WTP0178

0077-3

Internal Documents Unit,
HB1-151

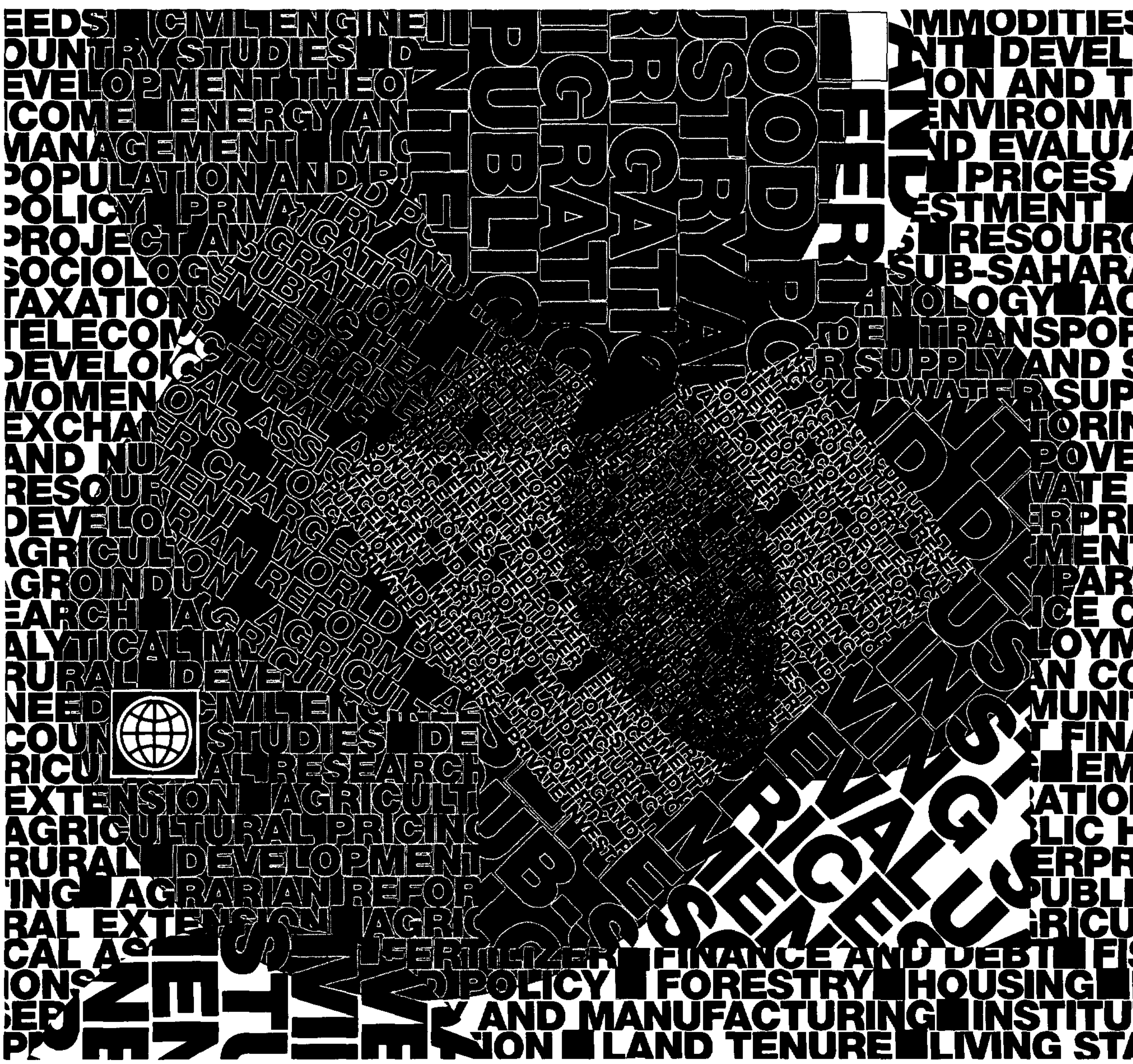
WORLD BANK TECHNICAL PAPER NUMBER 178

FILE COPY

Developing and Improving Irrigation and Drainage Systems

Selected Papers from World Bank Seminars

Guy Le Moigne, Shawki Barghouti, and Lisa Garbus



FILE COPY

Public Disclosure Authorized

Public Disclosure Authorized

RECENT WORLD BANK TECHNICAL PAPERS

No. 115 Le Moigne, Plusquellec, and Barghouti, *Dam Safety and the Environment*

No. 116 Nelson, *Dryland Management: The "Desertification" Problem*

No. 117 Barghouti, Timmer, and Siegel, *Rural Diversification: Lessons from East Asia*

No. 118 Pritchard, *Lending by the World Bank for Agricultural Research: A Review of the Years 1981 through 1987*

No. 119 Asia Region Technical Department, *Flood Control in Bangladesh: A Plan for Action*

No. 120 Plusquellec, *The Gezira Irrigation Scheme in Sudan: Objectives, Design, and Performance*

No. 121 Listorti, *Environmental Health Components for Water Supply, Sanitation, and Urban Projects*

No. 122 Dessing, *Support for Microenterprises: Lessons for Sub-Saharan Africa*

No. 123 Barghouti and Le Moigne, *Irrigation in Sub-Saharan Africa: The Development of Public and Private Systems*

No. 124 Zymelman, *Science, Education, and Development in Sub-Saharan Africa*

No. 125 van de Walle and Foster, *Fertility Decline in Africa: Assessment and Prospects*

No. 126 Davis, MacKnight, IMO Staff, and Others, *Environmental Considerations for Port and Harbor Developments*

No. 127 Doolette and Magrath, editors, *Watershed Development in Asia: Strategies and Technologies*

No. 128 Gastellu-Etchegorry, editor, *Satellite Remote Sensing for Agricultural Projects*

No. 129 Berkoff, *Irrigation Management on the Indo-Gangetic Plain*

No. 130 Agnes Kiss, editor, *Living with Wildlife: Wildlife Resource Management with Local Participation in Africa*

No. 131 Nair, *The Prospects for Agroforestry in the Tropics*

No. 132 Murphy, Casley, and Curry, *Farmers' Estimations as a Source of Production Data: Methodological Guidelines for Cereals in Africa*

No. 133 Agriculture and Rural Development Department, ACIAR, AIDAB, and ISNAR, *Agricultural Biotechnology: The Next "Green Revolution"?*

No. 134 de Haan and Bekure, *Animal Health in Sub-Saharan Africa: Initial Experiences with Alternative Approaches*

No. 135 Walshe, Grindle, Nell, and Bachmann, *Dairy Development in Sub-Saharan Africa: A Study of Issues and Options*

No. 136 Green, editor, *Coconut Production: Present Status and Priorities for Research*

No. 137 Constant and Sheldrick, *An Outlook for Fertilizer Demand, Supply, and Trade, 1988/89–1993/94*

No. 138 Steel and Webster, *Small Enterprises under Adjustment in Ghana*

No. 139 Environment Department, *Environmental Assessment Sourcebook*, vol. I: *Policies, Procedures, and Cross-Sectoral Issues*

No. 140 Environment Department, *Environmental Assessment Sourcebook*, vol. II: *Sectoral Guidelines*

No. 141 Riverson, Gaviria, and Thriscutt, *Rural Roads in Sub-Saharan Africa: Lessons from World Bank Experience*

No. 142 Kiss and Meerman, *Integrated Pest Management and African Agriculture*

No. 143 Grut, Gray, and Egli, *Forest Pricing and Concession Policies: Managing the High Forest of West and Central Africa*

No. 144 The World Bank/FAO/UNIDO/Industry Fertilizer Working Group, *World and Regional Supply and Demand Balances for Nitrogen, Phosphate, and Potash, 1989/90-1995/96*

No. 145 Ivanek, Nulty, and Holcer, *Manufacturing Telecommunications Equipment in Newly Industrializing Countries: The Effect of Technological Progress*

No. 146 Dejene and Olivares, *Integrating Environmental Issues into a Strategy for Sustainable Agricultural Development: The Case of Mozambique*

(List continues on the inside back cover)

WORLD BANK TECHNICAL PAPER NUMBER 178

Developing and Improving Irrigation and Drainage Systems

Selected Papers from World Bank Seminars

Guy Le Moigne, Shawki Barghouti, and Lisa Garbus

The World Bank
Washington, D.C.

Copyright © 1992
The International Bank for Reconstruction
and Development/THE WORLD BANK
1818 H Street, N.W.
Washington, D.C. 20433, U.S.A.

All rights reserved
Manufactured in the United States of America
First printing July 1992

Technical Papers are published to communicate the results of the Bank's work to the development community with the least possible delay. The typescript of this paper therefore has not been prepared in accordance with the procedures appropriate to formal printed texts, and the World Bank accepts no responsibility for errors.

The findings, interpretations, and conclusions expressed in this paper are entirely those of the author(s) and should not be attributed in any manner to the World Bank, to its affiliated organizations, or to members of its Board of Executive Directors or the countries they represent. The World Bank does not guarantee the accuracy of the data included in this publication and accepts no responsibility whatsoever for any consequence of their use. Any maps that accompany the text have been prepared solely for the convenience of readers; the designations and presentation of material in them do not imply the expression of any opinion whatsoever on the part of the World Bank, its affiliates, or its Board or member countries concerning the legal status of any country, territory, city, or area or of the authorities thereof or concerning the delimitation of its boundaries or its national affiliation.

The material in this publication is copyrighted. Requests for permission to reproduce portions of it should be sent to the Office of the Publisher at the address shown in the copyright notice above. The World Bank encourages dissemination of its work and will normally give permission promptly and, when the reproduction is for noncommercial purposes, without asking a fee. Permission to copy portions for classroom use is granted through the Copyright Clearance Center, 27 Congress Street, Salem, Massachusetts 01970, U.S.A.

The complete backlist of publications from the World Bank is shown in the annual *Index of Publications*, which contains an alphabetical title list (with full ordering information) and indexes of subjects, authors, and countries and regions. The latest edition is available free of charge from the Distribution Unit, Office of the Publisher, Department F, The World Bank, 1818 H Street, N.W., Washington, D.C. 20433, U.S.A., or from Publications, The World Bank, 66, avenue d'Iéna, 75116 Paris, France.

ISSN: 0253-7494

All of the editors are with the World Bank. Guy Le Moigne is senior advisor in the Office of the Director in the Agriculture and Rural Development Department. Shawki Barghouti is the chief of the Agriculture Operations Division in the South Asia Region Country Department II. Lisa Garbus is a consultant to the Agricultural Technology and Natural Resources Division of the Agriculture and Rural Development Department.

Library of Congress Cataloging-in-Publication Data

Developing and improving irrigation and drainage systems : selected
papers from World Bank seminars / [edited by] Guy Le Moigne, Shawki
Barghouti, and Lisa Garbus.
p. cm.—(World Bank technical paper, ISSN 0253-7494 ; 178)
ISBN 0-8213-2165-X
1. Irrigation engineering—Congresses. 2. Drainage—Congresses.
3. Water resources development—Congresses. I. Le Moigne, Guy J.
-M., 1932– II. Barghouti, Shawki M. III. Garbus, Lisa, 1963– .
IV. Series.
TC801.D48 1992
627'.52—dc20 92-17888
CIP

FOREWORD

The Bank's portfolio in irrigation and drainage has witnessed significant changes in recent years. Between 1974 and 1986, an average $1.5 billion a year, about one-third of Bank agricultural lending, was invested in irrigation. After 1986, lending for irrigation declined significantly, to an average 16.3 percent of agricultural lending, partly the result of commodity surpluses and consequent low international prices for most agricultural commodities in the mid-1980s and partly because the limits for expanding irrigation to new frontiers with attractive economic returns had been reached. In FY91, however, irrigation and drainage lending totaled $1.1 billion, representing 28.8 percent of total agricultural lending, and the volume of Bank lending in the subsector is gradually returning to previous levels.

Bank irrigation projects have been affected by design, construction, management, and operational problems, as well as the reliability of water supplies. The Bank is responding to these issues, and irrigation projects are now emphasizing institutional strengthening and rehabilitation of existing systems, with interventions increasingly national or regional in scope. A growing number of loans concentrate on organizational, policy, and financial reforms to improve institutions and reduce the burdens on government. Major project objectives include training—at all levels—and the creation of water user associations. Important environmental components include controlling erosion, siltation, waterlogging, and salinity.

Because technological improvements in irrigation systems have expanded production opportunities and facilitated agricultural diversification, technological development and innovation in the technical design of projects are being emphasized. The importance of technological research in Bank irrigation and drainage projects will increase through support of the International Program for Technology Research in Irrigation and Drainage (IPTRID). IPTRID was established to encourage and assist in technological development for irrigated areas, providing direct assistance to countries proposing research and training on irrigation operation and maintenance, waterlogging, and salinity and sodicity.

To address current problems and to present recent developments, the Bank's Agriculture and Rural Development Department annually sponsors an irrigation and drainage seminar. These seminars provide a forum for exchanging ideas and for exploring trends in innovation. The papers in this volume, selected from past seminars, represent the range of topics addressed and the issues that are at the forefront of the subsector. As we pursue strategies to improve agricultural performance, the papers in this publication illustrate the crucial relationship between water management and agricultural production.

M Petit

Michel Petit
Director
Agriculture and Rural Development Department

INTRODUCTION

For Bank irrigation and drainage (I&D) staff, there are two vital training formats: study tours and the annual irrigation and drainage seminar. These seminars were designed in 1983 by Guy Le Moigne, water resources adviser in the Bank's Agriculture and Rural Development Department (AGR). At the time, a two-day seminar was being held yearly for water supply and sanitation staff, and there was a recognized need for a similar seminar for I&D staff. In January 1984, the first I&D seminar was held, organized by AGR and the Bank's Training Division. Based on the positive reception it received, it has continued annually, held every December over three days.

About 100 people now attend the seminars, including 60 to 70 Bank staff; consultants; and representatives from multilateral agencies, nongovernmental organizations, and I&D agencies in developed and developing countries. With numerous I&D activities occurring throughout the regions, the seminar provides a forum for learning about recent developments in the subsector as Bank colleagues share their experiences and the status of regional projects. In addressing the seminar, senior Bank managers convey a Bank-wide perspective, delineating the role of I&D in the Bank's overall lending activities. National developments are presented by, among others, university faculty and staff from governmental agencies, while a global perspective is offered by representatives from international organizations, such the International Commission on Irrigation and Drainage and the International Irrigation Management Institute.

Topics addressed at I&D seminars have included:

- approaches to I&D sector reviews and studies;
- wastewater reclamation and reuse; economic and health aspects of water reuse;
- legal issues in water use;
- technology transfer; the role of extension;
- economic and environmental criteria for sustainability;
- water user associations.

Because not all interested staff can attend the I&D seminars, there was a request that the most salient papers from past seminars be made available. The papers in this volume span 1985 through 1991 and are arranged according to four areas: sectoral overview, institutional aspects, policy and research, and technology and environment. These foci reflect critical developmental components. For example, seeking an effective balance between public and private sector roles is vital, and the papers related to institutional aspects describe how these sectors are moving toward assuming complementary roles in the irrigation and drainage subsector. The policy and research section concentrates on how experience in different regions can be used in the formulation of lending policy. Research needs are also highlighted. The final section on technology and environment stresses the technical components of successful I&D projects; papers also address environmental externalities, encompassing environmental management and mitigation of adverse effects.

The I&D community is energized by the exchange of ideas and the *esprit de corps* engendered during the seminars. The knowledge base is also enhanced as colleagues from around the world share their expertise and perspectives. As the seminars continue to bring together experts and address vital issues, the role of the irrigation and drainage subsector in enhancing and sustaining agricultural performance will be strengthened.

The editors thank Walter Ochs, Hervé Plusquellec, and Ashok Subramanian (all of AGR) for their assistance in selecting articles for this publication.

TABLE OF CONTENTS

IV. Technology and Environment

THE GLOBAL PROBLEM OF LAND AND WATER CONSTRAINTS

Visvanathan Rajagopalan

The Seventh Irrigation and Drainage Seminar marks the end of an important decade in the water sector. We have seen, just in the past year, a flurry of articles and reports on water scarcity and poor water quality in developing countries in the popular press, academic journals, and official pronouncements. Many countries in the Middle East and North Africa are confronted with limitations on land and water availability. According to the FAO, for instance, countries in North Africa and the Near East have already utilized more than 95 percent of the arable land for agriculture. Similarly, in Asia—specifically, Bangladesh, Korea, India, and Pakistan—it is estimated that over 95 percent of arable land is already in use. Constraints to land expansion for agriculture are reflected in indications that the growth rate of the irrigated area in developing countries slackened considerably during the 1980s.

We face similar constraints regarding the availability of affordable water. Arid areas, in particular, are experiencing water shortages in irrigation because of intensified agricultural practices and competition from urban and industrial use. There are estimates that Israel, Jordan, and Tunisia, for instance, already use 100 percent of their annually available renewable water. Though there is still potential for water development for irrigation in some regions, additions to available water supplies for agriculture in many parts of the world will be quite expensive.

These shortages apply equally and even more dramatically to the urban water supply scene, especially in view of the rapid population increases expected in the urban areas of the developing world. By 2000, for instance, 17 of 21 cities in the world with more than 10 million inhabitants will be located in developing countries; in 1960, Shanghai was the only city of that size in the developing world. Major cities in Algeria, China, and Mexico, to name a few, already face severe water crises in urban water supplies.

The expected increase in demand, shortages in water supply, and costs of expansion of services will certainly intensify competition among users and require much greater attention than in the past to improvements in efficiency and sustainability of water distribution and use.

Given this situation, let me briefly examine Bank experience with irrigation and drainage projects to see what we can learn from them for the future.

Bank Experience with Irrigation and Drainage (I&D) Projects

Our own experience with I&D projects has clearly highlighted some of the problems and constraints in improving the efficiency and sustainability of irrigation systems. During the past decade, 144 Bank loans amounting to about $10 billion were approved by the Board for I&D projects. In the early 1980s, I&D projects represented about 35 percent of lending for agriculture and 10 percent of total Bank lending. The overall impression at that time was that I&D projects enjoyed a reasonable degree of success in terms of project performance.

Visvanathan Rajagopalan is vice president, Sector and Operations Policy, World Bank. This keynote address was presented in 1990.

Toward the end of the 1980s, however, the share of lending for irrigation dropped to less than 20 percent of agricultural lending and less than 5 percent of total Bank operations as lending to agriculture declined dramatically. There is also concern about decline in project performance and new questions about economic, environmental, institutional, and technical sustainability. According to the last annual OED report on Bank operations, the proportion of successful irrigation projects to total projects in the subsector has declined sharply over the last few years, from 80 to 50 percent. Moreover, an OED review of 21 impact evaluation studies points out that despite the projects' contribution to agricultural production, "the overall performance, in economic terms, has been less satisfactory at full development than at the completion of the investment phase."

Why is overall performance so poor? The reason lies, at least in part, with inadequate project analysis. First, we have to acknowledge that in our analysis of projects, problems of inefficiency in water distribution and use have often been overlooked. Second, estimates of benefits from increases in cropping intensity and yield have often been too optimistic. Third, environmental and social costs have generally been underestimated. Fourth, attention to technology development and testing and capacity building of users and of their organizations has been inadequate.

Needed Action on Policy, Institutional, and Technology Dimensions

We have to address efficiency and sustainability concerns in ways that are different from the past if we are to avoid repeating our mistakes and if we are to respond successfully to the challenges of the next century. These concerns demand concerted and comprehensive attention to policy, institutional, and technological dimensions.

We have made a modest beginning in this regard. Initiatives of both Operations and PRS [now OSP] in the last few years indicate that we *can* translate our potential into successful results for the benefit of developing countries. Examples of the initiatives underway include:

1. In terms of overall policy and planning in the recent past, Operations has begun or has continued to support integrated sector planning efforts in Bangladesh, Egypt, Jordan, Mexico, and Pakistan;

2. In Nigeria, we have recently aided in a review of the irrigation subsector and stand ready to help in follow-up activities;

3. Despite the formidable difficulties in implementing the concept of river basin planning, we have persisted with assistance to planning efforts in some countries—for example, Algeria, China, Mozambique, and Zimbabwe.

On the institutional and technology front, we have begun to support:

1. capacity building in local irrigation institutions in Ghana;

2. local capacity development through turnover of small schemes to user groups and initiation of service fees in Indonesia;

3. creation of water user associations in Mexico and Pakistan and, more generally, the development of these associations in other countries for local management functions;

4. attempts to determine methods of improved distribution of surface water in various states in India.

Let me now turn briefly to the policy and research area. We are taking steps within PRS [OSP] to assist in meeting the challenges of land and water scarcity on the one hand and of ineffective and unsustainable projects on the other. I am personally very interested in water development. I have followed the various efforts of the Bank to deal with water in the traditional sectors: water supply and sanitation, irrigation and drainage, hydropower, and, more recently, the environmental field. Some of you have already started building linkages among the departments to address common concerns. But we have to do much more. The Bank's organization, as indeed that of governments in the borrowing countries, is not often conducive to a comprehensive approach to water resources management. Special efforts are needed.

I have therefore asked Guy Le Moigne, as senior adviser on water resources, to lead an exercise for developing a comprehensive water resources management policy, in collaboration with the relevant departments within PRS [OSP] and with Operations. I am glad to hear that a significant amount of time at this seminar will be devoted to considerations of issues in formulating a comprehensive water resources management policy and that another workshop will be held in 1991 to address these issues.

Irrigation and Drainage Technology Research

While addressing important concerns from policy and institutional perspectives, we cannot forget the important contributions of technological development in the subsector. The evaluation reports of our projects indicate that engineering design is often as much a problem as policy and institutions. Applied and adaptive research is needed to deal with recurrent problems in irrigation and drainage. A review of research components in Bank irrigation projects, however, found that only about 0.5 percent of the total project cost of Bank-supported irrigation projects is devoted to research. This conforms to an earlier global estimate that less than 1 percent of investment in the subsector is devoted to research. We have therefore actively supported the formation of a new International Program for Technology Research in Irrigation and Drainage, supported by the Bank and UNDP. The program has already begun paying particular attention to modernization and maintenance of systems and to waterlogging and salinity control issues.

Conclusion

Still, many gaps remain. Our efforts in Operations and PRS [OSP] will be only a modest part of what the developing countries themselves and other external support agencies do in irrigation and drainage in the 1990s. However, there are many areas in which we should promote action. To identify these areas, let me return briefly to the OED studies. One view is that if evaluation measures used now had been used in the 1980s, we would have had a much weaker overall record for irrigation and drainage projects for all of the 1980s. That is all the more reason why we should be aware of the many obstacles to improved performance and the actions that need to be taken. These actions include the need to:

- focus attention on efficiency in water use. Excess availability and free or heavily subsidized supply have been disincentives to efficient use in many parts of the world;

- be aware that technological innovations to enhance efficiency require time for generation, local testing, and adoption. The question, then, is, Will the short-term project approach enable us to promote a program of technological research and development?

- consider long-term environmental costs in activities with short-term horizons. Similar problems arise with regard to sustainability;

- establish innovative arrangement and improved cost-recovery measures. Fiscal conditions in some countries constrain investments in maintenance, and we simply cannot repeat past mistakes by ignoring maintenance of existing systems while rushing into the construction of new systems.

It is also not easy to achieve the integration of the different interests in water, now organized along sectoral lines. We therefore face a major challenge: to confront the question of efficient and sustainable use of water in an integrated fashion and then to convince the borrowing countries that it is in their interest to approach the next century with a more integrated view. Political and institutional constraints in this exercise are formidable, but we cannot afford to wait because we have already started too late.

IRRIGATION IN THE 1990s: A ROLE FOR THE BANK

Robert Picciotto

Irrigation and drainage have a proud tradition in the Bank. Irrigation is the acid test of development. To build a successful irrigation project is like "meeting a payroll" in business, like winning the decathlon in sports. So many things—geological, physical, agricultural, social, and environmental—can go wrong that to "get it right" provides everyone concerned with a well-earned sense of achievement and professional satisfaction.

No wonder then that for decades the TVA was the metaphor for development and that the Bank has always conferred a special status on water resources development in its lending. The marriage of nature and humans, the cooperative involvement of many disciplines, the systematic approach to getting things done—all make irrigation an invaluable training ground for development managers.

Irrigation and Agriculture

Without irrigation, the phenomenal growth in agricultural productivity since the end of World War II could not have occurred. While the green revolution was a victory for cereal breeders, it spread primarily within the irrigated heartlands of Asia, Latin America, and North Africa and reached millions of small farmers. The combination of the new cereal technologies and controlled water helped to avert widespread famine during the second half of this century. The world, however, will expect different things of Bank irrigation specialists in the 1990s than it did in the late 1960s.

Prospects for the Bank

The Bank's future depends on the importance that the world will give to development in general. Despite the anxieties, it is a relatively hopeful future: we may be at the threshold of a new international order that could signal growing support for multilateral development initiatives. Current trends suggest that economic experimentation will continue based on market mechanisms. Politics will yield to economics. Trade liberalization will resume in fits and starts. Technology transfers, globalization of markets, and international migration will be the engines of economic growth. In this context, the advice of the Bank will be increasingly sought as we help to set the global development agenda, i.e., to articulate and document principles of economic management that will constitute a broad consensus among policymakers in both developed and developing countries. This will confer important responsibilities on each Bank staff member: we will have to live up to what our member countries expect of us.

Just as Japan is moving to build economic ties to its developing neighbors in Asia, the United States is rediscovering the importance of Latin America to its own economic fortunes, and Europe will be rich and powerful enough to assist not only Eastern Europe but also the Mediterranean countries—if only to avoid massive migration and the attendant problems of rampant poverty at the

Robert Picciotto is vice president, Corporate Planning and Budgeting, World Bank. This address was presented in 1990.

"threshold of the mansion." In this context, the Bank will act as a nerve center for a stronger development system. It will be a wholesaler of assistance and one of the arbiters of economic performance. We could be close to achieving the dream of the Bank's founders, becoming a truly global development institution.

Implications for Irrigation

The Bank's role in irrigation is likely to expand well beyond project finance. In some countries we may be asked to revert to the type of work we did in the 1960s when the Bank was called upon to provide leadership in integrated basin development. Increasingly, we will be asked to review entire irrigation and drainage investment programs. With domestic resources as scarce as external funds, member countries will increasingly engage the Bank as a partner in helping them to manage and fund public investment programs. The Bank will therefore be asked to assist in setting irrigation policy, standards, and institutions. This is, of course, a heavy responsibility, but one which falls naturally to this institution and one that Bank irrigation specialists must train themselves to assume.

Increasingly, the Bank will be called upon to provide advice to other donors or provide umbrellas for cofinancing or guarantees for private investment. Free-standing technical assistance interventions will increasingly be sought to assess water resources programs and to plan their use on a multidisciplinary basis.

To respond to these demands, the Bank will network with a wide variety of agencies and firms able to deliver the advisory services required to meet the rigorous standards that emerge. Other international agencies will be involved, as will the private consulting profession and, of course, NGOs: we cannot do it alone. So it is on the design and implementation of equitable, sustainable, and efficient irrigation and drainage programs that the Bank is likely to be judged in the water resources field. Projects will remain important (program design and management must rely on effective mastery of the project methodology), but other agencies can handle projects and, in irrigation as elsewhere, it will increasingly be the comparative advantage of the Bank to deal with institutional development and overall policy and program implementation.

Special Operational Emphases

The Bank's budget is constructed according to program categories, the most important of which are poverty reduction and food security, human resources development, environment, and private sector development-cum-public sector management. All are relevant to future irrigation and drainage work.

Concern with poverty will have to be demonstrated, e.g., in project selection. Ability to provide accurate diagnostics of public sector management issues will be necessary—especially regarding operation and maintenance—as will increased reliance on the private sector in project construction and operation. Most important, the buildup of domestic capacities will be the focus of Bank activity, requiring above all an increase in the supply of adequate skills in irrigation engineering, resources planning, and water management, i.e., human resources development. Finally, the impact of environmental assessment on irrigation lending will be profound and will have to be managed realistically. Irrigation and drainage work thus will embody all the policy directions that constitute the Bank's development agenda.

Conclusion

A new international order is emerging out of the ashes of the Cold War. It could usher in renewed interest in development and international cooperation. With the increased scarcity of water, the Bank may again be called upon to assist in the resolution of water disputes. Accordingly, there will need to be intensified commerce among environmentalists, economists, irrigation engineers, and political specialists.

We are one earth, but we are not one world. Yet people everywhere are nearing a cooperative vision of the future that will sustain the Bank in what are bound to be difficult times. The Bank's new responsibilities in the Global Environment Facility symbolize this trend, and, from this perspective, natural resources management is the business of irrigation specialists. The Bank is well positioned to play a major role in promoting more sensible planning, utilization, and pricing of water, working closely with other organizations. This is an exciting professional challenge, requiring the combination of global vision and local action upon which the Bank has built its reputation.

IRRIGATION AND DRAINAGE PROJECTS: SUSTAINABILITY, PERFORMANCE, AND IMPACT

John Hennessy

Irrigated agricultural production is a major, worldwide, multidisciplinary business activity. It merits attention from the international perspective, while also considering the regional and subregional environmental characteristics that affect the production factors. This presentation delineates the challenges confronting developing countries as they pursue sustainable agricultural production. Within this framework, the activities and role of the International Commission on Irrigation and Drainage are presented.

International Commission on Irrigation and Drainage

The International Commission on Irrigation and Drainage (ICID) was founded in New Delhi, India, in 1950 and is the leading international NGO concerned with irrigation, drainage, flood control, the management of environmental development, and change associated with these activities. The ICID family is composed of national committees representing 80 countries. There are 10 elected office bearers, currently including vice-presidents from China, Malaysia, India, Pakistan, and Egypt, demonstrating the strong involvement of developing countries within the ICID working leadership team.

The ICID Central Office is located in New Delhi, where the secretary-general leads a well-qualified professional team responsible for the daily management of the commission's affairs. Currently, the commission is giving renewed emphasis to its service mission: to meet the needs of the member national committees, with particular attention to developing country requirements. The service mission does not, however, stop at the national committee level but is directed to serve the public at large in the countries concerned. ICID operates at the national and international levels and presents meetings worldwide regularly. The foci of ICID activities are continuously reviewed to optimally address the perceived priorities of the membership. Presently, ICID has more than 10 working groups, with inputs drawn from a wide base of north-south experts from both the public and private sectors. Current work topics include environmental impact; operation, maintenance, and management; construction rehabilitation and modernization; irrigation performance assessment; and irrigation and drainage research needs. In particular, the commission's work is greatly enhanced by the interest shown by leading multilateral and bilateral funding agencies, and member services have been considerably improved both by the professional inputs from the funding agencies' staff and the direct financial support received.

Among other things, ICID acts as a forum for the discussion and development of institutional and attitudinal changes necessary to irrigation and drainage practitioners worldwide. At international gatherings, ICID listens, learns, and shares its experience to further the objective of increased agricultural production to alleviate famine and poverty.

John Hennessy is president, International Commission on Irrigation and Drainage, New Delhi. This address was presented in 1990.

Sustainability, Performance, and Impact

Major challenges exist for the agricultural production sector. The worldwide farming community fully understands that it is in the business of agricultural production. In a commercially and tightly competitive market, however, it is important that other multidisciplinary key team members also think and work within this framework; that is, the researchers, planners, designers, operators, agriculturalists, plant breeders, credit institutions, etc., must all work together—holistically—toward the common goal of optimal agricultural production. The first priority, therefore, should be performance, i.e., crop production of acceptable quality to meet demands on time and profitably. Profitable agricultural production, however, is not achievable on a "stop-and-go" basis; the output must be sustained for real success. Sustainability has several definitions, but perhaps the most widely used is that of the World Commission on Environment and Development:

> Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. . . . in essence . . . a process of change in which the exploitation of resources, the direction of investment, the orientation of technological development, and institutional change are all in harmony and enhance both the current and future potential to meet human needs and aspirations.

Sustainable performance is also affected—adversely—by factors such as poor-quality construction, inadequate maintenance, and ineffective management.

Just as sustainability is strongly linked with performance, so too is impact. In the specific project area, irrigation and drainage developments directly impact human and natural environments and provide opportunities for economic improvement. The indirect effects can apply both within and outside the immediate project locale. Accordingly, good planning, strong vision, and clear management are prerequisites for successful project development.

With specific reference to management of the environmental impact, the United Nations Center on Transnational Corporations has reported that about 80 percent of the world's land cultivated for export crops is affected by transnational corporations, that is, by large business enterprises. The UN paper "Criteria for Sustainable Development Management" proposes 10 criteria for adoption by corporate managements as the first steps toward the attitudinal and decisionmaking changes necessary for multinational companies to follow practices consistent with sustainable development. The paper is recommended to both developing and industrial countries and to both public sector organizations and private enterprises.

Challenges

What are the challenges for developing countries? Many remain from earlier decades, but additional challenges for the 1990s are also emerging and include:

- increasing population;
- increasing demand for food and other crops;
- poverty and famine;
- human resources constraints: health, education, and training;
- women in development;
- natural climatic constraints;
- natural resource constraints: land and water;
- fiscal disincentives;

- market competition from industrial and other countries;
- global warming.

The Intergovernmental Panel on Climate Change suggests that in future decades several main agricultural production areas in the developing world may face severe new climatic constraints. Since about 70 percent of greenhouse gases are produced by 25 percent of the world's population—who live primarily in industrial countries—the equity of this new challenge is questionable.

The FAO approach to global warming is summarized in the FAO position paper "Climate Change and Agriculture, Forestry and Fisheries," presented at the Second World Climate Conference in Geneva in October-November 1990. Briefly, the FAO strategy is to concentrate on activities to clarify the issues and response options concerning climate change and to alleviate or overcome the current problems that would be exacerbated by the impact of the projected climate change. The strategy is well argued and underscores the urgent need to use irrigation water more optimally and to apply fertilizers and other inputs more efficiently.

Today, many groups think that it will take the combined efforts of all concerned governments, landowners, farmers, banks and funding agencies, NGOs, and famine relief agencies to offer any real chance of success. ICID is well positioned to play its full part in rising to the challenge because "experience sharing" is an established ICID activity. This is where owners, managers, operators and planners, designers and researchers, funding agencies, constructors, and manufacturers come together in an east-west, south-north dialogue that assists developing countries in considering and then introducing the attitudinal and institutional changes essential for the sustainable improvement of agricultural production.

Summary

The challenges of the 1990s dictate that performance be judged against ever-increasing production targets and improved profitability. It must also be judged against appropriate sustainability criteria, which in turn link with the environmental impact aspects as outlined. Thus, in considering where to place future emphasis, performance sustainability and impact are inseparably linked, meaning that there are few, if any, shortcuts to success. To meet the emerging challenges, it is therefore suggested that the priority for the 1990s be to seek and develop the visionary leadership and holistic management skills needed to optimally utilize the available scarce resources.

References

FAO. 1990. "Climate Change and Agriculture, Forestry and Fisheries." Paper presented at the Second World Climate Conference, October-November, Geneva.

Intergovernmental Panel on Climate Change. 1990. "Climate Change." Reports of Working Groups I, II, and III.

International Commission on Irrigation and Drainage. Various publications.

UN Center on Transnational Corporations. 1990. "Criteria for Sustainable Development Management." New York.

World Bank. Various publications.

INSTITUTIONAL ASPECTS OF IRRIGATION DEVELOPMENT IN NORTH AFRICA: EXPERIENCE WITH MOROCCO

M. Salah Darghouth

This paper examines the major institutional aspects of irrigation development in North Africa. It is based on the Moroccan experience, which is the most comprehensive, though the Tunisian or Algerian experience will also be cited as necessary. The paper highlights the large-scale irrigation perimeters, which have been developed and managed by the government. Most small- and medium-scale irrigation areas have been built, operated, and maintained by traditional farmer groups, with little government intervention.

The paper will concentrate on the major principles underlying Moroccan irrigation, examining the policy framework; the legal basis for rationalized land tenure, improved production, cost recovery, and farmer organization; design guidelines for improved water management and increased water use; and organization for water development and management. First, the general characteristics of irrigation in Morocco, its present level of development, and its potential will be explored.

Background

The total irrigated area in Morocco has doubled over the last 20 years and presently covers about 1 million ha. This represents around 70 percent of the country's irrigable area (about 1.5 million ha), or 13 percent of the total arable area (7.5 million ha). The large-scale irrigation (LSI) schemes cover about 400,000 ha, or 40 percent of the total irrigated area, and are concentrated in nine large schemes controlled by nine regional agricultural development agencies (ORMVAs). These include Loukkos in the country's high-rainfall zone (over 600 mm annually); Moulouya and Gharb in the medium-rainfall zone (400 to 600 mm); and Doukkala, Tadla, Haouz, Souss, Tafilalet, and Ouarzazate in the low-rainfall zone (less than 400 mm). Water is provided to the irrigated areas through 12 major storage reservoirs or from tubewells (in the Souss area). Presently, surface irrigation covers 80 percent of the LSI area and sprinkler irrigation 20 percent. To provide water to all surface irrigation perimeters, to lift groundwater, and to generate the head needed for sprinkler irrigation, the government has constructed 90 large pumping stations, with an average capacity of 1,200 kW, and over 230 smaller pumping stations scattered throughout the country.

The land equipped for irrigation is fully irrigated, except for that planted in cereals in some high-rainfall areas. The overall cropping intensity is about 110 percent and is highest in the low- to medium-rainfall areas (131 percent in Doukkala and 147 percent in Ouarzazate). Although still insufficient, these figures compare favorably with most Mediterranean countries having similar climatologic conditions. Cropping patterns are characterized by high crop diversification and the predominance of high-value cash crops. The major crops are wheat (35 percent); sugar beet, sugarcane, and cotton (17 percent); citrus and fruit trees (16 percent); vegetables (12 percent); and

M. Salah Darghouth is chief, Agriculture Operations Division, Africa Region Country Department V, World Bank. This paper was presented in 1985.

forage crops (11 percent). Crop yields per perimeter have reached an average of 67 t/ha for sugar beet in Doukkala, 70 t/ha for sugarcane in Gharb, 4 t/ha for cereal in Tadla, and 70 t/ha for alfalfa in Doukkala. High-yielding milk production is mainly concentrated in the irrigated areas, which provide some 50 percent of domestic milk production.

Land distribution is characterized by the predominance of small farms, especially in Ouarzazate and Tafilalet, two oasis perimeters located in the country's most arid zone, south of the Atlas Mountains. The average farm size is about 3 ha, and about 85 percent of farms are less than 5 ha.

Irrigated agriculture, especially in the large national irrigation schemes, has contributed significantly to the growth of Moroccan agriculture. Currently, Morocco obtains about 45 percent of total agricultural value added and 60 percent of agricultural exports from irrigated crops. In addition to allocating a high proportion of agricultural investment resources to irrigation (60 to 70 percent), the government has designated most producer subsidies and the best talent to manage large-scale irrigation schemes. Progress in the use of improved farming techniques and production inputs for commodities grown under irrigation has been good. Between 1971 and 1985, irrigated output grew at an annual rate of 5.5 percent, and an increasing proportion of the agricultural value added is generated by the irrigated perimeters.

Despite the continuous improvements and the high performance levels reached, the potential of Moroccan irrigated agriculture has not been fully realized. Although water use and cropping intensity are relatively high compared with countries having a similar rainfall and climatic pattern,[1] increases in the existing schemes are still possible. Average water use per hectare is 80 percent of potential, and cropping intensity is about 110 percent, whereas it could be over 130 percent. There is also scope for increases in productivity through low-cost investments to improve water availability and management and to facilitate better farming practices. Average yields have steadily risen but could increase further, as demonstrated by the higher yields already achieved in some perimeters.

Policy Framework

Morocco has developed a coherent policy and institutional package for promoting its irrigation subsector. It has continually been governed by three basic principles: (1) agricultural aspects should not be separated from engineering aspects in designing and managing irrigation systems; (2) irrigation systems should be designed to achieve flexible and efficient water distribution, to facilitate system operation, and to ensure easy and prompt use of land and water at the farm level; and (3) farmers are required to maximize production, to fully use water resources available through government investments, and to repay part of these investments. This has resulted in the sound performance of irrigation schemes in Morocco, though it has involved a considerable and costly government role. This role is now being sizably reduced in favor of greater farmer and private sector participation. Government policy had been to assume major responsibility for ensuring that irrigation in the country got off to a good start during the 1960s and 1970s. It is now the policy to transfer activities that they are able to undertake to farmers and the private sector.

With organizational aspects in particular, the government has adopted a dynamic approach, reflected in changes in the responsibilities of government departments since irrigation began to be promoted on a large scale during the 1960s. Governmental organization has been adjusted according to three major phases:

1. Before 1962, irrigation development responsibilities were with the Ministry of Public Works, separate from agricultural production functions, which were the responsibility of the Ministry of Agriculture;

2. Between 1962 and 1968, all irrigation development and production activities were under the Ministry of Agriculture, but were carried out by a single multipurpose national government agency that supervised all irrigation-related operations countrywide;

3. Between 1968 and 1985, the activities in (2) were carried out by nine regional, multipurpose irrigation development agencies (see below), responsible for developing irrigation in the country's nine large-scale perimeters.

Whereas the first two phases were characterized by the promising expansion of irrigation systems—though also by poor production performance, except for industrial crops (sugar and cotton)—the third phase has been characterized by both a substantial expansion of the irrigation systems and a steady increase in the production generated by the irrigated perimeters. This has proved that the regional multipurpose agencies are the most viable organizational structures to promote irrigation in Morocco. The reforms the government has decided to introduce to improve organization and management of these agencies will not modify their basic functions: system construction, operation and maintenance (O&M), extension services, and related applied research.

Legal Framework

Moroccan policy in the LSI subsector has been supported by comprehensive legislation that has provided a valuable framework for promoting the rational use of water, land, and human resources in the irrigated schemes. The bulk of this legislation was issued in 1969 in a set of laws, decrees, and orders that constituted the Agricultural Investment Code. Other major laws include (a) the 1962 Land Consolidation Law, which provided procedures and mechanisms for consolidating existing fragmented holdings and for land registration; (b) the 1972 Agrarian Reform Law, which established the conditions for distributing state-owned land to smallholders and landless laborers; and (c) a 1924 law that governs the formation and functioning of water user associations. These laws delineated procedures in four major areas: (1) land tenure, (2) agricultural development requirements, (3) farmer organization, and (4) cost recovery.

Land Tenure

Land consolidation. About 300,000 ha have been brought under land consolidation in less than two decades. Using substantial legal and political means, the Moroccan government has consolidated and realigned the boundaries of about 100,000 previously fragmented farms (about 4 plots per farm on average). More viable family holdings were obtained by nearly eliminating fragmentation and prohibiting future subdivision. The law provides that consolidation is carried out by a special commission, including farmers' representatives, with the technical assistance of the Ministry of Agriculture. It requires that everyone receive land equal in value to that held previously, and it allows any complaints to be lodged with the commission, with any further division of holdings subject to the commission's authorization. A remarkable feature is that the lengthy process of land consolidation (usually two to four years) has systematically been carried out ahead of irrigation works construction, thus generally causing no delay in the start of irrigation projects.

Transfer of land to private freehold. A set of laws has also been issued to resolve land tenure problems involving tribal collective land (land to which a village, clan, or tribe has a right of usufruct and where the right is shared equally by all members of the collective group); public state land (land to which the general public has access, including state forests); private state land (land used by the government for a specific purpose, such as research and seed multiplication, as well as land expropriated from foreign settlers); and charitable trust land (including land donated to religious and charitable foundations). The provisions of the law aim at privatizing these various types of legal tenure. Private state land is distributed to individuals in viable family holdings of at least 5 ha; however, private state land planted with orchards has been retained by the government, which intends to distribute it to private farmers when a satisfactory management system under individual and communal private ownership is developed. For collective lands, the law set procedures for the replacement of collective tenure by joint or individual freehold ownership.

Agricultural Development Requirements

Under existing legislation, the state seeks to ensure optimum water and land use in the irrigated areas according to a specific plan. Farmers who benefit from irrigation works, the costs of which are borne by the government, are required to adhere to a development plan in terms of cropping pattern, water use, cultivation, and livestock-raising techniques. Before irrigation begins in a given sector, an order is issued defining the standards for each of these areas, based on recommendations made in feasibility studies for optimizing land and water use. Ministry of Agriculture staff monitor the farmers' application of the prescribed cropping patterns. In practice, however, farmers increasingly view these cropping patterns as more indicative than mandatory, except for sugar and cotton development, which are closely followed by Ministry of Agriculture staff to ensure that sufficient raw material is provided to mills. Overall, the tight discipline imposed by these measures has been an important factor in the successful development of irrigation in Morocco.

Cost Recovery

The current policy is to recover from farmers the full amount of O&M costs and up to 40 percent of all investment costs related to irrigation. Since 1980, after more than a decade of 1969-level water charges, substantial improvements have been introduced. Currently, the main characteristics of cost recovery are:

- Water charges include *volumetric water charges* applied per m^3 of water as measured at the farmgate (see below) and a *land betterment levy* applied per hectare. The former charges are meant to recover 100 percent of O&M and energy (if applicable) costs, and the latter up to 40 percent of actual capital investment costs;

- Reduced volumetric water charges are applied when farmers construct tertiary or secondary canals or assume full responsibility for their O&M when they are constructed by the government. The first 5 ha of holdings of less than 20 ha are exempt from the land betterment levy so that the revenues of small farmers are not affected;

- The law provides for a binomial formula under which all farmers are required to pay for a minimum of 3,000 m^3/ha, regardless of their farm's level of water use;

- Water charge levels are indexed to inflation according to a standardized price escalation formula established nationwide, considering the variation in unit prices of items constituting O&M expenses;

- Water charges (and land betterment levies) are levied similarly to taxes and are consequently collected by Ministry of Finance staff; the role of Ministry of Agriculture staff is to encourage farmers to pay their debts.

Farmer Organization

Government policy has always encouraged the grouping of farmers into service cooperatives. Current laws require the formation of service cooperatives among farmers who benefit from (a) state plots distributed under the agrarian reform law, and (b) government support in constructing and equipping milk collection centers or in purchasing farm machinery. The law also encourages the formation of water user associations.

Prospects for Improvement

Morocco has been successful in implementing laws on farmer organization, cost recovery, and land tenure (except for collectively owned lands), but it has been less successful in enforcing the law on agricultural development requirements. Farmers must accept land consolidation and are required to form cooperatives before they benefit from any government land or financial support. The most successful program has been the milk collection cooperatives. Almost 300 cooperatives have been established and are effectively functioning; they ensure the collection of about 60 percent of the milk processed in the country. Almost all farmers pay their water charges and land betterment levies, though with a delay averaging 18 months.[2] The collection rate is lowest in areas with complex collective land or water rights. Substantial political support and monitoring are still needed to pressure farmers to pay all their charges during the same year of water use or to resolve the complex tenure situation in tribal collective lands. The government has initiated measures to resolve these land problems in areas where they are most acute and to increase the collection rate of water charges to 95 percent in all areas by 1989.

Design Guidelines

Morocco has adopted a coherent systematic approach, including guidelines, for optimal water resource allocation and improved water management. It is an integrated, multipurpose approach that aims to satisfy the requirements of the various water users (irrigation, domestic, and industrial use) and to design irrigation systems that ensure optimal use of water and land resources while minimizing water management problems. The approach is based on the following concepts: (a) water master plans; (b) interdependence of system design and water management; and (c) integration of system layout with land consolidation, cropping patterns, and farming operations.

Water Master Plans

All irrigation development programs are drawn up based on recommendations formulated in water master plans. Five water master plans covering the country's 14 major river basins were developed in the late 1960s/early 1970s and are presently being revised to reflect changes in the relative price relationships among commodities, net income of farmers, farming techniques, pace of investments, and water users' needs. The plans seek to optimize the allocation of water resources among the various subsectors and propose the most viable scheme to develop these resources for agricultural use. Based on the plans' recommendations, nine irrigation development programs have been established and are being implemented by nine regional irrigation agencies.

Interdependence of Design and Water Management

Morocco has created design guidelines that seek to minimize conveyance losses, achieve efficient and flexible water distribution, ensure timely and reliable water delivery at the farmgate, simplify on-farm irrigation operations, and facilitate increased crop diversification and its adoption by farmers. Guidelines include:

- Government-built irrigation networks generally include a main canal, lined only where needed; a distribution system of secondary and tertiary precast concrete canals (or buried asbestos pipes for sprinkler irrigation); and on-farm earthen quaternary canals (or mobile metallic pipes in the sprinkler irrigation);

- All necessary works for open or tile drainage to intercept overland flows, drain percolated irrigation water, and lower water tables are carried out during construction of the irrigation system;

- Similarly, all necessary on-farm development works are implemented along with the irrigation works, including (1) in the surface irrigation areas, on-farm earthen quaternary canals, land leveling (where necessary), and on-farm drains; and (2) in the sprinkler irrigation areas, semimobile and mobile pipes and in some cases windbreaks;

- Water is distributed on a rotational basis among farmers in the surface irrigation areas and on a demand or mixed basis (canal rotation and free demand by farmers) in the sprinkler irrigation areas. In the surface irrigation areas, a constant water flow of generally 30 l/s is used at the tertiary canal level on a rotational basis by farmers. Water is distributed to farmers by turns of different durations depending on the area cultivated; water distribution continues 24 hours during most of the year (about 10 months in the low-rainfall areas), and neither the delivery time nor the delivery turns are restrained by the official working hours of government staff. In the sprinkler irrigation areas, the systems have been designed so that water is available when the hydrant is opened by the farmer. There is direct automatic hydraulic transmission of water through the pipes between the downstream hydrants and the upstream compensating reservoirs. During water shortages in the dam reservoirs (such as those caused by the severe drought of 1981-84), however, water is distributed according to a mixed system of pipe rotation and free demand; i.e., water is distributed by turns in the secondary pipes, and farmers take the water freely from those pipes;

- The irrigation systems are equipped with automatic, hydraulically controlled gates that control water levels. The main components of this equipment include upstream control radial gates that are float-controlled by water surface levels and that release or hold water automatically to maintain a constant pool level upstream of each gate. Similarly, the downstream control radial gates release or hold water to maintain a constant pool level downstream of each gate. Generally, the main canals are downstream-controlled and the distribution systems upstream-controlled. In addition, flows in the distribution canals are controlled by adjustable distribution modules that maintain a constant flow for any discharge to which they are set. These are easily adjusted and can be locked by the water masters at any setting. The main advantages of this automatic water control system are that it (a) maintains the irrigated area under command independently of discharges; (b) prevents canal deterioration by maintaining water levels within certain limits to avoid overtopping or erosion; (c) stores water in the network, thus permitting prompt delivery of water; and (d) requires fewer staff for its operation than do conventional irrigation systems.

Integration of System Layout with Land Consolidation, Cropping Patterns, and Farming Operations

Irrigation distribution systems are designed according to a layout (referred to as a rational layout) that considers the major requirements of land consolidation, cropping patterns, and farming operations. The layout is applied to farms of more than 1 ha. Its main characteristics are that (a) the areas of individual service units are about 30 ha (400 m wide and 700 m long), divided into two to six equal blocks, each with a different crop according to the crop rotation plans (most plans are four-year rotation plans with one free-crop block); (b) the farm boundaries run perpendicular to the crop blocks; and (c) water is delivered from a tertiary canal, serving quaternary earthen canals, which runs along the crop block boundaries. The layout facilitates extension service work and crop planning by farmers who are normally required to apply the prescribed crop rotation plans. It favors, though does not necessarily lead to, collective organization of farming operations by farmers in the same service unit. Each farmer remains responsible for irrigating, treating, and harvesting his or her own holding. Another major advantage of the layout concept is that the optimum economic and technical criteria for designing the irrigation system can be applied independently of farm size or boundaries.

Improvement Outlook

Although no comparison with other design approaches has been undertaken, in the Moroccan system the overall conveyance and distribution efficiency of most surface irrigation areas exceeds 75 percent, and delivery of water to farmers is usually timely, reliable, and equitable. Water charge bills are based on time of delivered flows measured at the adjustable module levels in the surface areas. The application of the rational layout based on specific cropping patterns has largely contributed to high crop diversification and cropping intensity and to the development of industrial crops, mainly sugar beet and sugarcane. In terms of management, the functions of the water masters are limited to patrolling and setting the farmgate modules at given flows. The main canals are operated by a few staff (3 in the 128-km Doukkala canal), and on average a water master handles about 400 ha in the surface areas and 700 ha in the sprinkler areas. The irrigation schemes have been designed to be simple, and their operation is normally smooth, except for sophisticated works (pumping stations or tubewells) in areas without sufficient specialized staff. The main problems after construction are in maintenance operations, which have been affected by the country's recent financial constraints. Future improvements will involve securing increased funds for adequate maintenance, designing preventive maintenance, training staff, and strengthening water scheduling.

Organization for Water Development and Management

While construction of dams and operation of their reservoirs are the responsibility of the Ministry of Public Works, all activities regarding irrigation development, water management, and agricultural production in irrigated areas are the responsibility of the Ministry of Agriculture. Operation and maintenance of on-farm facilities are the responsibility of farmers. High-level decisions on water policy are limited to the National Water Council, which includes representatives from the Ministry of Agriculture and the Ministry of Public Works. The council's main functions are to establish overall water policy and make recommendations on the allocation of funds and water resources. It also approves the water master plans administered by the Ministry of Public Works in consultation with the Ministry of Agriculture, which itself carries out the irrigation development programs derived from the master plans.

Central Organization of the Ministry of Agriculture

Each of the Ministry of Agriculture's central departments exercises an advisory and supervisory role in its field of concern (crop production, livestock, extension, etc.). Most irrigation functions, however, are confined to the Central Department for Rural Construction. This department prepares irrigation-related legislation; establishes national priorities and plans in the irrigation subsector; carries out interregional irrigation development studies; and reviews budgets, work programs, progress, and procurement related to irrigation activities. The department has no direct role in executing irrigation programs and works.

Regional Organization of the Ministry of Agriculture

Since 1968, the development and operation of the LSI schemes have been the responsibility of nine regional agricultural development agencies (ORMVAs), which are state-owned enterprises with separate legal and financial autonomy. They are multipurpose organizations that have played a key role in the growth of the irrigation subsector. Each controls 20,000 to 100,000 ha. Under their charter, ORMVAs are primarily responsible for expanding irrigation over new areas, operating and maintaining irrigation schemes, and providing technical assistance to farmers for crop and livestock production. In practice, however, they have expanded their operations by providing a growing number of commercial services to farmers. Currently, their activities can be grouped into four categories:

1. *irrigation development activities*—planning and design of irrigation development programs and projects and supervision of construction works;

2. *water management activities*—water distribution and system maintenance, water charge bookkeeping, assistance to the Ministry of Finance in collection of water charges, and assistance in on-farm water management;

3. *agricultural services*—extension and applied research activities (these have been conducted in all ORMVAs in competition with commercial services, to which technical staff tend to give priority);

4. *commercial services*—input supply; farm mechanization; numerous services provided for industrial crop growers (collective borrowing of seasonal credit, harvesting control, and bookkeeping); establishment and management of farmer cooperatives; and health control and genetic improvement of livestock.

ORMVAs' provision of commercial services was instrumental for the first 10 years in promoting irrigated agriculture, but it is no longer advisable nor justified, in view of the burden it imposes on the operating budget (since ORMVAs are largely subsidized) and its negative impact on private initiatives in areas where adequate and less costly alternatives exist. These services are time-consuming and take field staff away from their technical work, particularly in the five ORMVAs where industrial crops are grown. The government has decided to gradually transfer these services to the private sector and farmer cooperatives.

In comparison with the regional departments of the Ministry of Agriculture and Agrarian Reform (MARA) that control rainfed areas, ORMVAs' autonomy has enabled them to be more efficient, have considerable project preparation and implementation capacities, receive larger budgetary resources, and attract more competent staff by offering more benefits. Although requiring further improvements, the extension services they provide are far more efficient than those provided by MARA's regional departments. ORMVAs are generally organized according to seven service areas: administration and finance, crop production, livestock, construction, O&M, planning, and equipment and building. Because of the numerous operating responsibilities at the field level, most services have field subdivisional offices that supervise local development centers (*centre de mise en valeur* [CMV]). These centers are the field units through which all services to farmers are conveyed. ORMVAs have formal supervisory and consultative bodies that meet regularly where farmers are well represented, including (1) a board of directors chaired by the minister of agriculture and including the provincial governors concerned; Ministry of Agriculture central department directors; and representatives of other ministries, farmers, and the national agricultural credit bank (CNCA); (b) a regional committee chaired by a provincial governor and including representatives of concerned regional departments, farmers, and CNCA; and (c) local development committees established at the district level to advise on, monitor, and help resolve problems between ORMVAs and farmers during land consolidation, construction, water distribution, and crop production.

One determinant of ORMVAs' success has been the educational level of their staff. In the early 1970s, only key managers were university graduates. Currently, on average one university graduate engineer and five college graduate technicians serve 1,000 ha or 350 farmers in the ORMVA perimeters. All engineers have degrees in agriculture, and technicians have knowledge in both engineering and agriculture.

Future Perspective

The major problems now facing the ORMVAs' irrigation components are fourfold: (1) the overemphasis on commercial services has been at the expense of agricultural extension; (2) government's authoritative approach to growing industrial crops has resulted in nonviable production of these crops in some areas; (3) the government has tended to assume too much control of ORMVAs' operations, mainly because of their financial dependency on the government budget; and (4) farmer participation in ORMVA management and O&M is still insufficient. Over the next three years, the government plans major improvements in the ORMVAs' organization and management, field operations, and relations with the government and with farmers.

ORMVAs' responsibilities will revert to their basic functions. ORMVAs would discontinue providing commercial services to farmers because these services can now be efficiently provided elsewhere. This divestiture will be gradual to avoid any risk of decline in crop production. The government has decided to instruct ORMVAs not to buy any new machinery and to authorize them to rent their warehouses to private dealers for input supply. In the meantime, farmers will pay higher user charges so that ORMVAs can fully recover their handling costs. Additionally, higher priority will be given to strengthening extension services and improving system maintenance.

ORMVAs' organization and management will be improved by strengthening planning and monitoring functions through the introduction of standardized management information systems, based on restructuring accounting and financial procedures, introducing an internal system of performance control, restructuring budgetary procedures, and establishing an input/output monitoring system at the farm level.

ORMVAs' relationship with the government will be rationalized through less administrative and financial control, a shift from a priori to a posteriori control, and the adoption of three-year development contracts with the government beginning in 1986. These contracts will set forth

ORMVAs' development targets, programs of works, and operating and financial performance goals based on specific indicators agreed upon in advance. They also will specify the government's obligations with respect to staffing, institutional and pricing matters, and financial commitment objectives based on projected investment programs and operating revenues.

Increased farmer participation will be achieved through the formation of water user associations, which will assume responsibility for operating and maintaining irrigation and drainage systems to the tertiary-canal level. The associations will be small, involving 10 to 30 farmers. They will ensure satisfactory water distribution, canal and drain desilting, weeding, and repairs. The ORMVA O&M staff available as a result of this transfer will be assigned to operate future irrigation schemes.

Conclusion

This paper has briefly described the institutional and policy package that Morocco has created to ensure favorable conditions for developing its irrigation subsector. Lessons relevant to prevailing conditions in specific countries may be drawn; however, one major lesson may be universally applicable: to succeed, irrigation development should be planned and designed based on institutional and policy decisions sufficiently comprehensive to cover a wide array of issues, such as those described in this paper. The ultimate objective is to obtain the highest return from water available for irrigation. This can be achieved, however, only when the country concerned succeeds in developing local skilled staff capable of designing and implementing this package, as in Morocco.

Notes

1. Average water use per equipped hectare is almost double that of Tunisia (6,000 m^3/ha in Morocco, compared with 3,000 m^3/ha in Tunisia at the farmgate). Similarly, cropping intensity is about 110 percent in Morocco, compared with 75 percent in Tunisia.

2. In Tunisia, the collection rate is 100 percent because water charges are paid prior to water use.

PAKISTAN: PUBLIC AND PRIVATE IRRIGATION DEVELOPMENT

Petros Aklilu and Altaf Hussain

> *In acknowledging God's mercy in establishing this great empire my desire, purer than water, is to supply the wants of the poor and to leave permanent work of greatness of my empire by digging canals and founding cities by which too, the revenue of the empire will be increased.*
>
> —*King Akbar-Moghul, A.D. 1568*

Pakistan has three main hydrological units: the Indus basin, the Kharan Desert, and the Makran coastal basin. Irrigation development, however, is primarily confined to the Indus basin, which begins in the Himalayas in the north, stretching through the vast plains of Punjab and Sind and extending to the Arabian Sea. The irrigated area of Pakistan constitutes about 41 million acres, of which the Indus Plain covers 35 million acres.

The ancient Indus civilization developed a privately owned system of storage and check dams, inundation canals, and water-lifting structures. In the fourteenth century, governmental control of construction and maintenance of storage dams for irrigation began, concurrent with private development. The state, however, was vested with the power to assume control of "sick units," i.e., those inefficiently managed or neglected. In the subcontinent, the first regular canal, an off-take of the Jamuna River, was built in A.D. 1355 and still exists. During British rule from 1819 to 1947, major irrigation developments occurred.

The partition of Punjab was carried out disregarding Indus basin boundaries, thereby engendering numerous problems. A crucial problem was the dispute over the Indus waters: after partition, the head reaches of most rivers remained in India. This problem culminated in the signing of the Indus Waters Treaty in 1960, with the assistance of the World Bank. Under the treaty, the three western rivers—Indus, Chenab, and Jhelum—were given to Pakistan, and the eastern rivers—Ravi, Beas, and Sutlej—to India. Although the pace of development was affected by negotiations, a series of irrigation works and barrages was added during this period, under a development strategy of converting existing inundation canals into barrage-controlled canals.

To compensate for the loss of water from the three eastern rivers, Pakistan was awarded financial assistance (under the Indus Basin Project [IBP] treaty) to construct within 10 years Mangla and Tarbela dams, five barrages, one gated syphon, and eight link canals. It also was to remodel two existing barrages and three link canals.

As a result of the IBP, public and private institutions related to water resources engineering emerged, including the Water and Power Development Authority (WAPDA); National Engineering Services Pakistan (NESPAK); construction organizations, e.g., Mechanized Construction of Pakistan Limited (MCPL) and the National Tubewell Construction Corporation (NTCC); and a host of private consulting firms. NESPAK is providing purely consultancy services, but WAPDA is engaged in

---

Petros Aklilu is head, Projects Unit, World Bank resident mission, Islamabad. Altaf Hussain, now retired, was chief engineering adviser and chair, Federal Flood Commission, Pakistan. This paper was presented in 1986.

planning, development, operation and maintenance (O&M), and research vis-à-vis water resources. Both organizations are using satellite imagery in the planning and design of their projects. WAPDA is also using imagery in predicting snow and ice contribution to the flow of the Indus system.

Another dimension of water resources development in Pakistan is the exploitation of aquifers. With an extensive reservoir of utilizable groundwater at exploitable depths, public and private tubewells are operating in the vast plains of the Indus basin. Expansion of controlled irrigation has resulted in the increased recharge of groundwater aquifers, contributing to widespread waterlogging and salinity problems. The public sector wells, installed primarily to lower the groundwater table, have also provided supplementary irrigation water. In 1958 the Salinity Control and Reclamation Project (SCARP), a vertical drainage concept adopted to control waterlogging and salinity, was created. Today, there are about 12,500 public SCARP tubewells, with an average capacity of 2 m^3/s, operating in fresh and saline groundwater areas. The demonstration effect of the public tubewells has encouraged private tubewell development. Over 200,000 private tubewells (with an average capacity of 1 m^3/s) are used primarily for supplementary irrigation in fresh groundwater areas.

Water Resources Planning

This section reviews previous five-year plans, highlighting specific decisions on public and private irrigation development. A review of plan and master plan documents demonstrates the evolution of investment priorities during each plan period. Equally important are the contributions of the various water sector studies, notably the First Action Plan of 1967 and the Revised Action Plan (RAP) of 1979, which reversed the course of plan priorities from expansion to rehabilitation and improved performance of installed facilities.

An important element of water resources planning in Pakistan is the division of responsibilities between the federal and provincial governments. The federal government has assumed the financing responsibility for major dams (Tarbela, Mangla, and Chashma); drainage and reclamation (SCARPs); flood protection works; and other environmental protection works. The provincial governments are responsible for O&M, except for the major dams. Financing of rehabilitation, modernization of irrigation and drainage systems, and overall water management improvement is supported by provincial resources. In 1984/85, provincial governments' contribution to the total water resource development budget was about 25 percent, proportional to their share in current total national revenues. Selected federal revenue sources (taxes) are distributed among the provinces in proportion to population. The rigidity of the resource distribution mechanism among the provinces and type of investments financed has induced distortions in investment planning and choices.

During the first plan (1955-60), public policy began to address waterlogging and salinity issues, primarily by preparing plans for public sector tubewells. Although in the 1950s some limited credit facilities were extended for tubewell installation, private tubewell development was not specifically emphasized. The extent of groundwater resources was hardly known at that time. The second plan (1960-65) helped promote a substantial reallocation of public investment to the agricultural and water sectors, from 7 to 18 percent. The first SCARPs were initiated during this period, and private tubewells began to increase significantly, though with no direct policy support. The third plan (1965-70) included an increase in the development of groundwater through increased public and private tubewells, with a policy emphasis on accelerating SCARPs. To help promote private tubewells, the government did provide some incentives: liberal imports of pipe and accessories, credit, and electrical connections. Except for tariff subsidies, however, no specific tubewell subsidies were granted. The fourth plan (1970-75) continued to support SCARPs and provided subsidies and some credit incentives to encourage tubewell development by the private sector. A diesel tubewell subsidy scheme was introduced in 1972, which helped install almost 8,000 tubewells during this plan period (representing 20 percent of the total increase in private tubewells). Differential subsidies were granted, ranging from 32 to 46 percent, with the higher subsidies provided to areas with smaller water supplies. For example, *barani* (rainfed) and *sailaba* (flood) areas received higher tubewell subsidies than those located in the canal-irrigated areas. In addition, the amount of institutional credit extended for private tubewells doubled.

During 1975-78 (nonplan years), the basic government strategy continued to encourage private tubewell development through a subsidy for diesel tubewells, credit (for both diesel and electric tubewells), and extension of electrification facilities. Also, SCARP tubewell programs continued to expand. The fifth plan (1978-83) envisioned a continuation of policies, with an emphasis on (1) increasing SCARP tubewells to alleviate waterlogging and salinity problems, including the installation of 5,000 public tubewells in fresh groundwater areas to provide about 3 million acre-feet for supplemental irrigation; (2) increasing surface and groundwater supplies for irrigation, with water availability increasing at the farmgate from roughly 92 million to 103 million acre-feet; (3) supporting continued increases in the number of private tubewells (by about 8,000 per year), adding an additional 6 million acre-feet; (4) encouraging the development and use of fractional tubewells and farmer groups that would meet small-farmer needs; and (5) promoting integrated planning of locations for public and private tubewells to avoid overdevelopment. In principle, this plan approached groundwater development through a mixed public and private investment policy. In practice, however, the overall roles of public and private sectors in groundwater development did not fundamentally change, and measures to accelerate private tubewells—for example, under points 4 and 5 above—were not adopted by the government.

The strategy for the sixth plan (1983-88) encompassed protection, improvement, and extension: protection, to alleviate waterlogging and salinity; improvement, to rehabilitate irrigation and drainage systems; and extension, to expand the irrigated area by opening new areas and increasing cropping intensity. The federal government's priority was the reclamation of areas with a depth to the water table of up to 5 ft from the surface, categorized as disaster areas. This plan also reaffirmed the recommendations of the RAP by limiting public sector tubewell development to areas underlain by saline groundwater. To further promote private sector tubewell development in fresh groundwater areas (and recognizing the unsustainable replacement and O&M costs of SCARPs), the sixth plan initiated a SCARP Transition Pilot Project to privatize publicly owned SCARP tubewells.

Role of Irrigation in the Economy

Despite the continuous decline of agriculture's share in GDP, the irrigation subsector remains crucial to Pakistan's economy (table 1). Therefore, the performance of irrigation systems in delivering irrigation water supplies and the proper operation of private and public tubewells determine (a) the nation's ability to feed its population and meet industrial raw material requirements, and (b) the extent of the external trade balance. Since 1984, Pakistan has been self-sufficient in wheat.[1] Pakistan's recent policy resolution to promote crop diversification would also rely heavily on irrigated agriculture. In 1985 the four provincial irrigation departments (PIDs) spent US$130 million to operate and maintain this strategic subsector. Moreover, over 80,000 individuals are employed in the PIDs to plan, construct, manage, operate, and maintain the irrigation and drainage infrastructure.[2]

The role of irrigated agriculture in Pakistan should not be viewed only in the context of its vital economic contribution, but also as a growing problem. The development and management of Pakistan's water resources have resulted in environmental hazards, with rising water tables and salinity, which if unchecked could endanger the nation's agricultural productivity and ecosystems. (Table 2 compares water table depth surveys from 1961 and 1981.)

Table 1. Percentage Share of Irrigated Agriculture in Selected Indicators, 1988

Indicator	Percent
GDP	26
Export earnings[a]	20
Employment	50
Public investment	10
Cropped area	76
Crop production	90

a. Excluding exports of processed agricultural products.

Table 2. Water Table Depth

	Percent of Indus Plain in category			
Year	0-3 ft	3-6 ft	6-10 ft	10+ ft
1961	2	11	23	62
1981	7	15	20	55

As mentioned, the federal government categorizes areas with a water table depth within 5 ft as disaster areas. The figures in table 2 indicate that disaster areas have actually increased by about 70 percent over 20 years, despite the enormous investments and O&M expenditures on SCARP tubewells and surface drains. The spread of controlled irrigation through dams, barrages, and other regulators on the Indus has also diminished the survival capability of the natural habitat. These environmental impacts and their financial implications are challenging Pakistan's water resources planners and policymakers.

Public and Private Tubewell Development

Mechanical tubewell development in Pakistan began in 1958 with the first SCARP in Punjab.[3] In addition to alleviating waterlogging and salinity, SCARPs were designed to provide supplementary irrigation supplies. Currently, there are about 12,500 SCARP tubewells in Pakistan, with 75 percent located in Punjab. Prompted by the contribution of SCARP tubewells and the acute shortage of irrigation supplies during early and late *kharif* and *rabi* seasons, private tubewell development boomed in the 1960s, with over 200,000 private tubewells installed thus far.

Public Tubewell Development

Origin and coverage. The topography of the Indus Plain limits natural drainage capacity. The water table has been continuously rising because of this limitation and the construction of new link canals; a large increase in canal irrigation water supplies; the deterioration of drainage systems as a result of poor O&M; and poor water application efficiency. According to WAPDA, about 8 million acres of cultivable command area are underlain with groundwater within 5 ft of the surface. To contain the spread of waterlogging and salinity, vertical drainage technology to complement surface drains was adopted, with about half of post-water sector investment expenditures devoted to SCARP tubewells. SCARPs by province are shown in table 3; almost 90 percent of SCARP tubewells are in fresh groundwater areas contributing to irrigation supplies.

Physical impact. The following sections highlight the performance of SCARP tubewells by drawing on various project assessments. These studies were carried out during the 1970s and focused on analyzing the results of selected parameters that were monitored by WAPDA, particularly regarding waterlogging and salinity control; groundwater pumpage and availability of water for irrigation; water quality; and tubewell performance, including capacity deterioration and maintenance problems. Although some production-related data have been collected, such as yields and cropping intensities and patterns, impact evaluation studies of SCARPs are limited. Various reviews have shown that public tubewells have generally followed a cycle: initial improvement of waterlogging problems, along with an increase in irrigation water supplies, followed by a decline in pumpage, resulting in rising water tables. For example, the installed pumpage capacity of the 12 principal completed SCARPs was over 10 million acre-feet annually; however, in 1979 the actual pumpage of these approximately 10,200 tubewells was about 7 million acre-feet, with SCARP I pumpage declining from 2.5 million acre-feet in 1963/65 to about 1.5 million acre-feet in 1979/80. Consequently, SCARP tubewells are operating at low utilization, averaging about 30 percent in fresh groundwater areas and almost 40 percent in saline groundwater areas. Much of this decrease is due to deterioration of tubewell discharge capacity and protracted downtime before mechanical and electrical defects are repaired.

Waterlogging and salinity control. Declining pumpage and pumping capacities have significantly contributed to the general underachievement of the drainage and agricultural targets used to justify approval of SCARPs. Drainage targets were partially achieved in areas where waterlogging problems were mitigated, particularly in the critical range of 0 to 5 ft. Some available data, however, show that the water tables are rising, in some cases to their preproject levels. In the 0-to-15-ft range, 24 percent of SCARP commands are waterlogged, compared with about 22 percent for the entire Indus Plain. Available data do indicate that SCARPs *initially* fulfilled their drainage functions, with other studies showing that the waterlogging relief provided by SCARP tubewells is often temporary, because conditions tend to reverse as soon as a tubewell becomes inoperative.

Table 3. SCARP Tubewells by Province

		No. of tubewells installed		Area covered
	No. of projects	Fresh groundwater	Saline groundwater	('000 acre)
Punjab	13	8,065	1,031	5,390
Sind	9	2,376	365	1,190
NWFP	8	612	--	110
Total	30	11,053	1,396	6,690

Production impact. Production data generally show improvements in terms of higher yields, higher cropping intensities, and some shifts toward the relatively more water-intensive and higher-value crops (paddy and sugarcane). However, the optimistic targets set at the planning stage were generally not met by most SCARPs. For example, early studies assumed that cropping intensities would double, from about 75 to 150 percent. Rather, intensities in most areas stabilized at around 115 percent, with some increase in crop yields and the area under high-value crops. As discussed below, the operational deficiencies of most SCARPs are attributed to their inability to adequately meet crop water requirements, resulting in suboptimal use of the anticipated conjunctive surface and groundwater supplies.

Management and institutional factors. Numerous interrelated factors have contributed to the uneven and inefficient performance of SCARPs, but most of the underlying problems can be traced to inadequate planning. These shortcomings have been reviewed in several studies and can be classified in terms of (1) design and technology, (2) institutional arrangements and operational criteria, (3) maintenance, and (4) farmer organization and incentives.

SCARP tubewells were designed to maximize their technical efficiency to fulfill a multipurpose groundwater development program of drainage and supplemental irrigation. As a result, these tubewells used relatively sophisticated and large-capacity pumps—initially imported turbine pumps whose capacity ranged from 2 to 5 m^3/s—that assumed the presence of an efficient centralized management system. In the SCARP I area, tubewell capacities were fixed so that the combined water supply from surface and groundwater at the watercourse head was about 1 m^3/s per 150 acres. In subsequent SCARPs, cropping intensities for the area were projected, and the tubewell capacities were determined to provide the necessary water supply to meet this requirement of one to three watercourse commands. In practice, no provisions were made for constructing necessary link watercourses and for enlarging the main watercourse channel and distribution system, although the planners anticipated that the system would carry two to three times its previous flow quantity. In addition, appropriate mixing ratios between canal and tubewell water supplies fit for irrigation were frequently not achieved, in some cases because of several deficient design factors—particularly, an inappropriate siting of tubewells, resulting in closures of certain SCARP tubewells, and inappropriate tubewell design and mixing chambers, leading to undesirable mixing and distribution of both surface and groundwater supplies.

SCARP tubewells have been planned, designed, and constructed by WAPDA. Operation is initially the responsibility of WAPDA for one or two years; it is then handed over to PIDs. SCARP I was managed by a project director, under whom were field units responsible for O&M of tubewells, distribution of integrated irrigation supplies, and agricultural extension and cooperatives. In 1970, this approach was abandoned because it was considered top-heavy and expensive, and was creating unnecessary friction. The various activities were assumed by the regular provincial agencies. The SCARP in Khairpur was also organized under a project director, but surface irrigation management was under a senior PID engineer.

With the exception of the earlier (apparently unsuccessful) experiments under SCARP I and Khairpur, there has been no formal integration of canal and tubewell water supplies as envisaged by SCARP planners. The organizations responsible for canal operations, although part of the same PID, are parallel, with no institutional cross-links below the level of regional chief engineer. This arrangement is fundamentally problematic, because most day-to-day operating decisions for the irrigation system are made at the divisional level under the executive engineer. Moreover, even at the planning stage, the pumping schedules of SCARP tubewells were not adjusted to reflect estimated canal supplies and crop water requirements.[4] There was negligible consideration of the recommended plan-water relationship: the irrigation department fixed the tubewell operational schedules with minimal consultation with the extension personnel of the agriculture department; these consultations occurred only on an ad hoc basis. In theory, it would sometimes have been possible to divert canal supplies to water-short commands and to compensate for this deficit by pumping extra hours. In practice, this adjustment has never been pursued, with the separate, uncoordinated institutional roles of various concerned agencies severely restricting the potential benefits of the envisioned conjunctive system.

A major operational problem that has aggravated an already deficient operating schedule has been directly related to the difficulties of managing the tubewell operators. Poor operator performance is a major complaint about SCARP tubewells voiced by both farmers and irrigation department staff. Some commonly reported problems involve operators who (a) are frequently absent, with the result that tubewells may not be restarted if tripped off by protective devices because of temporary electrical supply problems; (b) disable the protective devices; (c) allow farmers to operate the tubewells, resulting in a high incidence of burned-out motors; and (4) provide preferential arrangements to some farmers in the tubewell command area. Attempts to discipline or dismiss operators have generally been unsuccessful because of the powerful operator labor union. Regardless of the veracity of these allegations, day-to-day tubewell operations are clearly supervised loosely if at all. An absence of effective control over field staff activities—by senior officials, by standardized cross-checking, or by farmers—demonstrates the inherent weakness of current public sector management of the SCARP tubewells.

PIDs are responsible for the O&M of SCARP tubewells. Although SCARP tubewells discharge about 9.4 million acre-feet of water annually, or 13 percent of total irrigation supplies to the watercourses, 51 percent of total O&M expenditures (canal and tubewell) are absorbed by SCARP tubewells. PIDs' O&M expenditures by category for 1983/84 are shown in table 4.

The underlying factors of poor O&M have been technical, institutional, and financial, and are ultimately tied to poor management. These problems have resulted in declining pumpage and excessive deterioration of SCARP tubewells. Various surveys have shown that, at any point in time, from 20 to 45 percent of SCARP tubewells were not operating due to a maintenance-related defect. This performance contrasts with the high operational functioning of private tubewells, which frequently exceeds 90 percent. Despite the high share of tubewell O&M expenditures, poor maintenance has been attributed to the inadequate O&M budget. This underfunding has also contributed to the deterioration of Pakistan's overall surface irrigation system.

Table 4. Irrigation Operation and Maintenance Expenditures, 1983/84 (thousand US$)

	Punjab	Sind	NWFP	Baluchistan	Total Pakistan
Canals	12.1	11.4	4.4	3.4	31.3
SCARP tubewells	43.9	5.6	1.7	na	51.2
Establishment[a]	30.4	17.3	3.0	2.4	53.1
Other[b]	03.9	7.0	1.4	0.5	12.8
Total	90.3	41.3	10.5	6.3	148.4

a. Includes salaries and other overhead.

b. Small dams, drainage and flood control, and research and design.

Another constraint to effective SCARP management is related to inadequate planning at the watercourse level, including unrealistic assumptions regarding farmer's incentives and responses to SCARP arrangements. Planners gave little thought to local conditions, particularly the role played by farmers in efficient use of additional water supplies. Field investigations during the planning stages would have revealed that farmers along a single watercourse have difficulty organizing O&M. The bulk of court cases originating in rural areas stem from conflicts over water and associated land. Provision of large, publicly owned and operated tubewells that were designed to serve two or more watercourses immediately created the potential for numerous conflicts. Adequate investigations of farmers' organizational capacities, as well as their technical ability to manage larger flows of water, would have indicated that smaller-capacity, more localized tubewells, primarily for irrigation, were better suited to existing conditions. The argument that larger public wells are more economic and efficient than smaller private wells rests on the unrealistic assumption that management under both systems would be similar. Planners failed to recognize farmers' limited capacity to cooperate at the watercourse level, particularly without established, appropriate forms of organization and incentives to redesign and enlarge the watercourses to carry the additional tubewell supplies.

Fiscal impact. The water charges levied on SCARP tubewell users cover an average of 20 percent of O&M expenditures. In contrast, recoveries from canal supply beneficiaries cover about 50 percent. In FY85 water charge revenues represented 43 percent of total O&M expenditures. The average O&M cost of canal irrigation (excluding SCARP tubewells) is estimated at about Rs 22 per irrigated acre, compared with an average water charge of about Rs 21 per irrigated acre. In contrast, the O&M costs for SCARP tubewells are estimated at about Rs 107 per irrigated acre, considerably higher than the corresponding water charges, which average about Rs 40 per acre.

Given the substantial required subsidies to cover gaps and the competing claims on the provincial nondevelopment budget, underfunding and undermaintenance have characterized Pakistan's irrigation system and SCARP tubewells, particularly since the mid-1970s. The financial burden of continued public sector responsibility for SCARP tubewells will worsen over the next decade, as aging tubewells need to be replaced.

Private Tubewell Development

Origin and coverage. The rapid development of private tubewells occurred during the 1960s and was largely induced by public tubewell development. In the following decades the declining performance of SCARP tubewells, as discussed earlier, contributed to further expansion of private development. The boom in private tubewells occurred mainly between 1964 and about 1976, when the number of private installations increased from 23,140 to 150,840. Given abundant exploitable groundwater supplies, particularly in relation to the other provinces, most tubewells (73 percent) were installed in Punjab. In addition, the majority of private tubewells, nearly 65 percent, are located in canal commands. This growth was largely unassisted by the public sector and represents a distinctive point in Pakistan's agricultural development, underscoring the attractive financial returns from investing in private tubewells. Today, over 200,000 private tubewells are operating, providing about 27 million acre-feet of irrigation supplies.

Survey results identify the following factors related to private tubewell development: First, farm size emerged as an important determinant, highlighting smaller farmers' limited access to financing as well as the nonavailability of fractional (less than 1 m^3/s) tubewell technology. Second, SCARP tubewells provided a qualified though positive demonstration effect, although many private tubewells were established partly to compensate for insufficient and unreliable water supplies from both public canals and tubewells. For example, in the SCARP I area, private tubewells in 1980/81 totaled almost 11,000 and pumped over 2.0 million acre-feet, substantially higher than the 1.3 million acre-feet pumped by 2,069 SCARP tubewells.

Technology. Compared with public tubewells, private tubewells have a smaller capacity (averaging 1 m^3/s) and lower pumping lifts. Approximately 95 percent of private tubewells are equipped with centrifugal pumps that are installed in pits to remain within the suction lifts. This limits the practical range for utilization of centrifugal pumps to water table depths generally between 15 and 20 ft, rarely exceeding 50 ft. About two-thirds of private tubewells are diesel-operated (primarily slow-speed diesel), with the remainder powered by electricity. Sample surveys have shown that the average power rating of the engines and motors installed on private tubewells is about 17.6 horsepower (HP), generally about 100 percent greater than the required HP for the discharges and lifts involved.

Physical impact. The importance of and dramatic increase in private tubewells are reflected in the level of and increase in groundwater pumpage attributed to them. Private pumpage increased from 3.3 million acre-feet in 1959-60 to about 27 million acre-feet in 1983/84. Private tubewells, 75 percent of which are in canal command areas, account for over 75 percent of total groundwater pumpage in the Indus Plain and contribute about 30 percent of total irrigation water supplies at the farmgate. WAPDA's most recent estimates of capacity utilization range from 15 to 25 percent: this is relatively low, primarily because tubewell water is used to supplement canal supplies. To meet crop water requirements, particularly during water shortages, the annual pumpage per tubewell is approximately 170 acre-feet, varying according to rainfall, availability and reliability of surface supplies, and cropping patterns and intensities. In sum, a substantial portion of drainage, reclamation, and groundwater supply functions are being performed by private tubewells.

Agricultural impact. WAPDA estimates that 65 percent of private tubewells in canal commands are used as supplemental sources of irrigation, whereas the remaining tubewells provide the principal source of irrigation. Although there are variations according to area, tubewells alone account for about 60 percent of total irrigation in the *rabi* and about 45 percent in the *kharif* season. WAPDA has found that the area irrigated per tubewell averages 38 acres. The total area served by private tubewells is difficult to quantify because of limited data; however, using indirect evidence, WAPDA has estimated that 7.5 million acres receive irrigation supplies from private tubewells and have irrigation on demand matched to crop water requirements.

The agricultural impact of private tubewells per acre and for different farm sizes has been reviewed by numerous field surveys. Although there is a wide variation in the key agricultural parameters, data reported in these surveys indicate that yields increased by 15 to 30 percent; cropping intensities rose to 120 to 140 percent; and cropping patterns frequently shifted to higher-value and delta crops, such as orchards, paddy, and sugarcane.

O&M management performance. Because private tubewells were established primarily by individual farmers for irrigation crop requirements, their management has been relatively efficient in ensuring quantity and timing of water supplies and avoiding prolonged delays in correcting malfunctions. This efficiency is aided by broadly available tubewell technology and town-level workshops. The private ownership of tubewells—usually by individuals—and their highly decentralized management are probably the main reasons for private tubewells' solid O&M performance. This positive experience, of course, contrasts sharply with the highly centralized management patterns that have hampered the O&M of SCARP tubewells.

Farmer organization. A dominant feature of private tubewells is the pattern of individual ownership and management. WAPDA has reported that nearly 75 percent of private tubewells are owned by individual farmers, with the remaining 25 percent jointly owned. Since the fifth five-year plan, the government has supported the concept of group ownership and management through water user associations or cooperatives. In practice, however, only a relatively small percentage of private tubewells are owned and/or operated by such farmer groups, largely because of favorable technology availability; farmers' traditional, mistrustful attitude toward cooperatives; and negligible government efforts to help organize farmers and finance their organizations.

The average farm size of tubewell owners is about 40 acres, and about 70 percent of tubewell owners have an average farm size greater than 25 acres. The percentage of jointly installed tubewells is high in small farm groups; for example, 44 percent of jointly owned tubewells are installed in the 0-to-5-acre farm-size category. Also, approximately 90 percent of tubewells have been financed entirely by farmers' own resources. Government financing facilities for private tubewells (credit and subsidy programs) have not provided any special facilities to spur the formation of farmer organizations.

Two important points emerge from this section. First, the greatest scope for future development of private tubewells lies in extending their use to smaller farmers (less than 12.5 acres) by promoting appropriate fractional tubewell capacity, credit facilities, electricity extension, reliability, and forms of farmer organization. Second, the limited evaluations of farmer group experiences in private tubewell management underscore the need for further field research that could suggest the most effective ways of strengthening farmer organizations, perhaps emulating the water user associations being promoted under on-farm water management (OFWM) projects.

Aquifer management. The absence of any control or aquifer management of private tubewell pumpage has led to close siting of tubewells, with a mean distance of about 1,500 ft. Except in a few areas, the growth of tubewells and pumpage has not seriously threatened groundwater quality. Uncontrolled pumpage, however, may pose a future problem, especially where there is a high concentration of private tubewells. Uncontrolled pumpage may induce differential private and social benefits and costs; therefore, the public sector will need to carefully monitor the aquifer and introduce appropriate and efficient measures that support a favorable pattern of tubewell development and groundwater recharge.

Fiscal impact. Punjab and Sind have budgets available for direct cost subsidies for construction of private tubewell facilities. Direct subsidies are also granted for power connections to tubewells. The agricultural engineering departments of Punjab and Sind have hand- and winch-operated drilling equipment, which farmers use at subsidized rates. All these subsidies are limited, to varying degrees, by the subsidy budgets of the government or semiautonomous government agencies concerned. Implicit operational subsidies are also available to private tubewell operators. The agricultural tariff for electrical energy is less than the actual cost of generation, transmission, and distribution, and the average price per energy unit is considerably lower for the agricultural consumer than for other consumers. A subsidy is also theoretically available for light diesel oil used for agricultural pumping, but is rarely claimed by tubewell operators with diesel engine-powered facilities. Also, agricultural credit is provided at favorable rates, compared with credit facilities for other types of investment.

The private tubewell boom has been a relatively small burden to the public sector. Excluding electrification capital costs and the subsidies on the electricity tariffs, the main direct public expenditure has been the diesel tubewell subsidy scheme introduced in 1972 for *barani*, *sailaba*, and canal command areas. These subsidy schemes were introduced despite the remarkable growth of private tubewells, which was largely unsupported by the public sector.

Equity consideration. Available data show that private tubewell ownership is concentrated on the larger farm holdings (see above). This ownership pattern suggests private tubewells' adverse effect on income distribution within agriculture. Available data show, however, that the existence of a private market for tubewell water is more widespread than is ownership. Small farmers buy water from tubewell owners with cash, crop shares, and/or labor. For example, considering different farm size intervals, tubewell ownership varies from about 6 to 20 percent of all farmers, whereas tubewell usage varies from about 20 to 34 percent of all farmers. Nonetheless, there is substantial scope for improving the equity effects of future investments in private tubewells. Improved arrangements for providing credit and power connections can be important instruments in making tubewells more accessible to small farmers.

Future Tubewell Development

The above performance review of public and private tubewell development in Pakistan raises a series of policy questions. First, given the problems associated with operation of SCARP tubewells, is there scope for improvement? Second, even if revitalizing the management and performance of SCARP tubewells is possible, should public resources be committed? Third, what is the fiscal implication of sustaining SCARPs, including O&M and, more important, the replacement of aging tubewells? It is estimated that by 1995 existing SCARP tubewells will have to be replaced, costing over US$600 million in addition to the increasing O&M bill.

The government has fully recognized the limitations of SCARP tubewells in fresh groundwater areas. Moreover, the related O&M budget requires a substantial transfer of resources away from other needs, including canal irrigation O&M. Encouraged by the response of the private sector to tubewell development, the federal government, in its sixth five-year plan and subsequent policy decisions, declared that future public tubewell development in fresh groundwater areas would be halted and a program to privatize the existing SCARP tubewells initiated. The World Bank, fully supporting this initiative, is currently assisting Pakistan in a SCARP Transition Pilot Project in the SCARP I area. The results of the feasibility study and other detailed project area surveys are favorable. The project would finance (a) installation of electric lines; (b) improvement of canals and watercourses; and (c) technical assistance for project supervision, monitoring, and evaluation. The Agricultural Development Bank of Pakistan, through its regional credit facilities, would meet the credit requirements of private tubewells. Under the pilot project, 213 SCARP tubewells would be phased out or transferred to group ownership. An estimated 2,100 private tubewells are expected to replace the SCARP tubewells to meet irrigation and drainage requirements.

The potential benefits of privatization are clear; however, the success of future SCARP transition is contingent upon the following critical factors: (a) availability of electrical connections; (b) monitoring of tubewell operation in conjunction with canal supplies; (c) legal implications, namely groundwater legislation to promote appropriate siting of tubewells and aquifer management to facilitate the necessary drainage and water supply function; (d) promotion of tubewell ownership among small farmers; and (e) raising O&M cost recovery for SCARP tubewell beneficiaries to spur them to shift to private tubewells.

Postscript

The SCARP Transition Pilot Project is near completion and has yielded satisfactory results. The lessons from the pilot project have been reflected in the design of the Second SCARP Transition Project, in Punjab and Sind provinces, for which an IDA credit of US$20 million was approved in

June 1991. The government of Pakistan is fully committed to the transfer of the management of fresh groundwater resources to farmers and to the privatization of public tubewells.

Notes

1. Since 1988, Pakistan has been importing an average 1 million mt of wheat annually.

2. This staff size roughly represents one employee per watercourse, which serves an average command area of about 400 acres. Elsewhere in Asia, the area allotted to one employee ranges from 300 to 1,240 acres.

3. This section draws heavily on World Bank data.

4. SCARP tubewells are supposed to operate on schedules developed in perennial, nonperennial, and uncommanded areas; schedules do not allow for rainfall or power failures. Data available on actual operating hours are sketchy and must be used with caution. Nevertheless, some general operating criteria have been developed as guides to lower the water table and to provide supplemental irrigation water. Generally, drainage objectives have aimed to pump water so that the water table remains below 10 feet, although in practice this guideline has not always been followed. Regarding supplemental irrigation, the proposed Lalian pumping schedules used for SCARPs vary little by month and bear little relationship to a schedule that attempts to match expected water supplies with expected demand, i.e., a schedule usually followed by private pump operators.

PUBLIC AND PRIVATE GROUNDWATER DEVELOPMENT IN INDIA: THE CASE OF UTTAR PRADESH

John F. Cunningham

In India, whether irrigation development will be undertaken by the private or public sector is determined by (a) the technical feasibility of developing a water source, and (b) the ability of individuals or groups of farmers to organize and arrange financing. Generally, farm size is small, so that, even for relatively limited schemes, many farmers will be involved. Thus, private development of even micro-diversion schemes is somewhat limited, mainly restricted to remote areas where farmers live in a strong social grouping (tribal or scheduled castes) and are able to collectively organize for this type of scheme.

The primary constraint to public groundwater development has been viable technology. Even with modernized designs, however, the number of public wells that can be installed is governed by budget allocations and implementation capacity. Both public and private well development is therefore essential and must be complementary if land and groundwater resources are to be effectively utilized. This paper examines the roles and performance of public and private sector groundwater development. It focuses on Uttar Pradesh, India's leading state in groundwater development, with 13 percent of the country's dug wells (primarily mechanized), 47 percent of the private tubewells, and about 50 percent of the public tubewells.

Private and Public Tubewell Development in Uttar Pradesh

Background

Private and public tubewell development in Uttar Pradesh, in terms of net irrigated area, is shown in table 1. Currently, there are about 1.6 million private tubewells and about 22,000 public tubewells operating in the state, although present groundwater extraction represents only about one-half of total resources. Of the private tubewells, about 1.1 million are diesel-powered, with the remainder using electric pump units. The state government plans to construct about 1,000 to 1,500 new public tubewells annually and anticipates that the private sector number will increase by about 100,000 units annually.

All landowners in the state have the implicit right to develop the exploitable groundwater resources within their landholding. Theoretically, the state could depend entirely on the private sector to develop groundwater resources if there were any certainty that most farmers (in time) would be able to afford their own irrigation source (or could buy water at a reasonable cost and in sufficient quantities to facilitate effective irrigated agriculture). In practice, however, private groundwater development can only be undertaken where the aquifer is shallow enough to use a simple water point, and by those farmers with the financial resources to invest in their own irrigation source.

John F. Cunningham is principal irrigation engineer, Agriculture Division, Asia Region Technical Department, World Bank.
This paper was presented in 1986.

Table 1. Net Irrigated Area Served by Public and Private Wells in Uttar Pradesh (thousand ha)

Well type	1960/61	1965/66	1970/71	1976/77	1979/80	1984/85	Increase (1960-85)
Public	495	721	877	1,067	770	860	365
Private	48	184	1,522	2,707	4,058	5,095	5,047

Because the private sector cannot achieve the full utilization of the available land and groundwater resources, complementary development in the public sector is required. However, budget allocations and implementation capacity restrict the rate at which groundwater resources can be developed by the public sector. To take advantage of both public and private groundwater development, public tubewells, each commanding 100 ha or more, are normally constructed in areas where gravity irrigation is not feasible and where the potential for construction of shallow tubewells (or boreholes with pump sets) is limited by the depth of the aquifer and the size and fragmentation of holdings. The government of Uttar Pradesh recognized the need for a continuing and substantial investment in both private and public groundwater development and has formulated its groundwater strategy accordingly.

Although groundwater development in Uttar Pradesh has been undertaken on an enormous scale compared with other states (table 2), there are private and public development issues that cannot be fully addressed because monitoring and evaluation have been incomplete. Performance data on private irrigation sources are limited, primarily because obtaining reliable data from private farmers is difficult. More information is available with respect to public tubewells, though again it is incomplete. A basic shortcoming of both subsectors' evaluations is that data collection has been restricted to the command areas served by the wells. Private sector evaluations have been equivalent to assessing the development impact on a small select sample of privileged farmers. In addition, there has been no comprehensive evaluation comparing public and private groundwater development, although there is strong evidence that resources have been mismanaged in both public and private schemes.

Public Groundwater Development

The public tubewell program in Uttar Pradesh was initiated in 1931/32. By 1950, about 2,000 public tubewells were in service, increasing to 10,000 by 1970 and to about 22,500 by 1984/85. The siting of the early public tubewells related to whether the farmers could be served by gravity irrigation sources; wells were often sited within the boundaries of these gravity schemes. Little attention was paid to possible or actual private groundwater development within the command areas. Once private tubewells were viable, the siting of new public tubewells tended to be more restricted. They were generally installed in areas where the water table was too deep for the centrifugal pumps commonly used for private wells, or in underdeveloped areas where private development was unlikely because of small farm size. Only public tubewells constructed under IDA-supported programs after about 1980 have been subject to specific siting conditions (see below).

Past performance. Although there have been some fluctuations in annual utilization related to high- or low-rainfall years, the general trend has been a decrease both in hours of operation and area irrigated per tubewell. In 1966/67, the average number of hours of utilization was 3,432 per well, decreasing to 1,012 per well in 1980/81. Average irrigated area per tubewell fell from 153 ha in

Table 2. Private and Public Groundwater Development in India (Number of Units)

State	Private dug wells		Private tubewells		Public tubewells	
	1968/69	1984/85	1968/69	1984/85	1968/69	1984/85
Andhra Pradesh	660,000	982,000	16,000	85,000	n/a	1,047
Assam	n/a	n/a	n/a	17,000	22	762
Bihar	225,000	352,000	12,000	405,000	1,273	6,039
Gujarat	565,000	673,000	1,000	4,500	927	3,924
Haryana	65,000	39,000	143,000	324,000	935	1,773
Himachel Pradesh	n/a	2,500	n/a	20	n/a	187
Jammu Kashmur	n/a	200	n/a	2,000	59	144
Karnataka	280,000	467,000	n/a	n/a	n/a	n/a
Kerala	5,000	150,000	n/a	600	n/a	n/a
Madhya Pradesh	610,000	1,113,000	2,000	7,600	70	209
Maharashtra	665,000	1,008,000	300	100	n/a	n/a
Orissa	15,000	497,000	n/a	7,900	213	4,324
Punjab	170,000	91,000	113,000	593,000	845	1,694
Rajasthan	605,000	778,000	7,400	14,000	32	76
Tamil Nadu	1,115,000	1,411,000	26,000	111,000	n/a	n/a
Uttar Pradesh	1,120,000	1,130,000	120,000	1,586,000	8,946	22,622
West Bengal	n/a	33,000	12,000	227,000	1,308	3,085
Northeast States	n/a	n/a	n/a	1,000	n/a	95
Union Territories	10,000	16,000	7,000	1,000	22	186
Total	6,110,000	8,742,700	459,700	3,386,720	14,652	46,167

n/a Not available.

1966/67 to 46 ha in 1980/81. Thus, although the number of tubewells doubled from 8,385 to 16,832 during this period, total area irrigated decreased by 40 percent, from 1.3 million ha to 800,000 ha.

Early public tubewells were planned to provide irrigation service at a low annual cropping intensity (about 80 percent) and with limited water application (2 to 3 irrigations). The surface distribution system was unable to effectively spread the limited supplies over the command area. Dissatisfied with the public irrigation service, many progressive farmers within the command areas of existing wells invested in private pump units. Rural electrification programs enabled private operators to adopt electric pump units, which became (and are now) a major factor in the deterioration in quantity and quality of rural power supply. Public tubewells are connected to the local rural grid and require more hours of reliable power supply than private wells. In addition, public wells require a level of power supply that recently has been unavailable in most rural areas.

Other design factors exacerbated deteriorating public tubewell service:

1. Incomplete distribution systems favored farmers close to the wells, who extracted scarce supplies to the detriment of farmers further away;

2. Inadequate operation and maintenance led to frequent breakdowns, delayed repairs, and service interruptions;

3. Unreliable water delivery encouraged operators to favor selected users.

The net result has been that the irrigation service provided by traditional public tubewells has become unreliable and inequitable. Despite these problems, the government has continued to support public groundwater development because it remains an attractive irrigation source for poor farmers with small holdings and—compared with the construction of surface irrigation schemes—has a shorter gestation period. In addition, public tubewells have the major advantage that they can be sited with more flexibility than surface irrigation schemes to reach selected beneficiaries.

Improved public tubewells. Under a Bank-supported program that began in 1978, public tubewell design was improved to eliminate the defects described above. The improved public tubewells had automated well points and buried pipe distribution systems, and since about 1982 have been connected to dedicated power lines. With these improvements, the state government now has a public tubewell design that can provide timely, reliable irrigation service. The siting of these improved tubewells depends on the level of private groundwater development within the potential command area to avoid constructing public tubewells in areas where there is already a substantial investment in private irrigation sources. The siting of new public tubewells has therefore been restricted to areas (a) where construction of private tubewells is difficult because of the drilling depth necessary to achieve a satisfactory yield, and (b) which are economically underdeveloped and where development of private wells will be slow. In addition, improved public tubewells are located in clusters so that they can be served effectively and efficiently by an independent power line.

The specific siting criteria for new public tubewells include an implicit judgment on the relative merits of private and public groundwater development. The level of private development within the potential command area of a public tubewell determines whether farmers without private irrigation sources will have public irrigation service.

There would be considerable advantages (both social and economic) to the state if the constraints to private and public groundwater development could be mitigated; for example, with the buried pipe distribution system of improved public tubewells, a noncontiguous command area can be served.

Private Groundwater Development

Private groundwater development has enabled vast areas with good land and irrigation potential to be brought under production more quickly than through the public sector. Private groundwater development has expanded rapidly in Uttar Pradesh because groundwater resources are generally easy to exploit, low-cost technology is available to farmers, and the government has strongly supported the program through credit and rural electrification programs. The dominant foundation of the green revolution—reliable irrigation—was provided by private groundwater development. (The number of private units in 1980/81 and proposed under the sixth five-year plan is found in table 3.)

Three types of private wells are common: masonry lined dug wells, cavity wells, and strainer-type tubewells. The masonry lined dug well usually yields about 8 m^3/hr when operated with a Persian wheel (about 20 percent of masonry wells). The remaining dug wells are equipped with leather or metal buckets, with animal-powered lifts and limited discharge rates. If the farmer can afford the investment, a borehole is drilled in the bottom to penetrate a shallow aquifer (usually to a depth of less than 30 m). These wells are frequently referred to as cavity wells because they usually lack a strainer. The casing is sealed into a convenient thick clay layer that acts as the "roof" of a cavity, formed by pumping out the sand around the end of the casing. The cavity well is usually equipped with a small centrifugal pump and motor that, if electric, is directly connected to the pump or, if diesel-powered, is connected to the pump by a belt drive. These wells usually have a capacity of about 25 m^3/hr. Strainer-type tubewells are small diameter boreholes equipped with a strainer section

Table 3. Private Wells
(thousands)

Unit type	As of 1980/81		Targeted under sixth plan (1980-85)	
	Total India	Uttar Pradesh	Total India	Uttar Pradesh
Diesel	4,360	809	900	n/a
Electric	2,830	409	2,500	n/a
Total	7,190	1,218	3,400	368

n/a Not available.

of pipe. These wells are usually drilled to about 45 m, depending on aquifer depth and desired capacity. They have capacities of about 35 m^3/hr and are equipped with centrifugal pumps. The pumps may have to be placed in a pit to maintain a suction lift of 5 m or less, the practical maximum for the pump to operate efficiently.

Distribution from private well points is through small, unlined channels and is generally limited to about 30 m for dug wells and up to 350 m for tubewells. Occasionally, the conveyance channel may be longer if the owner regularly sells water to farmers on adjacent holdings. In these cases, conveyance losses may be considerable, but are paid for by the buyer since water is sold on an hourly basis.

Of the millions of private irrigation sources installed in India, few are designed following sound technical standards. The common practice is for a local pump unit supplier and/or drilling contractor to build wells using available equipment and materials that provide the best profit margin. Contractors follow local practice or their clients' whims. Consequently, private units are generally designed and constructed to be price-competitive; because performance is seldom measured, unit efficiency is of little or no concern to either the farmer or well contractor.

Farmers' choices among the various types of private wells depend on many factors, including groundwater characteristics, electric power supply availability, holding size, available financing, and, to some extent, the experience of neighboring farmers and the drilling contractor or equipment supplier. During early private groundwater development in India, most pump sets were diesel-powered because diesel engines were readily available and rural power supply was limited. In recent years, the availability and cost of diesel fuel have become an increasing problem for minor irrigation and especially for the private sector. State fuel allocations have been reduced and in some cases rationed, while demand has increased. This has led to severe fuel shortages, often during critical periods in the cropping cycles.

The technical performance of private wells has received little attention, given the number of units installed in India and their economic importance. Recently, however, the technical shortcomings of typical private wells have been documented.[1] Private wells are poorly designed and inefficient because of the tremendous difficulties in promoting appropriate design standards. Knowledge of improved standards (and their enforcement) is likely to be available only to farmers seeking credit to help finance new wells.

Most private tubewells in Uttar Pradesh have a capacity greater than that required by owners' landholdings. It has been argued that this additional, spare capacity could be used to supply irrigation service to farmers unable or unwilling to invest in their own source. The common practice is for owners to rent their wells on an hourly basis. The limited data available indicate that the cost of water from rented private wells is so high (about Rs 0.7/m^3) that most small farmers buy only *protective* irrigation supplies, i.e., water to save their crop from drought. Few farmers can buy sufficient water to enable *productive* irrigated agriculture because when the need for irrigation is greatest, well owners often do not wish to sell water. To a private well renter, not only is the quantity of water for sale important but also the timeliness of the supply. The data on the renting of private irrigation sources have been mainly collected to evaluate the investment of well owners and not to study the use of water by the renter. Little analysis has been undertaken to assess the constraints of supply and demand, given the limits of both buyer and seller related to the location of their holdings. There is little likelihood, however, that supply will match demand on a scale that makes renting private wells a viable alternative to a public source for poorer farmers.

Comparing Private and Public Groundwater Development

Directly or indirectly, several determinants influence the intensity of private tubewell development and the likely benefits of public and private groundwater development. As mentioned above, the primary constraint to private groundwater development is the cost to the farmer; for public tubewells, the constraint has been viable technology. Even with improved designs, the number of public wells that can be installed is governed by groundwater availability, budget allocations, and implementation capacity. In addition to financial considerations and quality of service to farmers, there are three main issues in comparing public and private well development: (1) how public and private wells utilize land and groundwater resources, (2) the relative efficiencies of the two systems, and (3) the quality and quantity of the rural power supply.

Use of Physical Resources

Uncontrolled groundwater development may seriously limit full utilization of cultivable land and the usable groundwater beneath it. After considerable private tubewell development has occurred within an area, the present strategy is to designate that area for private sector development (the basis of the siting criteria for public tubewells under the second Uttar Pradesh public tubewells project). Because only some farmers can afford a private tubewell—and there are technical limitations to the minimum size of private wells—it is estimated that private well development will level off at about 30 percent of cultivable land in the local area around a group of wells. The only irrigation source for farmers unable to afford their own well in that local area would be to buy water in a "seller's" market. Most small farmers cannot afford to buy enough water from a private source for full irrigation. Thus, without complementary public sector development, poorer farmers who own or control a substantial part of the irrigable area will be permanently excluded from fully irrigated agriculture. Any evaluation of private groundwater development should therefore consider the economic costs of precluding small and marginal farmers from acquiring reliable, affordable irrigation service.

System Efficiencies

The overall efficiency of a tubewell system has two aspects: (1) wire-to-water efficiency, i.e., the ability of the pump unit to effectively use the power supplied; and (2) irrigation or conveyance efficiency, i.e., the proportion of water supplied at the well that usefully reaches the field. Little reliable data are available on system efficiencies. Table 4 illustrates average efficiencies for selected groundwater irrigation sources. Private wells are unlikely to be designed to improved standards if private groundwater development remains unregulated. Farmers investing in wells want to minimize their capital expenditure. Few will be able to analyze the marginal savings in annual cost that would

Table 4. Percentage Average Efficiencies for Selected Groundwater Irrigation Sources

Unit type	Wire to water	Conveyance efficiency to field	System efficiency
Public tubewells			
Traditional design	50	40	20
Improved design	60	60	36
Private tubewells			
Traditional design	30	60	18
Improved design	50	60	30

result from improved efficiency, particularly since the main operating cost (energy) varies according to the government's wishes. Therefore, the efficiencies to compare when formulating a groundwater strategy evaluation are those of traditional private units and improved public tubewells.

Improved public tubewells are far more efficient than private tubewells because they are designed (and constructed) by qualified technical staff. The submersible turbine pumps used on public tubewells have a higher wire-to-water efficiency than a centrifugal pump and motor used on a typical private well. Buried pipe distribution systems eliminate conveyance losses from the well point to the outlet close to a field. The irrigation efficiency of a public tubewell below the outlet is likely to be higher than that of a private well because the stream size delivered is greater (about 75 m^3/h, compared with about 30 m^3/h).

The main design flaw with private tubewells is that the electric motor or diesel engine is not matched to the pump size, and most wells have high suction lift and undersized suction and delivery pipes. Farmers can only afford simple equipment, which is relatively inefficient. Because there is no incentive for private well owners to run their units efficiently, maintenance is usually undertaken when the unit breaks down. For diesel private wells, present system efficiencies are, on average, much lower than those for electric private wells.[2] Throughout India, the annual excess expenditure on diesel fuel has been estimated at about Rs 1,500 million (US$110 million) on the 3.4 million units presently operating. Similar energy losses occur with electric private wells: once farmers have made the capital investment in a pump set, they are unlikely to make remedial capital investments to improve efficiency, even if they realize that they are incurring high operating costs. Even when existing private units require replacement, efficiency is unlikely to improve because replacement units are unlikely to be financed with institutional credit, which is currently the only way to teach or impose improved design standards. Furthermore, the average system efficiencies assumed in this paper for private wells are likely to be high, because in India it is common to use equipment beyond the recommended life span. A major educational effort will be required to improve present efficiencies.

Power Supply and Demand

Where a private well could be either electric- or diesel- powered, most farmers prefer electric units since operation and maintenance are easier and annual costs much lower. In addition, government policy has encouraged electrical connections to limit diesel fuel consumption, particularly given the low efficiency of diesel-powered units. Thus in Uttar Pradesh, both public and private wells compete for a limited power supply. Over the last decade, this competition had a disastrous effect on the performance of public tubewells, for which power availability must be near 16 hr/day at peak demand periods for the wells to operate as designed. Power supply in most of the state is now restricted to about 5 to 8 hours a day. This is sufficient for private tubewells to fully irrigate the holdings of most well owners, but it has limited public tubewells to serving at most about one-third of their designed command areas. Primarily because of the unplanned expansion of private tubewell connections, public tubewells serve only about 0.7 million ha, compared with the design potential of about 2.0 million ha. Uttar Pradesh plans to eliminate competition for poor supply between public and private wells through provision of dedicated feeder lines to public wells. The cost of dedicated power lines for all existing public wells would be about US$100 million (in 1986 dollars). All new public tubewells in the state will be connected to dedicated power lines, and theoretically power supply will be available to match the design requirements of new public or private groundwater development. Even if competition for power supply is eliminated, however, several important factors still require attention: the owner's incentive to efficiently use energy, the peak load requirement, and the cost of an electrical connection.

On average, private diesel well operators tend to underirrigate, compared with theoretical water requirements, to reduce fuel costs. This is generally not the practice with electric private wells, because power is charged in Uttar Pradesh at a flat rate per HP installed. There is therefore no incentive for owners of private electric wells to worry about energy costs or the efficiency of their installations. In fact, evidence indicates that farmers prefer larger units that can meet irrigation demand in a few hours of pumping a day and thus minimize the time needed to irrigate. In addition, because of limited power supply, farmers select equipment that enables them to complete their irrigation in a short period when power becomes available. Improved public tubewells, however, are planned to be effective and efficient power users, with a peak period demand that results in a least-cost design; this cannot be achieved with a limited and random power supply.

In the short term, Uttar Pradesh will be short of power. The inefficiencies of electric private wells and pump units will inevitably add to the statewide demand for energy and power transmission capacity. Unregulated expansion of private electric wells will further load the rural distribution network, often causing a voltage drop in the local 11-kV feeder lines. The drop in voltage tension applies an overload to motors already running, which can cause burnouts of motors, particularly for public tubewells but also for private wells. This impact on other power consumers should be carefully evaluated.

Capital and Operating Costs

Unlike surface irrigation projects, the operating cost of a groundwater irrigation source is substantial when compared with capital investment. For agricultural production, one must determine not only whether farmers can afford an irrigation source, but also whether they can afford to fully utilize that source. The annual cost per unit volume of water at the field is summarized in table 5.

For electric private wells, loans are advanced only to farmers who already have or are certain of obtaining a power connection. Generally, rural users are charged a nominal sum (Rs 600) for a power connection unless their location is considerably far from a rural transmission line. Thus, electric private wells have a subsidized capital cost of about Rs 18,400 per unit (excluding the cost of providing additional generation and power transmission lines). There is no financial support for diesel private wells except for subsidies to certain farmers if they use institutional credit. Annual costs of private wells assume efficient operation and maintenance (500 hours annual operation) and pump units lasting as long as the equipment manufacturers guarantee. The annual cost for an average private well owner may be higher, however, particularly for diesel wells, whose operating time may be far less than 500 hours annually.[3]

Table 5. Average Annual Cost per Unit Volume of Water at the Field, Uttar Pradesh (1985 Rs/m³)

	Traditional design		Improved design	
	Case		Case	
Costs[a]	A[b]	B[c]	A[b]	B[c]
Public tubewells	0.84	0.64	0.35	0.25
Private tubewells				
Electric	0.63	0.22	0.57	0.18
Diesel	0.45	0.40	0.42	0.36

a. Average annual costs for public tubewells are based on reasonably reliable data available from the state's irrigation department. For private wells, average annual costs are based on data collected for pump units, which are partly financed through bank credit. Such units account for less than 20 percent of private irrigation sources installed in Uttar Pradesh over the last decade and are generally the more efficient private wells because there is some control over design.
b. Full costs.
c. Net cost, allowing for government support of capital and/or operating costs.

The project-siting criteria, which limit the number of private irrigation sources in the potential command area of a public tubewell, have been formulated primarily to avoid substituting one irrigation investment for another. They will also limit local pressure to site project wells in areas where with many diesel-powered pump units. Diesel pump owners should use a cheap public irrigation source and perhaps retain their own well on standby. Should the flat rate tariff for power be changed to a metered rate, private well owners with electric units would probably respond in a way similar to owners with diesel-powered wells.

In sum, the annual financing cost, when subsidies are excluded, is higher for private electric tubewells compared with improved public tubewells. Thus, although private wells mobilize private savings, there may be no saving in investment costs (per unit area developed) to the state compared with public tubewell development. Furthermore, there is no advantage to the state in rapidly expanding the private groundwater sector when the support cost per unit volume of water delivered at the field is considered. Since the state's capacity to develop the public sector is limited, however, an overriding consideration should be to monitor and control private groundwater development so that the basic resources of land and groundwater within the state are developed as efficiently and as quickly as possible.

Conclusions

There are larger parts of the Gangetic Plain where the water and land resources are such that both public and private development of groundwater are possible. The improved public wells, demonstrated under the Uttar Pradesh public tubewell projects, have effectively dealt with the fundamental problems of existing public tubewells. For the first time, the public sector can provide a service as reliable as that of a private well. Thus, parallel private and public groundwater development has become a viable proposition.

The main factors that should be considered in planning mixed development of public and private wells are power load and energy requirements, investment evaluation, groundwater development priorities, and policy implications. The peak power load for electric-powered private wells would be much greater than that for a public tubewell commanding an equivalent area. Power transmission capacity already limits the number of private connections that can be provided in most of Uttar Pradesh. Generally, the progressive farmers who invested in private wells early on have taken the available power connections with present transmission capacity. Remaining farmers in most areas with groundwater potential have a limited (or often negligible) opportunity for an electric private well. Currently, energy consumption of private wells is about double that of improved public wells to provide the same irrigation service per unit area under comparable aquifer conditions.

Numerous project analyses have been undertaken to justify private and public groundwater development programs, but there is no comprehensive analysis that evaluates the total impact of such development or the consequences of allowing unregulated development of private wells. In particular, analysis of private groundwater development has not considered macroimplications such as the effect of private well density on power supply or the economic costs of private development when it has saturated a given area. Private (and public) wells are generally viewed as discrete developments in which the spatial relationship between wells is not considered, except in terms of groundwater availability. Furthermore, no evaluation has explicitly analyzed the subsidies or tariff support given to private groundwater development in the private sector in terms of investment and operating costs.

Private groundwater development has been a major success in Uttar Pradesh in terms of incremental agricultural production. It has utilized substantial private resources, but has also used institutional credit and heavily subsidized power connections and energy tariffs. In addition, once the investment is made, the farmer is motivated to achieve benefits quickly. Given the current scale of private groundwater development, however, the implications of a random exploitation of limited resources need to be systematically evaluated while there is time to adjust priorities and if necessary amend statewide planning strategies. For the government of Uttar Pradesh, these include a comprehensive, statewide study of public and private groundwater development that evaluates utilization of physical resources and energy and also considers financial implications to potential beneficiaries and fiscal implications to the state. Special attention should be given to cost subsidies and recovery of water charges and loans to farmers, as well as the rehabilitation/modernization strategy for existing public tubewells.

The government should invest in improved public tubewells (following strict siting criteria) at the maximum rate possible, given budgetary considerations and implementation capacity. The competition between the public and private sectors for energy should be eliminated by connecting all new public wells to dedicated feeder lines exclusively for public well use. Similar provisions should be made for existing public tubewells in the state as soon as possible.

Notes

1. The most comprehensive evaluation of private irrigation sources within Uttar Pradesh was undertaken as part of the Uttar Pradesh Agricultural Credit Project, under which about 100 units in 3 of the state's 56 districts were monitored and technically evaluated. In addition, since 1980, the Agricultural Refinance and Development Corporation has undertaken several technical studies of private tubewell technology.

2. This is according to data from pilot project studies for the quality control of agricultural pumpsets, Agricultural Refinance and Development Corporation, December 1980.

3. According to the Uttar Pradesh Agricultural Credit Project, utilization of a sample of 97 diesel-powered private wells averaged 183 hours annually; of these, only four operated for more than 500 hours a year.

DESIGN FOR WATER USER ASSOCIATIONS: ORGANIZATIONAL CHARACTERISTICS

Michael M. Cernea and Ruth Meinzen-Dick

This paper reviews how Bank-financed irrigation projects, in their design and approach, deal with the basic organizational features of water user associations (WUAs). It assesses whether these organizational characteristics are taken into account and what projects must do to strengthen or support them. The contextual and organizational characteristics examined include preexistence of water user organizations; new organizations; membership criteria; size of the base unit; federating base units; role specialization; accountability; and linkages with irrigation agencies. The paper also discusses the relative benefits of relying on organizations that already function among water users versus establishing new ones.

Although the research and conclusions presented in this paper derive from irrigation systems, many of the organizational principles apply to other resource management projects in which local resource users are expected to work with an outside government or private agency (Cernea 1989; Ostrom 1990).[1]

Investing or Disinvesting in Existing Organizations

WUA development under irrigation projects varies, depending on whether the project seeks to strengthen *existing* organizations or to help create *new* ones. Three types of situations have been encountered: those in which projects (1) work with existing irrigation associations, (2) build upon other local organizations to which water-related functions are added, or (3) create new WUAs.

The present review covers 16 years of Bank lending for irrigation, from FY1975 to FY1990. Table 1 indicates that nine appraisal reports from 1975, sixteen from 1984-86, and five from 1990 (representing 39, 35, and 55 percent of total projects, respectively) mentioned the preexistence of WUAs in the project areas and thus had, in theory, the opportunity to build on established organizations. Using preproject existing WUAs, however, should not be an automatic step. The adequacy and capacity of the area's existing traditional organizations need to be assessed before deciding whether to rely on them, whether they are in need of readaptation or strengthening, or whether to encourage the establishment of new WUAs.

Sociologists and anthropologists generally tend to recommend that designers of new projects build upon existing organizations, provided that equity goals are not seriously compromised by maintaining the traditional arrangement (Uphoff 1986). Indeed, where water user associations are already functioning, they can be expected to have legitimacy and a certain level of expertise in irrigation system management. Nevertheless, seven of the nine projects approved in 1975 for areas in which WUAs predated the project did not include them in the new programs (one of these seven

---

Michael M. Cernea is senior adviser, sociology and social policy, Environment Department, World Bank. Ruth Meinzen-Dick is a research fellow, International Food Policy Research Institute, Washington, D.C. This paper is a chapter from a forthcoming study, ***Organizational Capacity for Irrigation: Water User Associations in World Bank Projects***, which examines the Bank's lending for irrigation over a 16-year period (FY1975-90) and its experience with water user groups.

Table 1. Building upon Preexisting WUAs

	FY75	FY84	FY85	FY86	Total FY84-86	FY90
Total projects	23	13	18	14	45	9
SARs reporting existing WUAs	9	3	8	5	16	5
As % of total cases	39	23	44	36	35	55
If WUAs exist, SARs building on WUAs	2	3	5	5	13	4
Building new WUAs	1	0	0	0	0	3
No plans for WUAs	6	0	3	0	3	2

projects planned the establishment of new WUAs, and six staff appraisal reports [SARs] made no provision for involving WUAs in the project effort).

Greater recognition of the potential value of preexisting WUAs is apparent in 1984-86 projects, where only three of sixteen projects with preexisting WUAs made no provision for their inclusion. In 1987, all four projects with preexisting WUAs reincluded them, and in 1990 four out of five SARs did so.

If there are no valid reasons to avoid existing user organizations, then neglecting them—either by assigning them no role in the new development or by bypassing them to create new associations—amounts to *disinvestment* in valuable institutions.[2] Given the time, expense, and risks involved in establishing new local organizations, failure to build upon existing WUAs where feasible is a self-defeating weakness in project resource allocation, equal to losing available organizational capacity and "solidified" human capital. In past years, unfortunately, many development projects have bypassed or even helped disrupt such long-standing organizations (Coward 1991). Such neglect has been even more evident in the practice of domestic water agencies in various developing countries and has been resisted by Bank specialists.

Disinvestment in existing WUAs may sometimes backfire by causing active opposition to the project from local WUAs. In the 1975 Philippines Tarlac Irrigation Project, for example, the existing communal irrigation systems had already irrigated over 2,600 ha within the area to be covered by the new project. The project appraisal report made no provision for involving these existing communal irrigators' societies in the project. Several years later, the project completion report (PCR) found that because of the neglect of their societies, farmers within the communal irrigation systems had refused to join the irrigation project. Thus, this obvious disinvestment in, and rejection of, existing WUAs led to a shortfall of almost 10 percent of the area the Tarlac project intended to cover and to a loss of potential benefits. The lesson learned from the PCR, and from the country agency from this and similar cases, is:[3]

> . . . to make fuller use of Irrigator Associations and [to] . . . work on a program which would develop the capability of water management technicians to interface successfully with Irrigator Associations (PCR, para 17).

The principle of working with existing WUAs may seem obvious; its implementation, however, is not necessarily easy. First, traditional WUAs may often be informal groupings, without legal status or official recognition. A second problem arises if existing WUAs are not functioning well (e.g., if they are inactive, conflict-ridden, or dominated by a few wealthy landholders). In two projects in West Africa (Niger Irrigation and Senegal River Polders projects), the traditional forms of social organizations were deemed at appraisal to be inappropriate: they were dominated by chieftains using them for personal gains and were unsuitable for efficient agricultural production.

Where there have been no preexisting irrigation associations, Bank planners have sometimes looked for other active local organizations able to take on irrigation functions. Such examples have occurred in Bank projects in Mauritania and Turkey. Bank projects have also relied on, for example, the *ejido* (a local cooperative association) in Mexico (Chiapas); *panchayat* (local government council) for small-scale systems in India and Nepal; multipurpose cooperatives in Bangladesh; and tribal-based groupings in the Republic of Yemen.

This approach may require some assistance or training for members in water and systems management, but it bypasses many of the delays and ground-breaking problems of establishing new organizations with local legitimacy. The major precaution in such cases is to ensure that the organization's capacity is not overloaded. Experience has shown that consultations with leaders and members should ascertain their agreement on the proposed tasks under the new project and assess whether the leaders will have the time, interest, and resources to devote to irrigation activities.

Investing in New Organizations

Where no appropriate farmer organizations can be identified "on the ground," irrigation projects must initiate the creation of WUAs. This occurs primarily, though not exclusively, in new irrigation systems; often, WUAs are also needed in previously irrigated areas where users have not organized.

The last year of the period under review, FY1990, perhaps best illustrates the various ways in which Bank development investments trigger the establishment of new WUAs in a hands-on fashion, with explicit provisions for organization building. The Brazil Irrigation I Project (SAR January 1990) will create, in new settlements, six irrigation districts described as private associations under Brazilian law, encompassing all beneficiary farmers and thus supporting the simultaneous formation of both administrative structures and farmers' groups on the new lands. The Bangladesh Water Systems (BWDB) Rehabilitation Project (February 1990) will help establish a similar kind of grouping called inlet committees. Additional irrigation inlets would be constructed only after inlet committees have been formed and beneficiaries have agreed to make land available and to undertake all earthworks for the inlets and field canals. This project will promote the creation of associations of landless laborers, helping them enter the water market and purchase (through NGOs) low-level pumps and minor irrigation equipment. Comparable features are contained in projects approved in 1990 in Somalia (Farahaane Irrigation Rehabilitation Project), Mauritania (Gorgol Irrigation Rehabilitation Project), China (Hebei Agricultural Development Project), and Nepal (Bhairawa Lumbini Groundwater Irrigation III Project).

The projects under which substantial investments in grassroots organizations have been made and in which the formation of new WUAs has occurred on the largest scale are the two On-Farm Water Management projects (OFWM) in Pakistan: OFWM Stage I, begun in FY1981, and OFWM Stage II, begun in 1985. These projects will be continued under Stage III, approved in FY 1991. The establishment of a water user association for each individual *chak* (watercourse) covered by the project was made a condition of starting civil works on the watercourse. Because users have a strong interest in getting the canals lined, the response was prompt and on a mass scale. Over 15,000 WUAs were organized in Pakistan during the 1980s, a performance unequaled by any other projects (for details, see Byrnes, forthcoming; and Cernea and Meinzen-Dick, forthcoming). This, of course, required important investments in organization building. The investments paid off to a great extent during the construction works themselves, as the new WUAs mobilized considerable labor through their membership and thus assumed part of the capital construction costs.[4]

Experience with the OFWM projects, however, has also revealed unexpected difficulties and setbacks for WUAs: during civil works, WUA members are enthusiastic, and WUAs function at their peak. Subsequently, however, many WUAs become inactive and fail to maintain the installed works, although this causes members to lose some of the benefits for which they worked so hard. This may be a consequence of uneven roles assigned to WUAs, particularly their insufficient involvement in decisions about water allocation and distribution.[5]

Generally, the evidence from many projects shows that WUAs can be built either (a) on the organizational foundation offered by preexisting forms of farmer organizations, or (b) as new forms of association, created by technologically induced institutional needs. In many Bank-assisted projects, investing in farmer organizations has been coordinated with investment in the technical and physical infrastructure. Project designs often specify that tertiary system construction should occur only where WUAs have been established. This allows farmers to participate constructively in the design and development of the system. However, this requires considerable advance preparation because community organizers need lead time to help WUAs form and develop if they are to usefully contribute to the construction or rehabilitation project.

To properly design and create such organizations, sound social engineering is as necessary in these projects as good technical engineering. The use of institutional organizers is an effective tool for developing new WUAs, as demonstrated by programs in the Philippines (de los Reyes and Jopillo 1989; Illo 1989) and Sri Lanka (Uphoff 1986). With adequate guidance, these agents act as catalysts in bringing farmers together for WUAs, without imposing a particular structure or type of leadership on the groups. Organizers have also been useful in strengthening existing farmers' organizations in projects working with community irrigation systems (Manor et al. 1990).

Membership Recruitment

There are four alternative principles that may govern how water users arrange themselves into organized groups:

1. *hydrological*—field neighbors sharing water from a common facility, such as a turnout or watercourse;

2. *residential*—village neighbors, such as those from a given settlement;

3. *social unit*—membership in user groups based on primary ties, such as kinship;

4. *ownership*—membership based on joint investment.

The hydrological principle has been predominant in Bank projects with WUAs. Table 2 indicates that over 70 percent of all SARs that specified the type of membership in WUAs mentioned the users grouped around a certain type of irrigation facility. There is also a visible increase in the prevalence of this principle from 1975 to 1984-86 and to 1990. Only six cases specified residential neighborhood, and three cases were organizations based on other membership criteria, including kinship-based tribes (e.g., the Wadi Al Jawf Project in the Republic of Yemen) and investment-based cooperatives (e.g., the Bangladesh Barisal Irrigation Project).

When WUAs are composed of adjacent field cultivators, the users have a common interest in the operation and maintenance of that section of the irrigation system. The benefits of collective

Table 2. Membership in Project-related WUAs

	FY75	FY84-86	FY90	Total
Total no. of projects	23	45	9	77
Projects with WUAs	11	35	7	53
Projects specifying membership	7	22	7	36
Membership defined by				
Field neighborhood	4	16	6	26
Residential neighborhood	1	5	1	7
Other	2	1	0	3

action and the settlement of local disputes over water can thus be largely contained within the group. Consequently, this constructive principle has been recommended both in the sociological literature on WUAs (Coward 1980) and in most Bank-assisted projects.

Membership based on residential neighborhood or kinship is sometimes appropriate if forms of multipurpose social organization (e.g., tribes, local government, or functional cooperatives) also become involved in irrigation management. These arrangements do lack the directness and focus of a water-specialized organization and often may not include all the irrigators along a watercourse, thus having a somewhat limited mobilization capacity. But there are tradeoffs. Multipurpose organizations may have the advantage of preexisting on the ground and of established authority lines, roles, and rules. They may also link water management to other agricultural activities, marketing, tree planting, etc., or may provide a voice in system management to members of the community who depend on the irrigation system in other ways, such as for domestic water supply or employment.

The principle of ownership can be the basis for membership or can reinforce ties among WUAs. Joint investment and property rights are recognized as a powerful cohesive force (Coward 1991). This ownership can be established either at the outset of irrigation development (e.g., pump groups under a tubewell) or by transferring ownership of existing facilities to WUAs, as in the turnover program for small-scale irrigation systems in Indonesia (Vermillion and Vermillion 1990). The relative merits of the possible approaches, or of a combination of them, should be weighed for each irrigation project faced with developing a strategy for organization building.

Size of the Base Units

Size is an essential structural characteristic of any organization, and choices have to be made at appraisal among various options for the envisaged WUAs. Size refers to two characteristics: number of members in a WUA and command area. How large the lowest-level water user organization should be will depend on topography (e.g., the layout of the irrigation system); technology (the conveyance technology used); and socioeconomic variables (e.g., the average farm size in the system). The size of base units specified in the SARs reviewed ranged from 8 ha under the Gujarat Medium Irrigation II Project in India to 1,000 ha under the Madagascar Irrigation Rehabilitation Project. The median size was 40 ha, which is the typical upper limit for base-level WUAs cited by Uphoff (1986: 69-74). For some Latin American countries, Plusquellec has recently reported much larger sizes, up to several thousand hectares, because the average family farm size is in the tens (or sometimes hundreds) of hectares.

If base WUAs are too large, it is difficult for farmers to meet because their numbers are too great. Large size compounds the organizational and managerial tasks, sometimes beyond the capacity of local leaders. The Bangladesh Barisal Irrigation PCR noted that in the interests of standardization, two-cfs pumps were procured rather than one-cfs pumps as intended. However, because the potential command area of two-cfs pumps was approximately twice that of the smaller pumps, it was more difficult to organize all the farmers who were to receive water.

A similar problem in which the technology did not provide for workable base units was dealt with in the command area of the Nepal Narayani Irrigation Project by extending the distribution network down to the 50-ha level because the existing system had an "administratively impossible farmer grouping of 900 units" (SAR). The Tunisia Irrigation Management Improvement Project also planned to reduce the size of WUAs from 300 ha to the size of small pumping schemes or the tertiary units in larger schemes.

Other adjustments of group size may be appropriate to make the boundaries of WUAs coterminous with other existing local organizations. The Morocco Souss Groundwater Project began with units of 16 ha served by a single hydrant, but allowed for these groups to expand to 50 farmers to coincide with the service cooperatives.

Based on his review of the literature on collective action, Addison (1986: 46) concludes that the costs of maintaining an organization, particularly in terms of conflict resolution and information management, will increase with the size of an organization. There are no expected economies of scale in this respect. Groups should be large enough, however, to accomplish the designated tasks by collective action. The median size of approximately 40 ha found in the examination of Bank-sponsored projects appears to offer a reasonable compromise between these two factors, as also suggested by Uphoff et al. (1985: 12; see also Coward 1980: 206-8). Project planners may recommend a target size or range for base-level WUAs, but the farmers themselves are best able to determine the exact boundaries of actual units. Therefore, flexibility in the actual size of each unit must be allowed.

WUA Federations

The next step in the self-organization of water users, beyond the watercourse level, is to create associations of WUAs on a territorial basis. Federations are organizational structures in which base-level irrigation groups are members of a higher-level association, itself encompassing a larger part of the same irrigation system. Again, Bank projects may either include such federations—when they already exist—in their strategy, or be instrumental in promoting their creation, when it appears ripe and necessary.

Is aggregate organization of WUAs desirable? Although small groups of irrigators who share water from a common source are optimal for carrying out many ongoing activities at the level of their irrigation system section, other tasks arise that require a higher level of organization. Examples include water acquisition or allocation decisions, maintenance of facilities that serve several groups, or resolution of water conflicts among base-level WUAs. In many systems these tasks are performed exclusively by government agencies. A federated organizational structure allows WUAs to become involved in many of these activities (Freeman 1990). Ostrom (1990: 101-2) finds such a "nested enterprise" to be characteristic of enduring, complex institutions in dealing with common property rights because it allows them to deal with the different problems arising at different levels (e.g., tertiary distributaries and main canals).

The present review found that federated WUAs are still uncommon among Bank-assisted projects. Some increase in the use of this organizational pattern is shown in table 3. In 1975 only two projects, or 18 percent of those with WUAs, specified such an arrangement as already existing or to be developed during the course of the project. During 1984-86, 12 projects, or 34 percent of those with WUAs, had some form of federation. For example, in the Sri Lankan Major Irrigation Rehabilitation Project, field channel committees send representatives to distributary channel committees, which in turn are represented on a project management committee.

WUA federations offer advantages to both agencies and farmers. Federated WUAs enable farmers to exercise their rights and responsibilities in system management and conflict resolution to a greater degree. Representatives are clearly designated, and linkages between agency staff and farmers can be more easily established at several levels. The government agency can rely firmly on an apex organization to devolve some of its excessive responsibilities, and farmers receive a more powerful voice in negotiating with the state's service agencies. In large-scale systems in the Philippines, Bellekens reports: "[S]ome of the [irrigation associations] federated *among themselves* and formed apex organizations to improve their status with the NIA management and obtain contracts for maintenance of laterals" (1986: 20). Organizations that include representatives of each lower-level unit (e.g., distributary or lateral channel councils, in which every field channel is represented) may even be able to address some head-tail distribution problems within the organization, as intended in the Maharashtra Composite Irrigation III Project.

One reason for the low frequency of WUA federations is that federating WUAs entails additional transaction costs. Such costs limit the ability to establish multilevel farmer organizations. Furthermore, the empowerment of farmers through such bodies can present a perceived or actual threat to agencies' control of the main system. The establishment of user federations is not actively pursued by state agencies. For farmers, the costs in terms of time and other resources required to assume higher-level organizational and irrigation management activities are significant. The extent to which higher-level WUAs will become active will depend on the balance of advantages and costs, as well as the level of recognition by users that stronger organization is in their own interest.

A realistic way of building a federated WUA structure within the project framework is to plan for organizational development phases, beginning with base-level groups. Starting with grand federation plans when there are not yet stable watercourse-level WUAs is premature. New levels of organization should be added only after farmers and agencies have gained some experience in working together, with a clear commitment to building higher orders of WUAs. Furthermore, establishing mixed system management committees (essentially similar to those existing in Chinese irrigation systems) that would include both agency representatives and representatives of the irrigators' apex organizations will provide powerful organizational tools for improving system performance.

Role Specialization

The activities of WUAs may be performed either by the entire membership or by a set of leaders and specialists. Some tasks (e.g., clearing channels) are best done through an entire group effort; others (e.g., operating a pump) are more efficiently carried out by a selected and specialized individual. Technology and local custom are major factors in selecting the mode of operation. Where role differentiation occurs (president, treasurer, water master, etc.), the specific definition of needed leadership roles depends on the size of organizations and the range of functions WUAs are to perform.

For structural purposes, two broad categories of local leaders and roles can be distinguished: organizational and technical. Organizational leaders are primarily concerned with tasks such as decisionmaking, communication, conflict management, and resource mobilization. Their ranks may include hereditary chieftains, traditional village elders, or elected officers and representatives chosen by farmers. This leadership category provides coordination within local organizations and contact with outside entities, including government agencies and other farmer groups.

Table 3. Provisions for WUA Federations in Project Appraisal Reports

	FY75	FY84-86	FY90	Total
Total no. of projects	23	45	9	77
Projects with WUAs	11	35	7	53
Cases specifying federations	2	12	3	17
As % of projects with WUAs	18	34	43	32

Those in technical roles within the structure of WUAs are directly involved in the manipulation of the physical facilities or water in an irrigation system. These people can be either farmers who are responsible for irrigation tasks or employees of the WUAs. Examples of such roles include pump operators and common irrigators who open and close the water gates to each field, such as the traditional *sarraf* (an elected representative with authority to manage water) in the Wadi Al Jawf Project.

Organizational and technical roles may sometimes overlap, with the same individuals fulfilling both. The technical leadership discussed here includes only those who are chosen and/or employed by the farmer organizations (not the technical roles of agency staff).

Among the project appraisal reports examined, seven from 1975 and 16 from 1984-86 specified some type of leadership role in WUAs' structures. Table 4 shows the breakdown of these cases across years and between organizational and technical roles. Somewhat surprisingly, because Bank appraisal reports are written primarily by staff who are technical specialists, organizational roles are discussed in appraisal reports more than twice as often as technical roles during each period.[6,7] Noticeably absent is any mention of the basic roles to be performed in over half of the projects that do involve WUAs (nearly 70 percent of all projects). This reflects insufficient consideration of these structural issues in appraisal reports. Without some definition of the roles of WUA leaders and representatives, it is impossible to plan for precise activities and operational linkages between farmer organizations and agency staff. Project planners should therefore attempt to explicitly recognize leadership role needs for inclusion in the overall project design.

Accountability

Structured accountability of WUAs to their members is the most crucial principle of organizational structure for the long-term viability of the organizations and should underlie all efforts toward WUA development in projects. This principle has two dimensions: accountability to water users rather than to the agency, and accountability to all members, not just a subset such as large farmers or those in one part of the system. If accountability is not ensured, farmers cannot be expected to participate in the organizations through provision of their time or other resources, and WUAs will be weak, without active support from their members.

Ensuring the accountability of WUAs to farmers begins in project conceptualization of the role of local organizations. WUAs must be viewed as belonging to the water users, not as unpaid extensions of the irrigation agency. They are to be a forum for farmer participation, not a means of extracting resources from farmers or forcing them to perform certain tasks. The attitude expressed in one appraisal report that "[t]he main purpose of WUAs is to organize farmers' contributions of labor and cash for OFWM (on-farm water management) on a watercourse basis" (Pakistan Left Bank Outfall Drain Stage I Project SAR 5.06) should be avoided.

Table 4. WUA Leadership Roles Defined in Project Appraisal Reports

	FY75	FY84-86	FY90	Total
Total no. of projects	23	45	9	77
Projects with WUAs	11	35	7	53
Projects with leadership roles specified	7	16	3	26
As % of projects with WUAs	64	46	0	50
Organizational leaders mentioned	5	15	2	22
Technical leaders mentioned	2	7	1	10

Note: Six projects in 1984-86 specified both organizational and technical leadership roles.

Accountability to members should also be built into the organizational framework of WUAs. Definitions of membership and leadership are primary mechanisms for establishing this accountability (Coward 1980: 205-10). Membership definitions affect whether all farmers served by a facility are included in the organizations. Leaders should be selected by the farmers, not appointed by the agency. One of the clearest statements of this type of accountability is found in the appraisal report for the West Bengal Minor Irrigation Project in India:

> Beneficiaries will have direct access to staff responsible for the various activities and, in particular, the (pump) operator can be checked by both his direct supervisor (the Panchayat Committee) and the farmers he serves (SAR 5.14).

"Progressive farmers" or others chosen by officials should not be made heads of the organizations. Neither should the organizations be dominated by officials. For example, the Maharashtra Composite Irrigation III Project in India included two government employees—a canal inspector and a village extension worker—as members of even the lowest-level outlet committees for each 24-ha unit. The attendance of these government personnel at meetings of the base-level WUAs both strains their time and limits farmers' sense that the WUAs are their own, not an arm of the government.

Where the required leadership skills are not available locally, projects should include training components to strengthen them. The Niger Irrigation Rehabilitation Project provided perimeter directors on an interim basis, but ensured their accountability to the WUAs by making it clear that "[a]fter project completion, each cooperative would decide whether or not to hire its own manager, either the former perimeter director or someone else of the cooperative's choice" (SAR 3.15). Therefore, in the interest of job security, it benefited the directors to meet the interests of the farmers.

The specific mechanisms for selecting leaders can be left to the farmers; they may use formal elections, selection by consensus, or traditional hereditary roles. The decision should be made locally, and leaders should be in touch with other members to allow informal social sanctions to reinforce accountability. Projects should explicitly avoid interference from the agency or other project authorities in the management of WUAs. Decisions on the activities of the associations, and especially how they are to proceed, should be left to the farmers to the greatest extent possible. It is not sufficient to try to create a "sense of local ownership" in WUAs; the organizations must belong to the water users in fact. Only in this manner will strong farmer support for irrigation associations emerge and be sustained. Evidence from Bank-assisted projects confirms Ostrom's findings that "if external government officials presume that only they have the authority to set rules, then it will be very difficult for local appropriators to sustain a rule-governed CPR [common property resource] over the long run" (1990: 101).

In some instances, independent WUAs will not produce the same results the agency would desire, or will not produce results at the desired time. Strong farmer organizations may even be perceived as a threat to agencies and to their staff's monopoly over system operation. This was noted as a problem in the Colombia Irrigation Rehabilitation II Project, whose SAR stated that "at present most water users' associations function more as a body for voicing criticism or requests to HIMAT's district management, without showing much interest in the actual management of their district" (annex 1.15).

Unfortunately, farmer involvement is still viewed by some irrigation agencies as interference in the system, without recognizing potential contributions or the validity of farmer concerns. Encouraging more constructive interaction between agencies and WUAs may require bureaucratic reorientation, as was carried out in the National Irrigation Administration in the Philippines (Korten and Siy 1989). Moreover, WUAs cannot be expected to act uniformly throughout the entire project. For this reason the Niger Irrigation Rehabilitation Project obtained assurances that the project agency would not begin rehabilitation work on perimeters until the "cooperative has approved internal statutes consistent with the model satisfactory to IDA" (SAR 8.01d). Such provisions make the WUAs accountable to the agency and IDA, however, and not strictly to their membership; this undermines their adaptability to local conditions or farmers' needs. Some internal statutes may be necessary for the provision of credit to farmers, but the imposition of rules for other irrigation activities should be avoided. Although allowing WUAs to make decisions, with some resulting lack of uniformity throughout the project, is generally perceived as problematic for agency staff, it is also one of the strengths of involving WUAs: irrigation management can be tailored to local conditions far more effectively than by central agencies alone.

Conclusion

Two important conclusions emerge from this analysis of organizational structure in WUAs. First, project preparation and appraisals should pay greater attention to the structural characteristics of WUAs. Increased efforts should be made to identify existing organizations and learn how they work. General parameters of organization such as membership recruitment, size of base units and federations, and type of leadership roles (particularly when agencies need to interact with local leaders or representatives) should be carefully considered. Second, to ensure accountability of WUAs to farmers and to allow organizations to be tailored to local conditions, flexibility must be built into the project framework and agency dealings with WUAs. The process of tailoring to local conditions should begin by giving farmers a voice in shaping the organizations.

Notes

1. For an examination of the results of local participation in various USAID-assisted projects, see Finsterbush and Van Wicklin 1989.

2. Another telling case was the Rural Development Project in Mindoro Province, the Philippines, for which the SAR required a comprehensive plan for improving the existing, traditional WUAs in Mindoro, which managed and owned the communal irrigation systems.

3. This analysis is offered by Hervé Plusquellec, irrigation engineering adviser, World Bank. WUAs' decreased activity and organizational viability after completion of canal lining have puzzled many specialists and have been explored in several analyses. Little consensus, however, has been

reached, and the SAR for the 1991 Stage III project, noting that this situation is "difficult to understand," incorporates provisions aimed at studying its causes and correcting prior weaknesses.

4. For a well-documented description of the benefits and costs of WUA development in the Philippines, see Bagadion and Korten 1991.

5. Advanced WUAs in Colombia even employ lawyers to represent them (Laeyendecker, personal communication), while some indigenous *zanjeras* in the Philippines include a cook as part of the WUA staff (Ostrom 1990).

6. Treasurers or accountants, such as those specified in the Niger Irrigation Rehabilitation Project, could be considered technical personnel because of their specialized skills. In this analysis, however, they are considered in the capacity of functional leadership because they deal with organizational management, especially resource mobilization, rather then with water or the physical facilities.

7. The frequency with which organizational roles are cited may be the result of an automatic assumption that any organization requires a president, vice president, secretary, and treasurer.

References

Addison, Douglas M. 1986. "Membership Size and the Success of Local Development Organization." Master's thesis, University of Maryland.

Bagadion, Benjamin U., and France F. Korten. 1991. "Developing Irrigators' Organizations: A Learning Process Approach." In Michael M. Cernea, ed., *Putting People First: Sociological Variables in Rural Development*. 2d ed., rev. and enlarged. New York: Oxford University Press.

Bellekens, Yves. 1986. *An Impact Evaluation Study on Water Usage and Its Contribution to Agricultural Production in Irrigation Projects in the Philippines*. Manila: Asian Development Bank, Post-Evaluation Office.

Cernea, Michael M. 1989. *User Groups as Producers in Participatory Afforestation Strategies*. World Bank Discussion Paper 70. Washington, D.C.

Cernea, Michael M., and Ruth Meinzen-Dick. Forthcoming. *Organizational Capacity for Irrigation: Water User Associations in World Bank Projects*.

Coward, E. Walter. 1980. "Management Themes in Community Irrigation Systems." In E. Walter Coward, Jr., ed., *Irrigation and Agricultural Development in Asia: Perspectives from the Social Sciences*. Ithaca, N.Y.: Cornell University Press.

____. 1991. "Planning Technical and Social Change in Irrigated Areas." In Michael M. Cernea, ed., *Putting People First: Sociological Variables in Rural Development*. 2d ed., rev. and enlarged. New York: Oxford University Press.

de los Reyes, Romana P., and Sylvia Ma. G. Jopillo. 1989. "The Impact of Participation: An Evaluation of the NIA's Communal Irrigation Program. In Frances F. Korten and Robert Y. Siy, Jr., eds., *Transforming a Bureaucracy: The Experience of the Philippine National Irrigation Administration*. Manila: Ateneo de Manila University Press.

Finsterbush, Kurt, and Warren A. Van Wicklin, III. 1989. "Beneficiary Participation in Development Projects: Empirical Tests of Popular Theories." *Economic Development and Cultural Change* 39(3): 573-93.

Freeman, David M. 1990. "Designing Local Irrigation Organizations for Linking Water Demand with Supply." In R. K. Sampath and Robert A. Young, eds., *Social, Economic and Institutional Issues in Third World Irrigation Management*. Boulder, Colo.: Westview Press.

Illo, Jeanne Frances I. 1989. "Farmers, Engineers and Organizers: The Taisan Project." In Frances F. Korten and Robert Y. Siy, Jr., eds., *Transforming a Bureaucracy: The Experience of the Philippine National irrigation Administration*. Manila: Ateneo de Manila University Press.

Korten, Frances F., and Robert Y. Siy, Jr., eds. 1989. *Transforming a Bureaucracy: The Experience of the Philippine National Irrigation Administration*. Manila: Ateneo de Manila University Press.

Manor, Shaul, Sanguan Patamatamkul, and Manuel Olin, eds. 1990. *Role of Social Organizers in Assisting Farmer-Managed Irrigation Systems*. Colombo, Sri Lanka: International Irrigation Management Institute.

Ostrom, Elinor. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge, U.K.: Cambridge University Press.

Oya, Kenji, and Seji Aoyama. 1991. *Water Use Conflict Under Increasing Water Scarcity: A Case of the Yahagi River Basin, Central Japan*. Nagoya, Japan: UNCRD.

Tiffen, Mary. 1986. *Improving the Socio-Economic and Institutional Content of Irrigation Feasibility Studies*. Vol. 1. Research Scheme R4006. London: Overseas Development Administration.

Uphoff, Norman. 1986. *Getting the Process Right: Improving International Irrigation Management with Farmer Participations*. Boulder, Colo.: Westview Press.

____. 1991. "Fitting Projects to People." In Michael M. Cernea, ed., *Putting People First: Sociological Variables in Rural Development*. 2d ed., rev. and enlarged. New York: Oxford University Press.

Uphoff, Norman, Ruth Meinzen-Dick, and Nancy St. Julien. 1985. *Improving Policies and Programs for Farmer Organization and Participation in Irrigation Water Management*. Water Management Synthesis Professional Paper 1. Ithaca, N.Y.: Cornell University.

Vermillion, Helmi, and D. Vermillion. 1990. "Using Irrigation Agency Staff as Institutional Organizers: The Small Systems Turnover Program in Indonesia." In Shaul Manor, Sanguan Patamatamkul, and Manuel Olin, eds., *Role of Social Organizers in Assisting Farmer-Managed Irrigation Systems*. Colombo, Sri Lanka: International Irrigation Management Institute.

COMPREHENSIVE WATER RESOURCES MANAGEMENT

Guy Le Moigne

Water resources development has always been essential to human activities. Civilizations have been built along major rivers such as the Nile, and wars have been fought to preserve or obtain water rights. If countries now consider waging war to secure oil supplies, in the near future disputes over allocation of water resources could also be the catalyst for armed conflicts. For example, Israel and Jordan; Egypt and Ethiopia; Syria, Iraq, and Turkey; and India and Bangladesh are a few of the neighboring countries at odds over common water resources.

Water is a renewable natural resource serving several economic sectors. One of its unique features is that for some of its users, such as human consumption and irrigation, there are only limited substitution possibilities. But despite the water sector's obvious importance to economic welfare and growth, inadequate policies, weak regulatory and administrative systems, and insufficient political resolve and public awareness of inefficiencies prevail in many countries.

Three factors will play a key role in future development and management of water resources: rapid population growth, environmental degradation, and the large volume of investment funds needed for developing water resources. The combination of these three factors will lead to an era of increasing competition for water of suitable quality at affordable cost and greater complexity in water planning and management to achieve an optimal balance between the development of new resources and the reallocation of water resources.

Population

The foremost factor is the expected population growth in developing countries. Under the most optimistic scenario, which assumes successful population programs, world population will grow from the current 5 billion to 6.2 billion in the year 2000 and to at least 8 billion by the year 2025. This growth will increase the demand for food supplies and thus the demand for irrigated agricultural production necessary to produce sufficient food worldwide. This demand will in turn create serious water management challenges in countries where additional supplies of arable land and water at reasonable costs are almost exhausted. These problems are especially serious in countries where waterlogging and salinity are causing a reduction in the irrigated area. Also, the growth of urban centers sometimes requires that irrigation water be reallocated to meet urban water supply and sanitation needs, as in Cairo and Algiers.

The projected population growth will occur primarily in developing countries, with about 90 percent of growth in urban areas, where potable and industrial water demand will be concentrated. For example, by the year 2000, 17 of the world's 21 cities with over 10 million inhabitants will be in developing countries, compared with 1960, when Shanghai was the only city in the developing world of that size. This rapidly growing urban population will need a large volume of water of acceptable quality for domestic and industrial use. Existing water supply systems are often not adequate. Waterborne diseases, the main cause of death for children in developing countries, are still

Guy Le Moigne is senior adviser, Agriculture and Rural Development Department, World Bank. This address was presented in 1990.

widespread, even in urban areas. Diarrheal disease caused by unsafe water is estimated to be the main cause of death for 4 million children annually. The uncontrolled pollution of local water bodies caused by the wastewater of the growing urban population and industries will often prevent their use by downstream water users. For example, the discharge of effluents from the 1,300 industrial plants near Alexandria, Egypt, has polluted the groundwater that supplied the area's domestic needs, making it unsuitable for drinking purposes. Runoff from agricultural areas may contain high levels of fertilizers and pesticides and sometimes may also carry toxic materials, thereby causing serious pollution that may render water unavailable for other users, increasing the health risks of the population in general. This growing demand for water supply of acceptable quality at affordable cost to meet expected urban and industrial needs creates another major challenge for water resources management.

Environment

The enhanced global awareness of environmental stress and of the need to better manage environmental quality has important implications for future water management. First, there are new pressures to maintain natural habitats and wildlife, both to preserve genetic diversity and to provide areas for recreation and tourism development. Many of these natural areas are in locations with potential water development projects. New water projects are already often controversial and in the future may become politically infeasible in many countries. Second, in some countries rising incomes will lead to increased demands for improved water quality for recreation, fisheries, and other "in-stream" water uses. There will thus be increased pressure to maintain in-stream flows and groundwater supplies to enhance water quality and to reduce the discharge of industrial, municipal, and agricultural wastes into water bodies. Global warming increases the need for better planning and management of future water needs because in some places it may result in reduced or unreliable water supplies.

Investment

The third important factor is the widening gap between the financial resources needed for the investments in water resource development and the shrinking resources available for that purpose in many developing countries. In many countries, the funds needed for investments and operation and maintenance in the water sector alone represent up to 20 percent of public expenditures, and the need for investments is increasing with population growth. The backdrop for this situation is overall slow economic growth and sometimes declining real per capita income, particularly in poor African countries. The same countries, however, are paying large subsidies to water users, particularly in irrigation, which they can ill afford. Furthermore, the debt burden in some countries favors investments with quick and high rates of return and thus works against investments for water resources development with their long gestation periods. To deal with these problems, therefore, it will be necessary to reduce subsidies and increase efficiencies in the water sector. A comprehensive approach to water management can play an important role in this respect. Experience in some industrial countries, e.g., France, the U.K., and the United States, has shown that comprehensive water management that coalesces subregional water entities can, as a result of economies of scale, risk pooling, and planned reuse of water, lead to substantial reductions in investments and operation and maintenance costs.

The combination of the three factors briefly described above—rapid growth of populations and urban areas, degradation of the environment, and slow economic growth in many countries—will lead to an era of increasing competition for water and greater complexity in water planning and management, as well as to increasing competition for scarce funds. In many parts of the world, this era has already arrived. Large metropolitan centers are now searching for new water supplies. Some, such as Beijing, may have to transport water over long distances, whereas others must consider expensive pumping schemes, such as in Mexico City, which may have to pump water over a height of 2,000 m. Consequently, the cost of these additional supplies will often be much higher than those of current sources.

Most of the best dam sites around the world have already been used, and new water development projects will be increasingly expensive and possibly environmentally disruptive. For example, a recent review of Bank municipal water supply projects indicates that the cost of a cubic meter of water provided via "the next project" is often two to three times the cost of a cubic meter provided via "the current project." In areas around expanding urban and industrial activities, the higher value of water resulting from urban demand may often exceed the value of the marginal productivity of water in existing agricultural uses, thereby undermining the economic viability of the established customary and/or proprietary water rights of the irrigators. This will lead to increasing legal and institutional conflicts between existing users (e.g., irrigation) and emerging new users (e.g., urban/industrial activities).

Role of the Bank

Since its creation, the Bank has been a major actor in water resources development. In particular, it has worked closely with UN organizations in implementing the recommendations of the UN General Assembly, which proclaimed 1981-90 as the "Water Decade," with the fundamental goal of "safe water and sanitation for all." The goal has not been achieved, and despite major investment efforts in developing countries of about $10 billion a year, the UNDP estimates that over 1.2 billion people, or 31 percent of the population of its member countries, currently remain unserved by water supply and over 1.7 billion people, or 44 percent, have no sanitation facilities. Past efforts, however, have helped to draw attention to three important aspects of water resources management: political commitment, institutions with technical capacity and legal support, and involvement of communities and water user associations.

The July 1990 report of the Economic and Social Council of the UN dealing with the achievements of the water decade provides detailed recommendations. The report stresses that, because of the many interactions and nonmarket forces that shape and affect the water sector, investment planning, pricing, and management should be carried out within a comprehensive water resources planning framework because this facilitates analysis of the entire range of water policy options over a long period. The report also emphasizes the need for long-term sectoral planning, rather than the restriction of plans to an arbitrary 10-year period. This is particularly significant because major works associated with water resources development take several years to plan, design, finance, and construct; their costs and benefits to people and their environment should be estimated over a period of at least 20 years, and their overall impact should be evaluated over a period of 50 years. The report also recommends the establishment of effective linkages among various ministries and governmental organizations dealing with water resources, as well as overall economic planning and development. The report notes that present water sector constraints include funding limitations and poor cost recovery, frequently related to weak institutional systems and failure to meet the users' perceived needs.

A Comprehensive Approach

Although water resources development has always played a major role in Bank operations, the Bank has rarely taken a comprehensive approach to water resources lending. Bank lending for water development projects is characterized by the traditional division of the water sector into irrigation and drainage, water supply and sanitation, and hydropower generation. This fragmentation of Bank activities in the water sector generally mirrors the institutional structure in most countries, where specialized agencies are responsible for the various subsectors. Several Bank operational directives, manual statements, and policy notes address specific issues related to water resources development, including international water rights, dam safety, resettlement of affected populations, and, more recently, environmental concerns. The Bank, however, does not yet have an explicit policy for addressing intersectoral water resources issues comprehensively.

Improved water management requires that human interventions in the hydrological cycle not be viewed as isolated actions, but in terms of their system-wide consequences. To optimize the total benefits from water resources, it is necessary to consider the social, economic, and hydrological conditions; the geophysical relationships in the hydrological cycle; the linkages between the technologies used to harness water and the environment; the value of water to different users; and national policy objectives. This planning approach is commonly referred to as integrated water resources planning (IWRP).

Integrated Water Resources Planning

The conceptual framework for IWRP includes various levels at which water development should be examined. At the most aggregate level, the water sector must be viewed as part of the whole economy. At the second level, the water resources sector is treated as an entity composed of subsectors, such as potable water, irrigation, and hydropower. At this level, analysis focuses on the interactions among the different water subsectors and the resolution of any resulting policy conflicts. At the third and most disaggregated level, planning focuses separately on each of the water subsectors. Most of the detailed formulation, planning, and implementation of water resources development projects are carried out at this level. Any conflicts that arise from these subsector plans must be worked out at the second level.

In dealing with water issues in areas where marginal costs of additional supplies are rising rapidly, it is crucial to consider the interlinkages with the rest of the economy; the availability of water in view of its spatial and temporal distribution; the delivery and opportunity costs of water supply and allocation decisions in terms of the value of present and future uses forgone in various sectors; customary and/or proprietary rights to water resources; externalities; returns to scale; and the achievement of economic and social goals such as growth, poverty alleviation, and food security. The various characteristic of the water sector imply the need for government interventions to ensure technically sound and socially optimal outcomes.

The conceptual framework for IWRP suggests that the fundamental task of this comprehensive approach to water resources planning and management is to deal with the wide range of issues related to the optimal allocation of water resources among various uses. These issues pertain to economic, legal, institutional, environmental, and technological-environmental considerations.

Until recently, many countries have undertaken narrowly focused interventions to boost water supply for specific subsectors. With the growing demand for water and the significant rise in costs of additional supplies for competing users, economic issues of water allocation and management will be vital. As water allocation issues become more contentious, the water resources sector will place increasingly large demands on governmental budgets. Consequently, financing and cost recovery questions will become critical.

The Bank needs to identify and further develop appropriate analytical tools for defining optimal allocations of water both within and among sectors and countries. In addition, mechanisms that guide resource allocation (frequently market mechanisms such as pricing) need to be evaluated, and recommendations for policy reforms under various economic, social, and hydrological conditions should be formulated. The proper assessment of the opportunity costs of water in alternative use and of cost-effective means of transferring water across sectors is an important element of efficient allocation decisions, and the Bank should review methodologies to facilitate this assessment.

Institutional issues are affected by several factors. Government responses to increasing water demand and the emerging water allocation problems have typically been fragmented. Water resources planning and management are generally conducted with little interaction among agencies. In addition, staff training and incentives in many countries are inadequate for the tasks assigned to these agencies. Managers and staff often have little understanding of and no familiarity with the holistic approach to water management. Solutions to these problems will require organizational reforms, the strengthening of the agencies, training and educational programs, and changes in the legal and regulatory systems appropriate for comprehensive water resources management.

Degradation and depletion of water resources are a growing problem worldwide. Therefore, environmental protection will play a growing role in water planning and management. At the national level, one of the challenges countries have to face is defining an appropriate balance between environmental protection and income growth. The incorporation of environmental protection into water planning and management activities in the Bank requires analysis.

The comprehensive approach to water resources development requires addressing technical issues common to all subsectors, i.e., the comprehensive assessment of all water resources and their quantity and quality; the assessment of technical solutions to optimize overall water use, such as conjunctive use of surface and groundwater; the reuse of urban wastewater for irrigation; water quality monitoring to safeguard against public health and environmental hazards; and the promotion of technology transfer. Although sector-specific technical solutions have been developed and need to be continuously improved, a more systematic effort is required to address the intersectoral technical issues.

In many countries, the lack of technical capacities to develop appropriate water conservation and pollution control technologies and to adapt them to local conditions is an important issue. Mechanisms for technology transfer and training need to be reviewed. Appropriate strategies for promoting technological change and possible Bank assistance to support these strategies should also be examined.

Conclusion

If available water resources are not managed comprehensively, the growing and competing demands of water users in different economic sectors will not be properly addressed and will lead to inefficiency; lower economic growth; human suffering; and local, national, and international conflicts. Tools for comprehensive water resources management have been developed, but are rarely used consistently.

The Bank's proposed work plan calls for the submission by December 1992 of guidelines on comprehensive water resources management and recommendations to senior management on the Bank's evaluation and decisionmaking process in the water resources sector. To assist borrowing countries to prepare for increasing competition for water, the Bank will reassess its own approaches to determine if they are adequate to address this challenge.

NORTHEAST BRAZIL: DROUGHT AND THE DEVELOPMENT OF IRRIGATION

Carlos Emanuel and Phyllis Pomerantz

Since the late 1800s, northeast Brazil has been officially viewed as the country's foremost "problem area." It had been the nation's wealthiest region during the sugar boom of the colonial period, but subsequently lagged behind as industrial, agricultural, and commercial activity shifted to the south. Wide interregional income and socioeconomic disparities have persisted over many decades. Today, with nearly 30 percent of the nation's population, the Northeast accounts for only 13 percent of GDP. Over 70 percent of the region's families are poor, and the majority of these poor families reside in rural areas.

Consequently, development assistance to the Northeast involves rural areas, where concentrated land ownership severely restricts access to land by small farmers and severe droughts periodically rob families of their livelihood. Recently, irrigation projects have begun to play an increasingly important role in the World Bank's development assistance strategy for the Northeast. After providing some background on the rural Northeast, this paper outlines past government interventions related to both drought relief and rural development. The major elements of the current development strategy are presented. A short analysis of the key constraints to future irrigation development follows. The paper concludes by noting possible forms of future Bank assistance and the increasing role of irrigation in the wider context of Northeast drought management and rural development. (A postscript summarizes recent developments in irrigation in the region.)

Background

Geographical Characteristics

Northeast Brazil includes nine states—Maranhao, Piaui, Ceara, Rio Grande do Norte, Paraiba, Pernambuco, Alagoas, Sergipe, and Bahia—and the Federal Territory of Fernando de Noronha. Their combined area is about 1.5 million km^2, or 18.2 percent of the country's total land area. For planning purposes, a portion of Minas Gerais State, an area subject to severe drought, is also included in the Northeast, bringing the total to 2.1 million km^2.

The Northeast is heterogeneous in terms of climate, topography, and vegetation. The *zona da mata* (forest zone) stretches along the coast from Rio Grande do Norte to southern Bahia in a narrow strip ranging up to 150 km in width. The total land area of this subregion does not exceed 128,000 km^2, or about 8 percent of the region. It contains, however, approximately one-third of the regional population, six of the nine state capitals, and a major proportion of industry and plantation agriculture (largely sugarcane and cocoa). The zone's ecological conditions are generally favorable for agriculture, with good-quality soils and abundant and regular rainfall (exceeding 2,000 mm annually in some areas).

Carlos Emanuel is senior irrigation engineer, and Phyllis Pomerantz is chief, Agriculture Operations Division, Latin America and the Caribbean Country Department I, World Bank. This paper was presented in 1985.

The *agreste* is a transitional zone between the humid *zona da mata* and the semiarid *sertao*. Its land area is about twice that of the *zona da mata*. The landscape (a) is highly variable over short distances; (b) contains moist areas (*brejos*); (c) is generally of higher elevation; and (d) is contiguous with semiarid areas. Disregarding the wet areas, annual precipitation, concentrated between March and June, is almost always below 1,000 mm. Soil fertility is medium to low. The *agreste*'s rural economy is dominated by mixed farming for the domestic market, as well as cattle raising.

The *sertao*, totaling some 750,000 km^2, is the largest subregion and the most vulnerable to periodic droughts. It encompasses the greater part of Ceara, Rio Grande do Norte, Paraiba, Pernambuco, and Bahia and smaller portions of the other northeastern states except Maranhao. Its total population is, however, only slightly greater than that of the *zona da mata*. Annual rainfall averages 700 mm for the *sertao* as a whole, but ranges from 250 mm in the driest areas to over 1,000 mm in the humid uplands. Soils suitable for cultivation exist, but lithosols and regosols, unsuited to agriculture, are widespread. The variation in climate and soil permits a diverse rural economy, with extensive cattle raising and cultivation of drought-resistant plants predominating in the semiarid areas, and the production of fruits, vegetables, manioc, sugarcane and other crops in the cooler, more humid uplands.

The middle north, constituting Maranhao and most of Piaui, accounts for one-fourth of the Northeast's land area and about one-fifth of its population. Climatically, it represents a transition between the semiarid *sertao* and the humid Amazon region: annual precipitation ranges from less than 600 mm in eastern Piaui to over 2,000 mm in northern Maranhao. Soil quality varies. Most of Piaui and coastal Maranhao has been settled since colonial days, but large areas remain frontier. In older settlements, extensive cattle raising and subsistence agriculture predominate, with significant palm-related extractive activities in more humid areas. Rice is also an important cash crop. On the frontier, slash-and-burn agriculture followed by conversion to pasture has been the traditional form of land use.

The Sao Francisco is the most important river system in the Northeast. It is the main reliable water source, with a mean base flow of 2,100 m^3/s at its mouth, excellent water quality, and an annual discharge averaging about 100 billion m^3. Its basin occupies some 640,000 km^2. In the northern part of the region, most rivers have highly variable flows and remain dry during part of the year. An important exception is the Parnaiba River, which has a significant base flow as a result of higher and more regular rainfall and the presence of some sedimentary formulations. Rivers in the southern part of the region, between the southern limit of the Sao Francisco basin and the Atlantic, also have variable flows, peaking during and after heavy rainfall. Several do, however, have continuous flows, although usually of limited volume.

The hydrology of the Northeast is characterized by scarce and irregular rainfall and by the low permeability of most rock formations. The region's total surface runoff is estimated at 98 billion m^3, with an average specific yield of 3 $l/s/km^2$. The ministry of the interior has estimated annual groundwater resources of 17 billion m^3 in sedimentary and between 50 and 250 million m^3 in crystalline areas. The regional development authority, the Superintendency for the Development of the Northeast (SUDENE), estimates that about 1 million ha could be irrigated in the near future and 2 million in the long run.

Over the last 70 years, to conserve rainfall and reduce flood risks, the government has constructed some 265 major public reservoirs in the Northeast. These reservoirs have a total storage capacity of more than 12 billion m^3. In addition, there are some 600 major private reservoirs and several thousand smaller ones. Major dams at Tres Marias in the upper Sao Francisco Valley, Sobradinho in the middle valley, and the Paulo Afonso hydroelectric dam have regulated the river flow, as well as facilitated the use of large areas of inland water for fishery development, domestic and industrial use, and irrigation.

Socioeconomic Characteristics

The Northeast's 1980 population was almost 35 million, or about 29 percent of the national total. The region's average population density of 23 inhabitants per km^2 is approximately 65 percent higher than that of the country as a whole. The average rate of population growth (net of migration) between 1970 and 1980 was 2.2 percent (the estimated annual rate for Brazil as a whole was 2.5 percent). The Northeast remains the most rural of Brazil's five macroregions, accounting for about 45 percent of the country's rural inhabitants. Currently, the regional population is about equally distributed between urban and rural areas, with the former slightly predominant. A significant rural exodus occurred during the 1970s and early 1980s, and since 1970, population growth in rural areas has been negligible. Urban growth, however, has been pronounced in the northeastern states. Migration to other areas is also important. For decades, rural inhabitants, propelled by periodic droughts and insecure land tenure, have been leaving in search of better opportunities in the cities of the Northeast and Southeast or on the agricultural frontiers of Amazonia and the Center-West.

Despite rapid growth over the past decade, a wide socioeconomic gap remains between the population of the Northeast and that of Brazil generally. Per capita income is about 40 percent of the national average. Poverty is most severe and widespread in rural areas. As of 1980, over 80 percent of the rural population earned one minimum salary (about US$675 annually) or less, and the poorest 50 percent received only about 10 percent of total regional income. Just one-third of the adult rural population is literate; infant mortality is high; and average life expectancy is under 50 years. Other socioeconomic indicators also show low standards of living for the rural population.

Agricultural Production, Land Tenure, and Potential Land Use

The Northeast contributes about one-fifth of the total value of Brazilian crop production. Many regionally produced commodities, including sisal, manioc, sugar, and cotton, represent significant shares of national production. Agriculture still employs a little over one-half of the regional labor force, although its contribution to the gross regional product has declined from 30.4 percent in 1960 to 18.5 percent in 1980. Agricultural sector growth (from 1965 to 1980, annual average = 3.7 percent) has been highly uneven due to intermittent crop failures. Growth has been most dynamic in industrial and export crops (e.g., sugarcane, cacao), as well as in cattle production, but the value of basic food crops has declined relative to that of the sector as a whole. Output of some basic food crops has declined in absolute terms since the onset of the prolonged drought in 1978.

The pattern of sectoral development has been associated with the increasing failure of Northeast agriculture to incorporate the rural labor force. A highly concentrated land ownership structure, coupled with insecure land tenure arrangements for renters and sharecroppers, discourages increased factor use and productivity. Over two-thirds of farm establishments occupy lands under 10 ha on 5 percent of the land, whereas just over 6 percent of farm enterprises control nearly three-quarters of the agricultural land. On the smaller establishments, overcropping and outdated technology are common. Estimates indicate that the area in annual or perennial crops could be tripled with a different tenure structure and modern cultivation practices. Irrigation development to date has been limited: only about 140,000 irrigated ha have been developed.

Drought Conditions in Historical Perspective

Recurrent drought cycles are a dominant factor in the Northeast's agricultural development. The first recorded drought occurred in 1587, and 74 subsequent droughts are on record, with 18 in the twentieth century thus far. The 1877-79 drought was the most serious to date. Although only partial data are available, at least 0.5 million inhabitants died of drought-related causes. During the most recent drought (1978 to 1983), by 1983 over 80 percent of the Northeast was seriously affected and over 1.2 million families were being assisted by emergency relief programs. Rainfed crop losses, particularly in the *sertao*, averaged between 80 and 100 percent in 1983. In addition to the severe drain on public funds, the savings of many small farm families (usually in the form of livestock) were depleted. Hunger was widespread, and rural food prices rose to a record high; there were numerous lootings of food markets and storage facilities. Even water for human consumption was scarce in most rural areas. Many rural communities had no source of water other than government tanker trucks, which delivered water infrequently. In 1984, severe floods ensued and destroyed billions of dollars worth of public and private infrastructure and housing.

Past Government Interventions in the Rural Northeast

Federal government involvement in the Northeast began in the late nineteenth century. The severe droughts periodically affecting the region, coupled with persistent widespread poverty, prompted the creation of numerous programs, approaches, and strategies. Until the 1950s, most federal interventions were limited to drought relief works, short-term drought emergency programs, and crop-specific policies aimed at supporting major export crops grown on large farms. Despite these programs, relatively little progress was made in the Northeast's socioeconomic development or in decreasing the regional population's vulnerability to drought. By the late 1950s, the need for comprehensive regional planning and a multisectoral approach to development was increasingly recognized. In 1959, SUDENE was created and given a wide range of formal powers. These included coordination of all on-going activities and investments in the region; responsibility for drought emergency measures; and administration of a powerful array of incentives to attract new private investment, particularly industry. Agricultural development was essentially limited to small, directed settlement schemes; fiscal incentives for large agricultural producers; and study groups on water resource potential and increased food production in the *zona da mata*.

A severe drought in 1970 and its devastating impact on the rural population demonstrated that little had changed despite the activities of the past decade, and a major reformulation of regional development policy was undertaken. These efforts culminated in the creation of several new programs and financing mechanisms aimed primarily at settlement, land redistribution, and agroindustrial modernization. This trend continued through the mid-1970s as the federal government created several additional programs for the rural Northeast.

The Rural Programs of the 1970s and Early 1980s

The programs implemented throughout the 1970s and early 1980s were characterized by two major approaches: The first was based on the integrated development of selected geographic areas focusing on specific target groups. The major examples of this approach were POLONORDESTE (Development Program for Integrated Areas in the Northeast, 1974); SERTANEJO (Special Support Program for Development of the Semiarid Region of the Northeast, 1976); and PROCANOR (Special Support Program for the Poor Populations of the Sugarcane Production Areas, 1980). The second approach was largely concerned with alleviating the effects of the recurrent droughts. Several parallel programs attempted to provide temporary drought relief assistance and to increase and improve the use of scarce water resources. These included PROHIDRO (Water Resources Use Program, 1974), TSA (Semiarid Tropics Research Program, 1974), large irrigation projects, and the Emergency Drought Relief Program.

The results of these programs were mixed and, at times, difficult to assess. Although the Emergency Drought Relief Program applied the largest amount of resources, most funds went to short-term emergency assistance, including temporary employment, relief food supplies, and subsidized credit. Many public works were constructed under the program, though they did not have much permanent impact on decreasing drought vulnerability. SERTANEJO included the provision of short-term and investment credit, together with extension services and the construction of small reservoirs, dams, and wells on the lands of producers who had received investment credit. The program, with its costly administrative structure, was severely hampered by credit shortages. Most of the highly subsidized credit available went to farmers with 100 to 500 ha, instead of to small producers, and many beneficiaries were ranchers rather than farmers. Funding and credit shortages also restricted the impact of PROHIDRO. Viewed as complementary to the other special programs, PROHIDRO focused on increasing water availability to small and medium producers through the construction of local water supply systems; regulation of river water flows to permit intensified use of adjoining lands; and a special credit line for small, private well and reservoir construction. Limited design and execution capacity and credit shortages resulted in actual achievements far below initial targets.

POLONORDESTE was the oldest and largest (geographically) rural development program. Its geographical coverage peaked in 1981 and included 43 integrated rural development projects and 4 colonization projects providing a wide range of land tenure, credit, agricultural production, and marketing services—as well as physical and social infrastructure—to small farm families. Some success in raising production and productivity was achieved, at least among the 30 percent of farmers owning land in the target group. Nonetheless, implementation was hampered by land tenure insecurity among most target-group farmers; chronic funding shortfalls and delays; limited execution capacity of some state agencies; and coordination problems at local, regional, and federal levels. Water supply and small-scale irrigation achievements fell particularly short of initial goals.

The public irrigation programs managed by DNOCS and CODEVASF also experienced problems. DNOCS (National Department for Drought-related Works), the direct descendent of the first antidrought agency established in 1909, managed large-scale irrigation projects in the semiarid parts of the region; CODEVASF (Sao Francisco Valley Development Company) was responsible for irrigation projects in the Sao Francisco River valley. By the early 1980s, irrigation programs were considered costly and more successful in constructing dams and reservoirs than in utilizing water to increase small farmers' production capabilities. Irrigation projects were hampered by soil problems, poor management, inadequate training and assistance for small farmers, and marketing difficulties. The high incomes predicted materialized for only a small percentage of farmers. At most, only about 80,000 ha of irrigated land were developed under the projects.

World Bank Involvement

The World Bank has been directly involved in rural development in northeast Brazil for more than a decade. This involvement has included a continuing policy dialogue with federal, regional, and state officials, as well as the financing of various agricultural and rural development projects. Most projects financed were from POLONORDESTE (10 projects totaling US$351.5 million), but loans were also made to support irrigation projects in the Sao Francisco Valley (totaling US$51 million) and a settlement project in the Alto Turi area (US$6.7 million). The main focus of Bank lending, however, has been in support of small farmers' rainfed crop production. Large investments in the irrigation subsector have been precluded by the relatively small role assigned irrigation development in government planning for the Northeast; the various problems of large-scale irrigation projects; and the relatively poor institutional performance of the major irrigation agencies.

Current Focus: The Dual-Development Strategy

In April 1985, the Brazilian government officially launched the Projeto Nordeste, a 15-year comprehensive development program for northeast Brazil. Planning of this major new development initiative began in 1982, stimulated by the recognition that the aggregate contribution of the special programs and federal irrigation projects in alleviating rural poverty and unemployment had been limited. The exercise resulted in a new agricultural and rural development strategy to be implemented through a series of sectoral projects, including federal irrigation projects and a regionwide integrated rural development program. Although it borrows from past experience, the new strategy has several innovative aspects, including:

- unification of the special rural programs—PROHIDRO, SERTANEJO, PROCANOR, and POLONORDESTE—under the new regionwide rural development program;
- greater emphasis on land tenure improvement and beneficiary participation;
- a renewed effort to develop water resources efficiently.

Revitalized water resource development will be implemented in two ways. The first is through investments, which are an integral component of the rural development program. Investments include small and medium *state-managed* public irrigation schemes, investment credit for individual or group private irrigation, and related investments in fish farming. The second implementation method is through a national irrigation program, to be coordinated by SUDENE at the regional level, which will include institutional strengthening of the major agencies involved and the construction and rehabilitation of medium and large *federally managed* (DNOS [National Department of Sanitation], DNOCS, and CODEVASF) public irrigation schemes. One million hectares, much of it in the Northeast, is targeted for irrigation by the year 1990. Although this goal is ambitious, the dual development strategy for the irrigation subsector (both as part of the integrated rural development program and as a freestanding program) has given new impetus to increased investment in Northeast irrigation.

Constraints to Future Irrigation Development

Given the risks and low returns of rainfed cropping in much of the Northeast, the lack of a tradition of irrigation in the region is surprising. Although some investments have been made, the final results in terms of increased agricultural production have failed to correspond to initial expectations. Compounding the social and financial constraints have been several other problems that have inhibited irrigation development in the past and present a formidable challenge for the future. These problems are mainly related to technical factors, institutional limitations, markets, land tenure, producers' participation, and implementation costs.

Technical Factors

The number of locations in the semiarid Northeast with favorable physical conditions for the development of profitable irrigation is limited. General areas with adequate resource combinations exist, but the selection of specific projects requires a thorough analysis of soil fertility, water suitability, and development costs. Soils with adequate productivity potential are relatively scarce and erratically distributed within the region. Bringing surface water to these soils would necessitate the construction of large pumping stations in the Sao Francisco River basin. In other areas, it would be necessary to build enormous reservoirs with low yield coefficients. Tubewell development is limited by the scattered distribution of suitable aquifers. Consequently, significant technical factors impede large-scale irrigation development and can only be overcome through careful study and planning: this requires both time and considerable technical expertise.

Institutional Factors

In the past, the relatively poor performance of government agencies has made public irrigation a costly and slow process. Current figures indicate that under public irrigation schemes there has been an average of six technical-grade staff and five support staff, providing production-related support services for every 100 settled families. For staff on irrigation perimeters, offices, vehicles, and government housing have been provided. There has also been a tendency to provide comprehensive facilities for cooperatives at direct government expense, instead of beginning more modestly and letting members finance their own future expansion under available government credit lines. The total annual cost of operating production support services (agricultural extension and cooperatives) for public irrigation schemes has been about US$200/ha.

In addition to high operation costs, construction has been slow. Further delays have also occurred between the completion of public irrigation works and the start of their productive use. The average interval between the completion of construction on a given site and its complete occupation by irrigators has normally been over seven years. One reason for the delays has been budgetary restrictions. Inadequate designs have also compounded difficulties. Possible implementation problems were not foreseen, leading to higher unit costs. Budgets have been exhausted before construction is actually completed. Sometimes, the combination of ambitious regional targets and cost and time constraints has led physical planners to proceed on the basis of inadequate resource data. Finally, some delays in the use of public irrigation have occurred because agricultural production development plans were omitted from project designs.

For significant irrigation development, institutional performance must be improved in all three phases: design, construction, and operation. This will require a considerable revamping of the large federal irrigation institutions (DNOCS and CODEVASF); the development of state-level capacity, which is currently in its incipient stage; and the strengthening of SUDENE's (the regional coordinator of both the rural development and irrigation programs) capacity to effectively coordinate planning and resource allocation. Finally, increased efficiency and a less paternalistic attitude toward both irrigation staff and settlers will be necessary to keep operation costs reasonable.

Markets

Currently, only the introduction of high-value horticultural crops will guarantee favorable economic returns for public irrigation perimeters. Even if the current 6,000 ha of these crops now grown under public irrigation were doubled or even tripled, the total area would remain insignificant compared with the government's irrigation development targets for the region. At the same time, there are indications that present outlets, chiefly large regional metropolitan centers, may be close to saturation. Given the region's low per capita income and widespread poverty, effective demand for high-value crops is limited. Consequently, there is a need to expand high-value outlets, particularly through the creation of more commercial links, such as the COTIA/Pirapora partnership for fresh produce, and through the expansion of agroindustries to absorb products for processing. Also, as part of agricultural research, market studies are needed to determine whether other high-value crops might be introduced in the Northeast. Market studies should also explore the region's seasonal advantages, both domestically and internationally.

Land Tenure

As noted previously, landholdings are very concentrated in northeast Brazil. The need to ensure small farmers' increased access to land is now a principal issue for future agricultural development and the reduction of rural poverty in the Northeast. In the past, increased productivity through irrigation development may have been viewed as an alternative to more radical approaches, such as agrarian reform. It is now increasingly clear, however, that unequal land tenure itself constitutes a barrier to future irrigation development, particularly because Brazilian federal irrigation law stipulates that at least 80 percent of the beneficiaries of a public irrigation scheme be small farmers. Both the state and federal governments have shown considerable reluctance to expropriate underutilized irrigable land from large holders for implementing public irrigation schemes. Recently, however, this attitude has begun to change for several reasons: the new support being given to agrarian reform in general; the need to justify the high costs of irrigation development with equally high numbers of beneficiaries; and the reluctance of the World Bank and other lenders to support schemes where land tenure problems have not been adequately resolved.

Producers' Participation

In the past, regimentation of settlers on public irrigation schemes excluded farmers from participating in the agricultural development process. The assumption was that because of the initial settlers' lack of experience, the irrigation agencies would have to guide projects closely and virtually control farmers' activities. Because of this failure to develop farmer initiative, the possibility of realizing full potential returns from public investments in irrigation was considerably reduced. The need for a new attitude, however, has been recognized. It is accepted that increased settler involvement will limit project costs in two ways: first, by giving irrigators more responsibility for planning production, running cooperatives, operating schemes, and carrying out simple maintenance, and second, by encouraging irrigators to assume—from the outset—a higher proportion of on-farm and other investment costs.

Costs

Based on past experience, public scheme costs have been estimated at between US$5,500 and US$8,000/ha. The estimates include headworks and primary conveyance structures; the distribution network, down to the farm level; and on-farm development, including land leveling and internal roads. Not included are the costs of main dams or river-regulating structures, land acquisition, or construction of social support infrastructure. Additional government costs for supporting infrastructure on public schemes vary widely: for small farmers (settlers), these costs have been estimated at over US$4,000/ha, and for larger holdings, up to US$2,000/ha. The total investment cost per settled family on public schemes is now estimated at between US$34,000 and US$44,000. Present operation and maintenance costs vary from US$200/ha for irrigation schemes highly dependant on pumping to US$40/ha for gravity irrigation systems.

These costs must be evaluated considering the benefits that will be generated. Many schemes are economically justified, particularly when the cost of alternative expenditures, such as massive drought emergency relief programs and urban infrastructure and services for rural populations pushed to the cities, is considered. Nonetheless, irrigation development to date has been very expensive. In the future, increased attention must be given to designing schemes on a least-cost basis, increasing efficiency, and reducing implementation costs.

Future Perspectives

The Increased Role of Irrigation

As noted earlier, in April 1985 the Brazilian government launched its National Irrigation Plan to irrigate 1 million ha over five years and gave priority to the Northeast. Because the region already has relatively good infrastructure with paved roads, railways, and electrical facilities, a large portion of future public investment will undoubtedly be directed toward irrigated agricultural production for the benefit of small farmers. According to government estimates, one hectare placed under irrigation creates 0.7 jobs at the farm level and twice that amount of indirect employment. Public irrigation is therefore considered one of the cheapest ways of creating employment (about US$6,000/1 job) and alleviating rural poverty. At the same time, the government intends to develop private irrigation in the alluvial areas adjacent to major local rivers. Government incentives to private irrigation include the construction of drainage and flood control facilities and the installation of electrical transmission lines. Another main feature of the irrigation plan is that half of irrigated agricultural production will be industrially processed to benefit the regional economy. Although major challenges exist, irrigation development now enjoys widespread and continuing support from regional planners. It is viewed as one of the few ways of safeguarding against the collapse of the regional economy during drought. This is a significant development, and irrigation will undoubtedly play an increasingly important role in Northeast development.

Bank Support

World Bank involvement in supporting future irrigation development in the Northeast is probable, with two new lending operations for irrigation in the Northeast expected to be approved during this fiscal year. Bank support, however, will continue to be based on the merits of specific projects or sectoral activities. It will also have to consider both the public and private sectors. Public investment in agriculture will increase, and public institutions have to be improved. It is difficult to believe, however, that single projects, regardless of their size or technical capacity, can change the long-standing administrative culture of the society and the subsector. At the same time, the private sector cannot be exclusively relied upon when private developers are hampered by government credit policies and regulations. World Bank support, therefore, will probably involve a mix of both public and private sector investment, assuming that (a) irrigation can be suited, under certain circumstances, to either public or private control, and (b) drainage and flood protection works must be a collective or public responsibility. Public irrigation is favored by the considerable reserve of irrigable land held by CODEVASF and DNOCS, and by the potential development opportunities (with relatively low incremental costs) from the sunk costs in currently unused main works. There are also opportunities for rehabilitation and expansion of existing public irrigation areas. Private irrigation also has advantages in its rapid start-up and lower direct costs, and it can develop relatively small or scattered parcels of land without great diseconomies of scale.

Drought and Development

This paper has focused on irrigation development in northeast Brazil and its potential contribution to rural development, particularly the alleviation of the effects of drought. Irrigation, however, is not the only vehicle for combatting drought or alleviating poverty. Irrigation's role is important, though limited. Despite a massive effort, most of the rural poor—those most severely affected during droughts—will not benefit from irrigation activities. Consequently, further work in several areas is necessary, including increased support for research aimed at developing viable technical packages that consider the recurrent drought cycle and renewed efforts to increase nonfarm rural employment opportunities. Substantial investments in education and training, both on- and off-farm, are also required.

There are no easy, quick fixes for recurrent drought and massive rural poverty. There are, however, possibilities, and many, like irrigation, have been underdeveloped.

Postscript

Between 1986 and 1990, the irrigated area in the Northeast increased by about 250,000 ha, much of which was implanted by the private sector supported by federal government incentives. Because of severe budgetary restrictions, the role of the public sector was limited to the preparation of studies for future projects and the partial construction of hydraulic infrastructure for large irrigation schemes conceived earlier. At the same time, institutional arrangements for irrigation development in the region improved, beginning with the government's decision to transfer management of existing public irrigation schemes to water user associations.

To define a political and economic framework for future irrigation development in the country, the government and the Bank completed an irrigation subsector review in September 1990. The review incorporated many of this paper's recommendations and is being used to guide investment allocation in the subsector. For the Northeast, the review's mains conclusions and recommendations are:

- Irrigation development should be demand-driven; the initiative should come from either farmers, who request government assistance for supporting infrastructure, or irrigation associations, which would borrow the required development funds;

- Irrigation should be self-sustaining, i.e., farmers and entrepreneurs would repay, with interest, any government investment;

- Traditional settlement projects, which are highly subsidized, should be recognized as a social activity and financed from specifically earmarked federal and state funds, separate from normal irrigation development budgets.

Bank lending for irrigation will continue to support the required policy, institutional, and legal reforms while providing assistance for the investment priorities included in the government's development program. The Northeast Irrigation I project, which has been approved by the Bank, broadly embodies some of the new policies, institutional arrangements, and operational strategies for irrigation development in the region. A proposed irrigation subsector project for the Northeast would provide financial support for private irrigation development and technical assistance to strengthen the federal and state irrigation and environmental agencies operating in the region. Finally, through the Northeast Rural Development Program, an estimated US$400 million will be committed to settling small farmers. The government will provide them with irrigation infrastructure, down to and including on-farm works and agricultural support services, with only partial recovery of infrastructure costs, but full recovery of operation and maintenance costs.

IRRIGATION DEVELOPMENT IN SUB-SAHARAN AFRICA: FUTURE PERSPECTIVES

Akhtar Elahi

The African population is generally increasing at 3.2 percent annually, whereas food production has increased at about 2.3 percent a year and cereal output at only 1.8 percent. Food imports have thus been rising, with further increases as a result of the drought conditions of the past 10 years (although in 1988 some countries experienced floods). Whereas in 1970 Sub-Saharan Africa produced an estimated 90 percent of its cereal needs, this figure fell to 76 percent in 1985 and has continued to decline at an alarming rate.

FAO estimates that the region has an irrigation potential of some 33 million ha; about 5 million ha are presently under irrigation, representing 15 percent of the potential. For modern schemes, governments have developed some 2.1 million ha, and the private sector (estates and individuals) has developed 0.5 million ha, for a total 2.6 million ha under modern schemes. Traditional areas account for nearly 2.4 million ha. (Table 1 provides estimates of irrigated and irrigable areas.)

Half of the currently irrigated area is located in just two countries: Sudan and Madagascar. The total area under irrigation contributes an estimated 5.3 million tons, or 10 percent, toward meeting regional cereal demand, and 6 to 8 percent toward the demand for root crops and vegetables; sugarcane and cotton are also important crops.

There is considerable variation among estimates of potential irrigable areas produced by various surveys and studies. FAO estimates appear optimistic, but over half the estimated irrigable area is in countries (Angola, Zambia, Mozambique, Zaire, Tanzania, and Central African Republic) where irrigation may not be a priority or even feasible given various climatic factors (sufficient land and reasonable rainfall/water distribution). In certain countries with arid, semiarid, or humid zones, however, there are large areas (e.g., in Nigeria) where dryland irrigation is imperative to generating productive agriculture.

This paper focuses on arid and semiarid countries, as well as those countries with sizable areas under arid or semiarid climatic conditions (i.e., less than 400 mm annual rainfall and with variable precipitation patterns). In these countries the necessity of irrigation and its sustainability are assuming increasing importance, particularly in conjunction with population pressures.

The Role of Irrigation

Considering the heavy capital outlay involved, why do national planners select irrigation development in formulating and implementing county-specific strategies? One reason (in countries with reasonable land and water resources for development) is that in arid and semiarid zones there are sizable domestic demands that cannot be met by rainfed production alone, especially in light of population pressures. Marginal, erratic rainfall renders rainfed agriculture unreliable. Under these conditions, national planners anticipate that irrigated agriculture will provide a degree of self-

---

Akhtar Elahi is *senior irrigation engineer*, Agriculture Division, Africa Region Technical Department, World Bank. This paper was presented in 1988.

Table 1. Irrigated and Irrigable Area, Sub-Saharan Africa, 1982 (thousand ha)

Country	Irrigable area	Irrigated area: Modern	Irrigated area: Small-scale or traditional	Irrigated area: Total	Developed as % of potential
Angola	6,700	0	10	10	<1
Benin	86	7	15	22	26
Botswana	100	0	12	12	12
Burkina Faso	350	9	20	29	8
Burundi	52	2	50	52	100
Cameroon	240	11	9	20	8
C.A.R.	1,900	0	4	4	<1
Chad	1,200	10	40	50	4
Congo	340	3	5	8	2
Côte d'Ivoire	130	42	10	52	40
Equatorial Guinea	n/a	n/a	n/a	n/a	n/a
Ethiopia	670	82	5	87	13
Gabon	440	0	1	1	<1
The Gambia	72	6	20	26	36
Ghana	120	5	5	10	8
Guinea	150	15	30	45	30
Guinea Bissau	70	n/a	n/a	n/a	n/a
Kenya	350	21	28	49	14
Lesotho	8	0	1	1	13
Liberia	n/a	3	16	19	n/a
Madagascar	1,200	160	800	960	80
Malawi	290	16	4	20	7
Mali	340	100	60	160	47
Mauritania	39	3	20	23	59
Mauritius	n/a	9	5	14	n/a
Mozambique	2,400	66	4	70	3
Niger	100	10	20	30	30
Nigeria	2,000	50	800	850	43
Rwanda	44	0	15	15	34
Senegal	180	30	70	100	56
Sierra Leone	100	5	50	55	55
Somalia	87	40	40	80	92
Sudan	3,300	1,700	50	1,750	53
Swaziland	7	55	5	60	>100
Tanzania	2,300	25	115	140	6
Togo	86	3	10	13	15
Uganda	410	9	3	12	3
Zaire	4,000	4	20	24	1
Zambia	3,500	10	6	16	<1
Zimbabwe	280	127	3	130	46
Total	33,641	2,638	2,381	5,019	15

Source: FAO study team estimates of areas developed; irrigable-area estimates from FAO Land and Water Division, 1985 (see FAO Investment Centre Technical Paper 5, 1986).

sufficiency in food and fiber crops, or at least aid in ensuring national food security, equitably distributing income, raising the rural population's living standards, creating employment opportunities, and reducing urbanization pressures. Irrigation provides the means to maximize production with double- or multiple-cropping, taking full advantage of modern technologies and high-yielding crop varieties that involve intensive agriculture under controlled conditions.

For countries with arid and semiarid climates, the lack of or uncertainty about rainfall, along with rising demographic pressure on rainfed land, would strongly point to irrigation as a prime candidate to support future food strategies (as well as crop production to earn foreign exchange) in the medium and long term. Countries in this category include Senegal, Mauritania, Mali, Ethiopia, Somalia, Sudan, Burkina Faso, Niger, Nigeria, and Chad.

In terms of land area that can be brought under irrigation, the figures in absolute terms may not seem large. However, since irrigation is an intensive form of agriculture, the potential contribution to food and fiber crops per unit area is quite measurable, with surplus food crops produced under uncertain climatic conditions and food security and production of other crops positively influenced. To realize the range and impact of irrigated agriculture in Sub-Saharan Africa, and to appreciate the rationale behind the approach advocating judicious investments in irrigation, related data are presented in tables 2 and 3.

Cereals (mainly rice, wheat, maize, barley, millet, and sorghum) are the major product of Sub-Saharan Africa's irrigated land, accounting for over 50 percent of the total irrigated area. The next important crop is fodder, covering about 13 percent of total irrigated area. Fiber crops cover 8 percent of total irrigated area, most of it in cotton, with 90 percent grown in Egypt and Sudan.

Several issues and constraints (technological, environmental, social, economic, and institutional) need to be addressed adequately at the national level during the planning stage. At the implementation and operating stages, irrigation potential must be harnessed to facilitate and sustain existing and future developments. The success of any irrigation project, however, like any other developmental activity, is influenced by the macroeconomic environment as well as institutional weaknesses and inefficiencies pervading the public and private sectors.

Several of these factors have led to the deterioration of some initially productive irrigation systems and/or projects. The irrigation subsector in Sudan (constituting 1.8 million ha) is a vivid example: over the last 10 to 15 years, the delivery system has gradually deteriorated because of inappropriate reservoir operations, changing flows, and sediment/silt load patterns and releases designed to meet short-term demands, coupled with continued neglect of system maintenance. Other factors contributing to productivity decline include discouraging pricing and marketing policies, flawed macroeconomic policies, and overnationalization. The cumulative effect has been inefficient, less reliable irrigation, resulting in a loss of hectarage under irrigated agriculture. Sudan's irrigation system requires a massive rehabilitation effort just to restore productivity to levels of the 1970s.

Summary and Recommendations

Planners must realize that for long-term sustainability, production efficiency has to be achieved through a judicious combination of efforts related to technology, management, and policy. The debate on the strategic importance of certain investments such as rehabilitation of existing projects versus construction of new ones, small- versus large-scale projects, and private versus government involvement in irrigation will and should continue. A balance has to be sought in development plans, and an extreme emphasis on any one position should be avoided.

Irrigation offers protection against natural water deficiencies and should therefore be promoted, wherever possible, as protection against drought conditions. In many countries the construction of reservoirs has achieved a high degree of drought protection. Africa's climatic

Table 2. Sub-Saharan Africa: Total Area under Rainfed and Irrigated Agriculture and Production Values, 1980

	Area (million ha)	% of cultivated area	Production value (million US$)	% of value
Rainfed	116	93.5	29,376	80
Irrigated	8	6.5	7,475	20
Total	124	100.0	36,851	100

Note: The area under irrigation represents 6.5 percent of the total cultivated area, but accounts for 20 percent of total production value. The production value of an irrigated hectare is about 3.5 times that of a rainfed hectare.
Source: *Consultation on Irrigation in Africa*, FAO Irrigation and Drainage Paper 42, 1987.

Table 3. Sub-Saharan Africa: Major Irrigated Crops, 1980

Crop	% of irrigated area
Cereals	53
Fodder	13
Fiber	8
Vegetables	7
Oil crops-pulses	7
Fruits	6
Sugarcane	4
Root crops	2
Total	100

Source: *Consultation on Irrigation in Africa*, FAO Irrigation and Drainage Paper 42, 1987.

conditions require greatly increased investments in such facilities. After Australia, Africa is the driest continent and has the greatest degree of variability in terms of annual and interannual rainfall. Africa lags behind in building up water storage; it has 2 percent of the world's stored water, but 10 to 12 percent of the world's population and less favorable climatic conditions than many other regions. Creating storage over time (as a long-term strategy) in large and small reservoirs and seriously addressing environmental concerns may be a logical approach to recurring cycles of droughts and uncontrolled floods. Concurrently, utilization of existing groundwater reservoirs should be promoted. Investigations in many areas of Africa have indicated dependable groundwater reserves that should be rationally and responsibly exploited. Groundwater should also be considered a valuable reserve in view of possible drought conditions.

Despite its capital-intensive nature, irrigation is viable and sustainable in arid and semiarid areas and has a substantial contribution to make in food security and fiber-crop production. The rate of expansion in irrigated land, as well as Bank financing in the subsector, has declined considerably over the last decade. Irrigation development, however, would contribute measurably to expanding and stabilizing agricultural production in Sub-Saharan Africa and could play a significant role in contributing to agricultural production, food security for the region's growing population, and poverty alleviation—major Bank objectives. Some of the predominant constraints and issues that need to be addressed to realize this potential are:

- Irrigation investment should consider long-term agricultural demands, with irrigation planning part of national water resource development plans;

- All schemes, whether small, large, new, or requiring rehabilitation, should be included in national investment plans and assigned appropriate priorities. Exclusively pursuing small-scale irrigation—which prima facie entails fewer problems—and ignoring the planning and development of larger projects are imprudent, particularly considering that large-scale projects may be necessary to adequately utilize available land and water resources and to meet food and fiber demands in the long run;

- Increased cost-effectiveness of investments through appropriate design and construction technologies in irrigation engineering and in production techniques should be pursued; however, there is a need to resist oversimplification of design to achieve low initial investment costs, which may result in low productivity and higher operation and maintenance (O&M) costs;

- Irrigation should be practiced as an intensive form of agriculture to optimally utilize large capital outlays. It should be viewed within the framework of integrated agriculture to optimally exploit various inputs and their timely availability, as well as incentives, through the adoption of sound marketing and pricing policies;

- The improved efficiency of future irrigation projects should be a principal objective. There is also wide scope for efficiency improvement in existing projects. This underscores the need for precise water delivery, facilitated by technological advances; proper water management; and crop intensification, all of which could enhance irrigation schemes' economic sustainability;

- An increased emphasis on adaptive research is needed to develop crops/varieties for particular ecological zones as well as suitable agrotechniques and packages for field applications;

- Environmental considerations should be addressed during the early stages of the project cycle so that socioeconomic aspects are fully appraised and steps included in project formulation for corrective or mitigating measures;

- Cost recovery policies are still a contentious issue, largely because of the inability of governments and financing institutions to agree on apportionment of costs, considering social and equity elements on the one hand and the extent of recovery through direct and indirect charges on the other. Cost recovery policies should be conceived and agreed upon in advance. It may be judicious to separate cost recovery on investments from O&M charges. O&M can further be eased by greater user participation and the formation of water user groups that share responsibility for regular O&M;

- Greater private sector involvement is needed to ease fiscal and management burdens on government resources and to deliver services in the agricultural sector as a whole.

IRRIGATION IN THE U.S.S.R.

Rory O'Sullivan

Irrigation is important to agriculture in the Soviet Union since about 60 percent of agricultural land is subject to potentially damaging droughts and substantial water resources are available for irrigation development. The U.S.S.R. is the third most important country in the world, after India and China, regarding area equipped for irrigation. Currently, about 20 million ha, which cover 10 percent of the agricultural land, are equipped for irrigation. Production on irrigated lands accounts for at least 30 percent of the country's total agricultural production. Although major improvements in agricultural production have been achieved through irrigation, important environmental and economic concerns remain. The environmental issues include the Aral and Caspian sea problems, land drainage and salinization, and groundwater pollution. Technical problems have been caused by substandard materials used in construction, rather than by design problems. New prices introduced as a result of the move toward a market economy may cause major changes in the profitability of irrigation for users and thus the viability of some existing schemes, particularly because increases in energy prices may make some pumped schemes nonviable without significant subsidies. Although adjustments in prices of outputs such as cotton and vegetables will be offsetting factors, there is an urgent need to reassess the long-term sustainability of existing schemes in light of a market economy and to upgrade systems to ensure long-term technical sustainability.

This paper is part of the report of a mission that visited the Soviet Union in September 1990 for a general review of the economy. Most of the information on irrigation was obtained in discussions with government officials in Moscow and Tashkent and through analysis of printed materials. A limited number of field visits to existing irrigation schemes were possible, but the opportunity for field work was limited by time: the conclusions of the mission described in this paper should be read with this in mind.

Background

Agriculture is a key economic sector in the Soviet Union, accounting for about 20 percent of GNP and 20 percent of employment. Over 100 million people, or about one-third of the country's population, depend directly or indirectly on the sector for their livelihood. The area cultivated—from the fertile black soils in the center of the country to the poorer-quality soils to the north and the irrigated soils situated mainly in the south—covers about 230 million ha, giving the U.S.S.R. the most extensive land wealth of any country worldwide. Most of the rainfed land is planted to grains and fodder crops, while in the irrigated areas the supplementary irrigation of rainfed crops predominates, except in Central Asia where cotton is a major crop. Overall, half the value of production comes from livestock products. Ninety-seven percent of the land is farmed in the public sector, about equally among large state or collective farms. Despite the highly favorable resource endowment, the U.S.S.R. is a net importer of food, with imports—half of which are grains and sugar—averaging just under $20 billion annually.

Rory O'Sullivan is chief, Agriculture Operations Division, Europe and Central Asia Region Country Department II, World Bank. This paper was presented in 1990.

Soviet agriculture is now at a critical juncture. The sector is caught in the midst and is part of major economic and social changes currently sweeping the country. These involve the move to a market economy; the privatization of many services and eventually even of the land; sharp changes in the macroeconomic environment, including the exchange rate; and changing wage price and trade arrangements.

Soviet agriculture is subject to several weather hazards that increase the risks of farming and reduce the types of crops that can be grown. They also reduce yields, unless action is taken to limit their effects. The hazards include:

- *drought*. Much of the country is subject to droughts of varying severity. About 60 percent of agricultural land is considered drought-prone, and serious droughts have occurred in "rainfed" areas in about half of the last 50 years in some part of the country. The area at risk starts south of Moscow, including the famous high-fertility black soils of the Ukraine and the middle portion of the Russian Republic. Further south, in northern Kazakhstan, the risk of drought becomes more pronounced; in the southern republics of Azerbaijan and Georgia and in Central Asia, including southern Kazakhstan, rainfall is naturally relatively low, and drought is widespread;

- *hot wind storms*. These wind storms, *sukhovey*, rage across the flatlands of the country's center and can occur several days a month from April to October. They are most frequent, however, in summer when the crops are ripening. Damage to plants is usually quick and irreparable unless moisture content can be maintained artificially;

- *snow and cold*. Much of the northern part of the country is covered in snow and experiences freezing temperatures from November through April, so that the period available for cultivation is a short 150 days. Only in the southern republics of Azerbaijan and Central Asia is more extensive cropping possible, although even there, temperatures as low as minus 10 and 20 can be recorded in the desert steppe lands.

The negative effects of these natural hazards can to some extent be overcome by artificial irrigation. Irrigation can ensure an optimum watering of plants in drought-prone areas; it can accelerate planting dates where the cropping season is short because of low temperatures and enable the warm weather—when it occurs—to be maximally exploited; and it can help plants maintain moisture levels in areas hit by hot drying winds.

Currently, about 10 percent of the 200 million ha of agricultural land in the Soviet Union are equipped for irrigation, producing about 30 to 40 percent of the country's agricultural production. These schemes mobilize part of the Soviet Union's enormous water resources for diversion to farms where drought problems can occur or where moisture levels are insufficient, and they enable a significant improvement in crop yields and productivity.

Irrigation in the U.S.S.R.

Areas Equipped and Irrigated

The potential for irrigation development in the Soviet Union is often put at about 100 million ha, and by 1990 about 20 percent of this had been developed. The huge water and land resources of the country would certainly permit substantially more areas to be equipped for irrigation. Although the quantity of unused renewable freshwater resources available within the U.S.S.R. is still large, these resources are not generally distributed where planners would prefer. Eighty-four percent of the total flows north and west into the Pacific and Arctic oceans. Only 16 percent flows into the extreme west and southwestern parts of the country, which account for 75 percent of the population, 80 percent of economic activity, and 80 percent of cropland. Within these resource constraints, the Soviets have given high priority to irrigation to offset the effects of drought and to take advantage of favorable thermal conditions, particularly in the water-deficit areas of Central Asia and the Caucasus. With 20 million ha now developed, most of the more immediate possibilities for development have probably been carried out, and new projects would require unusual means of water mobilization, such as interbasin transfers or unusually high pumping lifts.

Since 1965 there has been a doubling of the area equipped for irrigation. Not surprisingly, the largest area equipped for irrigation is in the huge Russian Republic, where a total of 6 million ha is equipped; however, this is only 4 percent of the total area cultivated because much of the land in the northern part of the republic is well watered by rainfall and in the eastern part of the republic is not suitable for irrigation for climatic or soil quality reasons. The second largest irrigation area is in Uzbekistan, with 4.1 million ha irrigated, representing nearly 93 percent of all agricultural land in that republic. This is typical of the Central Asian republics such as Turkmenistan, where 100 percent of agricultural land is irrigated. Apart from Central Asia, a high proportion of land is also irrigated in the Caucasian republics of Georgia and Armenia, between 50 and 60 percent of all cultivated land.

The area equipped for irrigation is not necessarily the same as the area irrigated in any one year. No data were made available on the actual level of utilization of the various systems of irrigation in different parts of the country. There is some evidence that overall levels of utilization are considerably less than 100 percent because of the slow development of farming on new irrigation schemes or because of technical problems with certain parts of different systems. The view was expressed several times to the mission that the average utilization of systems is often not much more than 70 percent in the northern part of the country and is somewhat higher in the drier southern republics. A 70 percent average utilization rate overall would bring the area irrigated in any one year down to 14 million ha.

The mission was able to obtain data describing the status of some of the major schemes in the Soviet Union. Major schemes appear to cover only 15 to 20 percent of irrigation in the Soviet Union, suggesting that the main part of the area irrigated involves smaller localized schemes where farms use direct pumping from a river or groundwater for localized irrigation or central pivot systems. Most of the large schemes are near completion. The major exception is the Karakoum Project in Turkmenistan, where 600,000 ha of the targeted 1 million ha have been developed. There is probably insufficient water available in the region to permit the finalization of this project without transbasin diversions from the north.

As mentioned above, the two major areas for irrigation are in Soviet Central Asia, with about 40 percent of the country's irrigation, and Southeast European U.S.S.R., i.e., the area north and south of the Caucasus Mountains in the Volga region and the southern part of the Ukraine, where another 40 percent of irrigation is situated. Much of the growth in the last 20 years has been in the Southeast European region where supplementary irrigation of grain has been introduced in a significant effort to reduce the impact of droughts in this major grain-growing region. In Central Asia, agriculture is only possible with irrigation, which has played a vital role for centuries. Expansion of irrigation in the Far East has been minor, except in the Yakutsk area, though irrigation plays an important part in the development of areas along the border with China.

The approximately 7 million ha of irrigated land in Soviet Central Asia are mainly fed from the twin rivers of the Syrdarya and the Amudarya, which cut through Uzbekistan and Kazakhstan to the Aral Sea. These two rivers are reminiscent of the Tigris and Euphrates in Mesopotamia. A major water transfer from the Amudarya River across Turkmenistan through the Karakoum Canal withdraws considerable quantities of water from this river basin and transfers them toward the Caspian Sea to develop agriculture in the dry republic of Turkmenistan. At completion, the Karakoum Canal will be 1,450 km long, the longest canal of any type worldwide, and nine times the length of the Suez Canal. Presently, all the water resources of the twin rivers are mobilized, and the ecological impact of water diversion for irrigation on the Aral Sea, which is rapidly drying up, is a key environmental concern. Completion of some schemes in this part of the country depends now on the possibility of major water transfers from Siberia to the south, a highly controversial issue.

The Central Asia region is the major cotton-producing area of the Soviet Union. Some 8 million tons of seed cotton are produced there each year, with a border price value of about $4 billion. The effects of extensive cotton monoculture, as well as drainage and salinity problems, are of concern.

In the Southeast European part of the Soviet Union, the north Caucasus region contains the largest concentration of irrigated land, most of it along the lower Kuban and Don rivers, as well as the Terek and Kuma rivers, which flow into the Caspian Sea. North of this area, the Dnieper River in the Ukraine is a major source of water for irrigation in the northern Crimea area. Further east the Volga River—a key transport canal—is also mobilized for irrigation in the vicinity of Astrakhan and in separate schemes, mainly on the river's left bank. South of the Caucasus Mountains in Azerbaijan and Armenia, the Kura River provides the main source of water, and irrigation is concentrated in this river basin. Fodder crops are more important in Southeastern European irrigation schemes than in Central Asia because they account for about half the crops grown in these irrigated areas to provide feed for local livestock. Grain crops are also important in newly irrigated lands. Fields planted to rice account for more than half of the country's rice production. Industrial crops are less important in Southeast European U.S.S.R. than in Central Asia.

Furrow irrigation is still the principal type of irrigation practiced in the Soviet Union. Sprinkler irrigation, which covered less than 10 percent of the area 20 years ago, is now used on about 40 percent of the farms irrigated. There has been a major growth in the use of central pivot and line drive systems, particularly in the Ukraine, the lower Volga, and the north Caucasus. In Central Asia, in contrast, furrow irrigation is the norm because sprinkler irrigation is negatively affected by the region's strong winds and dry climate. Drip irrigation is being tested for use in Central Asia. Raised concrete *canaletti*-type canals are common in Soviet irrigation design, as are mobile plastic pipes to facilitate efficient furrow irrigation. Irrigation plot sizes vary considerably by republic, usually reflecting the labor density and the crops being grown. The difficulties of irrigating the larger plots in republics such as Kazakhstan are considerable without precision land leveling and effective water distribution control on the farm.

Organization of Irrigation

In recent years, the major growth in irrigation was financed by the Union Budget through the powerful Central Ministry of Land Reclamation and Water Management of the Central U.S.S.R. and equivalent local ministries in the republics. The Central Ministry was responsible for overall planning, financing, and provision of irrigation construction materials and equipment in the entire country, as well as the design and construction of irrigation projects. At the peak of activity in the 1970s, the ministry and its dependent agencies employed about 2 million people and reportedly achieved an annual construction rate of 800,000 to 900,000 ha. When completed, irrigated farms were handed over to state farm managements and further developed by the local republican ministries of agriculture. Operation and maintenance of projects were carried out by specific project management enterprises supervised by the U.S.S.R. Ministry of Land Reclamation and Water Management. Currently, there are over 1,000 of these regional and interregional boards supervising projects.

In the last two years, the organizational structure has moved toward delegation to the republics. The Central Ministry of Land Reclamation and Water Management has been disbanded and converted into what is meant to be a financially autonomous corporation. Budgets have been sharply reduced because of unavailable tax revenues. In contrast, republican ministries are becoming strengthened and are taking increasing responsibility for new construction, operation, and maintenance of existing projects. The situation is still in a state of flux, and the final institutional structure that will support irrigation in the future remains unclear. It is now certain, however, that the republics will play a greater role than before in the construction and management of schemes.

Investment in Water Resources Development

Investment in major irrigation schemes had been financed by the Union budget through direct budget lines to the Central Ministry of Land Reclamation and Water Management. This ministry typically maintained a budget allocation from the Union of 7 billion to 9 billion rubles a year from the mid-1970s to the early 1990s, two-thirds of which has been allocated to construction work on water resources structures (including drainage), with the balance allocated to rural infrastructure in irrigated areas and the development of on-farm agriculture. The major growth in expenditure during the 1970s and 1980s is shown in table 1, which provides a summary of the total capital expenditures between 1966 and 1990. In 1989 and 1990, there was a reduction in the allocation of financial resources for investment in irrigation, and this reduction is expected to continue in the coming years.

Major Issues

It was impossible during such a short mission to identify all the issues currently of concern regarding irrigation development in the Soviet Union. The mission was able, however, to identify several key areas that are presently of concern, because of the current physical condition of projects or because of the new economic situation developing in the country. These include:

- the Aral and Caspian sea problems;
- interbasin transfers;
- environmental effects;
- economic sustainability;
- technical sustainability;
- financial viability.

Table 1. U.S.S.R. Investment in Irrigation and Drainage (billions of 1984 rubles)

Period	Annual average
1966-70	1.7
1971-75	5.6
1976-80	8.0
1981-85	8.7
1986-88	9.2
1989-90	7.9

The Aral Sea Problem

This sea, situated east of the Caspian Sea, is dying. Historically, the sea's volume has been about 1 trillion m^3 of water, but because of huge water diversions, mainly during the last 50 years and particularly for irrigation, this volume has been reduced to about one-third of capacity, i.e., some 350 billion m^3. Consequently the sea has sharply diminished in size; the water has become increasingly saline; and the livelihood and health of some 100,000 people living near the sea and dependent on it for fishing, water supplies, etc., are threatened. In addition, vast areas of salty flatlands have appeared as the sea has receded. Salt from these areas is picked up by the strong dry winds that blow across the plains and is deposited in the agricultural land in the vicinity of the sea. The salt is also sometimes deposited as far as Afghanistan and beyond, causing ecological damage. Currently, the water from the sea is evaporating at a rate of some 35 billion m^3 a year, while remaining inflows from the two rivers that feed the sea are only 9 billion m^3 a year, for a net annual loss of 26 billion m^3. Within 10 to 15 years, therefore, if the current rate of water extraction continues, the sea will dry up completely.

Various proposals are under consideration for dealing with this environmental problem:

1. reduction of the substantial water losses currently being experienced on the 8 million ha under irrigation in Central Asia using the waters of the rivers that would normally flow into the Aral Sea. Here, water consumption of 8,000 m^3/ha is sought and has been achieved, compared with current averages of 14,000 m^3/ha and maxima (on rice areas adjacent to the Aral Sea) of 20,000 m^3/ha;

2. introduction of water-saving technology, which even on hydraulically efficient irrigation systems could induce further water savings. The water-saving technology currently being considered is drip irrigation, even for line crops such as cotton, and experimental results have been positive, demonstrating that large water savings are possible, concurrent with increased crop yields;

3. conversion of crops being irrigated into more water-efficient varieties, i.e., from rice to crops such as cotton and soybean;

4. improvement of drainage in irrigated areas to reduce the amount of water needed for application to the soil for leaching salts prior to crop planting;

5. water transfers from the north to supplement the supplies available to Central Asia;

6. diking the Aral Sea to reduce the area subject to evaporation and safeguard an economic area of water that can be used for fishing and water supplies, etc.

The major institute in the Soviet Union responsible for assessing the Aral Sea problem is SANIIRI, the Tashkent Water Resources Institute.

The Caspian Sea Problem

There is some controversy over whether this is actually a long-term problem. The level of this large sea remained fairly steady at 26 m below sea level (-26 m) throughout the 19th century and the first part of the 20th century. In the 1930s, the level fell sharply to -29 m, coinciding with major diversions from the Volga River and other rivers emptying into the Caspian Sea, prompting significant concern about this rapid drop in water level. In recent years, however, although diversions for irrigation have increased, the level in the sea has recovered to -28 m. There is evidence that this recovery is a short-term phenomenon, and most technicians expect the fall to continue. Estimates are that a further 3-m fall would all but destroy fishing in the Caspian and that this could occur in the next 30 years. Interbasin transfers to divert more water to the Volga River are viewed as a way of resolving this problem. Improved water use efficiency in irrigation, as proposed for the Aral Sea, would also help, although the Caspian Sea's size is such that it will be difficult to influence water level charges in the short to medium term.

Interbasin Transfers

The current slowdown in the expansion of irrigation in the U.S.S.R. is a function not only of the reduced financial resources being allocated to the subsector, but also of the almost complete exploitation of major water resources currently available to develop the trans-Caucasian and Central Asian areas. Further expansion can only come through major transbasin diversion schemes, including river reversal. Indeed, it appears that some existing projects have been designed assuming that these major river reversal schemes will be carried out, with headworks and reservoirs economically sized in anticipation. There is thus already a water deficit in regions where irrigation has been developed, most noticeably in Central Asia where the Aral Sea problem has already emerged as a major issue.

There are two major schemes being considered involving the diversion of water away from the Arctic Ocean, turning it southward to flow into the more populated areas of the south where water shortages are presently occurring. Both of these schemes have received much criticism within the Soviet Union because of the possible environmental implications for the Arctic Ocean of diverting fresh warmer water from the north to the south. Neither of these schemes is presently being seriously considered for implementation; however, both remain on the books and may be considered at some future date. The Kama-Vychegda-Pechora reversal scheme would divert water from the Vychegda and Pechora rivers into the Volga River basin so that the water could be used in the water-deficit southern basins near the Caucasus. It would also divert water to the Caspian Sea, generating hydroelectric power along the way. The amount of water being considered for the transfer scheme is 36 billion m^3 a year. The Ob-Irtysh-Tobol reversal scheme would take water from the Ob River basin and transfer it through a canal across the Kazakhstan Desert to the Aral Sea basin. Various options are under consideration, the most likely of which involves a 100-m lift pumping station followed by a 2,500-km canal across the desert to be built at various sizes depending on the quantities of water transferred. Rough cost figures given to the mission were 10 billion rubles for an annual transfer of 4 billion m^3 of water and three possible additional stages involving 14, 24, and 60 billion m^3 of water a year, respectively. The mission was not able to view the details of the project, but clearly a 2,500-km canal crossing a desert area with mobile dunes must be a major technical undertaking, apart from the high costs involved, and there must be some doubt that the project is technically viable.

Another striking example of a major water transfer is the existing Karakoum Canal, which extracts water from the Amudarya River, one of the two key rivers flowing through Uzbekistan to the Aral Sea, and diverts it westward toward the deserts of Turkmenistan and ultimately toward the Caspian Sea. At completion, the Karakoum Canal, which has been under construction since 1954, would be 1,450 km long.

Environmental Effects

Irrigation in the Soviet Union raises several environmental issues, particularly salient as a result of the rethinking of the direction of agriculture under *perestroika*. Soil salinity is widespread in Central Asia and has become a major environmental threat to people and to agriculture. Currently, some 3 million ha in Central Asia reportedly require drainage to control the salt buildup and permit the continuation of irrigated agriculture. In addition, heavy consumption of pesticides and fertilizers, again particularly in Central Asia in the vast cotton areas, has caused serious pollution of groundwater and of surface channels linked to the drainage system. Another concern is the elimination of biological flows in rivers as water has been diverted for irrigation and has left surface channels empty or with less than the biological minimum to maintain the ecosystem of the river channel. An extreme example is the Aral Sea problem described above. With the decision not to go forward with the river reversal schemes described above, current environmental concerns in the Soviet Union precluded adverse environmental effects. Concerns were expressed that the ecological damage from the transfer of major quantities of water from north to south could cause major climatic changes in the north of the country, and these concerns, among others, have so far led to the abandonment of the major schemes.

Economic Sustainability

Few of the schemes developed during the last 50 years have been subject to any conventional economic analysis, i.e., the type carried out in Western market economies. As the Soviet Union moves toward a market economy, will the enormous investments that have been undertaken in recent years be economically viable? Will the schemes developed contribute toward the creation of wealth in the country, or will they, because of their conception and design, siphon resources away from productive use? These questions cannot be answered without a detailed analysis of different schemes involved. However, based on experience in other countries with similar climatic conditions and similar technical designs, it appears that the bulk of Soviet schemes that have been developed are, and will remain, economically viable, particularly on a marginal cost and actual benefit basis, in the coming years, provided they are adequately maintained. There will be exceptions, of course, where technical constraints remain and require vigorous technical measures, such as interbasin transfers as an integral part of the implementation of a scheme or water pumped at unreasonably high heads to reach canal command areas (i.e., heads of over 200 to 300 m). The economic viability of continuing with such schemes will be questioned. For new schemes, however, the situation will be very different in that sunk costs cannot be ignored and all new investments must be carefully considered. Here, a new analysis capability to determine economic viability under market conditions will be required.

Technical Sustainability

The mission's brief visit to irrigated areas and consultations with specialists and with technical publications indicate that the technical sustainability of several projects completed in the past will be of great concern. Specific issues include rapidly evolving problems of salinity and lack of drainage; the widespread use of poorer-quality materials in construction, which will lead to the breakdown of irrigation and drainage systems and the need for extensive refurbishment and rehabilitation; the increasing difficulty of distributing overdeveloped and scarce water resources among numerous and various users, leading to frequent water shortages; and the increasing effects of the current power crisis, which limits the energy that can be allocated to pumping stations to maintain water availability. All these issues and others will be of concern for Soviet irrigation in the coming years, and a serious assessment of the technical status of projects is required so that necessary interventions can be made to avoid future technical problems. For some schemes, technical problems will be such that major rehabilitation or closure will be the only options.

Financial Viability

The new market system developing in the Soviet Union will provide an entirely new environment for farmers and irrigators. Relative and absolute prices will change substantially. Some crops, which may currently seem viable, may be completely nonviable in the future and vice versa. Water charges, currently nonexistent, will be introduced, and the costs of using water will have to be offset against production benefits. All these factors will lead to a new assessment of the financial sustainability of farms, in that farmers must be capable of paying operation costs if irrigation schemes are to survive. Changes in crops and cropping patterns may subsequently lead to the redesign of irrigation schemes to match the new economic circumstances of farmers or state farms.

Medium-Term Priorities

Although several general technical and economic issues have been identified, sustainability issues are of greatest concern for those existing schemes that will operate in the new economic environment created by the move to a market economy. The potential risks to sustainability in an economic, technical, and financial sense need to be assessed carefully for both public and on-farm schemes, so that authorities and owners can take the required steps to avoid sharp setbacks in Soviet irrigated agriculture in the coming years. Given Soviet agriculture's high level of dependence on irrigation, it is urgent that a program of technical and economic assessment of all major existing schemes begin, to evaluate current technical sustainability and to determine the interventions necessary to safeguard irrigation in the future. The creation of a market economy should make this exercise worthwhile because there will finally be an opportunity for the market to deliver the quality materials and services needed to support a successful irrigation industry. For example, substandard plastic pipes, currently used for subsurface drainage and highly subject to clogging, may be replaced by pipes of a satisfactory technical specification and facilitate more efficient agriculture. Also, currently inefficient vertical drainage through rusting mild steel screens attached to tubewells may be replaced by longer-life fiberglass or stainless steel screens and ensure more efficient drainage. Orders for spare parts may be filled without waiting for centrally planned allocations, allowing sprinkler equipment or central pivot systems to operate with lower downtimes and permitting pump stations to be maintained in good working order. Similarly, pipe systems can be improved to ensure a more reliable supply of water.

The organizations responsible for operation and maintenance—with more secure income resulting from water charges for farmers—should be able to establish more coherent plans for preventive maintenance and for better water distribution patterns, considering the new farm structures slated for development through privatization of farms. In addition, smaller farms that will result from privatization will require that large schemes be remodeled to provide for improved water distribution at the farm level, particularly for those schemes where current irrigation plots are very large.

Finally, agricultural extension will become important in advising the new farmers on water distribution methods and irrigation techniques. A completely new approach to providing these services will be vital to maintaining the economic performance of existing irrigation projects.

Conclusion: Assistance Options

The Soviet Union has highly qualified technical specialists who are at the cutting edge in many technical fields. There is a high level of technical expertise in irrigation, but specialists would benefit from increased contact with other countries. Economic and financial experience is more limited, and experience with operating in a market economy is nonexistent. In light of the above and given current changes underway in the country, technical assistance may be useful to help the Soviet Union and republican authorities develop assessments of:

- the long-term economic sustainability of irrigation schemes;
- the technical sustainability of irrigation schemes;
- the financial viability of irrigation schemes under the new economic and financial circumstances induced by the introduction of a market economy.

Technical assistance may also be useful in aiding the Soviet and republican authorities in establishing new operation and maintenance plans for the country's existing irrigation systems given the new economic circumstances and in establishing modern agricultural extension services that can help farmers deal with problems of water use and agricultural development under irrigated farming conditions.

AGRICULTURAL DIVERSIFICATION AND THE ROLE OF IRRIGATION

Shawki Barghouti

To promote agricultural development, policymakers and agricultural planners are increasingly focusing on agricultural diversification because it offers opportunities to reduce production and price risks, increase flexibility, increase agricultural incomes, and sustain productivity and growth. A vital component of diversification is technological improvement, for example of irrigation systems. Modern irrigation technologies in particular have increased water use efficiency, facilitated cultivation of marginal soils, and enabled regions with limited water supplies to shift from low-value crops with high water requirements to high-value crops with lower water requirements. The Bank's portfolio in irrigation and drainage has witnessed significant changes in recent years, and projects have been affected by design, construction, management, and operational factors, as well as the reliability of water supplies. The Bank is responding to these issues, with Bank irrigation projects now emphasizing institutional strengthening and lower-cost rehabilitation, as well as technological research.

This paper reviews recent developments in the agricultural sector and their implications. It examines the role of irrigation in expanding production opportunities, as well as the evolution of the Bank's irrigation and drainage portfolio, highlighting the Middle East and Southeast Asia. Last, policy reforms, essential components of future agricultural development strategies, are proposed.

Recent Developments in the Agricultural Sector

The most notable development in the agricultural sector is its declining contribution to the national economy (table 1). Farm incomes are lower than urban incomes, with the nonagricultural sectors drawing resources away from agriculture and low prices and incomes "pushing" farmers into urban jobs. Farmers are diversifying their income by seeking partial employment outside the farm sector. Growth in the rural nonfarm economy has been significant in most developing countries: nonfarm activities now account for 20 to 30 percent of rural employment in Asia and Latin America and 10 to 20 percent in Africa (World Bank 1990b). Most successful countries use this structured transformation for more efficient resource allocation and better income distribution.

The second important development involves the rapid progress in the development of advanced agricultural production technologies. The new technologies enabled farmers to increase their output and provided them with new production options and more flexible farming systems. Much of the increase in world food production since 1960 has resulted from intensified production of rice, wheat, maize, poultry, and dairy products. This production growth has been achieved primarily through yield increases. Baanante et al. (1989) projected that between 1982/84 and 2000, yield increases would account for approximately 50 to 80 percent of production growth in Latin America, the Near East and North Africa, Sub-Saharan Africa, and Asia; expansion of cultivated land and

---

Shawki Barghouti, formerly chief of the Agricultural Technology and Natural Resources Division, Agriculture and Rural Development Department, is chief of the Agriculture Operations Division, South Asia Region Country Department II, World Bank. This paper was presented in 1990.

Table 1. Percentage Share of Agriculture in GDP and Employment in Selected Countries, 1965, 1988

Country	% share of agriculture in GDP		% share of labor in agriculture	
	1965	1988	1965	1988
Southeast Asia				
Malaysia	28	21	60	36
Thailand	32	17	82	59
Philippines	26	23	57	49
Indonesia	56	24	71	55
Middle East and North Africa				
Egypt	29	20	55	42
Turkey	34	19	75	52
Syria	25	22	52	25
Morocco	22	18	61	40
Tunisia	20	17	49	32
Jordan	18	8	37	6
Algeria	13	8	57	24

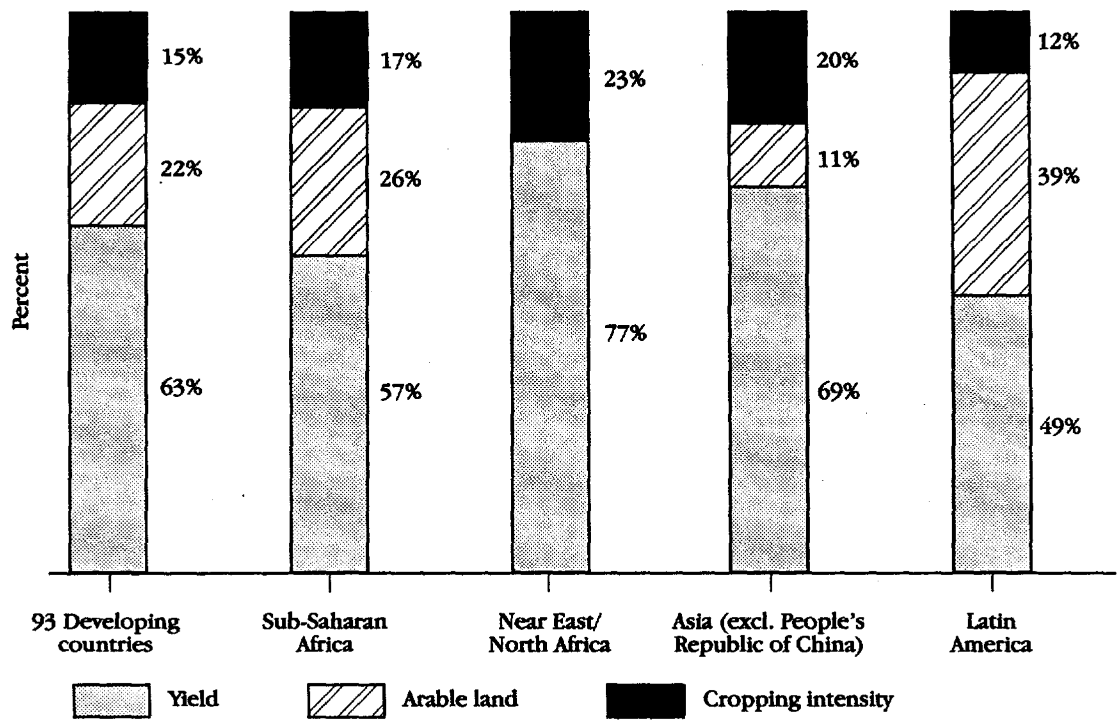
Source: World Bank 1982, 1990b.

increased cropping intensity will account for the remainder (figure 1). The basic technologies responsible for these output increases are improved plant varieties and animal breeds, agrochemicals, and irrigation systems. High-yielding varieties of rice, for example, largely contributed to the doubling of yields in several Asian countries (figure 2). These recent technological advances, however, were a double-edged sword. The technological changes in both crop production and irrigation were accompanied by an increasing scarcity of suitable and productive agricultural resources; scarce water resources and the diminishing availability of suitable lands with fertile soils are evident in many developing countries. Concurrently, global changes in output, particularly of cereals, resulted in lower commodity prices (Timmer 1988). Under these conditions, farmers, especially in countries that have narrowed their food self-sufficiency gap, have had to search for new crops, technology, and production systems to sustain their farming enterprises. In Southeast Asia and the Middle East, this has translated into the rapid growth in production of nontraditional agricultural commodities such as fruits, vegetables, roots and tubers, and poultry.

The third important development is the increasing awareness of and concern about the impact of current production practices on the environment. Environmental degradation resulting from intensive production practices is a growing problem in many developing countries. For example, the long-term decline in rice yields is the result of the combined effects of increased pest pressure, the rapid depletion of soil micronutrients, changes in soil chemistry induced by intensive cropping, and increased reliance on low-quality irrigation water (Flinn and De Datta 1984; Pingali et al. 1990). Agricultural diversification thus offers one approach for stemming further environmental degradation through the establishment of multicommodity production systems that are not only economically profitable, but also environmentally sound.

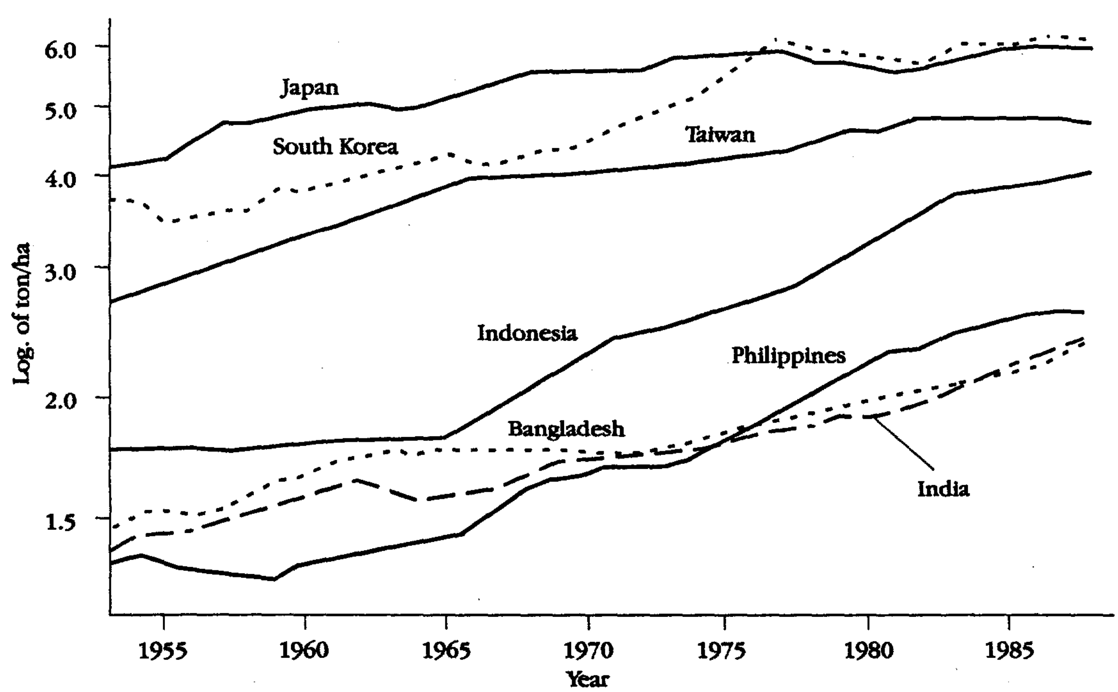
Last, the world market is characterized by shifting consumer demands and increased competition. Consumption patterns, especially among high-income communities, are shifting away

Figure 1. Projected Contribution to Production Growth of Yield, Land, and Cropping Intensity, 1982/84-2000



Source: Baanante et al. 1989.

Figure 2. Rice Yields per Hectare Harvested for Selected Asian Countries, Five-Year Moving Averages, 1953-88



Source: IRRI 1990.

from more traditional staples toward higher demands for livestock products, fruits, and vegetables. The sharp increases in fruit, nut, and vegetable exports of various Asian and Near Eastern countries underscore the rapidly increasing demand for these products.

The Role of Irrigation

Technological Improvements

Technological improvements in irrigation systems have expanded production opportunities, thereby facilitating agricultural diversification. Whereas traditional irrigation technologies (furrow, border, and flood irrigation), which involve water delivery to plants through gravitation, usually resulted in substantial water losses and limited uniformity in water distribution, modern irrigation technologies (particularly sprinkler and drip irrigation) are characterized by increased water use efficiency. Furthermore, they have provided greater opportunities to cultivate soils with low water-holding capacity (sandy and rocky soils) and to farm low-quality lands and steep slopes. This transition has also enabled regions facing limited water supplies to shift from low-value crops with high water requirements (e.g., cereals) to high-value crops with lower water requirements, such as fruits, vegetables, and oilseed. It has also allowed the use of low-quality (e.g., highly saline) water in regions with high temperatures and high evaporation rates.

The Bank's Irrigation and Drainage Portfolio

The Bank is a major participant in discussions of diversification because of its dominant role in agricultural lending. Between 1974 and 1986, the Bank lent almost $40 billion, representing 30 percent of its total lending, to support adjustment activity and agricultural projects, whose total cost exceeded $100 billion. An average $1.5 billion a year, about one-third of Bank agricultural lending, was invested in irrigation (Barghouti et al. 1990). After 1986, lending for irrigation declined significantly, to an average 16.3 percent of agricultural lending. In FY91, however, lending for irrigation and drainage represented 28.8 percent of total agricultural lending and is gradually returning to previous levels (World Bank data).

Bank investments and programs have had a major impact on agricultural production. Projects approved between 1974 and 1986 were expected to result in the incremental annual production of over 12 million tons each of rice, wheat, and corn, and to substantially increase the output of other commodities. The output level for rice was greater than the amount of rice traded in world markets in the mid-1980s, and the projected levels of output of other commodities represented sizable shares of world trade. The Bank's funding of irrigation schemes to expand rice output in Asia was largely responsible for these surpluses in world markets. Bank projects also increased demand for commodities in the developing Asian countries by raising real incomes and supporting the overall process of economic development. Although projects increased rice production and contributed to food security, surpluses and falling rice prices ensued, perhaps due to a lack of coordination across country projects and inaccurate price projections used in investment appraisals.

In response to the commodity surpluses of the mid-1980s, the Bank initiated wide-ranging policy debates with member counties about appropriate forms of intervention in the agricultural sector. The recent emphasis on policy-based lending has further increased the Bank's role in agriculture through efforts to improve the economic environment for farmers in countries where policies have generally penalized agricultural sectors. In light of the low international prices for most agricultural commodities in the mid-1980s, the Bank is concerned about the profitability of past and future agricultural loans. Many existing commodity-based projects would not have appeared profitable if prices that prevailed in world markets in the mid-1980s had been used in investment appraisals, and few investments would be deemed profitable on the basis of currently projected price trends.

Support for existing projects is also a concern, with lack of a cost recovery mechanism impeding the development of efficient irrigation systems. The poor record of cost recovery suggests that the full benefits of irrigation investments are not being realized. The ability to impose betterment levies depends on the actual betterment realized, which in turn depends on the reliability of timely water supplies to farmers, input and output prices, and the quality of extension services. In the mid-1980s, cost recovery problems were compounded by falling rice prices: just when more efficient irrigation systems were needed, farmers' ability to pay for water was lessened. Even in efficient systems, low prices for agricultural products reduce incentives for farmers to use costly water.

In some countries, existing irrigation systems have been neglected, and rehabilitation projects have become a higher priority than expansion into new areas. Because of poor operation and maintenance (O&M), the benefits from irrigation have often fallen short of the potential. The revenue generated from water charges and betterment levies is typically not adequate to cover O&M costs, which are about 10 to 15 percent of initial investment. Because of revenue shortfalls, O&M tend to be neglected. System deterioration has both short- and long-term effects, and rehabilitation is costly. O&M costs should be financed by proceeds from the project to link farmers's needs for timely water deliveries with incentives for system managers. To improve irrigation and drainage projects' O&M, Bank lending has evolved toward lower-cost rehabilitation and institutional strengthening, with interventions increasingly national or regional in scope. This new approach focuses on institutional development and the rehabilitation and improvement of existing irrigation systems, rather than the construction of new systems or the extension of old ones.

Diversification Experience in the Middle East and Southeast Asia

The diversification process in Southeast Asia and the Middle East has been spurred by several factors: (a) declining returns from cereal-based farming operations; (b) the availability of advanced irrigation technology; (c) the development and adoption of improved high-value crops; (d) increased domestic and regional demand for fruits, vegetables, and livestock products; (e) the growth of private agribusiness involved in processing and marketing; (f) the shift of labor out of agriculture as employment opportunities in other sectors became increasingly available and rewarding; and (g) the reduction of government intervention in farmers' decisionmaking and the removal of distortionary policies that favor selected crops and limited commodities (Timmer 1988; Tsakok 1989; Barghouti 1990; Barghouti et al. 1990; World Bank 1990a; Somel 1991).

Agricultural policy reforms have been an important factor in the promotion of agricultural diversification. In particular, preferential treatment for cereal production, such as subsidized water and fertilizers, has frequently been removed or at least reduced. Public services in research, extension, credit, and marketing have expanded to cover production and processing of both cereal and noncereal crops. For Southeast Asian and Middle Eastern countries, the main appeal of diversification is that the process identifies viable areas for investment in agriculture and rural development that may reduce the cost of price stabilization programs and transfer some of the burden of price instability to farmers and away from the budget. Because the large budgetary expenditures involved in the stabilization of agricultural prices are usually unsustainable in the long run, the promotion of more flexible agricultural systems can alleviate much of the political and economic need for such large budgetary expenditures (Timmer 1988).

Middle East and North Africa

In the Middle East and North Africa, diversification of agricultural systems has been made possible because of declining profits from cereal production, increasing scarcity of fertile lands and water, and substantial growth in demand for high-value crops (fruits and vegetables) in both domestic and regional markets (Tsakok 1989; Barghouti 1990; Somel 1991; Jaffee, forthcoming). The agricultural sector in several Middle Eastern countries has also witnessed remarkable changes and modernization. Much of this modernization has been made in the irrigation subsector. Irrigated agriculture in this region has benefited from a wide variety of products derived from the recent scientific advances in water and crop management, biotechnology and crop improvement, and marketing and processing facilities. These changes have been made possible because of effective and somewhat aggressive private sector companies that became involved in introducing (a) modern production technology, such as plastic houses, tunnels and mulches, soil fumigation chemicals, improved hybrid varieties, drip irrigation systems, and soluble fertilizers and herbicides; and (b) efficient marketing technology, such as suitable packaging and storage facilities, modern market information systems, and transport equipment with refrigeration for long hauls. These companies provided farmers with the necessary support to adopt modern technologies required for the cultivation of suitable, long-life varieties of fruits and vegetables.

Southeast Asia

During the 1970s, farmers in several Asian countries significantly increased total production of rice. In response to stable prices for rice and subsidized imports during that decade, rice output grew at an annual rate of 3.7 percent in Southeast Asia (IRRI 1990). The adoption of high-yielding varieties combined with the expansion of irrigation facilities and higher application rates of fertilizer led to much of the growth in production. Surpluses developed in the mid-1980s, forcing down rice prices in domestic and world markets. In response, farmers in some countries began, to varying degrees, to shift to the production of other commodities. For example, in Thailand, Sriarunrungreauang (1989) found that farmers increasingly diversified into the production of other agricultural commodities, such as vegetables, seasonal crops, cattle, and poultry, as rice prices declined. Farmers in rice-based agricultural systems in Southeast Asia, however, often experienced unexpected problems. Their efforts to shift to other crops and to invest in other agricultural enterprises were frequently hampered by traditional irrigation facilities and limited improved technological options for other crops. In addition, government policies; services (research, extension, and credit); and incentives for food crops have discriminated against the growth of high-value crops Timmer 1988; Barghouti et al. 1990; World Bank 1990a).

Constraints of traditional irrigation systems. Traditional irrigation facilities in Southeast Asia were primarily designed to provide a reliable supply of water during the wet season for the cultivation of rice under traditional wetland conditions. Irrigation during the dry season was a secondary consideration, and often the reduced supply of irrigation water was used to grow an additional rice crop on a more limited area. Irrigation project sites were originally selected based on their suitability for rice, although other crops can be grown. Agronomically, however, diversification from rice paddy to nonpaddy crops is limited by existing irrigation facilities, growing season, soil type, drainage capability, and land preparation methods for rice. These constraints are interrelated and largely shaped by the geography of Asia and the unique characteristic of the rice plant, which is tolerant of waterlogging and intolerant of water stress.

Lowland rice, essentially an aquatic plant, performs best if the soil is saturated from the seeding and transplanting stages to about two weeks before harvest. The best water environment for rice is a flooded condition, to a depth of 10 to 15 cm, which facilitates benefits related to weed control, nitrogen management, temperature control, and chemical application. Most areas in Asia where irrigated rice is grown have heavy clay soils, ideal for rice production because the soil's capacity for water retention (poor drainage) helps maintain the high-moisture conditions required for rice, whereas almost all other crops are sensitive to poor drainage and continuous high moisture. Because the availability of water in the wet season is excessive for upland crops, prospects for diversification in the wet season are thus limited in most irrigated areas, particularly those with poor drainage. Dry-season potential depends on, for example, whether the soil has adequate drainage capacity.

Rice and upland crops differ in their water requirements in terms of volume and schedule. Most upland crops require much less water than rice but greater control over the rate of application. The amount of water adequate for rice in the dry season is about twice the daily water requirement of upland crops, such as soybean, corn, peanut, and mung bean. In terms of water consumption, the area of upland crops that could be grown during the dry season is twice that of rice; however, upland crops need intermittent, rather than continuous, applications of irrigation water, thus requiring greater water control than most rice-based irrigation systems provide.

The traditional field-level irrigation method for rice production is basin irrigation. Fields are divided into small units so that each has a level (or nearly level) surface, and dikes are constructed around the areas to form basins, within which the irrigation water can be controlled. Traditionally, land is prepared by ponding a shallow depth of water and puddling it to obtain a perfectly flat surface. The basin irrigation system is well suited to continuous irrigation or flooding. In principle, some upland crops, fruit trees, and plantation-type crops can be grown using basin irrigation by flooding fields to a minimum depth and providing water at variable intervals.

In contrast to conventional basin irrigation, furrow irrigation is particularly suitable for irrigating crops that are subject to injury if water covers plant stems. Farmers can plant upland crops in raised beds, which are irrigated by furrows placed between the rows of plants. Because the entire soil surface is not covered by water, efficient irrigation depends on the lateral movement of water from the furrows. Considerable experience and labor are needed to divide water from the supply ditch into several furrow streams and to maintain correct rates of flow until irrigation is complete, with furrow construction requiring abundant labor or heavy earth-moving machinery. Furrow irrigation occurs within the confines of the basin, and farmers sometimes intercrop rice and upland crops. The dikes, or levees, that surround the basin are usually permanent and remodeled as necessary for repeated use.

There are inherent difficulties in switching between cultivation of irrigated rice and upland crops. The fundamental difference between the two irrigation methods—basin and furrow—has considerable impact on the necessary degree of water control in the distribution system and the channel network at the field level. The furrow method, supplying periodic and measured irrigation, requires greater control than the basin method of continuous irrigation and flooding. In addition, the puddling method of land preparation for rice requires areas of small units (basins) for the water supply to be level when flooding the field. A level field has to be maintained to ensure even distribution of water within the basin. Upland crops usually require some slope to ensure better drainage. The grading of fields can entail considerable expense.

Because large-scale irrigation projects are planned for rice production, systems are not geared toward crop diversification at the farm level. In almost all rice-growing areas, the dominant method of irrigation is basin to basin on a continuous basis. The size of irrigation service areas can vary from a few hectares to over 50, depending on topography and spacing between minor canals. Individual farmers' flexibility in cropping and water control is limited by collective irrigation and drainage practices.

Improvement of irrigation systems. Improvement or modernization of irrigation systems to permit diversification into nonrice crops has been complicated by the sharp drop in rice prices during the 1980s. Until that time, most rice irrigation projects were viable, including those for which all infrastructure—down to the on-farm water delivery works—was built. Currently, the only viable investments in rice irrigation are those that take advantage of sunk costs in existing infrastructure, with a detailed analysis of each project necessary because of the sensitivity of the rate of return to low rice prices. Investment in improving the tertiary system and the distribution system may not be justified unless, as a result of using the water saved through more efficient operation, there is a substantial increase in rice yields, an increase in cropping intensity, or both. Increased production of rice alone may not economically justify these improvements; the land may have to be planted to higher-value crops. The investment required for crop diversification should be undertaken only when there is sufficient indication that other preconditions, such as market demand, marketing facilities, and extension services, have been met.

A practical requirement for diversified cropping may be that rice and upland crops not be planted in the same service units, since seepage of water from neighboring basins is difficult to avoid. This does not, however, solve the problem of providing better water control and drainage for upland crops. The operation of irrigation systems for nonrice crops differs from that for rice cultivation, and a different orientation of operating staff is required. Nonrice crops require more intensive water management, both for the canal system and on the farm. In particular, these crops need a large intermittent delivery flow, rather than the small continuous flow required for rice. Constant attention is needed to rotate supply among canals or outlets, to supply water to individual fields for short periods, to adjust water delivery to match crop water needs, and to control water delivery to ensure suitable stream size and avoid waste.

Increased attention needs to be given to increasing farmers' flexibility in the dry season. Most irrigation projects lack dry-season storage capacity; only about 25 percent of the total service area in Thailand has this capacity. Improvements can be made in water control at the farm level, water storage facilities, and water conservation during the wet season by lining water channels and controlling the general inefficiencies of the water delivery system. Investment in these improvements would increase the flexibility of the present system.

Where farmers have suitable soils and sufficient water control, they have diversified production during the dry season. Rice-growing areas in Malaysia, Sri Lanka, Indonesia, and the Philippines have more dry-season irrigation than do other countries in South and Southeast Asia. Whether they plant one rice crop or more depends on the amount of water available for the second crop season—if insufficient for rice, a nonrice crop is grown. The crop seasons for rice vary with the differing climatic conditions of Asia. In some areas, farmers can plant a nonrice crop—such as corn, soybean, or vegetables that fit the crop calendar—in a third crop season that is irrigated if there is sufficient water. In Southeast Asia, the introduction of short-season rice varieties allowed farmers to plant the second rice crop with a short-season variety and follow it in the dry season with high-yielding corn or soybean with a longer growing season (100 days or more) than that of traditional varieties. Improved facilities for local research and extension could play a major role in adapting crop varieties to fit particular niches in the crop rotation and developing varieties resistant to local pests and disease.

Components of a New Agricultural Development Strategy

The challenge to agriculture is to sustain farming of traditional crops while expanding into a more flexible, diverse agriculture. The objective of this process should be to keep the adjustment costs relatively low and yet diversify the agricultural economy away from its heavy reliance on traditional crops and toward other items with more favorable income elasticities of demand: livestock products and fruits and vegetables, for example. Such demand-led diversification should be part of a broader process of developing an appropriate mix of agricultural policies and production technologies.

Governments tend to allocate resources to develop commodity-specific programs and set production targets for the crops for which the country, judging from world market prices, might have a comparative advantage. Target-oriented diversification programs, however, risk diversifying farmers into crops whose prices may fall (or even worse, the added output causes prices to fall), with farmers no better off than before. To avoid this situation, it is necessary to regard diversification as a process of adjustment, rather than the establishment of targets for cropping patterns, and to shift resources at the margin from specific crop or irrigation investment to more general and less crop-specific rural and marketing infrastructure and institutions. Such efforts may also help close the gap that exists in most agricultural development strategies, i.e., the "intermediate" agricultural sector that involves neither a basic food staple nor a traditional export crop.

The main lesson from the experiences in Southeast Asia and the Middle East is that investment in agriculture should preferably be for broad-based sectoral operations and less for commodity-specific, production-oriented projects. Furthermore, the success of government investment is contingent upon major changes in government policies, incentive programs, and agricultural services and upon the development of technological innovations promoting more efficient production.

Policy Framework for Diversification

Agricultural diversification will be facilitated by the increased use of multidisciplinary approaches in designing investment strategies, the removal of distortionary policies, the elimination of land use restrictions and improvement of land tenure security, the expansion of private sector involvement, and the avoidance of a "pick-the-winner" project approach. A balanced mix of skills is needed to plan strategies for agricultural diversification. There should be a multidisciplinary approach to project design and appraisal that goes beyond economic policy analysis and includes technology assessment in production, processing, and marketing. Project design must incorporate advanced technological concepts that could increase farmers' options for production, as well as mechanisms for effective management of agricultural input supply, marketing, and processing. Expertise is required in irrigation and water systems design and management, natural resources management, rural industry and infrastructure, and integrated farming systems.

Price stabilization policies should not be at the expense of secondary crops. Governments pursuing a policy of domestic price stabilization should minimize price distortions by maintaining appropriate relative prices between primary and secondary crops. Restrictions on land use and landholding size should be adjusted to encourage investments in land improvements and flexible farming systems. Land tenure arrangements should provide domestic and foreign investors land use security. Legal and institutional barriers that inhibit the economic activity of the private sector should also be removed. Attention should be given to reducing public sector monopolies on marketing and licensing requirements for agricultural production and processing, strengthening property rights, and rationalizing foreign exchange. Private sector participation may also be fostered through the promotion of joint ventures and contract farming. Governments should provide the right set of incentives and legal and institutional arrangements to attract foreign and domestic investors to participate in joint ventures and contract farming for the production of high-value crops and livestock.

To accommodate potential changes in farming patterns and to provide increased opportunities for off-farm employment, governments should devote more attention to promoting investment in small- and medium-scale industrialization in rural areas. Finally, it is necessary to perceive diversification as a process of adjustment, not the selection of specific cropping patterns. Farmers should be provided with options that encourage them to grow crops for which they have a comparative advantage based on agroecological and economic factors.

Essential Support Services

The focus of diversification is on improving farmers' responsiveness to changing market conditions and new technologies. Emphasis should be placed on providing farmers with a wider range of technological options and facilities to pursue diverse production patterns, as well as off-farm employment that will maximize household income. The scope of research, extension, marketing, and credit should be expanded from being crop-specific and production-oriented to cover both primary and secondary crops and livestock, supporting not only production but also processing and marketing. Extension workers, for example, should be able to deliver a range of agrotechnical messages for various crops and to provide marketing and price information, as well as information about off-farm economic activities. Assistance should also be provided to traders and processors.

Governments should encourage investment in the modernization of marketing facilities: they can improve marketing by developing rural buying stations and commodity exchanges; by promoting the construction of wholesale markets; and more generally, by investing in improved roads, communications systems, and storage. Market information services and access to international markets should also be expanded. Governments should aim at improving the quality and availability of market information for export crops. Radio broadcasts can provide market information on traditional and nontraditional commodities. Governments should finance market research and information dissemination, especially for small-scale farmers, and also encourage the establishment of growers' organizations. The identification of specific requirements of and market niches in both domestic and foreign markets is also needed. Governments should try to increase access to restricted international markets and devise a strategy that improves their bargaining position on agricultural trade issues. Standards for quality control will help facilitate private participation. Thus, governments should assist marketing agencies in establishing standards and grades to lower transaction costs and facilitate increased opportunities for domestic-foreign marketing and processing.

Greater emphasis on vertical diversification into the processing of both traditional and nontraditional agricultural commodities will help increase the value added of agricultural products and should be supported by governments. Investment in agriculture should not end at the farmgate, but should include postharvest handling and processing and continue to the final consumer. Last, diversification of the agricultural sector will require a wider variety of technical skills. Thus, investment in rural education is essential. Vocational education programs in rural areas should be expanded to provide improved training for on-farm jobs and also for off-farm jobs in the industrial and service sectors.

Role of New Technology

Agricultural diversification requires a comprehensive knowledge of agroecological resources, particularly information about agronomic potential and suitability for profitable production and marketing. Lending for agriculture should therefore include support for studies that improve the knowledge base regarding local agroecological resources (i.e., soil mappings, aerial surveys, hydrological surveys, climatological data, and past and present cropping practices). Effective diversification also requires the development of an appropriate analytic framework to evaluate its performance and progress. The economic analysis of diversification should include both the benefits and costs of increased flexibility of the agricultural system and the enhanced ability of the agricultural system to mitigate the effects of price fluctuations.

To achieve success, diversification will often require new or improved technologies, such as modern water delivery and drainage systems. Investments will be necessary to modernize water control, upgrade existing irrigation systems, and to develop new approaches to increase the flexibility of farming systems. The implementation of efficient water charge mechanisms is also required to improve the management of water resources for flexible cropping systems.

Specific technologies and practices can enhance local comparative advantage in production and marketing, and research strategies should also emphasize the development of innovations that reduce the unit cost of production and increase the quality of outputs to be more competitive in domestic and foreign markets. Concurrently, there is a need for more environmentally sound technologies to ensure sustainable agriculture. Attention should focus on the minimization of agrochemical requirements because of their negative environmental impacts and on the design of farming systems that reduce soil erosion, such as appropriate intercropping and agroforestry. Emphasis should also be placed on integrating crop-livestock farming systems and improved feed grain production and feeding efficiency with increased use of agricultural by-products and waste.

Conclusion

There have been dynamic changes in the agricultural sector, particularly during the last two decades. The Bank is responding to these changes and the related emerging issues through dialogue, research, and increased examination of the implications for investment in agriculture—and more generally for development policies. For diversification programs to succeed in the long run, productive agricultural technology—supported by responsive policies for crops and livestock—is needed. A critical element of this technology involves modernizing irrigation and drainage systems for maximum efficiency. Overall, increasing farmers' flexibility and facilitating their responsiveness to changing market conditions will be crucial to the success of diversification.

References

Baanante, C.A., B.L. Bumb, and T.D. Thompson. 1989. *The Benefits of Fertilizer Use in Developing Countries*. Muscle Shoals, Ala.: International Fertilizer Center.

Barghouti, S. 1990. "Agricultural Diversification: Implications for Crop Production—The Case in the Middle East and North Africa Region." *HortScience* 25(12): 1499-1506.

Barghouti, S., C. Timmer, and P. Siegel. 1990. *Rural Diversification: Lessons from East Asia*. World Bank Technical Paper 117. Washington, D.C.

Flinn, J.C., and K. De Datta. 1984. "Trends in Irrigated-Rice Yields under Intensive Cropping at Philippine Research Stations." *Field Crops Research* 9: 1-15.

Hayami, Y., and K. Otsuka. 1991. "Beyond the Green Revolution: Agricultural Development Strategy into the Next Century." Paper presented at the conference "Agricultural Technology: Current Policy Issues for the International Community and the World Bank," October 21-22, Airlie House, Virginia.

International Rice Research Institute (IRRI). 1990. *World Rice Statistics*. Los Baños, The Philippines.

Jaffee, S. Forthcoming. "Contract Farming in the Shadow of Competitive Markets: The Experience of Kenyan Horticulture." In M. Watts and P. Little, eds., *Peasants under Contract: Contract Farming and Agrarian Transformation in Sub-Saharan Africa.* Ithaca, N.Y.: Cornell University Press.

Pingali, P., P.F. Moya, and L.E. Velasco. 1990. *The Post-Green Revolution Blues in Asian Rice Production: The Diminished Gap between Experiment Station and Farmer Yields.* International Rice Research Institute, Social Sciences Division Paper 90-01. Los Baños, The Philippines.

Somel, K. 1991. "Agricultural Diversification in the Middle East and North Africa." Agricultural Technology and Natural Resources Division Working Paper. Washington, D.C.: World Bank.

Sriarunrungreauang, S. 1989. "The Impacts of Declining Price of Rice on Production, Allocation of Farm Resources and Farm Incomes: A Case Study of Small Rice Farms in Amphoe Don Chedi and Amphoe U-Thong, Changwat Suphan Buri." Master's thesis, Department of Agricultural Economics, Kasetsart University, Bangkok.

Timmer, C.P. 1988. "Crop Diversification in Rice-Based Agricultural Economies: Conceptual and Policy Issues." In Ray Goldberg, ed., *Research in Domestic and International Agribusiness Management,* vol. 8. Greenwich, Conn.: JAI Press.

Tsakok, I. 1989. "Rationalization for an Agricultural Export Diversification Project: The Case for Tree and Selected Horticultural Crops." Ghana Agricultural Diversification Project Working Paper, West Africa Department. Washington, D.C.: World Bank.

World Bank. 1982. *World Development Report 1982.* New York: Oxford University Press.

____. 1988. *World Development Report 1988.* New York: Oxford University Press.

____. 1990a. *Agricultural Diversification: Policies and Issues from East Asian Experience.* Policy and Research Series 11. Washington, D.C.

____. 1990b. *World Development Report 1990.* New York: Oxford University Press.

THE INTERNATIONAL PROGRAM FOR TECHNOLOGY RESEARCH IN IRRIGATION AND DRAINAGE: EARLY EXPERIENCES

Tom Brabben, Walter Ochs, Ashok Subramanian, and Hans Wolter

Population growth and shifting consumption patterns will pose a major challenge for agricultural production in the twenty-first century. Yields in irrigated agriculture will have to increase by an estimated 3 percent to meet future food and fiber demands. Yield growth will depend substantially on the productivity of existing irrigation systems, since there are limits to the expansion of land for irrigation in many parts of the developing world. Moreover, competition from nonagricultural uses is increasingly limiting the quantity of water available for irrigation. Action is needed, therefore, on the policy, management, and technological aspects of the subsector to enhance the productivity of irrigation systems in an environmentally sustainable manner.

Several national and international initiatives are underway to address productivity and sustainability concerns, led by both public and private organizations in developing and developed countries. The International Irrigation Management Institute (IIMI) was specifically set up to promote management innovation in irrigation systems. Multilateral development banks and donors involved in assistance for agricultural investments in developing countries have also made important contributions to policy reviews and irrigation project development.

The International Program for Technology Research in Irrigation and Drainage (IPTRID) was launched in 1991 to complement these efforts and to address gaps in technology research and development (R&D) in the subsector. IPTRID was sponsored by UNDP, the World Bank, and the International Commission on Irrigation and Drainage (ICID) and is a cooperative venture of numerous development agencies, professional bodies, and developed and developing countries aimed at promoting and strengthening adaptive technology research in the developing world. IPTRID does not carry out or finance research; its role is promotional. Donors have supported IPTRID through secondment of long-term experts—as with Germany, the U.K., and, more recently, the Netherlands—and the provision of short-term experts for IPTRID missions. This paper reviews IPTRID's objectives and its identification of priority research areas in sustainability, systems modernization, and maintenance.

IPTRID's Objectives

As the developing world faces the challenges of land and water constraints and environmental degradation, IPTRID's broad objective is the promotion of technology R&D in the irrigation subsector. Accordingly, IPTRID's short-term objectives are to:

Ashok Subramanian is executive secretary of the International Program for Technology Research in Irrigation and Drainage (IPTRID), to which Tom Brabben and Hans Wolter are on special assignment. Walter Ochs is drainage adviser, Agricultural Technology and Natural Resources Division, Agriculture and Rural Development Department, World Bank. This paper was presented in 1991.

- provide a framework for collaborative action for assessing technology R&D needs, formulating research proposals, and conducting research reviews. This collaboration could occur among governments, external supporting agencies (ESAs), national and international R&D agencies, and research users;

- assist developing countries and ESAs in identifying priority needs in R&D for irrigation and drainage technology by supporting the formulation of R&D policies, programs, and projects in line with sectoral plans;

- facilitate training and exchange of information and experience related to the above R&D activities.

Can promoting the technological aspects of irrigation independent of other factors be successful? This issue requires consideration of the main objectives of irrigation improvement:

- an enhanced level of irrigation services in terms of:
  - reliability
  - equity
  - flexibility and timeliness;

- environmental sustainability in terms of:
  - waterlogging prevention
  - salinity prevention
  - water use efficiency;

- economic sustainability in terms of:
  - efficient cost recovery mechanisms
  - reduction in operation and maintenance costs
  - reduction in investment costs in line with payment capacity.

These objectives reflect the perspective of an irrigation agency providing irrigation services to farmers and operating in a market-oriented context. Subsistence agriculture would require a different set of goals. The underlying assumption is that farmers are able and willing to make beneficial use of the irrigation services provided, within the constraints of the prevailing farming systems.

The potential sources of irrigation improvement are related to the following dimensions: (1) technology improvements (modernization), (2) management improvements, (3) farmer participation, and (4) institutional and policy changes. Any program would have maximum impact by addressing all four dimensions simultaneously. In reality, however, this is rarely feasible. Practical constraints make an integrated approach difficult to implement. Additionally, the demand side might exert differential pressure on each dimension's development. The four dimensions can develop independently for some time; however, once development in one dimension threatens the equilibrium of the system, changes in other dimensions are induced. One example is Pakistan, where technology is driving institutional development. Here, the development of more accessible tubewell technology has brought about profound institutional changes. Conversely, the recent drive to privatize irrigation schemes brings forth different technologies for water distribution and measurement. Technology, therefore, can play a leading role in the improvement of irrigation performance.

Expert Team Identification Missions

Between late 1990 and December 1991, IPTRID organized four expert team missions covering five countries: Egypt, Pakistan, Mexico, Morocco, and China. A typical mission has lasted three to four weeks. The composition of the expert team has varied by mission, depending on the focus. Overall, 27 expatriate experts and 19 national experts were used in the four missions. The teams were composed of experts from premier research institutions, technical professionals from donor agencies and consulting firms, and academicians with superior field experience. The teams always included an "external" group of experts and an "internal" counterpart group of national experts that collaborated. In two cases, the "external" group included other developing-country experts.

Observations

The missions' objective was to assist developing-country planners and research managers in identifying priority research areas and subjects that would contribute to productivity and sustainability improvements. On the basis of the missions completed, several observations may be made. First, a country can benefit from a national review of R&D needs. The assessment by a high-level expert team has provided an opportunity for governments to subject R&D work in irrigation to a broad review and has reinforced a current program or recommended changes. The validation by an international expert team also provides governments and donors with a starting point for drawing up detailed proposals for technical and financial assistance, where necessary.

Second, the need for priority setting has been highlighted. In the past, attempts to identify research needs have often led to inventories of topics that have been characterized as laundry lists. The difference now is that IPTRID's missions have assigned priorities among a list of topics. Selection of priorities implies the use of specific criteria to rank research projects. Discussion of these criteria has often led to useful debates on the respective importance of research and development, the time horizon of research, and the relationship of research to sectoral plans and programs;

Third, the missions have highlighted the linkages of research programs with national policies and programs. The preparation of background papers and the briefings by governments, senior irrigation managers, and research institutions have placed research in the context of national policies and programs. Thus, Mexico's declared policy of transferring irrigation management to district-level user associations and China's water-saving programs in the North China Plain provided the setting in which expert teams identified research priorities;

Fourth, utilizing mechanisms to link research to practitioners was discussed during the missions. As part of the assessment exercise, expert teams raised questions about how research agendas have been chosen and about the empirical basis of some of the research output. Field observations in research have sometimes been inadequate, or data gaps have led to unrealistic assumptions about irrigation system performance. In this context, although diagnosis of gaps between research and practice is possible, remedial interventions are complex and require much attention in follow-up discussions within government agencies;

Last, IPTRID's missions have emphasized the need for adaptive research. Pilot testing and large-scale field trials have been recommended for major problem areas, with the rationale that effective and environmentally sound technological innovations must be tested and demonstrated under field conditions so that modifications can be made to suit local economic, social, and agronomic conditions. The implication is that careful monitoring must follow field research. This is a gap in some donor-supported efforts to introduce technological innovations in irrigation systems.

Sustainability

Waterlogging and Salinity Control

All the countries that have invited IPTRID have indicated waterlogging and salinity control research as an important area. This is not a new research issue: Pakistan has been addressing this problem since the 1960s through salinity control and reclamation projects, and significant experience is available in China's more humid and arid zones. What is new is that changes have occurred in two key aspects of waterlogging and salinity:

1. The intensification of demand for land and water in the 1970s and 1980s led to a renewed interest in land and water conservation, and thereby in control of the "twin menace" of waterlogging and salinity;

2. New materials and techniques have been developed while old standards and criteria have been challenged with respect to drainage design, information systems, envelope material, reuse of drainage and urban wastewater, and effluent disposal. Some innovative techniques in these fields now seriously weigh the environmental and health consequences of poor drainage and poor soil and water quality.

Common Research Needs

Most research needs that have addressed sustainability and been identified by IPTRID expert missions involve the following measures:

- design criteria improvements for drainage systems based on operational experience and new developments;

- development of new criteria or improvement of existing criteria for the reuse of wastewater from drainage systems and treatment plants;

- improvements in drainage materials in terms of quality and cost-effectiveness;

- research to improve health factors related to waterborne disease and water quality factors relating to disposal of water from drainage sites;

- research on special problems such as:

    - subsurface drainage of rice paddies
    - drainage of heavy clay soils and problem soils
    - control of water tables for subirrigation;

- research to integrate waterlogging and salinity control with research on maintenance of drainage and irrigation channels.

Lessons Learned

The central lessons from the IPTRID missions on research to improve the sustainability of irrigated agriculture can be summarized in four areas. First, an internationally agreed upon research agenda is needed to refocus attention on sustainability and its direct implications for land and water quality. IPTRID's missions to Egypt and Pakistan revived interest where there was increasing country and donor "fatigue," and in Mexico, Morocco, and China, the need for new research was stressed.

Second, professional interchange among countries and research institutions on specific problems is necessary. Therefore, IPTRID proposed and is initiating an Egypt-Pakistan network to exchange knowledge and experience and to avoid repetition of past errors.

Third, there is an urgent need to review current practices and standards and formulate new criteria for various aspects of drainage system design, incorporating environmental safeguards. Fourth, research on waterlogging and salinity control must be linked to sound irrigation water management, including water-saving techniques and the proper maintenance of irrigation and drainage systems. It must be stressed that these issues are usually so interrelated that they all require some consideration.

Modernization of Irrigation Systems

Despite the impressive advances of drip and sprinkler irrigation, in canal regulation and instrumentation the irrigation technology in most large irrigation systems in Asia and elsewhere has changed little over the past 50 years. Perhaps there was no real need for modernization: traditional irrigation systems in Asia generated few difficulties and are well adapted to the monsoon climate and to the predominant rice cultivation, which provides considerable in-field storage and allows field-to-field irrigation. Severe problems only occurred as cropping intensities increased and farmers needed more reliable and flexible water deliveries to meet the requirements of modern crop varieties and increasingly complex farm operations. Furthermore, the intensification of agriculture without better water control aggravated drainage problems and increased the incidence of waterlogging and salinity. Crop diversification in traditional rice-growing areas in Asia requires some radical departures from old continuous-flow water delivery.

At present most irrigation canal systems in developing countries operate under upstream control, seeking to spread a certain amount of water evenly over the command area. Structures in the main canals are equipped with sliding gates for manual adjustment. Upstream control usually requires the preparation of delivery schedules, which optimally are based on field observations and crop data, though in many cases they are repetitions of outdated manuals or design reports. Upstream control requires estimates of distribution and conveyance efficiency as well as of the transmission time to determine the flow and the time of release at the headwork. Frequent adjustments of gates are necessary, and the establishment of stable flow or stable water level conditions requires considerable experience. Operational losses of well-managed upstream control systems frequently exceed 20 percent.

Modern irrigation system design and operation differ from the upstream-controlled irrigation system described above. The distinctive feature of modern systems is the service concept. Water is provided to the user as a service that should be as convenient and flexible as possible. This concept implies a different approach to design and operation. The process begins with a vision of the future operational procedures and performance standards for each project level, identifying performance objectives and an operational plan. A good modern design makes maximum use of advanced concepts in hydraulic engineering, agronomy, irrigation engineering, economics, and social sciences to provide equitable, timely, and reliable irrigation services in a sustainable manner to the ultimate turnout. Physical components are only selected as a final step in the design process. Some modern designs use simple water control devices, whereas others may require sophisticated controllers and communications to achieve a desired level of performance. Modern and effective design involves properly selecting, locating, and sizing equipment given a well-defined operational strategy.

It follows from the above that there are numerous concepts of modernization. Observation and analysis of recent technological trends can provide some guidance on the future of irrigation. In addition, the experience gained in IPTRID's five country missions has indicated that three directions for irrigation systems improvement have the greatest potential for convenient services and environmentally and economically sustainable operation: those with automatic control and structural improvements (advanced systems), integrated water use systems, and decentralized systems.

Advanced Irrigation Systems

Advanced irrigation systems follow the service concept: water is provided to the user as a service that should be as convenient and flexible as possible. Water supply is thus demand-based. In many aspects, advanced irrigation systems correspond to irrigation districts in the United States, France, and Spain. The schemes are operated for the farming community and other stakeholders by specialized agencies, which are under pressure to provide convenient and flexible irrigation service to meet the requirements of diversified cropping. The on-farm irrigation operation could be subcontracted by farmers to specialized companies that might operate sprinkler equipment over large tracts of land (artificial rain concept). The agencies are obliged to cover the costs of operation, maintenance, and replacement through volumetric water charges. This operational strategy favors efficient operation, the application of high construction standards, and the application of modern concepts of canal regulation and pump operation.

Much of the technology required for advanced irrigation systems is known. Since conditions vary by country, however, direct transfer of technologies developed elsewhere might not result in optimal solutions and could risk failure. Adaptive research to find cost-effective solutions suitable to the technological and socioeconomic environment of specific countries or regions is therefore required. The following research needs have been identified:

- optimization of system layout, e.g., determination of storage and canal capacities and sediment deposition under nonsteady flow operations;
- development of low-cost, low-maintenance regulation and automation equipment;
- development of low-cost, low-maintenance measuring, control, and communications equipment;
- low-cost methods of canal lining under frost and nonfrost conditions;
- methods for strengthening and rehabilitating aging structures;
- optimization of piped distribution systems.

Mexico, Morocco, Tunisia, Jordan, India, Indonesia, and China have expressed interest in the modernization of irrigation systems and have made this a component of their agricultural policy. Some Bank loans for the rehabilitation of irrigation schemes include provisions for pilot projects for the testing of modern design concepts, particularly in India, Brazil, and Indonesia. These activities should be expanded to other countries, especially Mexico and China.

Integrated Irrigation Systems

The basis of integrated irrigation as discussed here is the conjunctive use of surface and groundwater. However, whereas the use of groundwater is traditionally considered complementary to surface water, integrated irrigation proposes reversing the priorities and separating storage and water conveyance from field application, thereby avoiding the most critical and troublesome interface of irrigation operation. There are two crucial preconditions for this new concept: aquifer characteristics and access to energy. The latter in particular has precluded the application of the concept on a wide scale and favored traditional irrigation concepts. However, the spread of rural electrification, the increased availability of fuel in remote areas, and recent advances in the utilization of renewable energy indicate that conditions are ripe for a new irrigation concept. Examples can already be observed in China, India, Pakistan, and Spain. The Chinese experience is particularly noteworthy: in some areas in the North China Plain, traditional surface systems have been abandoned and replaced by systems of small tubewells and recharge facilities. Chinese irrigation engineers have developed the "four waters" concept, meaning integrated management of surface, subsurface, rainfall, and soil water.

Parts of India's and Pakistan's extended irrigation system are already operated similarly to the new concept, but the experience thus far has been inconclusive. A more systematic and scientific approach is needed, and a deliberate attempt should be made to manage groundwater instead of managing a canal network. To bring this about, applied research and development will be required to explore the potential, preconditions, design and operation criteria, and economic feasibility of the new concept. Particular research requirements have been identified in:

- methods for the assessment and monitoring of extended aquifers;
- methods for the monitoring and management of soil salinity and disposal of saline water;
- design criteria for water-spreading systems;
- cost-effective techniques for groundwater recharge;
- removal or deposition of sediment (warping techniques);
- pump technology, water- and energy-saving on-farm irrigation;
- well technology;
- verification of the concept in pilot schemes.

Promising possibilities for this concept exist in the large alluvial plains of Pakistan, northern India, Bangladesh, Thailand, and north China. Considerable experience already exists in these countries' extensive tubewell irrigation and conjunctive-use schemes. Nevertheless, the establishment of a regional network in Asia to accelerate dissemination of experience and the development of new concepts has been proposed.

Aquifer conditions in Africa are generally less favorable, but potential for groundwater development and recharge of aquifers exists. Research is required on optimizing the utilization of low-yielding aquifers. An African network comprising countries in the Sahelian zone would be useful.

Decentralized Irrigation

Recent studies on irrigation performance in Africa conclude that private minor irrigation—pump irrigation from dug wells, rivers, lakes, or canals—is the most successful and resilient type of irrigation. Many governments—particularly in West Africa, though also in India, Pakistan, Bangladesh, and China—have launched massive promotional programs. Related problems include overutilization and mismanagement of aquifers, rising energy costs, salinity buildup, and high labor requirements. Well-designed, adaptive research and exchange of experience are potential solutions, concentrating on the following issues:

- development of low-cost, low-pressure techniques for localized water application;
- utilization of renewable energy resources, particularly photovoltaic;
- transfer of minor irrigation features to large systems;
- development of common resource management methods.

Experience with low-pressure, localized irrigation is rapidly increasing, with various institutions, such as H.R. Wallingford in the U.K. and the Research Institute of the Negev in Israel, having recently developed such systems. These developments need to be applied and tested on a large scale. In India the private sector has developed drip systems for low-pressure, low-capacity pumps and has begun manufacturing and selling this equipment to smallholders. Chinese research institutions are also active in developing adapted technologies. Numerous articles on the subject are being published in professional journals. Because of variations in the natural and economic conditions among different regions, however, more country-specific, adaptive research is needed.

Utilization of solar energy for irrigation has been a dream of researchers and engineers for some time. Much progress has been made in the development and manufacture of solar panels. Under certain conditions, photovoltaic generators and pumps are competitive with conventional motors, especially in the range of less than 1 kW. There are still many gaps in the knowledge base, however, which limit wide-scale application. Research thus far has concentrated on the optimization of the solar panel's technical features and, to a lesser extent, on the regulation device and the motor/pump component. Far less research has been conducted on the irrigation system in toto, i.e., water source, panel, regulation, motor, pump, storage, and distribution, and on its integration into the farming system. Because of solar energy's low density and because the cost of the system's single most expensive item, the solar panel, increases linearly with its capacity, a careful matching of the different components is required. For example, an efficiency loss of 20 percent in the water distribution or application system would require a solar generator 20 percent larger and thus 20 percent more expensive, whereas in a conventional system a capacity increase of 20 percent would not lead to an equivalent increase in costs. Before the new technology can be applied on a wide scale, further reduction in the costs of the panel and increased efficiency will be necessary.

Another research item would be the transfer of the positive features of minor irrigation to large systems. A possible strategy would be for agencies to supply water in low-level canals. Individuals or groups of farmers would operate low-lift pumps and low-pressure pipes for on-farm irrigation. In Egypt, water has long been lifted from low-level canals to the field by *sakia* (animal-driven water wheels) or more recently by diesel pumps. This method has contributed to good overall water use efficiency in Egypt. The advantage is that the agency is no longer required to closely control the water level in various parts of the system. This in turn leads to simplified system design and therefore lower investment and operating costs. There is an built-in incentive for economic use of water, and operational losses through spills and percolation from canals and field ditches are substantially reduced. Individual farmers face higher costs but have greater control of their water supply; water scheduling is also easier. Recently, some pump irrigation schemes in West Africa have been designed in accordance with this concept, but systematic research is required for a comparison of system performance, investment and operating cost, management performance, and farmers' preference.

If minor irrigation from tubewells is to be sustainable, control and management of the aquifer as a common property resource will be essential. Present knowledge and technology are insufficient for cost-effective monitoring of extended aquifers and for assessment of the effects of recharge and abstractions. Additionally, more research is required on the various methods of regulating access to the water source and on the sociological implications.

Minor irrigation corresponds to most nations' agricultural development policies and meets the criteria of most donor organizations. UNDP has recently launched a regional network among North African and Near Eastern countries for research on water-saving irrigation technology and supplementary irrigation. The Bank has sometimes financed research in minor irrigation schemes (in India's Maharashtra Irrigation II and Uttar Pradesh Tubewell II projects, and in Pakistan, Bangladesh, and Colombia). The new Private Irrigation Project in Niger is promising. Various bilateral donor agencies and the EC have supported similar projects, including pilot projects for solar energy utilization. Research results, however, are frequently not well documented and difficult to access.

Conclusions

In implementing the research proposed, every effort should be made to increase efficiency and avoid duplication. Research should therefore preferably be organized in networks, and one of IPTRID's major tasks is to organize and promote these networks.

Little of the research proposed can be conducted in laboratories or research stations. New technologies and system optimization must be tested under field or on-farm conditions on a scale that allows assessment of overall impact. Relevant and sizable research components should be included in Bank loans. IPTRID is prepared to assume a role in arranging the design of research projects, providing regular supervision and monitoring, and disseminating results through publications and workshops.

A recent study indicated that of a total 256 irrigation projects financed by the Bank between FY74 and FY90, only 65 included a research component. The total investment in irrigation was $33.7 billion, with only $152 million (0.45 percent) spent on irrigation research. In Africa, the proportion spent on irrigation research was only 0.02 percent of the investment. Although these figures exclude other channels for providing support to research in irrigation and drainage, they indicate that the present level of funding for research is inadequate.

Improving Maintenance Technology

Technological improvements in maintenance are required to keep pace with modernization and to improve the standard and reliability of system operation. Information on system performance and improvements in diagnostic methods is needed to facilitate sound decisions on when, where, and how to undertake maintenance activities.

Changes in the way irrigation is organized (transfer to farmer groups, etc.) will require reliable, simple maintenance methods. A clear understanding of how irrigation and drainage systems deteriorate is necessary. With this knowledge, designers can adapt research results to accommodate a certain amount of deterioration and incorporate ways to minimize maintenance, or at least simplify it.

Maintenance, whether organized centrally or devolved to subcontractors, will require specialized skills integrating civil and mechanical engineering, hydraulics, and biology.

Research Needs

IPTRID expert missions have identified the following related research needs:

- aquatic weed control, with evaluation of mechanical, chemical, and biological controls;
- testing and evaluating weed-cutting and desilting machinery, as well as hand-cleaning methods for channels;
- development of guidelines for effective operation and maintenance of drainage systems at minimal cost (removing trash, desilting, weed clearing, etc.);
- development of an understanding of the system aging process;
- determination of stable channel cross-sections to minimize maintenance;
- development of techniques to remove sediment from channels (excavation, extraction, and exclusion);
- design of control and measuring structures with low-maintenance requirements;
- operational research to determine optimal maintenance for scheme infrastructure: roads, drains, and canals.

The common theme in considering problem areas is to minimize maintenance either by reducing the work required or by making actions more effective. This is especially important given the trend to delegate maintenance to farmers or farmer groups. Maintenance may be reduced in part by constructing or rehabilitating channels, lined or unlined, that require little or no maintenance and making them self-maintaining; providing an inappropriate habitat for vegetation; and providing information to irrigation and drainage engineers to enhance decisionmaking for effective maintenance. Studies to improve weed clearance techniques by choosing appropriate machinery and using it more selectively and effectively are required, as is research to improve prevention techniques for sediment reaching channels and to manage the sediment already in the channels. Adaptive field research is needed before these potential solutions can be integrated into existing maintenance strategies. An important first step is the establishment of networks bringing practicing maintenance professionals together with researchers from the hydraulic, biological, and engineering professions to help formulate and undertake this research and thereby provide human-resource development. During the next year, a concentrated effort will be made to promote this networked research.

IRRIGATION RESEARCH REQUIREMENTS

Charles M. Burt

Many new irrigation projects and modernization schemes contain a research component. Research must be focused on an objective: what is interesting must be distinguished from what is needed. Simply because some irrigation-related phenomenon is not completely understood does not justify funding a development project. Typical university research is often too generalized and lacks applicable conclusions for development projects.

A frequent characteristic of researchers is lack of familiarity with "field applications." This perpetuates research activities that tend to stay in the office, lab, and experiment station. Irrigation projects have research needs that require extensive field exposure and field activities.

Research Categories

There are essentially three categories of research: basic, applied, and diagnostic. Basic research can rarely be afforded in new irrigation projects. Diagnostic research is generally needed before applied research can be conducted.

Basic

Basic research has no immediate application in most situations. Examples of basic research include:

- the study of molecular movement in water waves;
- the physics of water movement through soil cracks;
- studies of plant stomatal resistance as a function of water stress;
- development of new equations to define unsteady flow in canals.

Basic research in irrigation should generally be funded in locations with excellent infrastructure and superior irrigation practices. Developing countries typically have more pressing needs for research dollars than spending them on basic research. Basic research, however, has great appeal for many researchers because it generally requires little or no field work and little or no communication with the eventual users of the information. With most basic research, the researcher only needs to deal with other members of the scientific community.

Applied

Applied research can have immediate applications. Examples include:

- studies of a type or size of spillway for use in a specific application;

Charles M. Burt is director, Irrigation Training and Research Center, California Polytechnic State University, San Luis Obispo. This paper was presented in 1990.

- development of a gate control algorithm for canal automation;
- study of the effects of rapid valve closure and water hammer on new pipe materials.

Researchers can identify valid needs in applied research only when they have a good understanding of present field conditions and existing solutions to present field problems.

An example of inappropriate applied research is the development of a new unsteady flow model for open channel flow. This type of project indicates a poor understanding of existing solutions, because many excellent unsteady flow models already exist.

Diagnostic

Diagnostic research often rates very low on the list of "acceptable" types of research by academics caught in the "publish or perish" trap of many universities and research organizations. Diagnostic research asks the question, "How are things working in the field, and why?" Examples of diagnostic research include:

- identification of water delivery reliability at all project levels;
- studies of water level and flow rate fluctuations throughout an irrigation project;
- determination of water user organization viability;
- study of the effects of different water delivery strategies on society, maintenance, personnel, hydraulic performance, and agronomy.

Research Requirements

For most irrigation projects in developing areas with limited budgets, the order of research priorities should be diagnostic; applied; and basic. Large amounts of untransferred irrigation knowledge already exist; this should influence decisions about what types of research are needed and the quantity of resources to be allocated to them.

For applied research, a well-defined problem and a clear understanding of it are required. Awareness of other work on the problem and of existing practical solutions to it are also necessary. Researchers must have excellent interchanges with other researchers and field operations and design personnel. To prevent duplication of efforts, they should also utilize outside expertise when defining new applied research projects.

An applied researcher must satisfy all these requirements to avoid efforts that are merely the "training of the researcher." Diagnostic research that "trains the researcher" is fine, as long as it is identified as such, because that is the nature of diagnostic research—the researcher is attempting to find out what is going on in the real world and is becoming educated in the process.

In most irrigation research, researchers should conduct a healthy mix of diagnostic and applied research. The diagnostic research will keep them in touch with the final recipients of their good applied research results and also help ensure that the applied research is on target. Unless irrigation researchers have conducted a healthy dose of diagnostic research, they should probably not be funded for new applied research projects.

Most irrigation projects fund research because there are definite problems to solve. The exact nature of the problems is usually not well defined, so diagnostic research is generally needed as a first step. When applied research is conducted, the goal should be to provide simple solutions. First, the result of most funded irrigation research should be solutions that can be applied, rather than a report requesting more funds to study the problem further. Second, the results should be simple enough to apply. The objective of sophisticated research is to develop simple and appropriate solutions. A true mark of success is a solution so simple that everyone says, "That's nothing special; it's so simple I could have figured it out myself."

The Irrigation Training and Research Center (ITRC) at California Polytechnic State University

The ITRC was primarily developed to support the major irrigation efforts in California and the western United States. There are so many challenges in that area of the world that the center has not devoted significant effort to international activities, although the interest does exists.

The two primary functions of the ITRC are training and diagnostic research, with some applied research. Through these two functions, the ITRC improves irrigation performance in the western United States and also enhances the large irrigation teaching program at the university. The ITRC is fairly unique in that its governing board is composed of irrigation faculty, which ensures that activities are harmonious with the university's teaching objectives.

The ITRC has access to the Cal Poly farm (about 300 irrigated ha) and local irrigated farms and projects. It also has some specialized facilities, including an ITRC office and conference room complex. In addition, a $1 million water delivery teaching facility includes three types of canals with various water delivery control hardware, pipelines, pumps, computers, etc. An on-farm irrigation practices field has small drip, sprinkler, linear move, furrow, and border strip irrigation systems that enable the ITRC to teach operation and management techniques.

ITRC activities include:

- assistance to irrigation projects in the development of modernization and farmer assistance strategies;

- technical short courses, generally lasting one to three days. These are usually designed for consultants, designers, and irrigation district personnel rather than individual farmers. Topics include water delivery automation, pumping, row crop drip, furrow irrigation, fertigation, and on-farm irrigation evaluation.

- development of expert systems and training packages. The ITRC has developed the procedures (and programs) used throughout California to evaluate on-farm irrigation, and its AGWATER expert system is used by farmers throughout the state to diagnose problems and receive training in on-farm irrigation management;

- diagnostic research. The ITRC works with irrigation districts and various agencies to determine irrigation performance in both water delivery and final application on-farm.

California's Imperial Irrigation District (IID)

IID exemplifies how diagnostic research and some limited applied research have combined to enhance major efforts toward modernization of a water delivery system and on-farm irrigation. IID is adjacent to the Mexican border and is characterized by 200,000 irrigated ha; 2,600 km of canals, primarily unlined; arranged delivery schedules; and manual upstream control.

IID is presently in the midst of a five-year, $160 million improvement program. The decision to make the improvements, and the improvement process itself, is the result of several simultaneous stimuli. First, IID seeks to provide farmers with the opportunity to irrigate properly. This may seem to be an obvious objective, but it is actually rare that all management levels of a project have such an objective. In the district, several influential farmers participate actively. When they speak, the district management acts. A key factor in change was that an "old guard" of employees recently retired. This left the door open to younger people in upper management and better reception to new ideas. The district has a permanent, stable professional staff, which is a critical element for change. However, the district also utilizes consultants to enhance staff capabilities. The consultants are generally aware of outside research results (both diagnostic and applied).

Another key stimulus for change was some excellent diagnostic research conducted by a few district employees. It focused on:

1. on-farm irrigation evaluations;
2. monitoring of water level fluctuations at various locations throughout the delivery system;
3. continuous monitoring of flow rates at critical points and at farmer turnouts;
4. monitoring of spills and surface and subsurface drainage.

Once problems were identified through diagnostic research, IID upper management encouraged staff training at all levels. What may be unusual is that upper management went to training programs (such as those at Cal Poly's ITRC) and then sent the field personnel. The across-the-board training helped to standardize objectives and the degree of awareness of problems and solutions. In addition, the training established a good *esprit de corps*, important when making major operational changes.

Finally, physical improvements began on-farm and in the water delivery system. The physical improvements were initially made as small trials. Feedback was solicited from farmers and employees, and limited applied research was conducted to determine the problems and benefits of various solutions.

Present work includes:

1. *relining of canals*. The canals are not simply relined using the original design criteria. New lining incorporates higher heads on the turnouts and larger capacities for increased farmer flexibility. Diagnostic research helped determine probabilities of water requests at critical levels in the district and also documented the need for higher heads on the turnout gates;

2. *a more flexible water delivery schedule*. In some areas of the district, farmers will be allowed to shut off their water at any time. Diagnostic research had targeted the need to allow farmers to shut off water at odd hours;

3. *on-farm irrigation improvements*. The district is funding tailwater return systems, new sprinkler methods, and row crop drip systems. The economic justification arises from diagnostic research results that identified the amount and value of unrecovered tailwater losses from fields;

4. *buffer reservoirs*. These are being installed at key points in the distribution system, and an additional 11 differentiated projects are being conducted.

Generally, improvements have been fairly simple and easy to implement and maintain. Buffer reservoirs, long-crested weirs, large tailwater return ponds, and larger canal capacities are all simple solutions that, if applied correctly, can make life much easier for operators and farmers.

Summary

Research is expensive and time-consuming. Most irrigation project research in developing countries should be directed toward providing solutions to well-defined problems. Excellent training of researchers is critical, and diagnostic research is essential for training researchers and for proper identification of problems. Good research, however, does not imply complicated results in the field.

RESEARCH ON THE CONJUNCTIVE USE OF RAINFALL AND IRRIGATION

B.A. Stewart

During this century, irrigation has expanded dramatically, particularly between 1950 and 1980, when land under irrigation increased worldwide from about 95 million to about 250 million ha. Irrigated land represents about 18 percent of cultivated land, but produces one-third of the world's food. The growth in irrigated land, over 3 percent annually during the period mentioned above, has now slowed to less than 1 percent a year (Higgins et al. 1987).

In many areas where irrigation is practiced, crop production depends entirely on added water. Under these conditions, water resources are usually developed first and then cropland is developed to utilize the water resources. Maximum crop production is generally the objective under such circumstances, and irrigation systems are designed to ensure that sufficient water is applied as uniformly as feasible.

Irrigation is also widely practiced in areas where there is sufficient rainfall for rainfed agriculture, but where the addition of irrigation water allows for significant yield increases or for a wider choice of crops. Irrigation in these areas also mitigates the effects of low-rainfall years and stabilizes food production. Again, the general objective is to always have sufficient water available to meet the needs of the growing crop.

The third situation where irrigation is practiced, and the one discussed in this paper, is when there are both limited rainfall and limited amounts of water available for irrigation. In these areas, crops are often grown under water stress conditions, although they may be supplemental irrigated. This type of irrigation is generally referred to as *limited* or *deficit irrigation*. The management strategy involves the use of limited water supplies that allows field crops or partial areas of field crops to experience periods of slight to moderate plant water stress. These systems are common in semiarid climates where deficit irrigation is practiced on the same drought-resistant crops also widely grown under dryland conditions. For example, in the southern Great Plains of the United States, wheat, grain sorghum, and cotton are widely grown, but seasonal rainfall normally provides only about 30 to 60 percent of the water required for high yields. Where there is water available for irrigation, it is often applied to these crops. In many cases, however, there is much more cropland suitable for irrigation than there is water available, so choices must be made about whether to concentrate the limited supply of irrigation water on a small area or to spread it over a larger area. The correct choice requires a good understanding of water application rates and the relationships of transpiration and evapotranspiration to dry matter and grain yields. It also depends on the relationship between irrigation cost and crop value.

The objective of this paper is to briefly examine some of these relationships and present some concepts that may be useful. The key to increasing production in these areas is to use the limited supply of irrigation water conjunctively with the rainfall so that the use efficiency of both water sources can be increased.

B.A. Stewart is director, Conservation and Production Research Laboratory, USDA Agricultural Research Service, Bushland, Texas. This paper was presented in 1988.

Deficit Irrigation

Crop Selection

Deficit irrigation is generally practiced on crops that have some drought resistance. In the semiarid areas of the United States, the major crops that are deficit irrigated are wheat, grain sorghum, and cotton; the minor crops are barley, sugar beet, sunflower, forage sorghum, cool-season grasses, alfalfa for seed production, and grapes. Drought resistance is expressed as tolerance or avoidance. Tolerance is expressed through physiological and morphological processes that either limit transpiration losses or condition plants to withstand lowered water potentials. Avoidance is accomplished by reducing the length of growing season or by increasing rooting depth and water extraction from the lower soil profile. Management can play a much larger role in avoidance than in tolerance, but crop selection is important in both instances.

Suitable Soils

Deficit irrigation should be limited to soils with plant available soil water storage that is moderate to high. This is an essential requirement if limited water supplies are used efficiently. The soils should also have a good infiltration rate. Conservation tillage, no-till, and other forms of reduced tillage systems have also been shown to be beneficial in some deficit-irrigated areas for increasing infiltration and also reducing evaporation losses. Furrow diking, or tied-ridges, is another practice that can improve the usefulness of some soils for deficit irrigation systems.

Systems for the Conjunctive Use of Rainfall and Irrigation

There are five outcomes for irrigation water applied to a growing crop: it can be transpired through the crop, evaporated from the soil surface, percolated below the root zone, run off the field, or remain in the soil profile after the growing season. Maximum use efficiency requires that the amount transpired be maximized while the remainder be minimized, because when yields are transpiration-limited, strong correlations usually occur between cumulative seasonal dry matter and cumulative seasonal transpiration (De Wit 1958). When irrigation is practiced in areas of substantial rainfall, as in deficit irrigation areas, the water use efficiency of added irrigation water can be very low. For example, rainfall occurring immediately following an irrigation can lead to large amounts of runoff and also increase percolation losses.

The example systems discussed below were designed and tested at the USDA Conservation and Production Research Laboratory, Bushland, Texas, located in the southern Great Plains. The management strategy for each system was to optimize production per unit of applied water, rather than to maximize yield per unit of land. These systems are somewhat site-specific, but the concepts utilized have broad applications.

Background

In Bushland, Texas, the annual average precipitation is 470 mm, ranging from a low of about 240 to a high of some 860 mm. The largest amounts of precipitation occur between May and August. The potential evaporation far exceeds the average precipitation for every month of the year. Because the maximum annual precipitation for the area is about 200 percent of the average, and the minimum is about 50 percent of the average, the distribution of annual rainfall is skewed. An unusually wet year raises the average more than an unusually dry year lowers it, so there are more years below average than above average. For Bushland, Texas, annual rainfall is less than average about 55 percent of the years.

Perhaps even more important than average annual rainfall is the amount that occurs during the irrigation season. For example, grain sorghum in the area is planted around June 1. The accumulated rainfall during the grain sorghum growing season in Bushland, Texas, for 42 years is illustrated in figure 1. Also shown is the average evapotranspiration requirement for grain sorghum grown under conditions of no, or very little, water stress. For wet and dry seasons with an average occurrence of one in three, the dry seasons contribute less than 25 percent of the seasonal water use needed for high yields, whereas the wet seasons contribute over 60 percent of that needed, with minor losses to surface runoff. When a wet season with reasonably good rainfall distribution is combined with a soil profile fully recharged at seeding time, irrigation may not be needed for high yields. At the other extreme, even with a fully recharged soil profile at seeding time, more than one-half of the water needed for high yields would need to be added by irrigation. Because rainfall cannot be accurately predicted, seasonal irrigations are often applied even during wet seasons, and in dry seasons the producer may not be able to irrigate as much area as planned.

Irrigation systems are often based on the assumption that near-average rainfall amounts will be received. This approach, however, can be unsatisfactory in both drought and wet years because the irrigation water supply in many areas is no greater in a drought year than during an average or wet year. This is particularly true when groundwater is the source, because the amount is determined by the well capacity. Also, in addition to providing less precipitation than in average seasons, drought seasons usually have higher evaporative demand because of higher air temperatures, more wind advection, and larger vapor pressure deficits.

The difficulty in optimizing the conjunctive use of irrigation and rainfall in semiarid regions lies in combining the use of limited irrigation water resources with inherently unpredictable rainfall. Because rainfall is so highly variable, there is no way to determine in advance the optimum amount of land to be irrigated in a given year: land is abundant in relation to water, and the amount of land that can be irrigated depends on the water resources. As already discussed, in semiarid regions the total water supply (irrigation water plus rainfall) varies greatly by year. When irrigation water is fairly abundant, the tendency is to ignore rainfall, resulting in the inefficient use of irrigation water. During wet years, the full potential of the irrigation water supplies may not be utilized because insufficient land area was planned for irrigation. Maximizing the irrigated land area requires the efficient management of rainfall on irrigated land.

Furrow irrigation practices generally involve running excess water off the end of fields for a considerable period, depending on the infiltration rate of the soil, to ensure adequate wetting of the lower portion of the field. If the time allowed is too short, the yields on the lower portion of the field may be drastically reduced; if the time allowed is too great, however, excessive runoff occurs, and the probability of percolation losses on the upper end of the field is greatly enhanced. Although irrigation runoff water can be caught in reuse systems, significant losses still occur. The USDA's Soil Conservation Service assumes an irrigation efficiency of 65 percent in designing reuse systems for the Texas High Plains. When substantial rainfall occurs within a few days of irrigation, storm water runoff results. Reuse systems are not ordinarily adequate to capture this runoff, so in-season rainfall is often of limited benefit to the irrigated crop. In addition, furrow irrigation of cropland that has had the surface wetted with rainfall results in much faster advance of the irrigation water, which increases the probability of incurring excessive irrigation water runoff. To improve the management of irrigation water, sprinkler systems have been installed on some land that was previously furrow-irrigated. Use of sprinkler systems allows the application of smaller amounts of irrigation water and eliminates the need for reuse systems. Their use does not, however, substantially reduce storm water runoff whenever rainfall closely follows an irrigation. Sprinkler systems are also capital-intensive, and many producers in semiarid areas with limited water supplies find them cost-prohibitive.

Limited Irrigation-Dryland Farming Systems

Stewart et al. (1983) developed and tested a limited irrigation-dryland (LID) farming system for the efficient use of limited supplies of irrigation water for grain sorghum production. The objective of the LID concept is to maximize the conjunctive use of growing-season rainfall, which varies by year, with a limited supply of irrigation water, which is frequently fixed for a given year. For example, when groundwater is the water source, the well yield determines the amount of available water. The unique feature of the LID system is the flexible adjustment of the amount of land irrigated during the crop growing season, allowing more land to be irrigated during above-average rainfall years than during dry years. The LID system concept is illustrated in figure 2. A graded furrow field, 600 m long on 0.3 to 0.4 percent slope, was divided into three water management sections. The upper half of the field was managed as "fully irrigated." The next one-fourth was managed as a "tailwater runoff" section that utilized furrow runoff from the fully irrigated section. Finally, the lower one-fourth was managed as a "dryland" section capable of receiving and utilizing any runoff resulting from either irrigation or rainfall on the wetter, fully irrigated and tailwater runoff sections. Plant densities were reduced down the field to alleviate stress because irrigation water decreased as the length of the field increased. Furrow dams (Clark and Hudspeth 1976) were placed about every 4 m throughout the length of the field. Alternate 76-cm furrows were irrigated, and the dams in the irrigated furrows were notched to ensure that irrigation water moved over the dams and down the furrow, rather than across the beds. The remaining furrow dams on the lower part of the field, and the dams in the nonirrigated furrows for the entire length of the field, prevented rainfall runoff. A predetermined amount of irrigation water was applied at regular intervals. The extent to which the entire field was irrigated depended on the rainfall received—the wetter the year, the greater the advance of a fixed application down the field. The objective was to prevent or greatly minimize any water from rainfall or irrigation from leaving the field.

A summary of the results for three years is presented in table 1. Irrigation water use efficiency (increase in grain yield due to irrigation per unit of irrigation water applied) averaged 0.92 kg/m^3, whereas the LID systems averaged 1.36 to 1.70 kg/m^3. The success of the LID system was the result of greatly reduced runoff, which averaged 178 mm from the fully irrigated system, compared with only 8 mm from the LID system (Stewart et al. 1983). The amount of soil water remaining in the soil profile at the end of the growing season was also much lower in the LID system than in the fully irrigated system. At the end of the growing season, a large amount of soil water stored in the profile leaves little opportunity for storing any precipitation received prior to the time of seeding the next crop. Musick (1970) showed a significant curvilinear relationship between antecedent soil water after harvest and preseason storage efficiency. As antecedent soil water increased, storage efficiency decreased. Highest storage efficiency values were in the 40 to 50 percent range when the soil profile was near the wilting point at harvest time, compared with less than 10 percent when the soil water storage capacity at harvest time was about 75 percent of capacity. These findings emphasize the importance of limiting irrigation, particularly late in the season, to prevent ending the growing season with a relatively wet profile, which minimizes the potential for efficient storage of the next crop's preseason rainfall. Such storage is essential to maximizing the conjunctive use of rainfall and irrigation water.

The primary disadvantage of the LID system, as originally designed, was that plant density was decreased with length of field. This was facilitated by a seeder modification that permitted on-the-go seeding rated changes to reduce plant densities on the tailwater and dryland sections. More recent studies with the LID system, however, have utilized a medium seeding rate throughout the field and furrow dams only in alternate furrows not used for irrigation. These changes make the system somewhat easier to implement and manage, and the benefits are similar. Another disadvantage of the LID system is that soil fertility requirements decrease with length of field. Fertilizer additions

Figure 1. Accumulated Rainfall during Grain Sorghum Growing Season at Bushland, Texas, for the Wettest 14 Years, the Middle 14 Years, and the Driest 14 Years, 1939-80

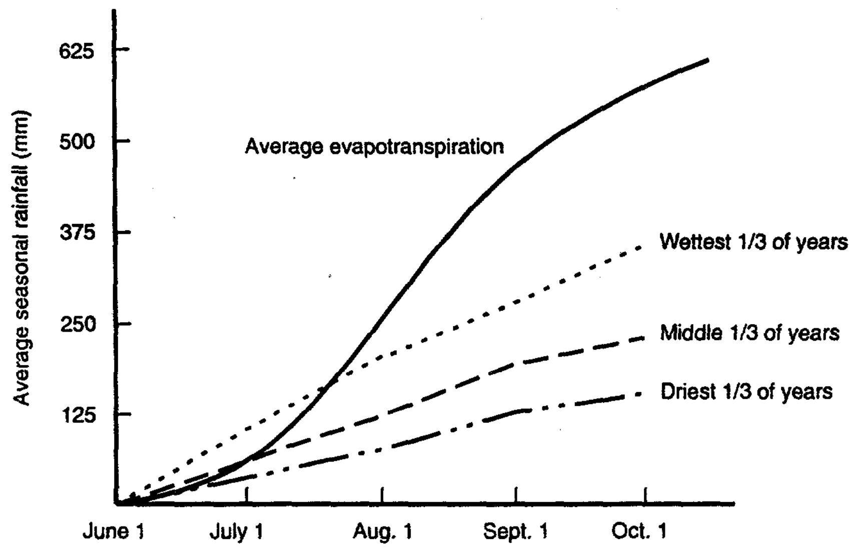
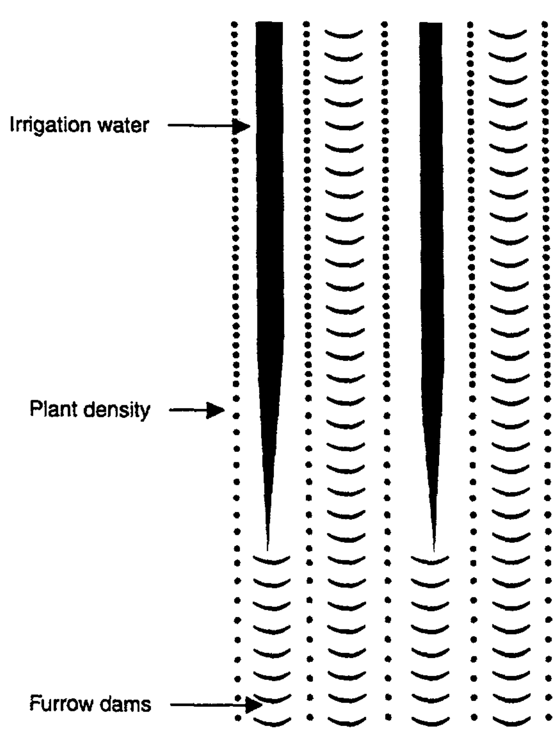


Figure 2. Schematic of a Limited Irrigation-Dryland Farming System That Self-Adjusts the Amount of Irrigated Land, Depending on Seasonal Precipitation



Source: Stewart et al. 1981.

Table 1. Dryland, Full Irrigation, and Limited Irrigation-Dryland (LID) Treatments (Three-Year Average), Bushland, Texas

Treatment	Applied irrigation (mm)	Grain yield (Mg/ha)	Seasonal ET (mm)	Water use efficiency (kg/m^3) ET	Irrigation
Dryland	n/a	2.53	292	0.84	n/a
Full irrigation	516	7.24	615	1.17	0.92
LID 1	234	5.69	521	1.08	1.36
LID 2	173	5.13	465	1.09	1.50
LID 3	119	4.47	411	1.08	1.70

ET = Evapotranspiration.
Note: Seasonal rainfall averaged 249 mm.
Source: Compiled from Stewart et al. 1983.

can be easily varied by fertilizing the field at right angles to the row direction prior to bedding the land, or a more efficient alternative may be to apply the fertilizer in the irrigation water. This would distribute the fertilizer in direct proportion to water distribution and could increase the use efficiencies of both. The quality of the groundwater in the study area used for irrigation was excellent, and there were no salinity problems. Salinity could be a problem in some areas, however, and should be carefully monitored.

Alternating Strips of Grain Sorghum and Wheat

Musick and Dusek (1975) conducted a six-year study in which grain sorghum and winter wheat were grown in alternating 4.5-m wide strips. Because the two crops have completely different growing seasons, outside crop rows could benefit from a border effect when no crop was growing on adjacent strips. Each strip contained six beds separated by five inside furrows. In one irrigation scheme, water was applied in two furrows in each six-bed strip. Each of the four inside beds had an irrigated furrow on one side and a nonirrigated furrow on the other. The two outside rows functioned as border rows and were not adjacent to an irrigated furrow. In other irrigation schemes, the number of furrows irrigated and the frequency of applications could be adjusted, depending on the amount of irrigation water available. The objective of the system was to utilize the rainfall during the nongrowing period of one crop more efficiently than it could be stored in the soil for the next crop. For example, rainfall during the nongrowing period of repeatedly grown wheat averaged 207 mm per season during the study. Storage efficiency measured at wheat seeding in another study averaged only 21 percent (Johnson and Davis 1972). In principle, alternating strips of grain sorghum with winter wheat should allow for more efficient use of much of the rainfall. The 4.5-m strip width was selected because of its compatibility with available field equipment. During the study, applied irrigation water was reduced by about 45 percent, and yields were reduced by about 24 percent in comparison with fully irrigated crops. Thus, the system offers considerable potential for increasing the use efficiency of both rainfall and limited irrigation water. The disadvantages of the system are that (a) it necessitates the management and movement of irrigation equipment over twice the area being irrigated during a growing season; (b) it requires greater precision of cultural practices, especially weed control; and (c) the probability of some runoff from rainfall still exists.

Surge Irrigation

Surge irrigation has been extensively adopted in the U.S. central and southern High Plains for reducing furrow intake rates, which allows the irrigation of a larger area with a limited water supply. Surge irrigation (Bishop et al. 1981), the cyclically interrupted supply of water to furrows and borders, decreases infiltration rates and thus increases water advance rates. Surge irrigation has the potential to increase the uniformity of surface irrigation application both by increasing advance rates and thus decreasing infiltration opportunity time differences across a field, and by decreasing the infiltration rate at the upstream ends of furrows or borders to compensate for their longer infiltration opportunity times. A normal practice in surge-flow application is to use an available water supply to irrigate a larger area than is irrigated by a conventional continuous flow by alternating the surges to a set of furrows on each side of a controller valve assembly.

The degree of infiltration reduction is variable and difficult to predict. Also, the mechanisms by which surge irrigation reduces infiltration rates are not fully understood. According to Kemper et al. (1988), important mechanisms are (a) consolidation of the furrow perimeter resulting from increased soil water tension during flow interruptions, (b) filling of cracks that develop during flow interruptions with bed load during the following surge, (c) forced settlement of suspended sediment on the furrow perimeter when the water supply is interrupted, and (d) greater sediment detachment and movement caused by more rapid advance of the surged stream front.

An evaluation of surge irrigation for corn on Olton clay loam showed that surge-flow effectively reduced intake by 32 percent when the surface soil was in a loosened condition by tillage and by an average of 17 percent for seasonal irrigations when the surface soil was consolidated from previous irrigations (Musick et al. 1987). When comparing effects of surge-flow application to nonwheel track furrows with furrow compaction from a tractor wheel on Olton clay loam, both were effective in reducing excessive water intake (Musick and Pringle 1986; Musick et al. 1987). Surge-flow, however, offers an additional benefit of managing reduced tailwater runoff. In the study by Musick et al. (1987), when surge-flow was used to reduce cumulative water intake from 992 to 733 mm during seven irrigations for corn, tailwater runoff was also successfully reduced from 189 to 82 mm without yield reduction.

Surge irrigation has also been studied in connection with the LID concept, and the results (as yet unpublished) were encouraging. The surge application of the limited amounts of irrigation used in the LID system was distributed further down the field, resulting in improved water use efficiency.

Irrigated-Dryland Crop Rotations

A successful system for the conjunctive use of rainfall and irrigation was developed by Unger and Wiese (1979) and involved irrigated winter wheat and dryland grain sorghum. The basic concept was to utilize the large amount of residue produced by the irrigated wheat to enhance the storage efficiency of precipitation during the fallow period. The rotation consisted of irrigated wheat (approximately 8-month growing season), an 11-month fallow period, dryland grain sorghum (approximately 4-month growing season), and another 11-month fallow period. This results in two crops within three years. Unger and Wiese compared no-, sweep-, and disk-tillage methods to manage wheat residues and control weeds and volunteer wheat during the fallow period between the wheat and grain sorghum (table 2). Water storage, water use, grain yields, and water use efficiency were highest with no-tillage. No-tillage allows the wheat residue to remain on the surface during the following fallow season: this increases infiltration, reduces runoff and erosion, and reduces evaporation. Because this system requires that only one-third of the land be irrigated each year, it is an excellent alternative to full irrigation where irrigation water is limited.

Table 2. Effects of Tillage in an Irrigated Winter Wheat-Fallow-Dryland Grain Sorghum Cropping System, Bushland, Texas, 1973-77

Tillage method	Plant available water at sorghum planting (mm)	Water storage efficiency[a] (%)	Grain yield (Mg/ha)	Total water use (mm)	Water use efficiency[b] (kg/m^3)
No-tillage	217a	35.2a	3.14a	350a	0.89a
Sweep	170b	22.7b	2.50b	324b	0.77b
Disk	152c	15.2c	1.93c	320b	0.66c

Note: Column values followed by the same letters are not significantly different at the 5 percent level (Duncan's multiple range test).
a. Precipitation averaged 347 mm during fallow.
b. Water use efficiency based on grain yields, growing-season precipitation, and soil water changes.
Source: Unger and Wiese 1979.

Other Methods

There are many other methods of enhancing the conjunctive use of rainfall with irrigation, but it is beyond the scope of this paper to discuss them all. Some notable methods studied include the use of tensiometers, runoff pits, snow management, crop breeding, and antitranspirants. The use of center-pivot sprinklers has also become increasingly popular in areas previously watered by furrow systems. The reasons for their increased use include improved water use efficiency and labor savings. Sprinklers allow much greater control of water application rates, particularly in permitting the application of smaller amounts. Sprinkler systems, however, require a considerable increase in capital investment.

Conclusion

Efficient use of water for crop production has been a major concern for centuries. Today, this concern is greater than ever because of the rising need for food and fiber, coupled with increasing irrigation development costs and the decreasing supplies of water in several major irrigation regions. In addition, the cost of energy for irrigation makes efficient use of water doubly important because efficient use of water automatically improves the efficiency of energy use in irrigated agriculture.

Water use efficiencies, as described above, can be improved in all climatic regions by reducing losses resulting from surface runoff, evaporation, and excessive percolation. Computerized irrigation scheduling (based on anticipated precipitation, available soil water, evapotranspiration of the crop as predicted by climatic data and crop coefficients, and capacity of the irrigation system) has proved effective in preventing overirrigation and in increasing water use efficiency. This practice, therefore, will undoubtedly be expanded and improved upon in the future.

In most arid regions, cropland was not developed until water resources were developed. So, with the ratio of water availability to cropland presumed to be optimal, limited or deficit irrigation is not usually practiced. Because rainfall supplies only a minute portion of the total crop water requirements in arid regions, the best strategy will probably continue to be to irrigate sufficiently to prevent water from being a limiting factor in crop production.

In humid areas, improved scheduling will result in a more consistent yield response to the water applied, less energy use, and less soil erosion. The control of erosion in cropland irrigated in humid areas presents a major challenge that will require new approaches. Because water resources in these regions are generally more than adequate, the tendency will be to maintain the soil profile sufficiently wet to prevent water from being a limiting factor in crop growth. Consequently, rainfall on these wet soils could accelerate erosion. The development of both surface and subsurface drainage systems on irrigated lands and of erosion control practices compatible with the irrigation system is essential in these regions.

Semiarid regions offer the greatest potential for limited irrigation and the conjunctive use of rainfall with irrigation because rainfall is a major part of the total water supply, even on irrigated land. Also, there is generally an abundance of cropland in semiarid regions and a shortage of irrigation water. Maximum water use efficiency can only be achieved when both rainfall and irrigation water are adequately managed. In the past, the tendency was frequently to manage the irrigation water and largely ignore the rainfall. In recent years, however, an increased awareness of declining water supplies and of increased energy costs has caused a shift in emphasis to more efficient conjunctive water use.

Maximizing water use efficiency in semiarid regions will generally involve deficit irrigation of drought-resistant crops. This will allow more cropland to be irrigated, at least partially, with the limited water resources available. Less rainfall will be lost to runoff and evaporation under these systems.

The most water-efficient systems may not be the most economic. The extent of the benefits, therefore, must be carefully weighed against the economics of the system. This depends on numerous factors, particularly the cost of irrigation and the value of the crop. When irrigation costs are low and crop value is high, net return is generally enhanced by spreading the limited amount of water over a larger area. If irrigation costs are high and the crop value is low, however, the net return is greatest when less crop area is irrigated sufficiently to obtain near maximum yields. Explicit in this assumption is that drought-resistant crops are being utilized in the deficit irrigation systems. Deficit irrigation has been particularly feasible in the southern High Plains of the United States because irrigation systems were already in place for a large area. As well yields dropped because of the declining water table, a choice could be made to either irrigate a portion of the field or spread the limited water over a larger area.

References

Bishop, A.A., W.R. Walker, N.L. Allen, and G.J. Poole. 1981. "Furrow Advance Rates under Surged Flow Systems." *Journal of Irrigation and Drainage* (ASCE) 107, no. IR3: 257-64.

Clark, R.N., and E.B. Hudspeth. 1987. "Runoff Control for Summer Crop Production in the Southern Plains." American Society of Agricultural Engineers Paper 76-2008. St. Joseph, Mich.

De Wit, C.T. 1958. *Transpiration and Crop Yields*. Wangeningen, The Netherlands: Institute of Biology and Chemistry Research on Field Crops and Herbage.

Higgins, G.M., P.J. Dieleman, and C.L. Abernathy. 1987. "Trends in Irrigation Development and Their Implications for Hydrologists." Paper presented at the International Symposium on Water for the Future, April, Rome.

Kemper, W.D., T.J. Trout, A.S. Humpherys, and M.S. Bullock. 1988. "Mechanisms by Which Surge Irrigation Reduces Furrow Infiltration Rates in a Silty Loam Soil." *Transactions of the American Society of Agricultural Engineers* 31: 821-29.

Musick, J.T. 1970. "Effect of Antecedent Soil Water on Preseason Rainfall Storage in a Slowly Permeable Irrigated Soil." *Journal of Soil and Water Conservation* 25: 99-101.

Musick, J.T., and D.A. Dusek. 1975. "Limited Irrigation of Grain Sorghum in Alternating Strips with Wheat." *Transactions of the American Society of Agricultural Engineers* 18: 544-48.

Musick, J.T,. and F.B. Pringle. 1986. "Tractor Wheel Compaction of Wide-spaced Irrigated Furrows for Reducing Water Application." *Applied Engineering in Agriculture* 2: 123-28.

Musick, J.T., J.D. Walker, A.D. Schneider, and F.B. Pringle. 1987. "Seasonal Evaluation of Surge Flow Irrigation for Corn." *Applied Engineering in Agriculture* 3: 247-51.

Stewart, B.A., D.A. Dusek, and J.T. Musick. 1981. "A Management System for the Conjunctive Use of Rainfall and Limited Irrigation of Graded Furrows." *Soil Science Society of America Journal* 45: 413-19.

Stewart, B.A., J.T. Musick, and D.A. Dusek. 1983. "Yield and Water Use Efficiency of Grain Sorghum in a Limited Irrigation-Dryland System." *Agronomy Journal* 75: 629-34.

Unger, P.W., and A.F. Wiese. 1979. "Managing Irrigated Winter Wheat Residues for Water Storage and Subsequent Dryland Grain Sorghum Production." *Soil Science Society of America Journal* 43: 528-88.

PROJECT DRAINAGE

Walter J. Ochs

Adequate drainage can be a critical element in the success or failure of any irrigation or agricultural development project. Irrigation specialists and other agricultural development specialists should be alert to potential drainage problems when preparing or reviewing project plans. These problems can vary and depend to a great degree on climatic zone, soil, topography, and crop. Other factors such as irrigation type, farming equipment, and harvest methods may also be important when evaluating proposed drainage systems.

Generally, agricultural crops require a root zone well aerated and thus normally free of water saturation. Excess water must be removed from the crop root zone either artificially or naturally to control salt buildup in some climatic zones and provide proper soil aeration in root-growing areas.

Drainage Requirements

Drainage requirements must be addressed during project planning. Many of the same factors required for irrigation planning and design are also needed when analyzing the need for artificial project drainage and the optimum timing of drainage installation. Pertinent factors in determining whether and when drains are needed and in undergirding successful drainage plans include:

1. *soil*. Important factors include the characteristics of soils, extent of individual soils, hydraulic conductivity by soil layers, quality of soils to produce after drainage, soil salinity levels by layers, and the underlying geology;

2. *crop type*. The rooting depth of plants anticipated in the project area often controls depth and spacing of drains. Individual crops also have varying tolerances to salinity in the soil and water. Thus, crop type may even be dictated by salinity and drainage levels achievable in the most reasonable project alternative;

3. *climate*. Arid climates often require the control of salinity as well as water table control. Humid climates normally require water table control and consideration of more intense surface water removal. The timing of rainy periods is obviously important to crop production and also to drainage requirements;

4. *topography*. Drainage problems often arise if subsurface stratification is not consistent with surface topography. Systems should be designed to minimize the handling of waters from upland areas or overflow areas from streams intersecting the project. Diversions, dams, and dikes are some of the measures that may be needed to minimize internal project drainage needs;

Walter J. Ochs is drainage adviser, Agricultural Technology and Natural Resources Division, Agriculture and Rural Development Department, World Bank. When this paper was presented in 1985, he was national drainage engineer, Soil Conservation Service, U.S. Department of Agriculture.

5. *water table depth*. Water tables are not static under most conditions. Irrigation facilities and water management practices—as well as precipitation timing, duration, and extent—contribute to the dynamic condition of water tables.

Natural Subsurface Drainage

All soils drain naturally if an outlet is available. The rate of drainage depends on the physical characteristics of the soil and the condition of the outlet. The capacity of soils to drain naturally depends on site and soil physical factors and on the recharge rate. During the early stages of project planning, the natural drainage capacity of the soil should be evaluated to determine the rate at which drainage problems may develop. Various factors should be evaluated, but the primary concern is to make realistic estimates of the dynamic water table position over time and under the anticipated rate of recharge from irrigation water, precipitation, natural overflow, artesian flows, and seepage sources. Consideration of the natural drainage capacity through deep percolation and water movements toward natural outlets should be made. Water balance calculations can be used to evaluate and predict future water levels and project drainage requirements.

Selecting Applicable Drainage Practices

Successful drainage systems can be installed using various practices. Normally, a group of practices is used together to achieve optimal water control with the least cost. If a continuous shallow aquifer has characteristics that provide good water transmission and the soil above the aquifer does not restrict vertical water movement to the aquifer, pumped well drains should be considered. Subsurface drainage conduits such as drain tile should be considered when the hydraulic conductivity decreases with soil depth or a layer of soil or rock provides a barrier to vertical water movement above shallow aquifers.

Surface drainage systems may be the only possible technique in some extremely heavy clay soils. Sandy soils sometimes can be drained feasibly with open drains, but artesian pressures or water table recharge conditions may dictate the use of pipe drains or manifold well point systems.

Normally, surface water control and subsurface water control should be evaluated and provided where needed. The application of a good surface water management system will sometimes delay the need for installation of a subsurface drainage system. The timing of individual practice installation is important and should be presented and supported in plan proposals.

The selection of a suitable outlet is critical to the success of a drainage system. A gravity outlet is normally the best alternative to select if available, and receiving water quality will not be impacted beyond acceptable limits. Pumped outlets are sometimes needed. When this is the case, two alternatives can be considered: distribution of small pumping plants throughout the project area with discharges into shallow open drains that outlet via gravity, or installation of an open ditch collection system with a larger pumping plant to discharge into a more shallow outlet or through a dike. Vertical drain discharge wells are seldom used because of concerns about the degradation of underground aquifers.

Open Drains

Open drains can function both as field water collection drains and project disposal drains. Open drains should be located and shaped so that water entering the channel does not cause unacceptable erosion. Channel cross sections must be designed to minimize erosion and deposition from the collected water. Field surface ditches are usually shallow (less than 1 m) and have flat side slopes (over 4:1) to permit equipment crossing if needed. Disposal drains are normally deeper (1 to 3 m), with side slopes designed for stability and ease of maintenance (normally 1:1 to 3:1).

Field surface drainage systems are classified into three broad categories:

1. *Random* systems provide drainage to problem areas scattered throughout a field by connecting the depressions with a series of drains;

2. *Parallel* systems have field drains in a paralleled though not necessarily equidistant pattern;

3. *Interceptor* systems contain one or more diversions, terraces, or interception field drains constructed across the slope.

Land forming is often an important element in the surface drainage system. If sprinkler irrigation is being contemplated on somewhat undulating land, a method of land smoothing may be needed to facilitate water movement to surface drains. When gravity irrigation methods are anticipated, land-grading criteria similar to those used for irrigation land leveling should be considered to improve irrigation and drainage efficiency.

Open drain designs for disposal of project water in irrigated areas usually involve flat or slightly sloping topography. The design procedure generally involves:

- collecting field information such as field elevations, location and size of existing drains, control points, soil borings, and elevation of water anticipated in the outlet with stage-frequency information if available;

- establishing control points and setting the hydraulic gradeline;

- determining watershed areas;

- computing design discharge for the lower end of each channel reach;

- selecting the appropriate design criteria, including values for channel roughness, side slopes, minimum bottom widths, and minimum depth below the hydraulic gradeline;

- designing the drain cross-section below the established hydraulic gradeline.

Detailed discussions on open drain design are covered in Smedema and Rycroft 1983; U.S. Department of Agriculture 1971; and U.S. Department of the Interior 1978.

Open drains should be designed to pass the required drainage flow throughout the length of the drain with the hydraulic gradeline sufficiently below the land elevation to provide good drainage. The hydraulic gradeline represents the surface of the water when the drain is operating at design flow. The slope of the hydraulic gradeline is used in the Manning formula to determine velocity. The grade or slope of the drain bottom may have a different value because the drain bottom is not always parallel to the hydraulic gradeline.

Uniform flow is ordinarily assumed in the design of drainage channels, except above culverts and in locations where the design requires backwater computations. With these exceptions, the drain bottom normally can be established parallel to the hydraulic gradeline and a uniform channel section used. Although nonuniform flow results where minor obstruction occurs or where minor local drainage enters, it is of little practical significance, and the general efficiency of the system is not impaired. The rate of water movement in open drains is influenced by:

- the size of the drainage area;
- the irrigation or rainfall rate;
- type of crop;
- watershed runoff characteristics such as soil, vegetation, and slope;
- height and frequency of flood waters, particularly as they affect the outlet;
- the degree of protection desired.

The degree of protection desired is often difficult to evaluate because economic losses from flood damage must be estimated and crops respond differently to given periods of flooding.

Once the rate of water removal or drain capacity is known, the drain channel can be designed. The required channel dimension for a given flow rate Q, hydraulic gradient(s), and channel roughness (n) is usually determined by solving the Manning equation to determine mean velocity (v) and by using the relation:

$$Q = Av$$

where Q = rate of flow in m^3/s; A = cross-sectional area of the channel in km^2; and v = mean velocity in m/s.

The drain grade is frequently determined either by the outlet elevation, the lowest area in the watershed, or by the depth of other drains in the system. In flat areas the drain grade should be the steepest possible, provided the maximum permissible velocity is not exceeded. Additional details regarding the determination of mean velocity, selection of channel roughness values, and channel shape can be found in U.S. Department of Agriculture 1971 and U.S. Department of the Interior 1978.

In addition to the above, the following factors regarding channel shape and cross-sectional area should be considered:

1. In irrigated areas depth of drain rather than capacity may be the dominant consideration;

2. A deep drain provides a higher velocity than a shallow one;

3. A deep drain requires less area than a shallow one;

4. A deep drain may expose unstable soil layers that a shallow one would not expose;

5. A deep drain may provide a better opportunity for future subsurface drainage in the area.

It is good practice to allow for sedimentation in a drain during the first two or three years after construction. This allows the drain to maintain design capacity after it stabilizes and is provided for by increasing the design size. The amount of this allowance depends on the expected sediment transported from the watershed, erodibility of soils exposed in the drain, and erosion from adjoining lands. After the sides of the drains are stabilized by vegetation, sedimentation normally decreases.

Drains should be located to provide the most effective drainage of the area. Topography, soils, existing drains, property lines, and cultural features all influence drain location. Natural outlets usually fix the location and elevation of a drain, but the alignment and efficiency of the channel can be improved by using curves and cutoffs. An open drain must terminate in an adequate outlet of sufficient capacity to carry the design discharge without causing stage increases and significant damage downstream.

In irrigated arid areas, open drains serve primarily to remove surface and subsurface irrigation wastewater and irrigation canal seepage water. Drains can be located either parallel or perpendicular to the direction of groundwater flow, generally depending on whether the drain is intended to control the water table or intercept subsurface flow. Drain location is usually affected by the irrigation or canal system and the depth and location of permeable aquifers.

Drain capacity is determined by the size of the area to be drained; the intensity of drainage required; and the potential amount of precipitation, irrigation wastewater, and natural runoff.

In arid and semiarid areas, the drainage requirement is usually expressed in terms of the amount of irrigation water supplied. Values of 10 to 40 percent of the applied irrigation water have been reported as drainage requirements for different sites in these areas. Because of the wide variation in these values by location, local sources of known values or estimated values based on experience should be consulted. For large areas where irrigation water is applied to only a portion of the total area, the drainage requirements can be expressed as a volume of water per unit area per unit of time on the basis of local experience.

Another method of determining the required rate of water removal, primarily for large watersheds, is by the empirical relationship:

$$Q = kM^x$$

where Q = runoff in m^3/s; k = a constant; M = watershed area in km^2; and x = an exponent.

The constants k and x vary with the drainage requirement and location. Values for these constants, as well as curves for the equation and various combinations of values for k and x, are available in U.S. Department of Agriculture 1971.

The construction and maintenance of open drains are similar to the methods, procedures, and equipment necessary for irrigation canals. These important items will not be covered in detail here (information can be found in Jensen 1980; U.S. Department of Agriculture 1971; and U.S. Department of the Interior 1978). A maintenance plan and accompanying funding program are significant long-term factors in determining the success or failure of a project.

Closed Subsurface Drains

Closed drains are underground pipe systems installed to collect and carry away excess groundwater. They normally are made using open-joint clay or concrete tile or pipe, or perforated plastic tubing or piping laid horizontally at depths of 1 to 3 m. The closed subsurface drains lower a high water table caused by excess groundwater.

Closed drains are often classed as interceptor or relief drains. Interceptor drains usually consist of a single drain installed to intercept the horizontal flow of groundwater from a known seepage source that is up slope. Relief drains consist of a system of parallel lateral drains and are connected to a main drain. The relief system is designed to lower a water table in the plant's root zone over the entire field, to provide relief from excessive waterlogging.

Design

Subsurface conduit drainage designs can be complex, and much information has already been written about adequate design (see most references). The design of a closed gravity drain system involves a determination of required depth, spacing, and size of drain, together with provision of an adequate outlet and appurtenant works. Depth and spacing are roughly proportional, depending on the permeability of the soil strata. Generally, the greater the depth of drain the wider the spacing between drains, with the choice of depth and spacing often an economic consideration.

The depth of the drain is often controlled by the depth of the outlet system. Where the outlet is not limiting, depth is determined by such factors as crop type, soil, drainable strata, and drain spacing. In arid areas with high water tables or where salts occur in the soil and groundwater, drains should be relatively deep. For irrigated areas, the drains should be approximately 2.5 m deep. In stratified soils, it is advisable to place the drain in the most permeable layer, provided it is below the depth to which the water table should be lowered and at a depth that can be economically reached. Where soil layers are undulating or discontinuous, it may not be possible to place the drain in the most permeable layer because the tubing must be on grade and continue on grade to a point of discharge.

Spacing between drains depends upon many factors, but the texture and permeability of the soil, and the depth of the drain below the soil surface, are significant. Groundwater usually moves through coarse-textured soil more rapidly than through fine-textured soils. Several theories covering the flow of groundwater to subsurface drains and consequent drain spacing equations have been proposed during the past 30 years. Most of the applicable equations are outlined in U.S. Department of Agriculture 1971 and U.S. Department of the Interior 1978. These theories have modified the approach the drainage engineer takes in obtaining a solution to the many drainage problems. Considerable progress has been made toward the rational design of drainage systems using these theories. In designing a closed gravity drain system, it is recommended that the engineer review the various drainage design equations, along with the conditions for which each equation applies. Then, depending on the drainage situation, available design parameters, and the degree of sophistication desired in the system design, the most appropriate of the several formulas can be used to arrive at a suitable design. Steady-state and transient equations are used in both humid and arid areas.

Sediment is likely to accumulate in buried subsurface drains laid with little or no grade. On flatlands, a minimum grade for drain lines should be established according to site conditions. For example, the drain line may be 2 m deep at the outlet, but to obtain a proper grade for the line, the up slope end is only 1.5 m deep. There must be a compromise between the depth of the line and the grade of the line to achieve an optimum balance. The Bureau of Reclamation minimum grade criteria are established by maintaining a velocity of 0.3 m/s when the conduit is flowing fully, and 0.001 grade is considered the minimum. The Soil Conservation Service minimum grade criteria indicate that velocity cannot fall below 0.15 m/s if there is no sedimentation hazard and 0.45 m/s if there is a sedimentation hazard.

The smallest diameter of drain tubing in general use in the United States is 75 mm. The problems in maintaining a precise grade and alignment and the possibility of some sediment intake encourage the use of larger sizes, although the larger size is not intended for hydraulic capacity. In designing drainage systems for hydraulic capacity, the size of the conduit is determined by the design flow, slope, and roughness coefficient. The Manning formula is commonly used to determine required size:

$$Q = CR^{2/3}S^{1/2}A$$

Where Q = rate of flow in m^3/s; $C = 1/n$; R = hydraulic radius in m; S = slope in m/m; A = cross-sectional area of flow in km^2; and n = roughness coefficient. The normal roughness coefficient (n) for clay and concrete tile is 0.013; for 76- to 203-mm corrugated plastic tubing, it is 0.015; for corrugated plastic tubing 254 mm and 305 mm, it is 0.017; and for the larger sizes of corrugated plastic tubing (>305 mm), it is 0.02. Corrugated metal *n* values are usually 0.025, and those for smooth wall tongue and grove or bell and spigot joint pipe are usually 0.012.

Installation

The installation of subsurface conduits for drainage is critical to continuing long-term system performance. The system should provide a minimum number of outlets and, whenever practical, should be planned to have a short main and long laterals. For economical installation, the laterals should be oriented to use the available field slope, and the main or collector line should be oriented to parallel the natural waterways. Often, however, the most effective drainage is provided if laterals are parallel with water table contours. The trench should be excavated, beginning at the outlet and proceeding upgrade. The collector or main drain should be installed first and then the laterals, again proceeding upgrade. The alignment of the drain should be such that the tubing can be laid in a straight line or with smooth curves. The use of manufactured connections is recommended. Furthermore, junction boxes or manholes are recommended wherever two main or collector lines meet or where two or more laterals connect to a collector line.

Closed drains must be installed so that the tubing is not excessively deformed by the soil loads placed on them. The load that usually governs the strength required is the weight of the earth covering the drain. The magnitude of the load that the drain can safely support depends on the unit weight of the soil, the width and depth of the trench, and the method of bedding and installing the drain. If the drain is less than 1 m deep, such as in humid-area irrigated sites, impact loads imposed by heavy farm vehicles could pose a danger. Rigid conduits such as clay and concrete tile fail by rupture of the pipe walls. Their principal load-supporting ability lies in the inherent strength of the pipe. Flexible conduits such as corrugated plastic tubing fail by deflection. They rely only partly on their inherent wall strength to resist external loads. For flexible tubing, deflection causes the horizontal diameter of the corrugated plastic tubing to increase the compression of the soil at the sides of the tube. This builds up resistance that, in turn, helps support the vertically applied load. Flexible tubing should be installed in the trench to ensure good soil support on each side of the conduit.

Drain Envelopes

Closed drains installed in irrigated areas are usually provided with well-graded envelope material or synthetic-fabric envelope material to prevent sediment from entering the drain. Envelope materials such as hay, straw, sawdust, wood chips, peat moss, and corncobs have been used primarily in humid areas; however, in the mechanical installation process, a more permanent installation can be achieved if a 75-mm or greater layer of well-graded aggregate envelope is laid directly behind the digging wheel. The tube is laid on the gravel and is surrounded with at least 75 mm of the aggregate envelope material. This envelope material has a threefold function: it serves as an ideal stabilized bed for the tubing and ensures good transfer of deflected load; it screens out soil particles that might otherwise migrate into the conduit; and it provides an improved zone of permeability around the conduit. The aggregate envelope is regarded as the most efficient and trouble-free protective envelope to use on closed drain systems. The unavailability of sand and gravel in many places has led to the use of cinders, slag, and crushed stone in some areas. Envelope materials of synthetic geotextile fabric filters such as nylon, polyester, and polyethylene, rather than the conventional aggregate envelopes, are being used in some locations. The synthetic-fabric envelopes have been quite successful in sands and sandy soils. In silts, problems are often noted, and the fabrics should not be recommended for these soils.

Outlet Requirements

An outlet for a closed subsurface drain system should provide for the free flow of drain water to an open drain or other disposal point. A good practice is to have a free-fall of at least 0.15 m in humid areas and 0.45 m in arid areas between the conduit invert and the level of water in an outlet drain. In some places, the design of the drain system and depth requirements of the lateral lines require an outlet deeper than the available disposal drain. In these places, the procedure is to install a sump with a pump to discharge the drain water into the outlet system at a higher level. Sumps are constructed by excavating a pit near the subsurface drain outlet and adjacent to the disposal drain. The excavated pit is lined with concrete, and the outlet of the drain enters the sump near the bottom. The sump usually extends about 0.3 to 0.6 m above the ground surface. The water is pumped from the sump into the outlet ditch with an automatic-float or electrode-activated pump.

Maintenance

A properly designed and installed closed-drain system is not difficult to maintain. Failure can occur, however, in an existing drain system. First, it is imperative to maintain a free flow at the outlet, thus preventing physical clogging of the drain at that point. Frequent observation of the drain flow will indicate whether the system is functioning properly. If there is a marked decrease in flow, the conduit could be physically clogged by silt, plant roots, or chemicals. It could also be damaged by animals, or it could collapse. Physical, high-pressure, water-jet cleaning techniques and chemical treatment by introducing sulfur dioxide to dissolve the oxide deposits have been developed to restore the flow in drain lines clogged by chemicals, roots, or sediment.

Drainage Pumping

Providing sumps and pumps for the disposal of water from both surface and subsurface drainage systems—if discharge by gravity flow is not practical—requires detailed investigation and a careful survey of site conditions for planning, design, and construction. Pumps can be used for disposal of drainage water from open drains where gravity outlets are not practical because of inadequate outlet conditions. For example, they can be used where backwater from storms or tidal flooding prevents the discharge of the drainage water into a natural outlet at frequent intervals or where the area is very flat and relift pumps and developed grades are required to keep the water moving. (Details on investigation, design, installation, and maintenance can be found in Jensen 1980 and U.S. Department of Agriculture 1971.)

Well Drainage

Drainage wells are groundwater wells designed, constructed, and spaced to relieve or control an existing or potential high water table or artesian condition. A well creates a cone of depression in the water table or piezometric surface, the shape and dimensions of which depend primarily on the aquifer characteristics, rate of discharge, and boundary conditions. Drainage occurs only within the influence of this cone of depression. Most drainage well installations consist of a group of wells spaced so that their individual cones of depression overlap sufficiently to lower the water table level at all points in the well field.

Two conditions must be present to permit drainage by wells: (1) an aquifer of adequate transmissivity, and (2) adequate vertical permeability between the root zone and the aquifer. Other conditions that favor well drainage are:

1. extremely flat surface terrains that preclude gravity outletting of drains (the costs for installing and operating wells are comparable to or lower than those for horizontal drains plus relift pumping facilities);

2. uneven topography that would require excessively deep excavation for drains;

3. subsurface conditions unsuitable for installing conventional drains, such as hard rock or unstable soils;

4. highly developed land where ample rights-of-way and/or high construction costs of drains might exceed costs of well installation and operation;

5. areas where materials, equipment, and labor for constructing drains are scarce or more expensive than the costs of installing and operating wells;

6. areas where drain construction may result in environmental damage;

7. availability of low-cost energy for pumping from wells;

8. local conditions such that the pumped drainage water can be used as a supplemental irrigation supply;

9. the lack of uniform subsurface conditions, making it extremely difficult to determine drain spacing.

Details on investigation, design, installation, and maintenance of well drainage systems can be found in Jensen 1980 and U.S. Department of the Interior 1978.

Conclusion

Many other facilities, practices, and issues must be considered and integrated with drainage project plans. A drainage project is seldom installed without a significant change in other infrastructure: in arid and semiarid climates it is usually the irrigation system, and in humid and tropical climates it is usually a flood control system. Project planners must be alert to the needs and opportunities of other facilities when preparing irrigation and drainage plans. Practice and facilities such as dikes, roads, diversions, impoundment reservoirs, evaporation ponds, and floodways should be considered.

In some irrigation and drainage projects, water quality and environmental concerns require a great deal of attention. Much evaluation may be necessary to predict the impacts of a major project and should be used to modify project measures whenever possible to minimize adverse impacts and enhance environmental improvement factors.

Some well-designed irrigation and drainage projects are not as productive as anticipated or even fail because of poor training of the people who operate the system and depend on the system service. Good on-farm practices and management are the key to achieving the most efficient and productive project. A good infrastructure is necessary, but without the on-farm elements the benefits envisioned will not be realized.

Maintenance is another key item necessary for acceptable long-term project performance. Detailed maintenance plans outlining responsibility roles, objectives, time frames, inspection and follow-up procedures, and particularly financing should be in place prior to the start of any work. Consideration of all relevant factors—both short- and long-term—will help create successful drainage systems.

Selected References

FAO. 1973. *Irrigation, Drainage and Salinity*. London: Hutchinson.

____. *Drainage Design Factors*. 1980. FAO Irrigation and Drainage Paper 38. Rome.

International Institute for Land Reclamation and Improvement (ILRI). *Drainage Principals and Applications*. Publication 16, nos. 1-4 (May 1972, April 1973, March 1974, and June 1974). Wageningen, The Netherlands: ILRI.

Jensen, M.E., ed. 1980. *Design and Operation of Farm Irrigation Systems*. (See chapter 7, "Drainage Requirements and Systems.") American Society of Agricultural Engineers Monograph 3. St. Joseph, Mich.

Luthin, J.N., ed. 1957. *Drainage for Agricultural Land*. Agronomy Monograph Series, volume 7. Madison, Wis.: American Society of Agronomy.

____. 1966. *Drainage Engineering*. New York: John Wiley.

Smedema, L.K., and D.W. Rycroft. 1983. *Land Drainage*. Ithaca, N.Y.: Cornell University Press.

U.S. Department of Agriculture, Soil Conservation Service. 1971. *Drainage of Agricultural Land*. Washington, D.C. (Also available [1973] from the Water Information Center Inc., 44 Sintsink Dr., East Port Washington, NY 11050.)

U.S. Department of the Interior, Bureau of Reclamation. 1978. *Drainage Manual*. Denver, Colo.

van Schilfgaarde, J., ed. 1974. *Drainage for Agriculture*. Agronomy Monograph Series, volume 17. Madison, Wis.: American Society of Agronomy.

TECHNOLOGY RESEARCH IN DRAINAGE: THE FRENCH EXPERIENCE

Benoît Lesaffre

Worldwide, both drainage requirements and technology have changed dramatically over the past thirty years. The area devoted to irrigated agriculture has increased threefold. Where drainage has been deficient, waterlogging and salinity have ensued in many arid areas, and their adverse effects particularly impede further crop intensification. In humid or tropical areas where other limiting factors have been mitigated, potential crop yield is often reduced because of excess water. Drainage technology has improved quickly in many fields. New materials, such as corrugated PVC pipes and geotextile envelopes, have been introduced. Drainage systems have been increasingly mechanically constructed, with trenchless machines presently used to install subsurface drainage systems more often than trenchers, resulting in reduced construction costs.

There are numerous drainage-related questions being asked in both developed and developing countries: What are the optimum drainage systems to ensure both a sustainable rise in farmers' incomes and sustainable watershed reclamation? How can the physical and economic input data required to properly design drainage systems be obtained in the most cost-effective manner? How can drainage systems effectively be maintained by individual farmers or relevant organizations? How can experience, gained either in country or abroad, be transferred and adapted to other situations? How can the potential adverse effects of drainage on the environment be avoided or mitigated? Some of these questions may receive appropriate theoretical answers, useful for a limited number of highly skilled and well-educated farmers and local representatives. Others, however, can only be answered using pragmatic approaches, based on a consensus among all concerned individuals and utilizing their knowledge and experience.

In the mid-1970s, when subsurface drainage accelerated throughout France, the country had to face all these concerns. Good though limited experience was available in some drainage-related fields, with much to be done to meet the rapidly increasing demand for subsurface drainage. This paper first explores drainage in France. Three areas where significant efforts have been undertaken will be examined: (1) drainage planning and organization, (2) quality of drainage construction, and (3) field experiments and investigations. The paper concludes with a look at future developments.

Drainage in France

In the early 1970s, only 20,000 ha were subsurface drained annually in France, involving cereals grown on sandy soils in the northern coastal plains and on loamy soils in the northern part of the country. Subsurface drainage boomed during the late 1970s, and in 1982 the annual area subsurface drained reached 130,000 ha, mainly located on dairy and mixed farms in western France. A total of 2 million ha has been subsurface drained, and about 5 million ha, representing 15 percent of the agricultural land area, are still to be drained. Of this amount, 500,000 ha are permanently

Benoît Lesaffre is head, Irrigation and Drainage Department, French Institute of Agricultural and Environmental Engineering Research (CEMAGREF), Antony, France. This paper was presented in 1990.

waterlogged due to a high groundwater table. The remaining hectarage is seasonally waterlogged because of either outside flow (runoff, springs) or winter storage of rainfall inside the permeable and often shallow soil lying above an impervious barrier, resulting in temporarily perched water tables. The main adverse effect of excess water is to delay farm operations in winter and spring, a typical scenario under temperate climates with evenly distributed rainfall.

Subsurface drainage systems are composed of corrugated PVC pipes, usually installed at a depth ranging from 0.8 to 1.2 m, and they sometimes include mole drains. Relief drainage systems are primarily random and composite; buried collectors and interception drains are often needed. Small structures (outlets, inlets, junction boxes) are made of plastic or prefabricated concrete. The main drainage systems are composed of ditches generally discharging into watercourses.

In 1970, the average area used for agriculture per farm was 25 ha. It is presently 30 ha. With land reallocation not yet completed, many farms are divided into several small plots. Consequently, the average size of drainage work sites is about 7 ha. The farmer or landowner is essentially the decisionmaker, so it will usually take years before a watershed is fully drained.

The French countryside has varied landscapes, mainly the result of diverse soil and climatic conditions and diverse farming systems throughout the country. There are 400 agricultural regions, categorized around these variables. Solutions to drainage problems must consider this variety at each stage of the drainage process:

- At the *planning stage,* main drainage systems and outlets have to be precisely located to avoid harming the water disposal of future drainage systems;

- At the *design stage,* all required data on farmers' objectives and on the environment have to be supplied to designers. This is a costly procedure, and it may be impossible to collect the data in a timely fashion;

- During the *construction stage,* contractors face a serious challenge: to effectively apply modern installation techniques to small drainage systems;

- *Operation and maintenance* of drainage systems have to be carried out consistently throughout a watershed.

Drainage systems have often been constructed in difficult soils (heavy clay and clogging soils) with strong economic constraints. Increased knowledge of drainage requirements, suitable techniques, and drainage effects on farm management has therefore been essential.

Drainage Planning and Organization

Drainage planning has been organized with an emphasis on acquiring regional data on the extent of waterlogged lands and on local drainage recommendations, using Waterlogged Land Zoning and the Reference Area Method. Based on these two methods, a national program has been established focusing on the preparation of drainage project design together with local and national institution building; design methods have also improved using the CADD package DACCORD.

Waterlogged Land Zoning

Waterlogged Land Zoning assesses the extent and cost of excess water within agricultural watersheds. In each parish, a local panel is formed, comprising farmers and local representatives involved in agricultural and environmental water management, an agricultural adviser, a drainage officer, and, when possible, an environmentalist. Lands are classified according to a relevant criterion, e.g., the spring drying-up duration in cereal areas or the grazing delay for livestock in pasture areas. Their boundaries are reported on a 1:10,000 map, as are existing or required drainage facilities and some environmental constraints. The final document is submitted to farmers and local representatives. In areas where limited input data are available, information is obtained within acceptable time limits and is either sufficiently precise at the planning stage or helps identify the main points. One advantage of this method is that farmers' experience is incorporated into documents intelligible to both technical and funding parties. Also, before the works are executed, all parties involved in the drainage process are acquainted; this has created mutual confidence, facilitating the consideration of human, environmental, and financial aspects (Lesaffre 1989).

The Reference Area Method

Collection and interpretation of input data for drainage design usually require more time than available. Farmers and landowners are reluctant to pay for preliminary surveys, even if highly subsidized. Moreover in France, because watersheds are not subsurface drained at once, drawing up a complete soil map of a large area from the outset is not cost-effective.

A pilot survey, conducted between 1975 and 1977 on a 40,000-ha agricultural region, indicated both that (a) numerous soil scientists should be engaged to meet the drainage demand throughout the country, and (b) the same relevant information could have been obtained on a much smaller area, properly selected and mapped at the 1:10,000 scale (Devillers et al. 1978). Based on this pilot survey and on other experiences (Favrot 1984; Horemans and Lesaffre 1984; Jannot and Schnäbele 1988), in the late 1970s the Reference Area Method was developed. The method combines (a) a 1:10,000 scale soil map; (b) in situ measurements of field-effective soil hydraulic properties using Guyon's pumping test (Lesaffre 1990a); (c) investigations of existing drainage systems; (d) specific recommendations and sometimes field experiments or pilot sites on difficult soils (heavy clay, clogging, and rocky soils; soils with spring lines); and (e) agronomic and economic surveys of different farm types. All data are reported in widely distributed documents, some of which are stored in a user friendly database. Then, from a simple map of the land to be drained, a surveyor can determine the drainage recommendations suiting the project under study without any additional analyses. The Reference Area Method has been applied to 100 regions covering 2 million ha.

Local and National Institution Building

Local drainage institutions are either permanent or ad hoc. Tasks can be assigned to local permanent institutions under existing laws and regulations. These institutions prepare drainage project proposals for funding, schedule survey and work execution, and oversee operation and maintenance of drainage systems (Poubelle 1990). There are two types of permanent institutions: borough syndicates and landowner associations. Borough syndicates manage most main drainage systems and small river training. Landowner associations deal with field drainage systems and presently cover more than half of the total drained surface.

Ad hoc organizations—local technical steering committees (LTSCs)—have been developed, comprising local representatives, farmers' representatives, surveyors, engineers, agricultural advisers, administrative staff, and, in some cases, contractors. Their main purposes are to (a) relate drainage works to farmers' general objectives; (b) define priorities among drainage projects; (c) coordinate the drainage process from planning to construction; (d) implement Waterlogged Land Zoning and the Reference Area Method and aid in selecting consultants for these investigations; (e) help landowner associations apply for grants; and (f) disseminate results of investigations and experiments through informational meetings and field trips.

To coordinate the work done by the LTSCs and to help them implement Waterlogged Land Zoning and the Reference Area Method, a national steering committee was established in 1981, composed of civil servants from the Ministry of Agriculture; representatives of agricultural organizations; and agronomists, soil scientists, and agricultural engineers from the national technical and research institutes (e.g., the French Institute of Agricultural and Environmental Engineering Research (CEMAGREF), the National Institute of Agronomy Research (INRA), and agricultural technique centers). This committee (a) advises the Ministry of Agriculture on local priorities; (b) prepares investigation specifications; (c) circulates information among local partners; (d) organizes training sessions (Hervé 1987); and (e) disseminates results by distributing reports, developing a soil-drainage data base, and organizing national workshops.

All these activities constitute the national program, proposed in the late 1970s by a national working group, which defined another priority: to review schedules of specifications dealing with design rules and supervision of work execution. The national program has mainly been subsidized by the Ministry of Agriculture and the National Cereal Council and sometimes financed by local or regional authorities. In the late 1970s, the National Cereal Council wished to improve cereal yield and quality in waterlogged areas and was prepared to allocate grants for drainage; according to the national working group's recommendations, it agreed to emphasize preliminary surveys and drainage project preparation, which received subsidies up to 100 percent within reference areas. In line with this agreement, the Ministry of Agriculture directed to field experiments and pilot sites subsidies amounting up to 80 percent of costs. As local and regional authorities became involved, they progressively financially contributed to the process.

The CADD Package DACCORD

Initiated in the late 1970s, a computer-aided design and drafting (CADD) package called DACCORD was developed during the 1980s by CEMAGREF with the help of consulting engineers (Penel 1989). It utilizes either screen graphics or a digitizing table for design and layout of subsurface drainage systems. After the creation of a terrain surface model from field survey data, DACCORD has four basic design phases: (1) laying out the drainage system pipelines, (2) burying the pipe system generated in the previous phase, (3) sizing pipes, and (4) plotting the design phases. DACCORD can be run on an IBM-PC (or compatible model) with a minimum 256,000-byte memory. Training sessions based on the package have been organized to improve designers' practices.

Drainage Construction Quality

About 400 drainage machines are in use in France; most (90 percent) have been imported. About 120,000 km of PVC pipes have been installed annually since 1982 and are manufactured domestically. Standardizing and labeling drainage materials (corrugated PVC pipes and geotextile envelopes) and improving installation quality have been stressed.

PVC Pipes

In France, standards for PVC pipes were developed in the early 1970s. Like those of most industrial countries (see Schultz 1990), they sought to (1) clearly identify the nature, type, and origin of the product; (2) evaluate pipe mechanical characteristics; and (3) evaluate pipe hydraulic performance. This was not sufficient, however, because ultimate users were not guaranteed that products met specifications. In 1982, a label for PVC pipes was created, according to the official process *marque NF*. In the mid-1980s a research program compared PVC pipe weathering under natural conditions with artificial weathering using ultraviolet lamps to derive a weathering standard based on a short-duration test. This standard was accepted in 1990. Present activities include standardizing larger-diameter PVC pipes and incorporating them into the labeling process, and formulating international—or at least European—standards.

Geotextile Envelopes

Investigations on envelopes have led to (1) an extension of general standards on geotextiles to drainage applications (identification, test of hydraulic and mechanical properties); (2) the development of specific drainage standards (permeameter test, wetting test); and (3) a schedule of specifications for selecting samples from work sites for laboratory testing. Items 1 and 2 have been applied to French and Hungarian fabrics (Bognar and Lennoz-Gratin 1990), and item 3 is widely applied in the sandy soils of France's northern coastal plains.

Improved Installation Quality

Connections of field drains and collectors had been one of the weakest links in drainage systems. Inverse slopes often appeared at the downstream ends of laterals, resulting in reduced discharge capacity, deposits in pipe hollows, and blockage of connections by annual crop roots. Numerous inquiries and field investigations revealed that when bad-quality connections reduced the effective section of pipes, blockages occurred regardless of crop root type. When properly designed connections became widely used, the incidence of such problems decreased significantly.

Because of the boom in drainage and technology in the 1970s, there was an urgent need to train drainage workers, primarily machine drivers, in the new technologies. To do so, the French Association of Drainage Contractors (SNED) established a Training Center for Drainage Machine Drivers in the late 1970s (Moulinier 1990). Thus far, the total duration of all sessions has reached 6,300 hours; session participants have been drivers as well as consulting engineers. Sessions have addressed operating drainage machines and using rotating laser beams to control installation (see Schultz 1990: 213-19).

Field Experiments and Investigations

Field Experiments

Drainage is not an exact science, but depends on many advanced disciplines. Drainage specialists are not only skilled scientists, but also experts with much field experience. Present drainage criteria and technologies are semiempirical, and despite advances in knowledge, formulas will never be sufficient for decisionmaking. Local specific criteria and technologies have to be developed, modified, and checked using monitored systems such as field experiments or pilot testing. Field experiments may have four basic functions, often combined within a given experimental site:

1. creating awareness of drainage and demonstrating effective techniques;

2. evaluating drainage system aging and determining factors affecting the sustainability of drainage systems;

3. testing drainage criteria, related to design (e.g., drain spacing or depth); construction (e.g., type of envelope); or operation (e.g., farming practices);

4. evaluating the impact of drainage on the environment (river flooding or water quality).

(For a full discussion of these functions, see Wesseling 1979; Ochs and Willardson 1983; Saavalainen and Vakkilainen 1986; Smith and Rycroft 1986; Nolte 1987; Daniane 1990; Lesaffre 1990; for details on the French experience, see Lesaffre and Morel 1986; Lesaffre and Zimmer 1988; Penel and Lesaffre 1989; Zimmer and Lesaffre 1989; Arlot 1990).

Functions 3 and 4 are best fulfilled using calibrated models versus field data. Present scientific debate mainly focuses on topics related to these functions and to the use of models. Some agreement has been reached within the scientific community: (a) various types of models have to be developed according to different objectives; (b) for management, field data should be used, measured on a scale consistent with the size of hydraulic systems to obtain field-effective values; and (c) with drainage criteria, investigations on agronomic input data should be as developed as those on hydraulic input data.

Other aspects are still under discussion. How can the complex mechanisms involved in flow and solute transport be incorporated into water management tools, whose performance significantly depends on the quality of input data? How can spatial variability of environmental variables be taken into account? How can specific approaches on drainage design and management be related to a holistic approach dealing with all aspects of water resources management?

Fewer scientific investigations deal with functions 1 and 2. Nevertheless, there is much experience developed by actors involved in the drainage process. This knowledge is seldom widely shared, mainly because of a paucity of publications; even in developed countries such as France, technology transfer to farmers remains a challenge. In response, six national experiment and demonstration networks were established in France in 1981; five deal with agriculture and food industry sectors (cereals, cattle, ovine race, swine, and fruit and vegetables) and one with irrigation and drainage. The objective was to make technical and economic material relevant to farming systems available to farmers and extension agents. To meet this objective, inquiries and reviews were carried out, and ad hoc working groups were created, involving scientists, engineers, extension agents, teachers, and agricultural advisers. The drainage working group edited and distributed three reviews regarding (1) technical and economic prerequisites for optimum drainage system design and construction; (2) maintenance of main drainage systems; and (3) a national index of field drainage experiments, which can also be consulted using the French telematic system Minitel.

Hydraulic data collection and processing systems have evolved rapidly over the last 15 years, resulting in automated monitoring systems, data stored on magnetic files, and improved system quality with reduced costs (Penel 1990). The water-level-measuring system developed in 1984 by CR2M, a specialized company, and CEMAGREF is widely used; water levels are (a) measured using an ultrasonic probe installed at the bottom of piezometers and V-notch boxes, (b) recorded by a monitoring device powered by solar panels combined with a buffer battery, (c) regularly recovered by field microcomputers or remotely transmitted, and (d) stored on laboratory microcomputers where they are processed and utilized.

Soil hydraulic properties are required to determine field drain spacing, which is a critical parameter for drainage cost-effectiveness. As stated above, they are best obtained using field investigations. For scientific purposes they can be derived from analysis of hydraulic sequences measured on field experiments. For design purposes, however, they have to be measured on every type of soil prior to the design stage using suitable methods. The method developed in France is Guyon's pumping test (see details and field procedure in Guyon and Wolsack 1978; Lesaffre 1990a). Both saturated hydraulic conductivity and drainable porosity are measured and incorporated in unsteady state equations to compute field drain spacing; to reproduce drainage operation, these equations are usually considered better than steady state equations. The model used to determine both soil hydraulic properties is based on the same theoretical principles as the unsteady state equations. The method's radius of influence is a few meters, i.e., soil hydraulic properties are measured at the field drainage system scale. A semiautomated pumping package has been specifically designed by CEMAGREF and has been used by 25 consulting agencies within reference areas to characterize the soil series defined by the soil surveyor.

Specific Investigations on Difficult Soils

Specific technology research programs have been developed for difficult soils to derive practical recommendations related to design and construction. Below is a short description of programs on heavy clay, shallow, mineral-clogging, and rocky soils, and on soils with spring lines.

Heavy clay soils. In France heavy clay soils account for about 20 percent of the waterlogged land surface (Bouzigues et al. 1982). Based on field experiments in reference areas, secondary drainage treatments are often the most efficient drainage techniques, even if local experience shows that, in some cases, moling or subsoiling are not necessary. The objective of initial investigations and experiments in the 1970s was to test secondary drainage treatments in some heavy clay soils where conventional drainage techniques failed. They were mainly based on the United Kingdom's extensive experience, since most British soils are heavy and are drained using mole drainage.

Present investigations focus on three complementary directions:

1. *design criteria.* The objective is to derive technical recommendations from both analysis of soil-water retention properties and water pressure profiles of representative heavy clay soils; this approach has provided practical indications on the usefulness of secondary drainage techniques (Zimmer and Lesaffre 1989);

2. *farmers' awareness.* The goal is to demonstrate that for many heavy soils moling is the most appropriate drainage technique; this is difficult because conventional drainage techniques often improve farm management (though slightly), although they are not cost-effective;

3. *construction techniques.* The objective is to help contractors buy appropriate moling equipment and modify work organization.

Shallow soils. Shallow soils usually are much easier to drain than heavy clay soils. Drainage design criteria are well established and widely used throughout the country, in connection with the data collected within reference areas (Lesaffre 1989). Nevertheless, recent investigations have shown that, if deep seepage were taken into account, drain spacing would increase substantially, resulting in reduced drainage costs. Results from field experiments, theoretical considerations, and soil surveys have proved the high variability of the "impervious" barrier in some soils, as well as its influence on deep seepage intensity (Zimmer and Lesaffre 1989; Favrot et al. 1990).

Mineral-clogging soils. In France, several investigations have dealt with ocher-clogging soils (Houot et al. 1984). Most investigations have been carried out on mineral-clogging soils in connection with the use of drain envelopes (Stuyt and Cestre 1986; Dierickx et al. 1987; Lennoz-Gratin 1987, 1989; Lennoz-Gratin and Bognar 1990). Mineral-clogging hazards are found in many soil types: salt-affected heavy soils (Lagacherie et al 1984) and loamy and silty soils (Lennoz-Gratin 1987). A general recommendation is to install pipes with a regular slope.

Mineral clogging is due to soil particle invasion into pipes. This occurs in unstable soils, where particles are pulled out of the soil matrix because of high hydraulic gradients in the vicinity of the pipe. Consequently, pipes become blocked, and drainage systems are inoperable. Pipes can be cleaned using flushing devices, but it is less expensive and more effective to use preventive measures such as envelope material around the pipe.

To define clogging hazards and to prepare recommendations on the use of envelopes, research performed at CEMAGREF during the 1980s combined laboratory experiments with field investigations carried out with other institutes and local partners. Water and soil particle transport in the vicinity of the pipe was investigated using a laboratory sand tank and a 2D-finite element numerical model; bare versus wrapped pipe behavior was compared. Then a simple laboratory device, based on the permeameter principle, was developed to define the critical hydraulic gradient (CHG) for a given soil/drain combination. CHG is the mean hydraulic gradient near the pipe at which soil particles begin to move. i.e., the early stage of the clogging process is reached.

Unstable soils have low CHGs. The upper limit of harmful CHGs was derived from the analysis of the performance of 16 drainage systems installed on silty or loamy soils. The permeameter test has been standardized and is now conducted in laboratories involved in preliminary drainage surveys.

Rocky soils and soils with spring lines. For design and construction of drainage systems in mountainous areas, there are two specific problems: (1) excess water may be generated by spring lines as a result of complex underground organization and steep slopes, which may lead to severe drainage failures if spring lines are not properly caught; and (2) large rocks may be present just below the ground surface, so that drainage machines must slow down; they can also break, thereby increasing drainage costs.

Conventional soil surveys are unable to detect these problems, even within reference areas. Therefore radiomagnetotellurics (RMT), which proved to be efficient for public works and for archeological investigations, has been adapted for preliminary drainage surveys (Gauthier et al. 1988). The principle is to compare broadcast long waves before and after they have been modified by soil properties to derive soil resistivity profiles. A self-propelled system, designed by the National Center for Scientific Research (CNRS) and the State Laboratory of Civil Engineering (LCPC), pulls a conducting cloth on the ground surface; this cloth collects the electromagnetic signal received from the soil. Because resistivity varies according to the nature of underground material, organization, porosity, and moisture content, the method can effectively distinguish rocks from loose soils and locate the deep spring lines, provided that appropriate calibration of basic data is carried out.

This program was performed in two regions by CNRS researchers and technology researchers from CEMAGREF and LCPC. Steering committees were established, including these researchers, soil scientists, contractors and their national association (SNED), consulting engineers, local farmers' representatives, and local Ministry of Agriculture staff. Informational meetings and technical tours were organized to demonstrate the method, and draft schedules of specifications have been prepared.

Summary and Future Developments

Technology research is a complicated and continuous process, involving many actors. It includes acquiring in-depth knowledge of mechanisms suitable for the specific field under study. It also aims, however, at creating awareness of techniques, demonstrating the use of relevant methods and disseminating experience and results.

Long-term local and national programs must be developed by all partners involved at each stage of the process, from planning to operation and maintenance. Technology research programs should be implemented in close relation to drainage projects. Consequently, networks are needed to put partners in contact to meet the objectives of demonstration and dissemination and to help research institutes adapt their programs to the needs of ultimate users.

Presently, networking is widely recommended by donors, which was not the case decades ago. In France, technology research in the 1960s was undertaken by individual scientists and small research teams. They were directly in touch with a few local partners, to whom they often provided consulting services while carrying out scientific field investigations. Initial links were created, but were limited and disorganized.

Different networks gradually emerged. They were financially supported and in some cases developed by the authorities. Most, however, were the result of formal or informal associations, pooling people eager to work together. There are now numerous drainage networks: local technical steering committees and the national steering committee; the national experiment and demonstration network; standardization commissions and the Labeling Steering Committee of the French Standardization Association (AFNOR); and the French committees of ICID (AFEID) and ICAE (AFGR). In addition, many regional and national informational meetings were organized by these networks as well as other associations (e.g., farmers' councils) and regional authorities. With all these networks, some efforts overlap, but generally efforts are effectively coordinated.

Technology transfer within and among developed countries is a challenge, as is helping developing countries attain food self-sufficiency with successful technology transfer. For example, a field drainage experiment is being prepared in the Gharb Plain of Morocco by the Gharb Region Agricultural Reclamation Agency (ORMVAG) and CEMAGREF. This program is presently funded by the French government and will be supported by the International Program for Technology Research in Irrigation and Drainage (IPTRID).

As for drainage technology research in France, efforts will be directed toward (a) evaluation of the influence of drainage on soil-bearing strength, to improve trafficability prediction and farm management practices; (b) analysis of the impact of drainage on the environment, in connection with continued investigations on soil-water and solute transport, to enhance positive effects and alleviate adverse effects; (c) development and implementation throughout the country of methods to evaluate field drainage system performance and to define cost-effective rehabilitation (Favrot and Lesaffre 1987; Zimmer 1990); and (d) development of economic models simulating the impact of drainage on farming systems.

Acknowledgements

The technology research reported in this paper has benefited from much financial support, including that of the Ministry of Research and Technology, the Ministry of Agriculture, farmers' councils, produce councils, the National Association for Agricultural Development (ANDA), the National Association of Drainage Contractors (SNED), the National Association of Corrugated Pipe Manufacturers (SNFDA), and regional and local authorities. These partners have been involved in the development and follow-up of the research program, together with scientists and engineers from numerous institutes and organizations (e.g., CEMAGREF, INRA, agricultural technique centers, CNRS, and LCPC).

The author acknowledges the work performed by all those who contributed to these programs and gratefully thanks his colleagues from CEMAGREF's Drainage Division—M.P. Arlot, C. Lennoz-Gratin, M. Penel, B. Vincent, and D. Zimmer—and J.C. Favrot of INRA, all of whom kindly helped him prepare this document and reviewed the first draft.

References

Arlot, M.P. 1990. "Exportations d'Azote par les Eaux de Drainage Souterrain." Paper presented at the 14th ICID Congress, Rio de Janeiro.

Bognar, N., and C. Lennoz-Gratin. 1990. "Essais de Caractérisation de Produits d'Enrobage de Drains Français et Hongrois." *Canadian Agricultural Engineering* 32: 11-16.

Bouzigues, R., J.C. Favrot, and V. Hallaire. 1982. "French Heavy Soils: Characterization and Cartography in Relation to Drainage." Paper presented at Land Drainage Seminar, July 22-31, Cambridge, U.K.

Daniane, M., ed. 1990. *Entretien et Gestion du Drainage: Proceedings of the International Drainage Workshop*, November 27-30, Rabat, Morocco.

Devillers, J.L., J.C. Favrot, and W. Poubelle. 1978. "Approche Originale d'une Opération d'Assainissement-Drainage au Niveau d'une Petite Région Naturelle." Paper presented at the 10th ICID Congress, Athens.

Dierickx, W., Ch. Lennoz-Gratin, and L.C.P.M. Stuyt. 1987. "Joint European Research into Land Drainage Envelopes." Paper presented at the Fifth American Society of Agricultural Engineers Symposium, Chicago.

Favrot, J.C. 1984. "Acquisition des Données Nécessaires au Drainage des Sols Difficiles par la Méthode des Secteurs de Références." Paper presented at the 12th ICID Congress, Fort Collins, Colorado.

Favrot, J.C., and B. Lesaffre. 1987. "Défauts de Fonctionnement et Réhabilitation des Réseaux de Drainage Souterrain." Paper presented at the 13th ICID Congress, Rabat, Morocco.

Favrot, J.C., R. Bouzigues, C. Longueval, J.C. Chossat, and F. Bourgeat. 1990. "Structure du Sol, Drainage et Environnement: Rôle de la Structure du Sol sur le Fonctionnement Hydraulique et la Qualité des Eaux." Paper presented at the 14th ICID Congress, Rio de Janeiro.

Gauthier, F., B. Vincent, A. Hollier-Larousse, and P. Moulinier. 1988. "Applications d'une Méthode Géophysique, la Radio Magnéto-tellurique, aux Etudes Pédologiques Préalables au Drainage Agricole." Paper presented at the 15th ICID European Regional Conference on Agricultural Water Management, Dubrovnik, Yugoslavia.

Guyon, G. 1980. "Transient State Equations of Watertable Recession in Heterogeneous and Anisotropic Soils." *Transactions of the American Society of Agricultural Engineers* 23(3): 653-56.

Guyon, G., and J. Wolsack. 1978. "The Hydraulic Conductivity in Heterogeneous and Anisotropic Media and Its Estimation in Situ." Paper presented at the First International Drainage Workshop, Wageningen, The Netherlands.

Hervé, J.J. 1987. "Secteurs de Référence: Formation des Agriculteurs et de Leurs Conseillers." Paper presented at the 13th ICID Congress, Rabat, Morocco.

Horemans, P., and B. Lesaffre. 1984. "Le Drainage des Sols de Sologne: Application de la Méthode des Secteurs de Références à une Région aux Sols Difficiles." Paper presented at the 12th ICID Congress, Fort Collins, Colorado.

Houot, S., T. Cestre, and J. Berthelin. 1984. "Origine du Fer et Conditions de Formation du Colmatage Ferrique: Etude de Différentes Situations en France." Paper presented at the 12th ICID Congress, Fort Collins, Colorado.

Jannot, P., and D. Schnäbele. 1988. "The French Programme of Drainage Reference Areas: Methodology and First Results." *Agricultural Water Management* 14: 53-60.

Lagacherie, P., R. Bouzigues, and J.C. Favrot. 1984. "Caractérisation et Conditions de Formation des Colmatages Argileux et Ferriques en Sols Argileux Halomorphes (Solontchaks 'Sodiques') du Littoral Languedocien (France)." Paper presented at the 12th ICID Congress, Fort Collins, Colorado.

Lennoz-Gratin, C. 1987. "The Use of Geotextiles as Drain Envelopes in France in Connection with Mineral Clogging Risks." *Geotextiles and Geomembranes* 5: 71-89.

____. 1989. "Effect of Envelopes on Flow Pattern near Drain Pipe." *Journal of Irrigation and Drainage Engineering* 115(4): 626-41.

Lesaffre, B. 1989. "Drainage Design Practices in France." *Irrigation and Drainage Systems* 3(2): 181-91.

____. 1990a. "Field Measurement of Saturated Hydraulic Conductivity and Drainable Porosity Using Guyon's Pumping Test." *Transactions of the American Society of Agricultural Engineers* 33(1): 173-78.

____, ed., 1990b. *Proceedings of the Fourth International Drainage Workshop*, February 23-24, Cairo.

Lesaffre, B., and R. Morel. 1986. "Use of Hydrographs to Survey Subsurface Drainage Networks Aging and Hydraulic Operating." Paper presented at Agricultural Water Management Seminar, June 18-21, Arnhem, The Netherlands.

Lesaffre, B., and D. Zimmer. 1988. "Subsurface Drainage Peak-flows in Shallow Soil." *Journal of Irrigation and Drainage Engineering* 114(3): 387-406.

Moulinier, P. 1990. "Gestion, Installation et Entretien du Drainage." Paper presented at the International Drainage Workshop, November 27-30 Rabat, Morocco.

Nolte, B.H., ed. 1987. *Proceedings of the Third International Workshop on Land Drainage*, December 7-11, Columbus, Ohio.

Ochs, W.J., and L.S. Willardson, eds. 1983. *Proceedings of the Second International Drainage Workshop*, December 5-11, 1982, Washington D.C.

Penel, M. 1989. "DACCORD: A CAD Program for Subsurface Drainage." Paper (No. 892142) presented at the ASAE-CSAE Summer Meeting, Quebec City, Canada.

____. 1990. "La Métrologie Hydrométrique en Drainage." Paper presented at the International Drainage Workshop, November 27-30, Rabat, Morocco.

Penel, M., and B. Lesaffre. 1989. "Surface Runoff on Drained and Undrained Plots." Paper (No. 892104) presented at the ASAE-CSAE Summer Meeting, Quebec City, Canada.

Poubelle, W. 1990. "Maintenance des Réseaux d'Assainissement Agricole." Paper presented at the International Drainage Workshop, November 27-30, Rabat, Morocco.

Saavalainen, J., and P. Vakkilainen P., eds. 1986. *Proceedings of the International Seminar on Land Drainage*, June 9-11, Helsinki.

Schultz, B., ed. 1990. *Guidelines on the Construction of Horizontal Subsurface Drainage Systems*. New Delhi: ICID.

Smith, K.V.H., and D.W. Rycroft, eds. 1986. *Proceedings of the Second International Conference on Hydraulic Design in Water Resources Engineering: Land Drainage*, April, Southampton, U.K.

Stuyt, L.C.P.M., and T. Cestre. 1986. "Common Lines in Research on Drainage Envelopes in France and in The Netherlands." Paper presented at the Agricultural Water Management Seminar, June 18-21, Arnhem, The Netherlands.

Wesseling, J., ed. 1979. *Proceedings of the First International Drainage Workshop*, May 16-20, 1978, Wageningen, The Netherlands.

Zimmer, D. 1990. "Méthodologie d'Evaluation du Fonctionnement des Réseaux de Drainage." Paper presented at the International Drainage Workshop, November 27-30, Rabat, Morocco.

Zimmer, D., and B. Lesaffre. 1989. "Subsurface Drainage Flow patterns and Soil Types." Paper (No. 892139) presented at the ASAE-CSAE Summer Meeting, Quebec City, Canada.

HYDROLOGICAL ASSESSMENT STUDIES: EXPERIENCE WITH SUB-SAHARAN AFRICA

Ulrich Küffner

Africa represents formidable developmental challenges. In addition to bleak socioeconomic indicators, including declining food production, it is adversely affected by unfavorable climatic conditions. Large parts of Africa are arid or semiarid, where rains are frequently insufficient to support crops. Even more devastating than the low rainfall and resulting water deficit is the interannual variability of precipitation—the percent of departure from normal or average rainfall—which reaches 30 to 40 percent over much of the continent. Consequently, droughts, induced by several years of below-average rainfall, are typical climatic features in Africa.

Precise long-term data on rainfall and river flows in Africa have been available only since about 1900. Although there is a clear trend toward diminishing water availability over this period—strongly affected by the low rainfall of the 1970s and 1980s—information on rainfall, harvests, rivers, and lakes that have been recorded since the early 1800s indicate that Africa has experienced long-term cycles of dry and wet years.

In recent years, rainfall variability has received increasing attention because average or normal precipitation in arid and semiarid regions is insufficient to determine water availability. Droughts occur at irregular intervals. In Africa, three serious droughts have already occurred during this century. The prolonged dry period since the early 1970s would suggest that Africa is facing a trend of gradually diminishing rains and a southward expansion of the Sahara Desert, accelerated by human activities, deforestation, increased livestock herds, and overexploitation of aquifers. Floods in 1988, however, demonstrated that this trend of diminishing rains does have at least temporary interruptions.

The high interannual variability of rainfall affects farming; livestock raising; groundwater recharge; and, for major water development projects, the determination of water availability, particularly for large reservoirs. The unanticipated low levels of the Aswan and Volta river reservoirs in the 1980s have shown that the determination of water availability, and the management of the available water, is inadequate and requires some revision.

The Hydrological Assessment

Background

The droughts in Sub-Saharan Africa, with associated starvation, desertification, and poor agricultural performance, have put increasing pressure on African decisionmakers to pursue more vigorous programs in the development of water resources for human and animal consumption; irrigation; and multipurpose dams, which will enhance both agriculture and energy supplies. Although groundwater has been exploited extensively through simple low-yielding wells, improvement is

Ulrich Küffner is principal water resources engineer, Water Resources Management Unit, Europe and Central Asia/Middle East and North Africa Regions Technical Department, World Bank. This paper was presented in 1988.

urgently needed, particularly to serve existing settlements in drought-affected areas. With the exception of Sudan, Madagascar, and parts of Nigeria, the growth in irrigated area in Sub-Saharan Africa has been minuscule, with negligible impact on crop production. A primary factor in this slow progress has been the limitations of both surface and groundwater resources.

Although many parts of Sub-Saharan Africa experience a combination of hydrological deficiencies, the region does have several good-quality, unexploited rivers, some of which traverse drought zones. Furthermore, there are extensive groundwater aquifers, which, although difficult to exploit, do contain large reservoirs of unused water; many of these reservoirs are located below drought-affected zones.

Governments and funding agencies have had some success in the water sector, but much more can be done to better utilize Sub-Saharan Africa's water resources and, in particular, to alleviate some of the worst effects of drought. There are several options, including major, intensive irrigation projects served by the waters of the main rivers; more reliable water supplies in villages and towns served by both surface and groundwater resources; and better distribution of animal-watering points. In more favorable situations, tubewell development could encompass several functions by providing human and animal supplies and serving microirrigated areas. On the main rivers there are large unexploited hydroelectric resources that need to be evaluated in more detail, either as single or multipurpose projects.

Superimposed upon the inherent physical deficiencies of Africa's water resources is that in some areas hydrological (both surface and groundwater) data have not been collected in a central and systematic manner. In addition, knowledge of the regional potential, required for rational exploitation, is deficient, with much of it unpublished or inadequately analyzed. Groundwater resource inventories are limited, and hydrological mapping has been successfully undertaken in only a few countries. Hydrological data are often scattered among government agencies, aid donors, consulting firms, and the former colonial offices. This poor information dissemination leads to the repetition of data acquisition and the formulation of projects and programs based on incomplete information.

As part of the effort to find practical solutions to the growing problems of water supply, governments and international agencies are increasingly focusing on the quality and quantity of basic data related to meteorology, surface water hydrology, and hydrogeology. These data form a vital prerequisite to the formulation of sound water development projects. Examples of recent activities in data collection are the agrometeorological stations and drought-monitoring systems being established with the support of UNDP, FAO, the World Meteorological Organization (WMO), and others. In surface and groundwater hydrology, numerous projects have been implemented by governments, and many are supported by multilateral and bilateral agencies, including FAO, UNESCO, UNICEF, UNDP, and the World Bank. Although some countries have set up effective hydrological networks and operating institutions, all can benefit substantially from further inputs of both equipment and expertise.

Over the past years, the weakness of hydrological information was exacerbated by government budget deficits and urgent demands to deal with droughts, famine, and economic crises. The shortage of staff, equipment, and operating funds has been the main reason why hydrometric work declined and some hydrometric stations were abandoned, creating permanent gaps in long-term records.

A review of operating hydrometric stations carried out in several northeastern and southeastern African countries (in connection with the study described in this paper) revealed that only 34 percent of previously established rainfall stations and 39 percent of flow-measuring stations were still operating (country ranges were between 11 and 70 percent, and 5 and 59 percent, respectively). According to the UNESCO/UNECA Conference on Socioeconomic Policy Aspects of Water Resources Management in Africa, held in Addis Ababa in June 1986:

There are inadequate networks of stations for monitoring the quantity and quality of surface and groundwaters and of sediment transport. Even the networks which existed in 1977 have since deteriorated in a number of countries. Poor data collection for existing networks, their processing and dissemination, and the lack of data banks are common problems. Water balance elements have not been regionalized in many cases. Planning and design parameters have not been organized and analyzed. It is recommended that corrective measures be taken, and that the efforts of institutions involved in water resources assessments be coordinated at the national level.

The governments concerned have made urgent calls for expert assistance and funding to search for viable solutions, considering the magnitude of the backlogs that have arisen. In response to a request from African governments, and in view of the difficult and unsatisfactory state of hydrometric work, Bank staff developed a project in collaboration with UNDP to address the relevant problems.

The project's aim is to assist governments in obtaining support from multilateral and bilateral agencies for priority data collection and processing necessary to fill the gaps. The reports to be prepared under the project should enable all agencies, governments, and international and bilateral donors to achieve a higher degree of coordination in their activities with more specific focus on critical issues and urgent development projects.

Project Objectives

Specifically, the objective of the project is to assist Sub-Saharan African countries in the creation and/or improvement of a sound hydrometric base for planning and evaluating water resource development programs and projects. Because water resources are widely shared by groups of countries, the project was designed with a regional focus. The project will evaluate the status of all existing water resource data and make recommendations for filling important gaps and generally enhancing the capability to measure, retrieve, process, and publish hydrological data and information. The investigations apply to surface and groundwater resources and hydrometeorology.

Major Components

The project will be carried out in three main steps:

1. catalog the present status of data collection, processing, and publication, including bibliographies;

2. identify the crucial gaps in present programs;

3. make recommendations on priority programs to fill the gaps, including institutional and training aspects.

An important feature of this project is that these steps will be undertaken against the backdrop of the existing national water resource development plans in the countries concerned, in close collaboration with local officials and experts. In this way, the adequacy of existing programs for hydrometric networks and data retrieval and processing will be judged against the immediate and medium-term demands of current and future project planning strategies. This approach should lead to an efficient allocation of resources for hydrometric work, with the expenditures on data collection providing early returns.

Project actions related to both surface and groundwater hydrology are to:

1. prepare an inventory of available water resources and assess its quality;

2. examine existing and proposed plans for water resources development;

3. identify gaps in the data collected, considering the immediate and medium-term demands of water resources development plans and longer-term strategic requirements;

4. make recommendations on measures required to fill identified gaps;

5. review the institutional aspects of the hydrometric work necessary for the collection and dissemination of water resources data and make recommendations on improvements necessary to fill gaps, including personnel training;

6. present findings in both report and map form.

Regional Concept

Water is a resource frequently shared by several countries. The preparation of integrated development plans for water resources, therefore, often demands a regional approach, with good collaboration among riparian states of major river basins and sometimes among countries sharing a groundwater aquifer. Because water resources are essentially a national responsibility, the studies will be carried out on a country-by-country basis; however, the project studies should stimulate regional concepts in planning wherever feasible. Some progress has been made in this direction in African countries, for example in the Senegal and Niger basins, but the river basin organizations formed thus far need to be greatly strengthened in their capacities to collect data and plan and implement projects. The project should help river basin organizations in achieving their objectives. At the same time, it will provide a valuable base for dialogue on water resources issues and improved joint water management activities among riparian states.

For project implementation, the countries covered by the project have been divided into five groups. For each, a consulting firm will carry out the field work. The five groups have been established on the basis of regional and hydrological criteria and the existence of regional agencies:

Group 1. regional agency: the Intergovernmental Authority on Drought and Development (IGADD); major river basin: Nile;

Group 2. regional agency: the Southern Africa Development Coordination Conference (SADCC); major river basin: Zambezi;

Group 3. main regional agency: the Comité Interafricain d'Etudes Hydrauliques (CIEH); major river basins: Niger and Senegal;

Group 4. regional agency: the Communauté Economique des Etats des Grands Lacs (CEPGL), involving Burundi, Rwanda, and Zaire; major river basin: Congo;

Group 5. Madagascar and the Indian Ocean islands.

Institutional Framework

The project is being implemented through close collaboration among the World Bank, UNDP, UNDTCD, and WMO, thus responding to a 1986 UN resolution (of the General Assembly's Special Session on Africa) that called for better collaboration among UN agencies. In addition, regional agencies, such as IGADD, SADCC, CEPGL, and CIEH are collaborating on the project's implementation.

A steering committee, comprising representatives of the funding agencies (UNDP, the World Bank, the African Development Bank, the EC, and the French government); UNDTCD; WMO; IGADD; SADCC; CEPGL; CIEH; and other agencies concerned with water development, has been formed to assist in the overall direction and supervision of the assessments. It is chaired by the UNDP representative and meets at least once a year. Coordination of the project's activities is being carried out by a project coordinator, appointed and paid by the Bank, the project's executing agency.

Detailed project preparation, supervision, and review have to be carried out by the Bank as executing agency, assisted (part-time) by experts from UNDP, UNDTCD, and WMO. The extensive data collections available at these agencies, as well as at FAO and UNESCO, also are being utilized.

The field work in the five groups of Sub-Saharan African countries is being carried out by consultants with extensive experience in the relevant subject area and the countries concerned. Workshops will be organized with the regional agencies concerned to review the consultants' recommendations, share experiences gained during the project, and agree on joint actions among the government agencies involved.

Initial Results

The consultants' studies in the IGADD and SADCC regions confirmed the serious decline in hydrometric work in this part of Africa. In view of this situation, the consultants formulated some preliminary recommendations for actions to reverse this trend.

Hydrometeorology. A major concern in water resources planning is the extrapolation of past events to the future in light of the well-documented decrease in rainfall in Africa in recent decades. The consultants who studied the situation in the IGADD countries do not consider it reliable to extrapolate downward trends, but do believe that it is correct to assume that the average over recent years is more relevant to the next decade than the 1931-60 average, which is usually cited. They have chosen, therefore, to use data since 1970 to ensure an adequate data set.

Given the accuracy required of the rainfall and runoff figures, the density of a network needed in a particular area can be specified in terms of the number of climatological stations to estimate evaporation and the number of rainfall stations. In some countries, however, consultants consider it more cost-effective to use fewer rain gauges, supplementing them with rainfall estimates derived from satellite data. These methods are already available. Estimates of actual evaporation may also be improved with satellite data, though more research is needed before the methods can be considered operational.

The investigations have shown that there is a need for a WMO initiative in introducing the CLICOM system worldwide, to extend it not only to meteorological services but also to other national organizations that acquire and archive rainfall and meteorological data. CLICOM is an IBM PC-based management system for meteorological data. Several African countries have already adopted this system. Because other national organizations concerned with water resources and agriculture may wish to operate their own networks and archives, they should be encouraged to use the CLICOM system for their meteorological data.

Surface water. A shortage of equipment and, in particular, transport, has meant that field calibration of gauging stations has also deteriorated in recent years. This is largely because the collection of basic hydrological data has not received priority in governments' spending plans. The consultants have argued that the allocation of specific funding to recurrent expenditures of this type, without setting up an expensive project team, would greatly enhance the status of this work. Relatively modest financial assistance could produce significant improvements in the hydrological records to support development.

The computerized processing of hydrological data is now feasible with modern microcomputers. The software for this processing exists, and it is now opportune to install standardized analytical procedures and equipment for this purpose. A comparatively small staff, with limited qualifications, can be trained to undertake the routine work, leaving qualified hydrologists free to carry out analyses and investigations, in addition to supervising the processing.

Groundwater. The existing data bases are typically manual systems that are time-consuming to manipulate or analyze statistically. The archival records of groundwater data are usually standardized and basic, but show no particular correlation with the special needs of individual aquifers. Prior to computerization, some additional data inputs could usefully be incorporated, by reference to either original borehole completion records or topographic maps where location with respect to relief could be significant. Pumping test data are frequently inadequate regarding drawdown, testing duration, and other essential facts that may be available in the original records.

Routine hydrogeological monitoring is rarely being undertaken in the countries reviewed. This monitoring is essential to estimating groundwater recharge, particularly important in semiarid regions.

Sedimentation. The consultants propose that networks be concentrated in areas of steep relief and high rainfall, considering population densities and projected development of water resources and intensive agriculture. Areas where erosion will present problems have been determined using soil and physiographic maps and have been related to key river systems.

Postscript

A reduction in hydrological activities and diminished networks of hydrological stations have been proposed for some countries to enable agencies to operate more efficiently under conditions of limited resources. Unless a comprehensive quality control system is in place, however, the efficiency of traditional data collection systems—reliance on local observers and transmission of data via mail—will be questionable.

A new approach to hydrological work has recently been initiated through the introduction of automated and satellite-assisted modern hydrological monitoring equipment. A network of automatic hydrological stations with satellite transmission is technically feasible and appears to be economically justified. In addition to hydrological monitoring, the system could provide environmental monitoring and essential data for climate change observation. The data would complement traditional observations and also serve as benchmarks to verify other data. As the hydrological assessment project described in this paper nears completion (in 1992), project staff are working on a proposal to develop this new system for Africa, which is expected to alleviate some of the prevailing problems in the region's hydrological work.

IRRIGATION AND ENVIRONMENTAL MANAGEMENT: SOME MAJOR ISSUES FOR DEVELOPING COUNTRIES

Asit K. Biswas

Nearly two decades after the United Nations Conference on the Human Environment, held in Stockholm in June 1972, and in view of the forthcoming United Nations Conference on Environment and Development, to be held in Brazil in June 1992, a brief review of developments in irrigation and environmental management during this intervening period warrants attention. Irrigation development was and is still dominated by engineering. During the 1970s the mainstream of the profession thought that they were being unfairly criticized by environmentalists, because they were constructing projects that could only benefit people. They also felt that the environmental movement was a passing fad, and if they ignored it, it would disappear. Although public interest in environmental issues declined during the early 1980s, fortunately it did not disappear, and interest has been rekindled during the past five years.

Irrigation and Environment

Although there are still some dissenters, those in the irrigation field have in principle accepted that irrigation development and environmental management should proceed as complementary activities. Currently, the overriding concern is how to ensure operationally that irrigation projects can be developed and managed in an environmentally sound fashion, within economic, social, political, and institutional constraints. Conceptually and rhetorically there are some answers, but in operational terms there are many questions that need to be answered before irrigation projects can be developed and managed on a long-term sustainable basis.

A comprehensive and critical analysis of existing literature on environmental aspects of irrigation development indicates that there are many problems limiting the potential application of available knowledge in developing countries. From this analysis, the following five major problems can be identified. These constraints are not discrete, but are often closely interrelated.

1. an incomplete framework for analysis;
2. a lack of appropriate methodology;
3. inadequate knowledge;
4. institutional constraints;
5. the absence of monitoring and evaluation as part of the management process.

An Incomplete Framework for Analysis

The framework currently used for analyzing and considering various environmental issues associated with irrigation projects is overwhelmingly biased toward reviewing only negative impacts. Realistically, any irrigation project will have discernible impacts on rural development and the

Asit K. Biswas is president, International Water Resources Association, Oxford, England. This paper was presented in 1990.

environment, though the magnitude and extent of these impacts will vary by project. Indeed, any given project's approval for implementation clearly indicates that decisionmakers expect it to have positive impacts on society; otherwise, there is no reason to waste scarce resources.

Although it is axiomatic that large irrigation projects will have certain impacts, "impact" in this context has developed primarily negative connotations. While any large development project, regardless of its nature, will have both positive and negative impacts, at present analyses of environmental and social impacts generally consider only adverse impacts and their potential amelioration.

To a certain extent the emphasis on the negative factors of projects and programs is not difficult to explain. In the 1960s analyses of water development projects considered primarily technical and economic factors; environmental and social issues were generally ignored. Concerned about the adverse impacts of many development projects on society and the environment, a movement gradually evolved to protect and preserve the environment. Environmental protection became an important item on the political agenda in the late 1960s, at least in many developed countries, through the activities of environmental pressure groups and nongovernmental organizations.

This attitude toward and perception of environmental protection was reflected in the United Nations Conference on the Human Environment held in Stockholm in 1972. An analysis of the Stockholm Action Plan finally approved by all the member countries of the United Nations would clearly indicate its negative approach to environmental management: stop all pollution stemming from any development activity, stop exhausting nonrenewable resources, and stop using renewable resources faster than their generation. The emphasis thus was primarily on adverse impacts of development. Not surprisingly, environmental impact analysis, made mandatory in many developed countries in the late 1960s and early 1970s, was primarily concerned with the identification and amelioration of negative impacts; positive impacts were generally not considered, and "impact" has continued to have only negative connotations.

Increasing numbers of environmental impact analyses of irrigation projects have been carried out during the past decade. The emphasis, however, has continued to be on the identification of only the negative impacts of water development and ways to ameliorate them. Numerous examples can be provided of this all-pervasive bias; two will be cited here, one general and the other case-specific.

Conceptually, each time the health implications of irrigation projects are reviewed, the main consideration has been the presence of vector-borne diseases such as schistosomiasis and malaria. Regardless of whether the evidence of increase in the prevalence of waterborne disease as a result of irrigation projects is reliable, this approach is not only highly biased but also somewhat simplistic and erroneous.

Viewed in any fashion, irrigation is an integral part of rural development. As a project develops, agricultural production also increases. With better per capita food availability and more diversified crop production, food and nutrition levels increase (figure 1). The situation is further improved by increased livestock holdings and the development of inland fisheries in reservoirs. An increase in the availability of animal protein is an important factor in many irrigated agricultural projects, but it has usually been neglected. For example, midterm evaluation of the Bhima Command Area Development Project in Maharashtra, India, clearly indicates the impact of increased livestock holdings, even among landless laborers, on the local population's nutritional standards. In addition, the health of rural populations is further improved as a result of advances in education, health facilities, the role of women, and the overall quality of life. Currently, rather than consider the overall health situation in a project area, analysts are accentuating only the negative impacts.

The case-specific example concerns the overall impact of the Aswan High Dam on fish production in Egypt. Since Sterling's articles, much has been written on the decline of the fish catch in the eastern Mediterranean because of the dam. Fish production in Egypt in the High Dam Lake, the Mediterranean, and other areas for 1963-82 is shown in figure 2, which indicates that fish

Figure 1. Interrelationships between Irrigated Agriculture and Health

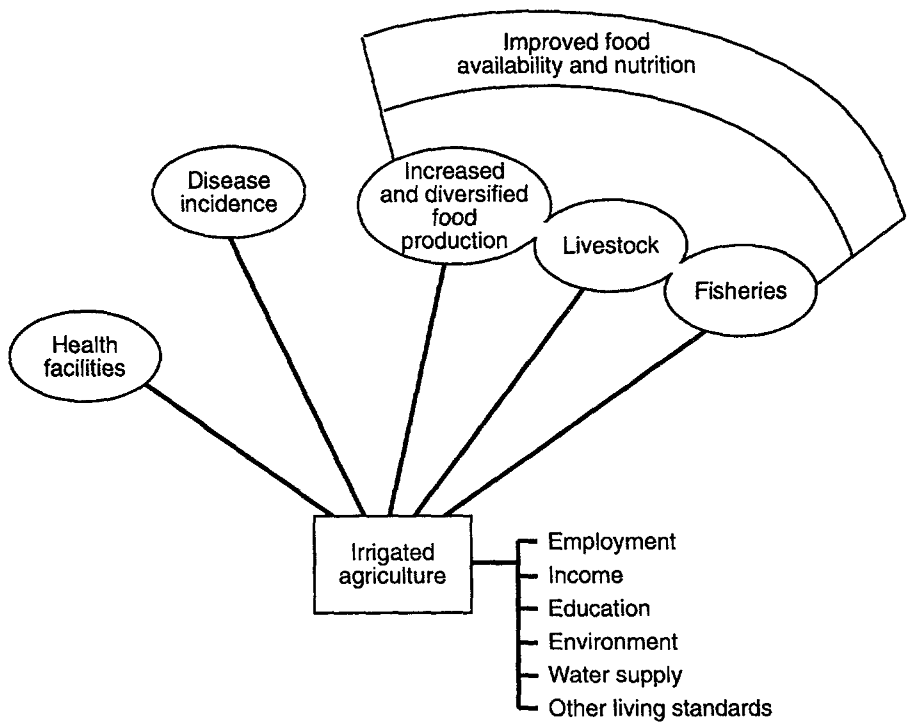
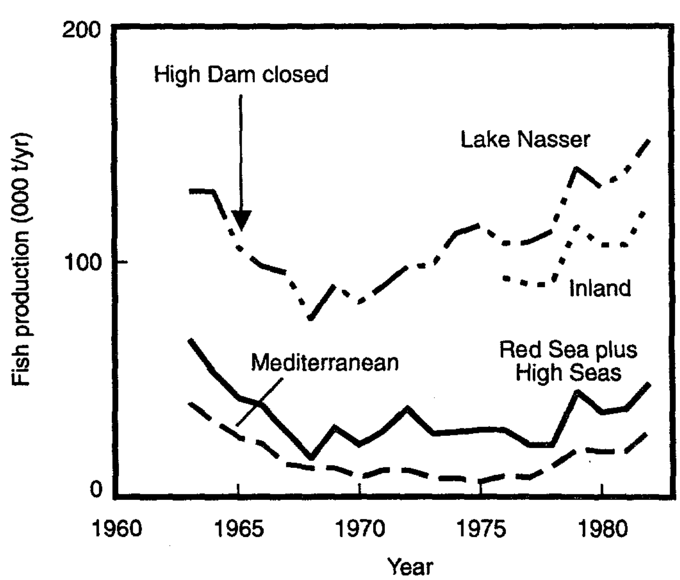


Figure 2. Contribution of Lake Nasser to Fish Production in Egypt, 1963-82



production from the Mediterranean began to decline from about 1963. Production was lowest in 1975, but since then catches have been steadily rising. If the "new" fish production system in the High Dam Lake is considered, total catches have always been significantly higher than at any time in the Mediterranean. Fish production started to decline in the High Dam Lake around the time of the closing of the dam, but it has now not only recovered, but is higher than it was initially. If the combined fish production in the Mediterranean and the High Dam Lake is considered, it undoubtedly has always been significantly higher than production from the Mediterranean alone before the dam was built. Accordingly, the overall impact of the Aswan Dam on fish production in Egypt is overwhelmingly positive, not negative as most environmental literature indicates. Not everyone, however, has benefited. Mediterranean fishermen, who did not wish to be relocated to the High Dam Lake area, have suffered serious economic hardships.

What is needed, therefore, is a balanced framework for analysis, which will identify both positive and negative impacts. The next step should be to decide how to maximize the positive impacts and minimize the negative ones. A framework that considers only negative impacts and ignores the positive is both incomplete and counterproductive.

Lack of Appropriate Methodology

A review of the processes currently used by developing countries to incorporate environmental issues in water management indicates that the methodologies currently available do not satisfy the special requirements of developing countries. Although environmental impact assessment (EIA) was made mandatory in the United States in 1969 through the National Environmental Protection Act, its application thus far in developing countries has been slow. The reason for this is not because of concern about whether the methodology is valid and applicable to irrigation projects, but because of the lack of an operational methodology that can be successfully applied in developing countries with limited expertise, resources, and time. The EIA methodologies used in industrial countries are not directly transferable to developing countries for various socioeconomic and institutional reasons. Even in developing countries where multilateral and bilateral aid agencies have carried out fairly comprehensive environmental impact analyses of water development projects, primarily with foreign experts and consultants, their overall real impact has generally been minor. This is because these EIAs were carried out primarily to satisfy the internal requirements of the bilateral donor countries and the multilateral funding agencies and generally not at the behest of the developing countries in which the projects were located. Not surprisingly, the involvement and interest of developing countries in such primarily external analyses have been minimal and somewhat superficial.

Complex, lengthy, expensive, and time-consuming EIAs, as undertaken in developed countries, are not the correct tool to assess the impacts of water development projects in developing countries. Under certain conditions, complex EIAs may even prove to be detrimental and may hinder rather than enhance the overall process of water development. For developing countries, an operationally sound EIA methodology that is flexible and at the same time able to be carried out with limited finance, time, and expertise is urgently needed.

Lack of Adequate Knowledge

There are many areas where adequate technical knowledge may not exist to provide reliable answers. Similarly, there are areas where "conventional" knowledge can at best be dubious and at worst completely erroneous. There are also many areas where the right questions are not even being asked. For example, for the two most widespread and important vector-borne diseases, malaria and schistosomiasis, it is not known to what extent an irrigation project per se may increase their incidence. An exhaustive study by the Indian Malaria Research Centre indicated that the resurgence of malaria occurred independently of the green revolution. Irrigation, agricultural practices, rice cultivation, and migration of agricultural labor, however, have an important bearing on mosquito vector fauna and malaria transmission. The linkages are not clear, and there is no evidence to indicate a one-to-one relationship between irrigation development and additional incidences of malaria.

The average annual parasite rate (API) registers the number of malaria cases per thousand population in one year. For large parts of India, with sizable areas under paddy, malarial rates are negligible (API less than/equal to 0.5) or extremely low (API less than 2). There are some rice-growing areas where the incidence of malaria is moderate (API between 2 and 10) or high (API greater than 10). There does not appear to be any specific relationship between the area under rice cultivation and API: other parameters appear to govern disease transmission.

There are other complex issues that need to be considered for malaria. A study of two villages in the Kano plains of Kenya, one a newly established village within the 800-hectare Ahero rice irrigation scheme and the other an older village nearby in a nonirrigated area with traditional mixed agriculture, showed remarkable differences in terms of different mosquito species. In the new village 65 percent of mosquito bites were from the *Anopheles Gambiae* complex (the principal vectors of malaria in tropical Africa); 28 percent were from the *Mansonia* species (vectors of lymphatic filariasis and Rift Valley fever); and 5 percent were of the *Culex quinquefasciatus* variety (another vector of lymphatic filariasis). In contrast, 99 percent of the mosquitoes in the older village belonged to the *Mansonia* species and less than 1 percent were from the *Anopheles Gambiae* complex. Thus irrigation can change the transmission patterns of mosquito-borne diseases. This is especially important for tropical Africa, where most of the over 1 million global deaths due to malaria now occur.

Stratification is also an issue. Evaluation of the Bhima command area development indicates that malaria is attacking women more than it is men. How widespread this stratification is, in India or elsewhere, is unknown because this type of question is not being asked at present, let alone answered.

For schistosomiasis, the presence of an irrigation system in a developing country, with extended shorelines of reservoirs and banks of canals, contributes to a better habitat for snails than before construction. This will naturally tend to increase the incidence of schistosomiasis, but given the present state of knowledge, it is difficult, if not impossible, to answer to what extent irrigation practices alone contribute to this increase.

A perusal of the available literature indicates a plethora of statements and so-called facts and figures on the increase in schistosomiasis and other vector-borne diseases resulting from the construction of irrigation systems. Such general statements played an important role in the late 1960s and the 1970s in sensitizing engineers, decisionmakers, and the general public to the importance of vector-borne diseases, but very little progress was made in the 1980s toward giving water planners and administrators the specific information they need to improve planning and management processes.

A major problem with the incidence of vector-borne diseases resulting from irrigation projects stems from the lack of scientifically rigorous studies. The subject is replete with poor and conflicting information, the repetition of data that have seldom been critically examined, and the elaboration of personal biases. To a certain extent international organizations have contributed, albeit not deliberately, to this unsatisfactory situation. For example, the World Health Organization estimate that globally about 200 million people are infected with schistosomiasis has remained remarkably constant since at least 1969. UNEP has incorrectly stated in the past that schistosomiasis has been completely eradicated in China. Recent publications from FAO have erroneously stated that water development significantly increases onchocerciasis, whereas all available evidence indicates the opposite. In 1987 FAO again repeated examples of increases in schistosomiasis resulting from water development projects based on poor and somewhat dubious data first published in 1978. A major problem in this area is the uncritical acceptance and repetition of published information, regardless of its quality. Because these types of dubious data have been published repeatedly, they have gradually gained "respectability."

Another problem is the absence of data on preproject environmental conditions. Even now, when some baseline surveys are being carried out on preproject conditions, environmental issues receive scant attention. Without knowledge of preproject conditions, it is impossible to state with any degree of certainty how the environment has changed over time in any project area.

A third problem arises because objective and comprehensive evaluation of irrigation projects is never carried out at regular intervals. Accordingly, very little information exists on which realistic conclusions can be drawn.

Institutional Constraints

The sectoral approach to water development is a major institutional constraint in all developed and developing countries and has an important bearing on the sustainability of projects. Large- to medium-scale water development projects not only increase agricultural production and change the environment, but have other substantial impacts, for example, on employment generation, education, health facilities, communication, energy availability (fuelwood and electricity), domestic water supply, and women. These impacts are transmitted through a series of interconnected pathways, both direct and indirect, and are not always easy to identify or predict. They may also vary substantially by project in both their nature and their magnitude. Unfortunately, a holistic approach to land and water management that considers all these issues is rare, though a few attempts to develop this approach are being undertaken.

There are many reasons for this situation, but one of the most important is the division of responsibilities among a country's various ministries. Typically, the ministry of irrigation or water development is responsible for irrigation development, the ministry of agriculture for agriculture-related issues, the ministry of health for health promotion, the ministry of the environment for environmental matters, the ministry of education for schools, the ministry of rural development for rural issues, etc. Because of long-standing rivalries, coordination and cooperation among the various ministries are inadequate. Yet in any large-scale water development project, all these issues must be integrated within the project area. How this integration can be effected in reality in the field is a complex and daunting problem; there have not been many success stories.

Monitoring and Evaluation

If irrigation projects are to be sustainable, monitoring and evaluation must be integral to the management process. Although some literature exists on the integrated monitoring and evaluation of water development projects, more reports are available on the pseudo- or superficial evaluations carried out in the recent past at both national and donor agency (bilateral and multilateral) levels. These are primarily concerned with the protection and enhancement of the reputation of the organizations and individuals associated with the projects. These evaluations can have no beneficial impact on the management process because they do not identify major problems and bottlenecks, or, if they do, they play down their importance. In the long run these evaluations not only reduce the effectiveness of water projects, but also damage the perceived usefulness of the monitoring and evaluation processes.

A comprehensive and objective analysis of irrigation projects supported by the U.S. Agency for International Development in various developing countries indicated in 1983 that the monitoring and evaluation practices of both donor and recipient countries have "come in for criticism from each group about its own organization and about the activities of its counterpart" and that "too little gets done by either group."

Conclusion

Although currently no precise definition of sustainability is available, the concept clearly extends beyond purely conventional economic and engineering approaches. A fundamental question is, What are the overall long-term impacts of a project on the biosphere? These impacts must be examined with the related uncertainties and risks taken into account. Values should be placed upon risks taken or not taken, and explicit statements about the benefits of risk reduction should be made. Decision criteria must extend beyond engineering and economics. This will not be easy, but this has to be our future approach.

Sustainable irrigation development and management present many important challenges, and there are several approaches through which this concept may be promoted and translated into action. Sustainability, however, is inseparable from society's overall social and economic development, because it invariably depends on the interaction between water development and the economic, social, cultural, and environmental implications of that development. Thus, explicit tradeoffs between different short- and long-term objectives are important. Because quantitative and qualitative dimensions are mutually reinforcing and inseparable, the degree of sustainability is not easily measured. Furthermore, operationalizing the concept of sustainable development is complex under the best circumstances.

Irrigation development can be sustainable only when planners and politicians have adequate knowledge of resources and the constraints within which the resources must be managed. Developing countries seldom have adequate information about their water and related land resources, and without an adequate and reliable data base, management is difficult.

Sustainable irrigation development in any region is directly affected by land use patterns and practices. Uncontrolled deforestation, unplanned urban growth, and unmanaged industrial development directly affect the availability of water resources and the quality of both surface and groundwater. These and other impacts directly affect irrigation development, and water management in turn affects the aforementioned factors. It is not through the management of any one resource but in the interrelated management of all resources that the sustainability of the development of individual countries can be ensured.

IRRIGATION-INDUCED CONTAMINATION: NEW FINDINGS ABOUT AN OLD PROBLEM

Jonathan P. Deason

Since 1986, the U.S. Department of the Interior has been identifying and responding to irrigation-induced contamination problems involving the department's management responsibilities. The impetus for this effort was the Kesterson National Wildlife Refuge in the San Joaquin Valley of California. Beginning in 1983 severe fish- and wildlife-related problems (waterfowl mortality, embryonic deformities, and reproductive failures) were found at Kesterson. These problems were subsequently linked to elevated levels of the trace element selenium contained in the irrigation drainage water that flowed into Kesterson from the San Luis Unit of the Bureau of Reclamation's Central Valley Project. As a result of that discovery, the department began checking existing information to determine whether similar problems existed at other irrigation projects, national wildlife refuges, or other important wetland areas for which the department has responsibilities under the Endangered Species Act, Migratory Bird Treaty Act, and other legislation. It discovered evidence that irrigation drainage water might have been adversely affecting fish and wildlife resources or have had the potential to affect human health at several other locations.

To determine the severity of these problems, reconnaissance investigations were undertaken at 20 locations in 14 states/regions (see below). The objective of this paper is not to present the results of each individual investigation; rather, it is to provide a summary of the broad knowledge gained collectively from all investigations, which may be relevant to the lending activities of the World Bank in irrigation worldwide.

Investigation Locations

Arizona-California	Lower Colorado River Valley area
California	Salton Sea area
	Tulare Lake area
	Upper Sacramento River area
California-Oregon	Klamath River Basin refuge complex
Colorado	Gunnison River area
	Pine River area
Colorado-Kansas	Middle Arkansas River area
Idaho	American Falls Reservoir area
Montana	Sun River Reclamation Project area
	Milk River Reclamation Project area
Nevada	Stillwater Wildlife Management Area
New Mexico	Bosque del Apache National Wildlife Refuge area
Oregon	Malheur National Wildlife Refuge area
South Dakota	Angostura Reclamation Unit area
	Belle Fourche Reclamation Project area

Jonathan P. Deason is director, Office of Environmental Affairs, U.S. Department of the Interior. This paper was presented in 1989.

Texas	Lower Rio Grande-Laguna Atascosa National Wildlife Refuge area
Utah	Middle Green River Basin area
Wyoming	Riverton Reclamation Unit area
	Kendrick Reclamation Project area

Reconnaissance Investigations

Each reconnaissance investigation involved sampling several environmental media (surface and groundwater, sediment, and biological organisms) over a broad geographical area. Samples were analyzed for a large number of trace elements, organic pesticides, and radiochemicals. Each investigation was designed to provide the maximum amount of information possible with a relatively modest investment.

Because of unique ecological systems and different geochemical conditions at each study area, each study design was somewhat different in terms of sampling schedules, number of samples at each site, biota sampled, and analytes. At the same time, however, each investigation was designed to make the results comparable among areas to the extent possible. Each was guided by a common protocol developed collectively by the agencies performing the field work: the U.S. Geological Survey, U.S. Fish and Wildlife Service, and U.S. Bureau of Reclamation. Following is a list of inorganic constituents that were sample analytes in all studies:

Arsenic	Nickel
Barium	Selenium
Boron	Silver
Cadmium	Radium 226
Chromium	Uranium
Copper	Vanadium
Lead	Zinc
Mercury	Gross Alpha Radioactivity
Molybdenum	

Data Interpretations

Laboratory data alone are relatively meaningless until they are subjected to an interpretive process. A critical link between data from the sampling program and decisions by the Interior Department regarding further actions involves accurate and objective interpretations of the data. Many factors influence the expression of an adverse biological effect resulting from exposure to potentially toxic contaminants. Not only must the type and concentration (or burden) be considered, but also the form of the contaminant (chemical species); nature of the aquatic environment (water hardness, pH, TDS, etc.); interactions among contaminants (antagonistic or synergistic effects); types of biological species exposed; age, sex, and physiological condition of the organism; data distributions; and analytical errors.

Recognizing the difficulties inherent in the interpretation process and the need to provide for consistency among field teams in making interpretations, the department developed guidelines to assist the field teams with that task. The guidelines provide essentially five types of information relevant to the interpretive process:

1. a compilation of standards and criteria for potentially toxic constituents promulgated by various organizations;

2. a data base of contaminant residues and biological effects from laboratory testing developed by the U.S. Fish and Wildlife Service;

3. geochemical baselines for inorganic trace elements from soils in the western United States, developed by the U.S. Geological Survey's Geologic Division;

4. baseline concentrations for contaminants in fish based on data from the National Contaminant Biomonitoring Program of the U.S. Fish and Wildlife Service;

5. baseline concentrations for contaminants in water based on data from the National Stream Quality Accounting Network of the U.S. Geological Survey and the National Water Quality Surveillance System of the U.S. Environmental Protection Agency.

Results

The first general observation drawn from the study results is that knowledge of geologic sources of trace elements is very important in determining where problems with irrigation-induced contamination are likely. The Kendrick Project area (Wyoming), Middle Green River basin (Utah), and the west side of the Tulare Lake basin (California), for example, all contain geologic formations known to be sources of trace elements, particularly selenium. In each case, the source rocks are pervasive, and soils in the area are primarily derived from such rocks.

In the Kendrick Reclamation Project area, soils are derived from cretaceous formations of marine origin, several of which are seleniferous, and soils in the area are high in selenium. Irrigated lands in the Middle Green River basin are located on soils that overlie the Mancos Shale. This shale contains concentrations of selenium as high as 140 parts per million (ppm) and is the formation in which the Green River flows throughout much of the study area. Soils in the western part of the Tulare Lake basin are derived from cretaceous and tertiary marine rock that contains selenium. Soils on the west side of the basin are high in selenium. The Kendrick Reclamation Project area, Middle Green River, and Westfarmers Ponds in the western part of the Tulare Lake basin all have concentrations of trace elements, principally selenium, in water, bottom sediment, and biota, which can harm wildlife. Geologic sources of trace elements (particularly selenium) appear to be directly related to elevated concentrations of these elements in the study areas, especially if such sources are pervasive and substantial enough to have a primary effect on concentrations of trace elements in soils and bottom sediments.

Second, an area's meteorological characteristics can be significant to the potential for irrigation-induced contamination problems. Conditions of low precipitation (i.e., less than or equal to 12 inches per year) and high evaporation or evapotranspiration (several times precipitation) occur in all the study areas except Laguna Atascosa in Texas. Evaporation of water in streams, ponds, and wetlands in the study areas doubtlessly increased salt concentrations in water and soil. Nevertheless, neither evaporation nor evapotranspiration appears to be the primary factor controlling trace element concentrations in the study areas, because some areas had relatively low concentrations and others relatively high concentrations despite similar precipitation and evaporation conditions.

Third, closed watersheds were an important physical characteristic of locations that may tend to exhibit symptoms of irrigation-induced contamination. The greatest trace element and dissolved solids concentrations in the Milk and Sun rivers study areas generally were found in terminal drainages with no outlet (Dry Lake Unit and Benton Lake, respectively). Selenium concentrations in biota were greatest in the Westfarmers Ponds (evaporation ponds with no outlet) in the Tulare Lake study area and in shallow ponds and reservoirs with little or no flow through or surface water release in the Kendrick Reclamation Project area. These water bodies all contained elevated selenium concentrations that could result in adverse effects on wildlife reproduction and growth.

The fourth observation concerns proportional contributions of irrigation drainage water to wetlands, ponds, and refuges in the study areas. Irrigated agriculture occurs in all of the study areas. At the study areas where concentrations of selenium were found to be at levels that could adversely affect wildlife reproduction and growth (Kendrick Reclamation Project, Middle Green River, and Tulare Lake study areas), extensive irrigation and drainage activities occur. Unfortunately, a clear relation cannot be determined between elevated trace element concentrations and the proportional contributions of irrigation drainage water to receiving waters in the study areas because of the paucity of quantitative information and the apparent lack of consistent patterns among study areas.

The fifth observation is that selenium is the constituent of concern most commonly found at elevated concentrations in wetland ecological systems receiving irrigation drainage water. Although selenium was not detected at elevated concentrations in all areas studied, nor was it found to be the constituent of greatest concern in all areas with elevated concentrations, it clearly was the constituent most frequently detected at elevated levels.

Sixth, concentrations of analytes were found to vary widely on a spatial basis in all environmental media sampled. This observation leads to the conclusion that irrigation-induced contamination problems are likely to be very site-specific, that is, problems can be quite severe on a local basis with little relative regional significance.

Seventh, yearly variations in precipitation and streamflow make accurate assessments of conditions in a given area difficult without a long period of analysis. The Milk, Colorado, and Green river basins all had greater than normal precipitation prior to or during the studies, resulting in greater than normal streamflows. Larger than usual flows in the Milk and Colorado rivers raised refuge water levels and helped flush accumulated salts from the wetlands. The flushing of Stewart Lake WMA due to large flows in the Green River since 1982 probably has also diluted concentrations of trace elements in the lake.

The last observation concerns pesticides. Little quantitative information on pesticide applications was obtained during the reconnaissance investigations, and thus no quantitative relations can be determined between usage and occurrence in water, bottom sediment, or biota. Nevertheless, some qualitative statements can be made. Organochlorine pesticides generally were detected only in study areas where applications have been large (Lower Colorado River and Laguna Atascosa). DDE was the principal compound detected. Concentrations were low in water and sediment (less than 0.01 parts per billion [ppb] and generally less than 10 ppb, dry weight, respectively). Concentrations in biota also were low (generally less than 1.0 ppm, wet weight). The occurrence of DDE is indicative of the persistence of this breakdown product of DDT, which was widely used from the 1940s to the early 1970s (when it was banned in the United States). Other pesticides were not detected, or their occurrence was localized.

Implications

To translate the results of the reconnaissance investigations into programmatic actions, the Interior Department depended heavily on an objective evaluation model involving linear weighting. In that model, a set of evaluation criteria were identified (table 1), and a weight was assigned to each criterion. The results of each investigation were then evaluated (scored) against each criterion. Next, the scores were multiplied by the respective weights and summed over all criteria to obtain a

Table 1. Reconnaissance Investigation Evaluation Criteria

Level of Interior Department involvement
Irrigation project constructed, funded, or managed by the department
National Wildlife Refuge or Waterfowl Management Area
State or private waterfowl area
Migratory waterfowl use of the area
Endangered/threatened species use of the area

Study area and downstream uses
Public water supply/drinking water
-Municipal
-Rural
Fish and wildlife
-Wetland
-Fishery
Recreation (fishing/swimming/boating)
Agriculture
-Irrigation
-Livestock

Human health
Exceedance of standards or criteria
-Drinking water
Health advisories
-Drinking water
-Wildlife/fish consumption

Other beneficial uses
Exceedance of standards or criteria
-Irrigation
-Livestock

Bottom sediment
Comparisons to geochemical baselines for soil

Fish and wildlife health
Field Observations
Fish
-Die-offs
-Behavioral effects
-Growth effects
Wildlife
-Die-offs
-Behavioral effects
-Growth effects
-Deformities noted

Experimental data comparisons
Exceedance of water quality criteria
-Freshwater aquatic life
-Marine aquatic life
Fish (body burden)
-Levels above 85th percentile, NCBP
-Levels indicating reproductive effects
-Levels indicating lethal effects
Wildlife (body burden)
-Levels indicating reproductive effects
-Levels indicating growth effects
-Levels indicating lethal effects
Aquatic invertebrates and plants
Exceedance of target levels to protect fish and wildlife

weighted sum for each study location. These scores were used to determine which areas were of sufficient concern regarding irrigation-induced contamination to warrant additional actions.

At several locations, in-depth investigations were undertaken to provide the scientific understanding needed for development of alternatives to mitigate or resolve identified problems. As part of these studies, the severity of impacts is now being examined by investigating possible bioaccumulation and toxic effects at each site. An important part of this work will include characterization of potentially exposed human and fish and wildlife populations, as well as determination of expected exposure levels and duration at each exposure level. This involves intensive wildlife pollution observation studies, including nest monitoring to determine reproductive success and to gather data on embryos.

Generally, the in-depth studies will focus on gaining detailed, site-specific information on potentially toxic constituents and on improving understanding of the movement of those constituents through the environment in each area. Cause and effect linkages between contaminant sources and impacts will be established, including the identification of known or potential human and fish and wildlife exposure pathways.

At several other locations where in-depth investigations were not deemed warranted, long-term monitoring activities are planned. The objective is to use the results of the reconnaissance studies at each area to identify optimal locations for monitoring stations, select appropriate environmental media and types of organisms for biological media to be sampled, develop sampling schedules, select constituents for laboratory analysis, and decide on other required variables. In this manner, the department will "keep its finger on the pulse" of the areas in question without large additional expenses.

Conclusion

The identification of irrigation-induced contamination as a significant concern in irrigation and drainage project developments and the consequent investigative program of the U.S. Department of the Interior mark an important milestone in the evaluation of efforts to increase the productivity of land and water resources. The studies mentioned in this paper represent the first interdisciplinary evaluation of the magnitude and extent of irrigation-induced contamination problems on a large scale.

From these results, we are beginning to understand in a macroscopic sense the nature of the problem. We know, for example, that irrigation-induced contamination problems tend to be site-specific, that is, problems can be significant in a given location, whereas no problems are evident at nearby areas.

On a more technical level, we are increasing our body of knowledge concerning the sources, mobilization, transport mechanisms, fate, and impacts of potentially toxic constituents in irrigation drainwater. This new knowledge should increase the capability of development organizations to predict—from planned or existing irrigation developments—where irrigation-induced contamination problems will occur.

Solutions to these types of problems cannot normally be accomplished by a single institution. They generally require a coordinated response by multiple levels of government and, in some cases, private entities. Undoubtedly, our knowledge base about these complex and difficult problems will continue to expand as we continue to work toward their ultimate resolution.

Distributors of World Bank Publications

ARGENTINA
Carlos Hirsch, SRL
Galeria Guemes
Florida 165, 4th Floor-Ofc. 453/465
1333 Buenos Aires

AUSTRALIA, PAPUA NEW GUINEA, FIJI, SOLOMON ISLANDS, VANUATU, AND WESTERN SAMOA
D.A. Books & Journals
648 Whitehorse Road
Mitcham 3132
Victoria

AUSTRIA
Gerold and Co.
Graben 31
A-1011 Wien

BAHRAIN
Bahrain Research and Consultancy Associates Ltd.
Esterad Building No. 42
Diplomatic Area
P.O. Box 2750
Manama Town 317

BANGLADESH
Micro Industries Development Assistance Society (MIDAS)
House 5, Road 16
Dhanmondi R/Area
Dhaka 1209

Branch offices:
156, Nur Ahmed Sarak
Chittagong 4000

76, K.D.A. Avenue
Kulna

BELGIUM
Jean De Lannoy
Av. du Roi 202
1060 Brussels

CANADA
Le Diffuseur
C.P. 85, 1501B rue Ampère
Boucherville, Québec
J4B 5E6

CHINA
China Financial & Economic Publishing House
8, Da Fo Si Dong Jie
Beijing

COLOMBIA
Infoenlace Ltda.
Apartado Aereo 34270
Bogota D.E.

COTE D'IVOIRE
Centre d'Edition et de Diffusion Africaines (CEDA)
04 B.P. 541
Abidjan 04 Plateau

CYPRUS
MEMRB Information Services
P.O. Box 2098
Nicosia

DENMARK
SamfundsLitteratur
Rosenoerns Allé 11
DK-1970 Frederiksberg C

DOMINICAN REPUBLIC
Editora Taller, C. por A.
Restauración e Isabel la Católica 309
Apartado Postal 2190
Santo Domingo

EGYPT, ARAB REPUBLIC OF
Al Ahram
Al Galaa Street
Cairo

The Middle East Observer
41, Sherif Street
Cairo

EL SALVADOR
Fusades
Avenida Manuel Enrique Araujo #3530
Edificio SISA, 1er. Piso
San Salvador

FINLAND
Akateeminen Kirjakauppa
P.O. Box 128
Helsinki 10
SF-00101

FRANCE
World Bank Publications
66, avenue d'Iéna
75116 Paris

GERMANY
UNO-Verlag
Poppelsdorfer Allee 55
D-5300 Bonn 1

GREECE
KEME
24, Ippodamou Street Platia Plastiras
Athens-11635

GUATEMALA
Librerias Piedra Santa
5a. Calle 7-55
Zona 1
Guatemala City

HONG KONG, MACAO
Asia 2000 Ltd.
48-48 Wyndham Street
Winning Centre
2nd Floor
Central Hong Kong

INDIA
Allied Publishers Private Ltd.
751 Mount Road
Madras - 600 002

Branch offices:
15 J.N. Heredia Marg
Ballard Estate
Bombay - 400 038

13/14 Asaf Ali Road
New Delhi - 110 002

17 Chittaranjan Avenue
Calcutta - 700 072

Jayadeva Hostel Building
5th Main Road Gandhinagar
Bangalore - 560 009

3-5-1129 Kachiguda Cross Road
Hyderabad - 500 027

Prarthana Flats, 2nd Floor
Near Thakore Baug, Navrangpura
Ahmedabad - 380 009

Patiala House
16-A Ashok Marg
Lucknow - 226 001

INDONESIA
Pt. Indira Limited
Jl. Sam Ratulangi 37
P.O. Box 181
Jakarta Pusat

ISRAEL
Yozmot Literature Ltd.
P.O. Box 56055
Tel Aviv 61560
Israel

ITALY
Licosa Commissionaria Sansoni SPA
Via Duca Di Calabria, 1/1
Casella Postale 552
50125 Florence

JAPAN
Eastern Book Service
37-3, Hongo 3-Chome, Bunkyo-ku 113
Tokyo

KENYA
Africa Book Service (E.A.) Ltd.
P.O. Box 45245
Nairobi

KOREA, REPUBLIC OF
Pan Korea Book Corporation
P.O. Box 101, Kwangwhamun
Seoul

KUWAIT
MEMRB Information Services
P.O. Box 5465

MALAYSIA
University of Malaya Cooperative Bookshop, Limited
P.O. Box 1127, Jalan Pantai Baru
Kuala Lumpur

MEXICO
INFOTEC
Apartado Postal 22-860
14060 Tlalpan, Mexico D.F.

MOROCCO
Société d'Etudes Marketing Marocaine
12 rue Mozart, Bd. d'Anfa
Casablanca

NETHERLANDS
De Lindeboom/InOr-Publikaties
P.O. Box 202
7480 AE Haaksbergen

NEW ZEALAND
Hills Library and Information Service
Private Bag
New Market
Auckland

NIGERIA
University Press Limited
Three Crowns Building Jericho
Private Mail Bag 5095
Ibadan

NORWAY
Narvesen Information Center
Book Department
P.O. Box 6125 Etterstad
N-0602 Oslo 6

OMAN
MEMRB Information Services
P.O. Box 1613, Seeb Airport
Muscat

PAKISTAN
Mirza Book Agency
65, Shahrah-e-Quaid-e-Azam
P.O. Box No. 729
Lahore 3

PERU
Editorial Desarrollo SA
Apartado 3824
Lima

PHILIPPINES
International Book Center
Fifth Floor, Filipinas Life Building
Ayala Avenue, Makati
Metro Manila

PORTUGAL
Livraria Portugal
Rua Do Carmo 70-74
1200 Lisbon

SAUDI ARABIA, QATAR
Jarir Book Store
P.O. Box 3196
Riyadh 11471

MEMRB Information Services
Branch offices:
Al Alsa Street
Al Dahna Center
First Floor
P.O. Box 7188
Riyadh

Haji Abdullah Alireza Building
King Khaled Street
P.O. Box 3969
Damman

33, Mohammed Hassan Awad Street
P.O. Box 5978
Jeddah

SINGAPORE, TAIWAN, MYANMAR, BRUNEI
Information Publications Private, Ltd.
02-06 1st Fl., Pei-Fu Industrial Bldg.
24 New Industrial Road
Singapore 1953

SOUTH AFRICA, BOTSWANA
For single titles:
Oxford University Press Southern Africa
P.O. Box 1141
Cape Town 8000

For subscription orders:
International Subscription Service
P.O. Box 41095
Craighall
Johannesburg 2024

SPAIN
Mundi-Prensa Libros, S.A.
Castello 37
28001 Madrid

Librería Internacional AEDOS
Consell de Cent, 391
08009 Barcelona

SRI LANKA AND THE MALDIVES
Lake House Bookshop
P.O. Box 244
100, Sir Chittampalam A. Gardiner Mawatha
Colombo 2

SWEDEN
For single titles:
Fritzes Fackboksforetaget
Regeringsgatan 12, Box 16356
S-103 27 Stockholm

For subscription orders:
Wennergren-Williams AB
Box 30004
S-104 25 Stockholm

SWITZERLAND
For single titles:
Librairie Payot
6, rue Grenus
Case postale 381
CH 1211 Geneva 11

For subscription orders:
Librairie Payot
Service des Abonnements
Case postale 3312
CH 1002 Lausanne

TANZANIA
Oxford University Press
P.O. Box 5299
Dar es Salaam

THAILAND
Central Department Store
306 Silom Road
Bangkok

TRINIDAD & TOBAGO, ANTIGUA BARBUDA, BARBADOS, DOMINICA, GRENADA, GUYANA, JAMAICA, MONTSERRAT, ST. KITTS & NEVIS, ST. LUCIA, ST. VINCENT & GRENADINES
Systematics Studies Unit
#9 Watts Street
Curepe
Trinidad, West Indies

UNITED ARAB EMIRATES
MEMRB Gulf Co.
P.O. Box 6097
Sharjah

UNITED KINGDOM
Microinfo Ltd.
P.O. Box 3
Alton, Hampshire GU34 2PG
England

VENEZUELA
Libreria del Este
Aptdo. 60.337
Caracas 1060-A

RECENT WORLD BANK TECHNICAL PAPERS *(continued)*

No. 147	The World Bank/UNDP/CEC/FAO, *Fisheries and Aquaculture Research Capabilities and Needs in Asia: Studies of India, Thailand, Malaysia, Indonesia, the Philippines, and the ASEAN Region*
No. 148	The World Bank/UNDP/CEC/FAO, *Fisheries and Aquaculture Research Capabilities and Needs in Latin America: Studies of Uruguay, Argentina, Chile, Ecuador, and Peru*
No. 149	The World Bank/UNDP/CEC/FAO, *Fisheries and Aquaculture Research Capabilities and Needs in Africa: Studies of Kenya, Malawi, Mozambique, Zimbabwe, Mauritania, Morocco, and Senegal*
No. 150	The World Bank/UNDP/CEC/FAO, *International Cooperation in Fisheries Research*
No. 151	The World Bank/UNDP/CEC/FAO, *Tropical Aquaculture Development: Research Needs*
No. 152	The World Bank/UNDP/CEC/FAO, *Small-Scale Fisheries: Research Needs*
No. 153	The World Bank/UNDP/CEC/FAO, *Small Pelagic Fish Utilization: Research Needs*
No. 154	Environment Department, *Environmental Assessment Sourcebook*, vol. III: *Guidelines for Environmental Assessment of Energy and Industry Projects*
No. 155	Bélot and Weigel, *Programs in Industrial Countries to Promote Foreign Direct Investment in Developing Countries*
No. 156	De Geyndt, *Managing Health Expenditures under National Health Insurance: The Case of Korea*
No. 157	Critchley, Reij, and Seznec, *Water Harvesting for Plant Production*, vol. II: *Case Studies and Conclusions for Sub-Saharan Africa*
No. 158	Hay and Paul, *Regulation and Taxation of Commercial Banks during the International Debt Crisis*
No. 159	Liese, Sachdeva, and Cochrane, *Organizing and Managing Tropical Disease Control Programs: Lessons of Success*
No. 160	Boner and Krueger, *The Basics of Antitrust Policy: A Review of Ten Nations and the European Communities*
No. 161	Riverson and Carapetis, *Intermediate Means of Transport in Sub-Saharan Africa: Its Potential for Improving Rural Travel and Transport*
No. 162	Replogle, *Non-Motorized Vehicles in Asian Cities*
No. 163	Shilling, editor, *Beyond Syndicated Loans: Sources of Credit for Developing Countries*
No. 164	Schwartz and Kampen, *Agricultural Extension in East Africa*
No. 165	Kellaghan and Greaney, *Using Examinations to Improve Education: A Study in Fourteen African Countries*
No. 166	Ahmad and Kutcher, *Irrigation Planning with Environmental Considerations: A Case Study of Pakistan's Indus Basin*
No. 167	Liese, Sachdeva, and Cochrane, *Organizing and Managing Tropical Disease Control Programs: Case Studies*
No. 168	Industry and Energy Department, *An Introduction and Update on the Technology, Performance, Costs and Economics*
No. 169	Westoff, *Age at Marriage, Age at First Birth, and Fertility in Africa*
No. 170	Sung and Troia, *Developments in Debt Conversion Programs and Conversion Activities*
No. 171	Brown and Nooter, *Successful Small-Scale Irrigation in the Sahel*
No. 172	Thomas and Shaw, *Issues in the Development of Multigrade Schools*
No. 173	Byrnes, *Water Users Associations in World Bank–Assisted Irrigation Projects in Pakistan*
No. 174	Constant and Sheldrick, *World Nitrogen Survey*
No. 175	Le Moigne and others, editors, *Country Experiences with Water Resources Management: Economic, Institutional, Technological and Environmental Issues*
No. 176	The World Bank/FAO/UNIDO/Industry Fertilizer Working Group, *World and Regional Supply and Demand Balances for Nitrogen, Phosphate, and Potash, 1990/91–1996/97*
No. 177	Adams, *The World Bank's Treatment of Employment and Labor Market Issues*

The World Bank

Headquarters
1818 H Street, N.W.
Washington, D.C. 20433, U.S.A.

Telephone: (202) 477-1234
Facsimile: (202) 477-6391
Telex: WUI 64145 WORLDBANK
RCA 248423 WORLDBK
Cable Address: INTBAFRAD
WASHINGTONDC

European Office
66, avenue d'Iéna
75116 Paris, France

Telephone: (1) 40.69.30.00
Facsimile: (1) 40.69.30.66
Telex: 640651

Tokyo Office
Kokusai Building
1-1 Marunouchi 3-chome
Chiyoda-ku, Tokyo 100, Japan

Telephone: (3) 3214-5001
Facsimile: (3) 3214-3657
Telex: 26838

Cover design by Walton Rosenquist

ISBN 0-8213-2165-X