely available. Microfinance with social collateral, pioneered by the Grameen Bank in Bangladesh but supported by many organizations today, is integral to full engagement of the private sector.

Recent empirical economic analysis has shown that rates of economic growth are higher in countries with greater income equality. A very plausible explanation for this finding is that profitable investment opportunities recognized by those closest to the investments are not always recognized by those with capital to invest. When greater income equality exists, informal loans from friends, relatives, or local lenders are more available, allowing these investment opportunities to be captured. Societies with

greater income inequality may be failing to take advantage of profitable opportunities recognized by their poorer citizens.

## INSTITUTE PAYMENT SYSTEMS THAT ENSURE ADEQUATE REVENUE

The worst environmental and production problems are usually caused by inadequate revenue for operation and maintenance, for completing the initial system design (e.g., drainage components), or for replacing capital facilities as they decay. Revenue and financial issues have an important strategic environmental dimension, which is usually too late to address at the EA stage of the project cycle.

Revenue is limited by the willingness of those who benefit from the I&D system to pay for services. Irrigation water has often been subsidized because of the perceived benefit to the nation from agricultural development. As that perception has changed, political support for these subsidies has declined. Avoiding revenue shortfalls in the long run depends on identifying the real benefits and costs of rehabilitating the I&D system and getting the beneficiaries to recognize the benefits and pay for them. As discussed above, this is best achieved with a PIM approach. Although getting irrigation water users to fully cover costs will result in a sustainable system, there are other sustainable pricing systems, including ones that don't impose the full cost of I&D on purchasers of irrigation water.

For example, downstream water users may be willing to help pay for drainage improvements that improve water quality. Thus, irrigators will pay less than the full cost of drainage. Of course, there is an argument in favor of the "polluter pays principle." But that is not always possible, given historical and political conditions, and sharing the costs of a drainage scheme between the polluters and those affected downstream can still result in an economically efficient solution that is more acceptable to the most powerful stakeholder groups. Any payment system where all beneficiaries feel they are getting more than they are paying, and where all costs are cov-

ered, will be sustainable. An innovative cost-sharing example that involved payment by an external beneficiary for water quantity rather than water quality improvements is presented in Box 4.

## CREATE SYSTEM PERFORMANCE AND IMPACT MONITORING AND FEEDBACK LOOPS

The outcomes of irrigation and drainage rehabilitation should be monitored and communicated to

the stakeholders in I&D systems. In turn, they can put pressure on those who manage the systems to recognize and resolve problems before they become significant. Feedback loops of this sort are most effective when they are explicitly discussed by stakeholders during conceptual development of a project and formalized as a condition of project financing. Identification and strengthening of feedback loops is especially important for control of off-site environmental impacts. Unfortunately, very few arrangements of this type seem to have been made in irrigation and drainage projects.

## UNDERTAKING REHABILITATION AND MODERNIZATION

Few irrigation and drainage projects in developing countries are reasonably maintained, largely because of inadequate financial resources for maintenance activities caused by either low government budgetary allocations and/or insufficient fees collected from farmers. Even with reasonable maintenance, over a period of time project water requirements could change, perhaps as a result of a shift in cropping patterns. Water supply and water quality no longer match the project as originally planned, and existing facilities need some changes.

The most common reason to consider a rehabilitation or modernization of an irrigation project is the deterioration of the physical infrastructure of the irrigation and drainage system. However, in most cases, this deterioration is only a symptom of the poor performance of the management of the water delivery system.

Most projects never reached their original expected level of performance. In some cases, they may have caused severe negative impacts to the off-site and

### Box 4.

#### COST-SHARING FOR I&D IMPROVEMENTS IN THE IMPERIAL VALLEY, CALIFORNIA

The Imperial Irrigation District (IID) services approximately 184,000 hectares of irrigated desert in southern California. The district irrigation efficiency is 75 percent, including on-farm losses and conveyance losses. The IID is supplied by canals, most of which were unlined when constructed. All drainage water from the IID ends up in the Salton Sea, a salt sink.

Drought-related water shortages in California, population and water demand growth projections, and limits on withdrawals from surface water sources such as the Colorado River and the San Joaquin-Sacramento River Delta have spurred interest in water conservation for both urban and agricultural uses. Because water conservation in the IID is less expensive than in the urban areas served by the Metropolitan Water District (MWD), a cost-sharing arrangement was organized in the early 1990s to transfer \$150 million from MWD to IID. Funds were spent to modernize IID operations, with the "saved" water being transferred to MWD. Improvements included canal lining to reduce seepage; improved remote monitoring (microwave) of water levels and flows; automation of key canals; increased reservoir storage to buffer the timing of deliveries within IID from the timing of deliveries to IID by external suppliers; lateral interceptors to capture and re-use spills from the ends of lateral canals; and increased training of employees to increase responsiveness to water users' needs and requests.

MWD, IID, and environmental groups generally agree that this cost-sharing arrangement is a success.

Source: Plusquellec, H. et al. (1994).

on-site environment. In most cases, a simple restoration of the physical infrastructure “as it was” would only repeat the vicious cycle of deterioration and rehabilitation. A number of donor-financed projects during the last two decades have supported rehabilitation projects consisting mostly of infrastructure repairs, such as leaks and rusted gates, erosion, and instability of earthworks. However, the actual causes of poor performance need to be identified through an in-depth diagnosis. Only a systematic diagnosis will provide insight into whether the project should be rehabilitated or upgraded (Box 5) through physical modifications or whether managerial changes are also needed.

A diagnostic should include first a review of the original objectives of the project to establish a baseline for further evaluation, and then an analysis of the existing system.

The quantity and quality of surface and groundwater resources available to the project when it was initially conceived and developed should be reviewed to determine if such supply was ever made available, and if the amount was adequate to meet project demand. Questions concerning the adequacy of the original project’s water quantity and quality should include:

- Were water allocations for other water activities—irrigation, flood control, power generation,

municipal and domestic water use, navigation, recreation, fish and wildlife—considered?

- Was the water supply adequate during drought periods? What was the magnitude and frequency of shortages expected?
- Was the use of groundwater considered as a water supply component?
- Was the water quality of surface and groundwater adequate for the purposes of the original project during the years of operation?
- Were the assumptions regarding conveyance, distribution, and on-farm efficiencies realistic, given the level of control technology of the irrigation system and the long-term effectiveness of the canal lining design and quality standards?

Subsequent modifications to the original features and objectives of the project should be identified. During their operation, many projects are affected by physical, social, and environmental events. Changes in land use, types of crops, and cropping intensities are most frequent. Groundwater largely contributed to the intensification of irrigation in some alluvial, irrigated areas. Abundant water supplies may have decreased considerably due to upstream irrigation expansion. On-site waterlogging and salinization may have impacted a large portion of the project area.

### Box 5.

#### DEFINITIONS: MAINTENANCE, REHABILITATION AND MODERNIZATION

These definitions are based on the ICID Guidelines for rehabilitation and modernization of irrigation projects.

- Maintenance, a routine activity, is the process of keeping irrigation and drainage facilities in good working condition so that all parts can fulfill the purpose for which they were originally designed.
- Rehabilitation is the renovation or carrying out of remedial work on existing facilities in need of repair, and on those facilities whose performance fails to meet the original criteria and needs of the project. If the original performance criteria were inadequate or no longer meet the needs of the users, rehabilitation by itself could perpetuate the vicious cycle of poor recovery of recurrent cost, inadequate maintenance, deterioration and rehabilitation.
- Modernization is the process of improving and enhancing an existing irrigation system to meet new performance criteria. The process includes changes in existing facilities, operational procedures, and institutional aspects. Unlike rehabilitation, modernization is not renovation of project facilities in need of repair.

A more specific definition of modernization was adopted during an FAO expert consultation held in Bangkok in 1996: “A process of technical and managerial upgrading (as opposed to mere rehabilitation) of irrigation schemes combined with institutional reform, with the objective to improve resource mobilization (labor, water, economic, environmental) and water delivery service to farmers.”

The diagnostic of the present performance should evaluate whether the project has ever reached its objectives in terms of hydraulic, agronomic, economic, financial, and environmental performance, including:

- Hydraulic performance: conveyance, distribution and on-farm efficiency
- Agronomic performance: cropping intensities, crop yields
- Economic performance: rate of return
- Financial performance: cost recovery, farmers income.

Performance indicators have been developed by several organizations (ICID, IWMI, FAO and World Bank/IPTRID) to assess the performance of projects by comparing inputs and outputs in terms of water and monetary values. These indicators are useful to determine if a project is performing well compared with similar projects, or if its performance is deteriorating over time. However, more complex investigations are needed to understand the causes of poor performance. These include an examination of the water allocation, water control strategy, control equipment, and the performance of the management agency. Thus, irrigation projects aiming to deliver water according to crop requirements through a canal system equipped with manually operated gates or through fixed structures to divide water inflows according to agreed proportions (flow dividers) are doomed to failure—first, because of their operational complexity; and second, because they have no capability to adjust to actual water needs. Both designs cannot reach the efficiencies of more advanced projects. Furthermore, the rigid or unreliable water delivery supplied by these systems constrains farmers' incentive to adopt on-farm water-saving techniques (see Note F.2).

## THE NEED FOR A NEW APPROACH TO IRRIGATION DEVELOPMENT AND REHABILITATION

Irrigation rehabilitation is not just a matter of improving or replacing physical infrastructure. As

described in the first section, many of the problems ultimately arise from unachievable policy objectives, inadequate prices for scarce water, insufficient management capacity, and conflicting institutional objectives. Many countries have now instituted reforms of these institutional and financial issues as part of overall rehabilitation of the I&D sector. For example, the State of Victoria, Australia has undertaken a comprehensive reform process in its I&D operations, including:

- Separating the functions of water resources policy development, enforcement of standards, and undertaking technical operations
- Regionalizing the management of irrigation districts
- Encouraging the involvement of local irrigators in the management of their districts
- Changing the pricing structure for water supply to better (but not fully) reflect the cost of operations.

These reforms have allowed greater investment in modern irrigation infrastructure, a more profitable irrigation industry and a more sustainable industry in the long term.

Simple infrastructure rehabilitation in the face of inadequate institutions and policies is a short-term solution that is likely to fail. Experience shows that simple rehabilitation will lead to a cycle of rehabilitation, followed by degradation, followed by rehabilitation. This cycle can be seen in certain regions impacted by substantial changes in water supplies and land use—such as Pakistan—or in regions where design criteria are either faulty or unrealistic. Very few countries have adopted the full spectrum of reforms to I&D operations. Nevertheless, it is common to find some level of institutional reforms and capacity strengthening included as part of I&D rehabilitation projects. Improvements in the responsiveness of I&D management, coupled with changes in water pricing as well as technical improvements, all contribute toward more efficient and productive I&D systems.



## FURTHER INFORMATION

A useful general reference is:

Masood, Ahmad, and Gary Kutcher. 1992. *Irrigation planning with environmental considerations*. World Bank Technical Paper No. 166. Washington: World Bank.

Participatory management of I&D schemes is discussed, with examples, in:

Groenfeldt, D. and M. Svendsen. 2000. *Case studies in participatory irrigation management*. Washington: World Bank Institute.

Oblitas, K. and J. R. Peter. 1999. *Transferring irrigation management to farmers in Andhra Pradesh, India*. World Bank Technical Paper No. 449. Washington: World Bank.

Subramanian, A., N. Vijay Jagannathan, R. Meinzen-Dick, eds. 1997. *User organizations for sustainable water services*. World Bank Technical Paper No. 354. Washington: World Bank.

There have been a number of evaluations of the performance of I&D schemes, including:

Jones, W. I. 1995. *The World Bank and Irrigation*. OED Department Report. Washington: World Bank.

World Bank Operations Evaluation Department (OED). 1996. *Irrigation O&M and system performance in southeast Asia: an OED impact study*. OED Report No. 15824. Washington: World Bank.

Umali, D. L. 1995. *Irrigation-Induced Salinity*. World Bank Technical Paper No. 215. Washington: World Bank.

Modern I&D systems that show both economically and environmentally improved performance are described in:

Plusquellec, H., C. Burt, and H. W. Wolter. 1994. *Modern water control in irrigation*. World Bank Technical Paper No. 246. Washington: World Bank.

Langford, K. J., C. L. Forster, and D. M. Malcolm. 1998. *Toward a financially sustainable irrigation system*. World Bank Technical Paper No. 413. Washington: World Bank.

Setting the price for irrigation water as part of rehabilitation is described in:

Tsur, Y. and A. Dinar. 1995. *Efficiency and equity considerations in pricing and allocating irrigation water*. Policy Research Working Paper No. 1460. Washington: World Bank.

Skaggs, R. W., M.A. Breve, and J.W. Gilliam. 1994. "Hydrologic and water quality impacts of agricultural drainage," in *Critical reviews in environmental science and technology*, 24(1): 1-32.