An Audiovisual Production

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The Economic Development Institute
and The Agriculture and Rural Development
Department of The World Bank
Improving the Operation of Canal Irrigation Systems

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French and Spanish language versions are forthcoming.

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Improving the Operation of Canal Irrigation Systems

Foreword

This audiovisual presentation is the result of a joint effort between the Economic Development Institute and the Agriculture and Rural Development Department of the World Bank. The objectives of the project are (1) to share some of the lessons learned from the Bank's experience in canal irrigation projects worldwide with operational personnel and policy makers in developing countries, and (2) to provide in a visual form a comprehensive overview of the methods to be considered in the planning, design, and rehabilitation of irrigation projects.

The central importance of irrigation to agricultural productivity cannot be overemphasized. Likewise, the potential negative social and environmental effects of poorly designed and managed systems should not be underestimated. Careful selection of appropriate irrigation methods can help ensure that a project will sustain agricultural production and growth over time. This presentation focuses on systems and methods that minimize dependence on overly complex management requirements while at the same time maximizing efficiency of water use and reliability of water delivery to farmers and alleviating environmental effects.

We believe that these materials will be of use to a broad audience of planners and designers and serve as a basis for the fruitful exchange of ideas and experience across borders.

G. E. Schuh
Director
Agriculture and Rural Development Department

C. R. Willoughby
Director
Economic Development Institute
This audiovisual program responds to the need to raise awareness of the advantages and limitations of various design criteria for canal irrigation systems currently in use in selected countries. It also aims to disseminate information on the advanced approaches to canal system operation developed over the last 50 years.

In many parts of the world, irrigation systems are performing well below their potential. There is unanimous agreement in the irrigation community on the need to improve the operation of irrigation systems in order to increase agricultural productivity. Most countries now place great importance on programs for the rehabilitation, operation, and maintenance of existing projects. However, these works are often limited to canal lining, land levelling, rehabilitation of existing control structures, improvement of access roads, and non-physical components, such as staff training, better maintenance procedures, and improvement of cost recovery systems. Although rehabilitation combined with improved operation and maintenance can achieve a great deal, the attainment of high levels of productivity from many existing irrigation systems requires certain physical improvements. In particular, it is necessary to reduce water losses and develop better control structures in order to ensure timely delivery and correct amounts of water to the crops.

Better performance of irrigation systems is becoming more and more important as growth in world population steadily increases the competition for water. Planning and design have crucial implications for the success or failure of an irrigation system. Although experts will always have different views on the appropriate technology for various irrigation systems, such disagreements may simply reflect the need to adapt to local conditions and to make best use of available resources. In some cases lack of information about successful developments in other parts of the world can be an important constraint.
Adoption of new technology in the field of canal and pipeline control structures is slow. Some countries still follow operational procedures and design criteria adopted decades ago in response to prevailing conditions, but which are now inadequate for the needs of modern agriculture or do not make best use of recently regulated water resources. Outmoded design and methods of operation limit the performance of many newly rehabilitated systems. Adoption of advanced concepts of canal and pipeline operation can have a decisive influence on the success of a project. Too often, however, this technical question is either ignored or is insufficiently addressed at the planning and design stage of both new projects and rehabilitation projects. Familiar and long-established practices often prevail over new techniques.

A variety of approaches exist to irrigation management and system operation. Great care should be taken in selecting the appropriate method for new or for rehabilitation/modernization projects. All offer different advantages and drawbacks, and have different implications for the water users. The selection of appropriate irrigation technologies best suited to particular cropping patterns under different physical and socio-economic conditions involves numerous complex and often conflicting considerations.

The need to improve existing systems results from a number of factors, including the following:

- outdated system objectives and purposes;
- aging of systems and changes in demand patterns;
- increased costs of operation and maintenance;
- excessive operational spillage; and
- mismatches between demand and delivery.
Most important is the increased awareness of the need for flexibility in delivery to maximize on-farm yield, and the need for greater efficiency through more effective on-farm use.

The printed documentation on modern irrigation often seems too voluminous and fragmented. Information on design is difficult to communicate through written reports and handbooks. The authors believe that an audiovisual program is well-suited to demonstrate the broad range of experience accumulated in different countries and to present the state of the art in technology for upgrading, rehabilitating, operating, and automating irrigation systems.

This program attempts to distill and summarize current information on canal irrigation and to present it as simply as possible in an effort to reach a broad audience ranging from planners and design engineers to agronomists and project managers. Treatment of the topic is limited in scope and is selective rather than comprehensive. Even so, some may find the presentation to be too theoretical, while others may consider it too simplistic. This risk is implicit in any attempt to communicate a comprehensive body of knowledge to a diverse readership.

This program is therefore not the equivalent of a design manual. Those interested in gaining a deeper understanding of the topics should refer to:

- hydraulic handbooks for details on conventional hydraulic structures such as long crest weirs, orifices, flow dividers;
- technical brochures produced by manufacturers of control equipment; and
- specialists in the theories of remote and local remote control in open channel systems.

This audiovisual project began in 1982 as a joint effort of the World Bank and the California Polytechnic State University in San Luis Obispo, California. The first production comprising only three parts was completed in late 1984. It was then considerably revised and expanded to include a more systematic presentation of the conventional and modern approaches to water management, canal operation,
and control equipment. The script attempts to present an objective overview of the approaches developed in different parts of the world. Nevertheless, there may still be some opinions expressed in this program which are not universally shared by irrigation practitioners. EDI recognizes that further improvements and refinements in the program are possible, and indeed welcomes comments and suggestions from viewers.

The scope of this program is focused, as the title suggests, on improving the operation of the main and distribution canal system. However, the program also refers to non-engineering aspects such as crop water requirements, water user organizations, and cost recovery through volumetric water charges. Such references relate to the general objective of a modern system: namely to deliver water to the crops on time and in proper quantities, and this at the convenience of farmers and in the most economic way.

The program should prove useful to engineers involved in the planning, design, construction, and operation of water delivery systems. It should also stimulate the exchange of ideas and information on techniques which to date are neither widespread nor well understood.

This program advocates modernization and automation of irrigation systems. In both developed and developing countries, manual adjustments of control structures should be minimized. Frequent resetting of manually operated gates requires a large number of trained and dedicated technical staff. It also requires good transmission and communication networks and transportation equipment. In many countries these conditions are often lacking. In others, the cost of operating personnel represents a substantial proportion of total recurrent costs. These financial and human resource constraints can be partly eliminated by introducing some degree of automation in the control systems. Contrary to popular belief, automation is not necessarily highly sophisticated. The program shows some examples of automation using simple but effective devices that do not depend on external sources of energy.
Summary of the program

Part I: Overview: The Need for Better Irrigation (80 slides) gives an overview of the issues related to water distribution, and summarizes the methods of water control that are described in later parts of the program. It also discusses important considerations in the planning and design of irrigation systems for effective operation and management.

Part II: Old Conceptual Approaches (49 slides) deals with small-scale traditional irrigation schemes and conventional large-scale projects. It reviews the principles of water distribution used in most traditional irrigation schemes. Then it discusses the shortcomings of these principles when they were applied to some large-scale projects in the late 19th century. Finally, it describes the operational difficulties of operating conventional large-scale projects equipped with a large number of adjustable, manually controlled structures.

Part III: The Hydraulic Problem of Canal Water Control (45 slides) formulates the objectives of modern irrigation in engineering terms. First it examines the two basic aspects of canal water control: water flow control and water level control. It then reviews the basic methods of water level control in open channels under variable flow conditions.

Part IV: System Operation: Local and Remote Local Control (48 slides) examines the operation of an entire irrigation system consisting of a complex network of main and tertiary canals and discusses the advantages and disadvantages of upstream and downstream control methods and their possible combinations.

Part V: Centralized Control (62 slides) reviews the operator-oriented and user-oriented approaches to centralized control of canal systems and presents the main features of some examples: The Salt River project, the California
Aqueduct, the Central Arizona Project in the USA, and the Canal de Provence in France.

**Part VI: Control Equipment (97 slides)** examines the alternative solutions for local control at various points in an irrigation system for flow division, water level control, combined flow and water level control, flow controls at offtakes, and a combination of all these. Then the features of certain types of equipment used in remote and centralized control are briefly described.

**Part VII: Selection of Appropriate Method of Operation (73 slides)** reviews the factors that influence the selection of operational concepts and associated technologies for construction of new projects and modernization of existing systems. It concludes with some general recommendations on the selection of technologies.

**Suggestions to Presenters**

1. Presenters should familiarize themselves with the contents of the slides and the script before showing to an audience.

2. Presentation of the entire seven parts should be distributed over a period of at least two days, and preferably more. Normally, discussions or other activities can be carried out between parts.

3. **Part I** has two purposes: It can be used as an introduction to **Parts II** through **VII** by helping to focus attention on the major issues. It can also be used alone as an executive summary for decision makers or for irrigation staff not directly involved with design or operation of irrigation systems.
4. Before showing each module it is useful, first, to give a brief oral introduction highlighting the main points of the module, then to proceed with the audiovisual presentation and afterwards to project selected slides again to summarize, to make additional comments, or to focus discussion on the most important aspects.

5. The slide/tape program includes 35 mm slides synchronized with the narration on the accompanying audiocassettes. The narration on each audiocassette is pulsed with audible tones. These tones are cues that the slide projector should be advanced immediately to the next slide. The narration is recorded on Side 1 of each of the audiocassettes; Side 2 is blank.

6. When you are ready to begin showing the slide/tape program, turn on the equipment and make sure the title slide is already projected when the music at the start of the program begins. When you hear the first tone, advance the slide projector immediately to the next slide. Continue advancing the slides at the sound of the tone until the end of Part I. Follow the same procedure for the other parts.

7. Operation of the slide projector and audiocassette player should be checked prior to the presentation. At that time it is advisable to arrange for any necessary power cords and extra projector bulbs. It is also useful to determine who should be contacted if assistance is needed from an engineer or audiovisual specialist. It is important to check that each participant will be able to see and hear the slide/tape program easily. To view the slides clearly, overhead and back lighting should be kept to a minimum.
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## Improving the Operation of Canal Irrigation Systems

### CONTENTS

<table>
<thead>
<tr>
<th>Part</th>
<th>Title</th>
<th>Frame Number</th>
<th>Running Time (mins.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part I</td>
<td>Overview: The Need for Better Irrigation</td>
<td>1 to 80</td>
<td>24:35</td>
</tr>
<tr>
<td>Part II</td>
<td>Old Conceptual Approaches</td>
<td>81 to 129</td>
<td>19:10</td>
</tr>
<tr>
<td>Part III</td>
<td>The Hydraulic Problem of Canal Water Control</td>
<td>130 to 174</td>
<td>12:09</td>
</tr>
<tr>
<td>Part IV</td>
<td>System Operation: Local and Remote Local Control</td>
<td>175 to 222</td>
<td>15:05</td>
</tr>
<tr>
<td>Part V</td>
<td>Centralized Control</td>
<td>223 to 284</td>
<td>18:30</td>
</tr>
<tr>
<td>Part VI</td>
<td>Control Equipment</td>
<td>285 to 381</td>
<td>25:00</td>
</tr>
<tr>
<td>Part VII</td>
<td>Selection of Appropriate Method of Operation</td>
<td>382 to 454</td>
<td>21:27</td>
</tr>
</tbody>
</table>
1. Title Slide. PART I: Overview
   The Need for Better Irrigation

2. Over 275 million gross hectares of land are currently irrigated in the world today.

3. The importance of irrigation and drainage is indicated by the agricultural production that irrigation supports, by the increased size of investments in irrigation projects, and by its significance to social and economic development.

4. Over the last thirty years, there has been a steady increase in newly irrigated lands on the order of four million hectares per year. These projects have produced a remarkable increase in the production of rice, wheat, and other crops. Several countries project a doubling of their irrigated areas by the end of this century.
Despite these impressive increases, policy and decision makers in governments and in financing institutions are concerned that irrigation systems are performing below their potential.

There are many factors that indicate the low performance of irrigation systems. First, the overall water use efficiency of many systems may be as low as 30 percent or less, while well-managed systems show efficiencies of 50 percent or more.

Second, inequalities in the pattern of water distribution to farmers are common, causing excess water in some places and deficits in others. Headreach farmers often take advantage of their location and take an unfair share of water when the supply is insufficient or uncertain.
Third, in arid regions environmental problems such as water logging and salinity develop.

Fourth, because of the severe deficiencies in irrigation water management, benefits derived from many irrigation projects are far short of expectations. As a result, irrigated areas are smaller and crop yields lower than estimated at the planning stage.

For example, the yield of paddy rice in a number of countries varies from 2 to 3 tons per hectare but, under better control of water supply and drainage, average yields of 5 to 6 tons per hectare have been obtained.
Fifth, when the water supply is unreliable, beneficiaries are not motivated to organize themselves and participate in operating and maintaining the tertiary distribution network. And they are less willing to pay service charges if service is poor.

Sixth, the operational problems with many projects are aggravated when maintenance is deferred because of inadequate recurrent funds. The lack of maintenance results in a rapid deterioration of public investments.

There is unanimous agreement on the need to improve operations of irrigation systems throughout the world in order to increase productivity. The management solutions that are frequently recommended include improved water resources management, better coordination between agriculture and irrigation agencies, training, larger budget allocations for recurrent costs, higher water charges and farmer participation. But these solutions have not always appreciably improved the situation.
In many cases, the most obvious operational problems are water wastage below the outlet caused by a lack of field channels. In the 1970s, a common response was to promote on-farm development and the organization of water user associations. This response addressed only part of the problem.

Now it is recognized that problems at the farm level often result from mismanagement of the canal system upstream. This farm channel, for example, is not receiving an adequate supply because the water level in the secondary canal is too low. Adequate management of the main system is a prerequisite to the farmers' participation in operation and maintenance below the farm outlet.

Some significant results have been achieved through improved system management in several pilot projects such as this one in Thailand. To push the performance of these systems to a higher level, changes in physical infrastructure are often needed. Improved system management by itself is not enough. Moreover, because of financial and training constraints, many agencies are not in a position to raise staffing to the level needed for improved management.
It is often said that water measurement is essential to effective water management. However, water measurement in irrigation should be adapted to the complex operations of irrigation systems which are very different from measurements in hydrology and hydraulics research. Repetitive use of conventional measuring devices requires training and dedication of operators, may create sources of errors, and does not prevent malfunctioning of control structures. Flow self-control of water is an alternative approach which will be discussed in this program.

The planning, design and construction process must produce a system and conditions capable of accommodating effective management practices.

In this program we will review the important considerations in the planning and design of irrigation systems for effective operation and management.
This part of the program is an overview of the issues related to water distribution, and methods of water control that will be described in later parts of the program.

In Part II, we will review the old conceptual approaches to water management in both small-scale and conventional large-scale projects.

In Part III we will define the basic hydraulic problem of canal water control.
In Parts IV and V we will present the modern methods of local, remote localized, and centralized control of irrigation systems.

In Part VI we will review the control equipment available for use in irrigation systems.

And in Part VII we will examine the issue of selecting the appropriate methods of operation and associated technology for both construction of new projects and modernization of existing systems.
Now let's turn our attention in this overview to the need for better irrigation in terms of both water demand and water supply.

Let's begin by defining the objectives that irrigation systems are intended to meet from three different perspectives - first, the farmers, second, the authority responsible for the system's operation, and third, the country.

The farmer's first concern is to produce enough food for subsistence or to maximize family income.
The ideal mode of water delivery from a farmer's viewpoint is delivery at will or "on demand." In this way, he can match water scheduling to soil and crop needs and to rainfall.

He can coordinate irrigation with other farming practices, such as land preparation ...

...or spraying for weed control. This kind of flexibility in water supply results in maximum crop yields for the farmer.
To obtain the maximum yields, the farmer requires flexibility in water distribution in terms of frequency, rate, and duration.

The frequency of irrigation must be scheduled flexibly to prevent crop stress and to avoid interference with other activities.

The rate of water delivery determines its uniformity of distribution and efficient use of labor.
The duration or length of time that water is applied to a field is also critical. Too much water will percolate below root zones and contribute to leaching of fertilizers and to drainage problems.

However, in most surface irrigation projects, farmers do not enjoy the flexibility of water delivery on demand. The concerns of most farmers are, first, the predictability of the water they will receive; second, how much water; and third, for how long.

Now let's look at the objectives from the point of view of the authority that is responsible for managing the system. It can be either a farmers' association or a government agency.
The objectives of the authority may in fact be in conflict with the individual farmer's interests. They include equitable water allocation, simple operating procedures, and efficient distribution where water is scarce.

Where water resources are limited - and this is often the case - the authority must restrain individuals from competing in their own self-interest. This requires the enforcement of rules governing water distribution.

On the one hand, in indigenous societies with long traditions of irrigation development, equity - or the respect of established water rights - and even some degree of flexibility in water distribution are achieved in small irrigation schemes. They are based on widely accepted cultural norms for water distribution and allocation.
On the other hand, if irrigation is introduced through the external intervention of a government, irrigation practices are often imposed on farmer groups in order to ensure equitable distribution through simple but **rigid** operating rules. The autonomy of the farmer is limited by the central control of water delivery. This board shows a weekly irrigation schedule set by a central authority.

The authority that manages an irrigation system also faces staffing and financial constraints in operating the system. Control structures, therefore, should be designed to minimize the frequency of staff intervention.

Furthermore, operation of the control structures should be simple - although accurate - to minimize the level of technical training required for canal operators. This generally will result in more efficient distribution.
But in many projects minimizing staff intervention and training have not been taken into account during the design stage. As a result, many structures are unreliable, they require frequent adjustment to perform adequately ...

... and their operation is complicated and not well understood by operators. Trying to improve irrigation performance by increasing staff intervention and training is often ineffective.

From the point of view of a country's economic objectives, an irrigation system may be intended to increase food production, to generate employment or foreign exchange, or to help alleviate rural poverty. Poverty alleviation can be achieved by adopting a policy of extensive irrigation by spreading water to benefit as many farmers as possible. In some countries, this approach to irrigation has considerable impact on the rules of water distribution and system design as well.
From the country's point of view, it is also important in planning a project to consider the environmental impact. The objective is to provide sustainable irrigation performance without negative environmental effects such as water logging, groundwater depletion, and salinization as shown in this picture.

In summary, we have seen that an irrigation project is expected to fulfill a wide range of objectives, some of which may not always be compatible. In particular, the interests of individual farmers, rightly concerned with their water allocation and the flexibility in water delivery, may not necessarily be in harmony with the interests of the community at large.

Now that we have looked at water operation and management from the demand side, let's look at the supply side of the problem. Water is not a "good" like other farming inputs; it is a natural resource of a different nature and difficult to handle.
Because of its variability between locations and over time, water is difficult to use efficiently.

Because of its mobility, it is difficult to measure and apportion.

Daily and seasonal variations of stream flows reflect the variability of rainfall over catchment areas. But with few exceptions, the water supply pattern does not follow the demand pattern. Efficient water use and intensive irrigation throughout the year therefore are hard to achieve.
Storage dams are a solution to the problem of interseasonal irrigation if they are economically and technically feasible.

However, many irrigation projects still depend on unregulated or semi-regulated river flows for their water supply.

Increasing the complexity of operating large-scale irrigation systems is the unpredictability of rainfall over an irrigated area. For example, how do we respond to the sudden shut off of farmers' turnouts without wasting water already running in the canals and channelling it into the drainage system?
The challenge, then, is to allocate water, in an equitable, efficient, reliable and timely way—while minimizing staff and operating costs. Admittedly, there are trade-offs among all these objectives.

In the last part of this overview, we will briefly describe some of the systems that have been developed in modern times. A hundred years ago, modern irrigation system design was still in its infancy. Many systems were designed to meet only limited objectives, not the needs of modern agriculture. The technical constraints of these systems, therefore, often limit possibilities for improvement through better management.

For example, the irrigation system in the Indus basin was conceived in the 1870s for conditions and objectives that are different from today's. This system was designed to provide fair distribution of water. For that narrow purpose it can be operated efficiently by a small staff. But the water delivery offers little flexibility. It is up to the farmers to adjust their cropping calendars as best they can to make the best use of the timing and the volume of water they receive.
Other systems were designed to provide both fair and flexible delivery of water to meet irrigation needs. Efficient operation relies on large numbers of trained and dedicated employees, rapid communications, and adequate transportation. When all these conditions are met, the systems perform well. However, in practice, these operational requirements are often not met, which limits the systems' performance.

One answer to the problems we just reviewed lies in the advanced concepts of canal regulation and control devices which were developed during the last 50 years and are now used successfully in several countries, especially those indicated here.

Irrigation systems under advanced concepts of canal regulation provide a higher level of service with simpler operation and fewer staff requirements.
The shortage of qualified staff in some countries and the cost of manpower in others are major constraints in operating conventional irrigation systems which require frequent adjustments. Considerable simplification of operations, therefore, has been the main objective in developing modern regulation concepts and associated techniques of control of irrigation systems.

These simplified designs can provide an improved water supply to farmers.

Just as other public facilities, like power utilities or water supply enterprises, are operated without constant attention to every part of the system, irrigation systems must be able to operate without large numbers of highly trained staff.
For example, the hydraulic or electrically-assisted devices that have been developed make it possible to automatically control the water level in a canal.

Other devices offer additional features important to water regulation. For example, the gates on the left automatically adjust flow releases to the demand at each control point along a canal. This eliminates the need for elaborate advanced scheduling of system operations, which reduces flexibility in operation. The photo on the right is the control room of a centralized system.

Other examples are this flow limitor which automatically spills any flow which exceeds canal transit capacity where the canal cross-section is reduced...
...and these modules, which maintain a nearly constant flow at any branching point, including users' turnouts.

The variety of modern technological options available to improve irrigation performance will be discussed in Parts IV, V, and VI of this program. They range from very simple devices based on elementary hydraulic principles...

...to the most sophisticated centralized remote control systems.
These control devices have several advantages: efficient use of limited water resources, better service to water users, low cost operation with minimum manpower, harmony between users and operators, the possibility of volumetric billing of water charges and annual volumetric allocation, and, in some projects, substantial reduction of pumping costs and fewer environmental problems such as water logging and salinity.

In most cases, the total cost of a modern irrigation system is about 5 to 10 percent above the cost of a conventional system with the same canal capacities. However, modern designs offer substantial benefits in terms of agricultural production and savings in operating costs which outweigh the marginal increase in capital cost.

As we will see in later parts of the program, a variety of approaches to design and management of irrigation systems exist. But care should be taken in selecting the one to be used in new or upgrading projects. This chart shows the different levels of efficiency, equity, design complexity, and operational staff requirements of three different irrigation systems. All the approaches offer different advantages and disadvantages, different risks for conflicts among water users, and different financial and staff needs for operation and maintenance.
In some instances, the most appropriate technology is the most rudimentary.

In any case, it is important for planners to evaluate and select the most appropriate approach and associated technology at the earliest stage of project development.

Planners must realize that effective irrigation management is not a post-construction matter and that it must be integrated into the planning, design and construction process.
Some countries have now oriented their investments in irrigation toward better use of water resources through the modernization of existing irrigation projects and better water management. But other irrigation systems continue to be built year after year based on conventional concepts, with only a few limited but necessary structural improvements.

The variety of advanced concepts and technologies is little known and not always understood. It is important, therefore, to disseminate information about these advanced concepts to the irrigation community throughout the world. There is an urgent need to design and operate irrigation systems that use the earth's limited water resources more effectively. There are many options that can meet a variety of physical, social and economic conditions ...

... And improve the performance of irrigation systems which will contribute to increased food production and sustain the diversification of crops to feed populations throughout the world.
End of Part I.
Title Slide. **PART II: Old Conceptual Approaches**

This part of the program deals with small-scale traditional irrigation schemes and conventional large-scale projects. We will review the principles of water distribution used in most traditional irrigation schemes. Then we will discuss the shortcomings of these principles when they were applied to some large-scale projects in the late 19th century. And last, we will discuss the operational difficulties of operating conventional large-scale projects equipped with a large number of adjustable, manually-controlled structures.

Traditional irrigation is rooted far back in history. It is defined as small-scale projects varying from a few hectares to generally less than 1,000 hectares. They have been built and maintained by local communities with little or no government support.
Although traditional irrigation schemes now represent a small percentage (probably less than 10 percent) of the 275 million hectares currently under irrigation worldwide, they still play an important role in countries such as Indonesia, Nepal, Morocco, Peru, Afghanistan, and Spain.

Local customs regarding water allocation and distribution in these systems have evolved over time and are well adapted to local ecological and sociological conditions.

These systems feature a large variety of approaches to compensate for the variability of the natural water supply.
There is also a great deal of flexibility in water distribution between members of traditional societies through, for instance, interseasonal shifts in distribution practices.

Although the term "local customs" in water management may imply primitivism to some people, these rules are in fact precise and sophisticated, and their complexity often increases with the degree of water scarcity. Definition and enforcement of the rules could be the subject of lengthy debates between members of water user associations, like the one shown in this picture.

Key factors in the success of traditional schemes are the cohesion of local communities, the small size of the schemes, and a reliable or at least predictable water supply at the outlet point.
Let's look at the basic techniques of water distribution in traditional irrigation. These are supply at will, time sharing and flow sharing or, in other terms, on demand, rotation, and partition.

Wherever or whenever water supplies are abundant, farmers are free to use water at will. The practice of supply at will is common in tropical and even in some semi-arid countries during the rainy season -- but is generally of little use in large-scale projects. Farmers adopt continuous or intermittent irrigation depending on their crops. The irrigator therefore has the freedom to match irrigation to soil and crop needs and to coordinate irrigation with other farming activities.

If water is scarce, time sharing, or rationing is used to ensure equitable distribution. Where the flow pattern is predictable and not too variable in the medium-term, say a few weeks, a common practice is to rotate the flows among individuals or farmer groups.
There are many kinds of rotational arrangements depending on three variables: flow rate, duration, and frequency. These can be modified over time depending on the water supply and crop needs.

Where the supply is unpredictable, a common practice is to divide the flow—and not the time—in fixed proportions which are socially accepted and often predetermined by water rights. This principle of partition or proportional division is found in many traditional irrigation systems, for example in Bali, Nepal, Spain, North Africa, and Latin America.

In practice, these two basic techniques of water distribution, flow sharing and time sharing are combined together within the same scheme.
To illustrate the variety of approaches to water distribution, let's look at the main features of water distribution in three traditional schemes in eastern Spain, in Valencia, Alicante, and Murcia.

In the famous 16,000 hectare Valencia scheme, the operational procedures prescribe different rules for three levels of water availability: abundant, ordinary low water, and extraordinary drought.

During periods of low water, each of the seven main canals can draw off only its assigned share of water from the river. The water is then channeled into many separate streams by canal dividers.
Farmers along the same canal take water in turn. Each farmer can take water as long as he needs once it is his turn. Frequency is therefore unscheduled but the duration of each irrigation is at the discretion of the individual farmer. In periods of drought, however, restrictions are imposed and ultimately priorities are given to certain crops.

The disputes or farmers' claims are examined by a tribunal which has met every Sunday for nearly 1,000 years.

In the Murcia project in Spain, the main canals also receive a fixed proportion of a variable river flow but each farmer has an assigned time period in which to irrigate. The flow rate is variable but the frequency and duration of irrigation are fixed. In these two cases, the water right is inseparable from the land.
In the nearby Alicante project of 37,000 hectares, the highly irregular regime of the river was corrected by construction of a large dam in the 16th century.

Unlike the other two projects, water is delivered at a fixed rate (150 liters per second) but the duration and frequency are determined by the farmer who buys or sells water shares weekly on the market, as shown in this picture. The water right, therefore, is divorced from the land.

Rationing by flow sharing is precise and egalitarian. Operation under this technique is automatic. It does not require human intervention other than patrolling against tampering which may be dealt with harshly by traditional groups. Any shortages are proportionally spread over all irrigators. Interference with the distribution system is clearly visible unlike in systems with gated structures.
In contrast, rationing by time sharing requires a staff of watermen and supervisors to open or close the outlets. It also requires strong adherence to the rules by the entire farmer community.

In summary, in the three examples of traditional Spanish irrigation, the members of the associations have developed different rules to allocate water. In the case of Valencia and Murcia where water is unregulated, farmers have two different approaches to uncertainty in distribution. In the case of Alicante, the regulated water is a saleable commodity.

Next, we'll turn our attention to water management in conventional large-scale projects.
Through the process of technological diffusion, some of the early concepts underlying traditional irrigation were later applied to the large-scale irrigation projects in the 19th century. The organizational principles established then are still in practice today.

Consider, for example, the case of projects built in the Indus Basin in the 1870s to provide water to the greatest number of farmers. The physical layout and design of the canal system evolved primarily to fit the pattern of water supplies from unregulated rivers.

The basic design concept was to provide equitable distribution of water with minimum opportunity for human interference and low cost operation by a small staff with limited means of rapid communication over the long distance involved. This is simple but effective.
The system depends on a combination of flow and time sharing. Distributary canals are operated in an "off" or "on" system by rotation of the flow available in the continuously running main system. Ungated outlets discharge water in a fixed proportion for distribution to the water courses when the distributary is "on". When the distributary is "on" all the water courses are automatically "on", and receive a fixed proportion of the flow. Distribution to farmers who are served by the same water course is done under a rotation system called "Warabundi." The time allocated to each farmer is proportional to the size of his land holding.

However effective and equitable this system is, it is not directly related to crop requirements. It is up to the farmer to arrange his cropping and watering to suit the delivery of water at a fixed flow and at predetermined times. Usually, the farmer deliberately underwaters to maximize his production per unit of water and not per unit of land.
The rigidity of this method of water allocation is a constraint for modern water management at the farm level. The dramatic development of groundwater in the Indus basin during the last decades was an answer to the farmers' needs for flexibility and additional water.

In this case, the design was mainly dictated by hydraulic requirements to achieve a non-silting regime in the canal systems and by the need to minimize manpower for operations.

The same approach was adopted for the main and distributary canals in the Nile valley in Egypt - with, however, major differences in the hydraulic design of distributary canals and the organization of water distribution.
Water levels in most canals are lower than the area to be served. Individuals or groups of farmers have the freedom to pump at any time in their common water course when the distributary is "on". Having more autonomy than his Punjabi fellow, the Egyptian farmer has a higher potential for production but pumping adds to his production costs.

Since most of the pumping is still done by using animal power, the flow rate entering the water course is generally not enough for most efficient surface irrigation. Pumping by animal power limits the amount of water that the farmer can pump. Therefore, inequity in water allocation is not as severe as in some gravity flow schemes.

Since pumping stops at night, the water running in the distributary spills into the drainage system but is reused farther down in the system.
In the Fayoum depression in Egypt, just beside the Nile Valley, water is supplied by gravity. The flow sharing method, indicated by the arrows, is commonly used.

The examples from the Indus Basin and Egypt have illustrated the fact that designing large-scale projects cannot be a simple extrapolation of the design and operational rules of the traditional systems. The size of the system adds another dimension to the problem for the following reasons: the large number of farmers to be served, the problem of communication over long distances, and the handling of water running in canals when demand is variable, for example, when irrigation is not practiced at night, or during heavy rainfall in tropical countries. In large scale systems, equity can be achieved through simple design but may not be accompanied by efficiency and flexibility.
In the mid 20th century, the design of large-scale projects evolved. Construction of a number of storage dams improved the reliability of water resources. Designs also reflected a better understanding of the soil-crop-water relationship. The objective was to provide not only fair but flexible delivery of water that would match actual irrigation needs.

These large-scale systems were built with a large number of gated cross-regulators and off-takes to control water flows and water levels at each branching point in the system. In theory these systems should make it possible to meet all the criteria for successful irrigation. In practice, however, they present difficulties in actual operation.

The operating difficulties are caused by a number of factors. For example, the time lag in the transmission of water over long distances and the inaccuracy of settings of adjustable control structures may cause variations of water levels and flows which are difficult to predict. As a result, the supply of water to "tail enders" is often unreliable.
These large-scale conventional gated systems are also cumbersome to operate. They require a large number of competent staff. In many cases, these systems suffer from low water use efficiency, low yields, low cropping intensity, inequity, and hostility between farmers and management. However, a few examples do exist of well-managed projects of this type, for example, in the northwest region of Mexico. In summary, the search for better performance through complicated operational systems with many measurement and control points may result in low efficiencies due to operational mismanagement.

One solution to the problem of inflexible or unreliable water delivery has been the construction of on-farm reservoirs by individuals or groups of farmers. These reservoirs provide flexibility in flow rate, frequency, and duration.

For example, small reservoirs make sprinkler irrigation possible in a gravity supply system. However, small reservoirs, like these, may not be feasible where land is scarce or where the topography is flat.
Large-scale projects in Sudan have an interesting feature. Since the main system has little control capability, the tertiary canals are oversized to serve as terminal reservoirs for daily storage.

In summary, we have seen that many conventional large-scale projects are not meeting the objectives of modern irrigation: high water efficiency, equity and timely distribution to farmers, simplicity, and low cost of operation. The following parts of this program will review a number of ways to achieve these objectives.

End of Part II.
Title Slide. PART III: The Hydraulic Problem of Canal Water Control

Irrigation is the art of correcting the natural distribution of water. It involves the mobilizing, conveying, and applying of water to the field. Conveying water in open canals is the most critical aspect of irrigation management, and is the subject of this part of the program.

Specifically, we will formulate in engineering terms the objectives of modern irrigation. First we will examine the two basic aspects of canal water control: water flow control and water level control. Then we will describe the methods of canal control under variable flow conditions.
The hydraulic engineer has a critical role in project design. He has the two-fold task of, first, designing the layout of a complex network of canals from the source of water down to the individual plots through an intricate system of distribution channels. Second, he must ensure the permanent and effective control of water throughout the system.

Just as an electrical engineer has to control voltage and amperage, the hydraulic engineer has to control pressure and flow in a piped system, and water level and flow in a free-flow canal. This is the double problem of canal hydraulics.

First, we will examine the reasons for controlling the water flow and the water level in a single canal.
There are four reasons for flow control in a canal system: meeting water requirements of crops in order to achieve optimum production; water savings; safety of operation; and recovery of operating costs. We will review each of these in greater detail.

Water requirements vary with the type of crop, the stage of growth, seasonal variations in climate, and daily variations in weather, especially rainfall. Both too much and too little water affect crop yields, especially at certain critical stages of growth like tillering and flowering for paddy rice. The response of irrigation supply to demand must be accurate and immediate.

The need to save water is especially important when water is scarce as in arid and semi-arid countries. But even in tropical countries, lack of water can limit further expansion of irrigated agriculture. Systems should be designed to accommodate any sudden fall in demand, as at night or during a sudden rainstorm.
To ensure safe operations, the flow released into a canal should not exceed its carrying capacity, which generally decreases from upstream to downstream. Although overtopping of canals can be avoided by means of suitable escape structures provided to spill excess water into the drainage system, this is a loss of precious water.

The fourth reason for accurate control of water flow is to provide a basis for cost recovery. Farmers can be charged for irrigation services on a volumetric basis.

Now let's turn our attention to water level control.
Control of a canal's water level is important, and the acceptable limits of variation are not very large. The four reasons for level control are to keep command of the service area through gravity, canal protection against deterioration, canal safety, and flow control at offtakes.

The higher the level in a canal, the larger the area which can be irrigated by gravity, without pumping....

... an important consideration for the users.
Remember that in some conventional systems, canals operated under a rigid on/off system are run only at full supply to ensure a constant water level at each offtake.

However, to meet the requirements of modern irrigation, canals have to be operated under variable flow conditions. Since there is a direct relationship between flow and water level in a canal under uniform flow conditions, steps have to be taken to raise the level in the canal by artificial means.

The next reasons for controlling water level are canal safety and protection. The water level should not exceed an upper limit in order to avoid overtopping and wasting water through escape structures.
But if the water level drops too low and too fast, canals may deteriorate because of back-pressure on canal lining and the instability of canal slopes in difficult soils. It is important, therefore, to keep the water level between a maximum, which is imposed for safety reasons, and a minimum which is needed to supply the land by gravity.

By keeping water levels high enough, erosion from rain falling in an empty earth canal is prevented.

The fourth reason for controlling water level variations in a canal is to facilitate the flow control and measurement of water at offtakes.
The flow delivered through an offtake - either an orifice or a weir - depends on the water level upstream. Limiting variations in the water level at canal offtakes to facilitate control of flow releases, therefore, is a crucial task of the designer.

Water level control is a basic concept which has been incorporated into traditional irrigation schemes. Farmers have always known how to dam their streams and canals when and where necessary.

The same concept is used also in the simplest design of new canals: water level is controlled through cross-regulators (sometimes called check structures) of varying complexity. The cross regulators can consist of: simple weirs,
or gated cross-regulators,

or a combination of the two.

Farmers are quick to correct deficiencies in design in systems not built by themselves.
By damming a canal with cross-regulators, the water surface profile varies with the discharge from a line parallel to the canal bed at maximum flow to a horizontal line at zero flow. The volume contained between the two profiles is called the wedge volume.

In other words, the basic design of an irrigation system operated continually with variable flows is to divide the canals into successive pools and to locate the regulators and the offtakes in such a way that the differential water level variations remain within certain limits.

In each pool, the water level should remain within a maximum and minimum level but the surface profile can take any position within the two extreme lines.
In upstream control, the berm, that is, the top of the canal, is defined by maximum flow conditions and is normally parallel to the canal bottom. In downstream control, the berm is defined by zero flow conditions and must be horizontal.

Downstream control, therefore, may require additional civil works in the fill sections of the canal embankment.

Target levels can be fixed or may even be adjustable. Adjustable target levels offer some flexibility in operating a canal carrying silt-laden water. This prevents sedimentation during periods of low flow demand, for example, during the early stage of project development.
The target level in any section could also be between two regulators. When the control point is approximately in the middle of a pool, this method is called constant volume.

The fourth method is a variant of downstream control where the control point could be at the downstream end of a pool controlled by its upstream gate. In this variant of downstream control, there is no extra cost for additional earthworks because the berm can be designed to parallel the canal bottom.

We have just reviewed these four concepts of canal operation: upstream control, downstream control, constant volume and a variant of downstream control.
If we now examine the physical connections between the target level points and the gates which ensure the target levels, we can distinguish three methods of control: local control, remote localized control, and remote centralized control.

In local control, the target level is set in the immediate vicinity of the gate.

In remote local control, the target point could be anywhere along the pool controlled by a gate.
In remote centralized control, all information on water demand, water level, gate settings, and storage volume is transmitted to an operation center which controls the entire canal.

In the next two parts of the program, we will examine the operation of an entire irrigation system, through local and remote localized control and centralized control.

End of Part III.
In Part III, we examined the double hydraulic problem of flow and water level control in a single irrigation canal. In this part of the program we will turn to the operation of an entire irrigation system which consists of a main canal and a complex network of secondary and tertiary canals.

A crucial decision to be taken at the planning stage of an irrigation system is how much flexibility to give to the farmers. Should they be authorized to draw water at will? With or without an annual allocation? Should the system be designed to allow the farmers to request variations in flow rate, duration, or frequency of irrigation? Can this be done without affecting the supply to their neighbors?
In this part of the program, we will examine how these questions are addressed in surface irrigation systems under local or remote localized control.

So far, there are no examples of large irrigation projects in which individual farmers have complete autonomy all of the time over the water supply unless they appropriate it illegally. The authority should exercise some control over the allocation of water. Some coordination between farmers and the authority, therefore, is necessary.

In cases where farmers have the most flexibility, they order their water one or more days in advance and they can select the flow rate and duration of each irrigation. This is called arranged-demand. Arranged-demand gives farmers some control over water delivery, so these systems are called user-oriented.
In cases where farmers have the least flexibility, water is distributed according to a rigid rotation system in which all parameters are fixed in advance. These systems dictate the farmer's irrigation practices and, therefore, are called operator-oriented or supply systems.

The typical management of a surface system is as follows: the operators add up all the daily individual water needs for each canal whether requested by the farmer or fixed by the project management. The information on total demand is then transmitted farther upstream.

The information transfer can be done by either of two basic modes of canal operation—upstream or downstream control. Upstream controlled canal systems require the aggregation of individual farm demands up to the water source. With downstream-controlled canal systems, the demand is transmitted hydraulically. Let's look at the relative advantages and disadvantages of the two methods and their possible combination, beginning with upstream-controlled systems.
In upstream-controlled systems, the daily demands for each offtake are transmitted a few days in advance to the supervisors responsible for the canal offtakes. The supervisors, in turn, report the offtakes' demand to the system's operation center.

Estimates are then made of the transmission time needed for the change in flow rate to travel from the headworks to the various offtakes. These computations must also account for the change in wedge storage volumes. The flow rate is then changed at the system's headworks.

A canal under upstream control is divided into successive pools by means of cross regulators.
If the cross regulators are manually operated, each one should be adjusted at frequent intervals as the flow change moves downstream.

Many small adjustments may be necessary because the change in flow rate arrives gradually at the various regulators. It is difficult to make predictions of the necessary adjustments in control gates because of the large number of hydraulic variables.

However, upstream control can be considerably improved with the use of automatic devices, which maintain a constant level upstream of each regulator.
With automatic upstream control, the only required operations are setting the gates at the headworks — and at the offtakes.

However, gate automation will not alleviate two inherent disadvantages of upstream control. One is a slow response to changes in demand and the second is water losses.

It is almost impossible to set the flow released at the headworks to exactly the amount needed to meet cumulative demand and to compensate for seepage and evaporation losses on the way. To ensure that the lowest offtake is adequately supplied, the flow released at the headworks must include an additional amount as a safety margin.
When there is an unscheduled fall in demand due, for example, to a rainstorm, the offtakes are closed to avoid crop damage from overwatering. Water stored in the wedge volumes is then lost through the tail escape to the drains.

Next, we will review the second method of canal system operation, downstream-controlled systems based on hydraulic transmission.

In downstream-controlled systems, the changes in demand are hydraulically transmitted through the different pools up to the headworks. Each offtake can be opened or shut at any time without advance notice.
196. In most canals under downstream control, the regulators are equipped with gates that respond automatically to variations of water level in their downstream pool.

197. An increased flow requirement in a pool will cause the water level to drop at that point. A negative wave then starts moving upstream.

198. Where the water level drops at the target level control point, the gate at the upstream end of the pool opens and additional flows enter the pool.
This process is automatically repeated in each upstream pool.

Downstream control has three advantages: no operational losses, fully automatic distribution, and accurate and immediate response to all demands.

There is no need for system scheduling beyond the offtakes on a canal under downstream control as long as there is enough water at the headworks. This means less work for the watermaster.
The problem of transmission time associated with upstream-controlled systems is eliminated and the organization of system scheduling is considerably simplified. This is because each area served by a distribution canal becomes an independent subsystem. The source of water for the group of farmers in each subsystem is the pool of the feeder canal under downstream control which in some ways plays the role of a terminal reservoir.

Downstream control reduces the work of canal operators because much less information has to be transmitted.

An outstanding feature of the downstream control and constant volume methods is that no water is wasted if demand suddenly drops. The water released during the time required for the hydraulic transmission of demand is temporarily stored in the wedge volumes. Downstream control saves water because the volume of water released at any check structure and headworks exactly matches the amount of water diverted at the offtakes, including seepages.
However, downstream control has one economic limitation. The longitudinal slope of a canal should not exceed approximately 20 to 25 centimeters per kilometer. Otherwise the civil works required to raise the canal embankment in fill sections may be too costly.

Another problem related to downstream control is when demand exceeds the water available at the headworks. If the total flows diverted at offtakes exceed the supply, the canal gradually drains from upstream to downstream. This deprives the headreach farmers of water while the tail enders get their full supply. There are two solutions to this problem.

One solution is to ration the flows diverted at each offtake which are generally not under the farmers' direct control.
A second solution is to install composite gates designed to operate under downstream control, while preventing the upstream level from falling below a predetermined minimum.

In the typical example of system operation we just reviewed, downstream control is used in order to simplify the operation of the main canal. It avoids complex system scheduling or the use of computerized canal modelling. The distribution system under upstream control is supervised by an operational staff to avoid unfair, wasteful supply to users. Downstream control should not be confused with a distribution system on pure demand at the farm level.

The combination of upstream and downstream control can have operational and economic advantages under certain topographic conditions and depending on the layout of a canal network.
We will examine three examples of systems in Morocco where upstream and downstream control along the main canals have been combined.

In the Doukkala project, the upper half of the main canal is under upstream control and the lower half is under downstream control. Water is released from the storage dam on the basis of a crude projection of demand. Excesses or deficits are automatically passed downstream in this portion of the canal.

A regulating reservoir at the mid-point of the main canal acts as a buffer for the variations in flow rate.
The lower half of the Doukkala canal is under downstream control with level top pools. Water is automatically withdrawn from the buffer reservoir as needed.

Releases from the storage dam are simply based upon the next day's cumulative demand and adjusted depending on whether the buffer reservoir is filling or emptying. The small storage capacity of this reservoir has proven to be adequate enough to absorb variations between supply and demand. In this example, the reservoir is placed on the side of the canal and links with the main canal through a dual-way structure.

The reservoir can also be located above the canal since pumping requirements are small. Only the differential flows between supply and demand must pass into and out of the reservoir.
217. In the Beni-Moussa project, the upper part of the two main canals is under downstream control. These canals start from the tailpool of a hydropower plant which releases water daily during peak hours.

218. Since the capacity of the tailpool is far too small to store the volume of water released during peak hours...

219. ... special gates have been installed to store these volumes in the two canals while maintaining the downstream control operation.
The Beni-Amir canal, now being modernized, will include a succession of downstream and upstream control sections to minimize the investment costs in conveyance sections without offtakes.

The combination of upstream and downstream control can provide an economic solution in a number of situations. Downstream control is not necessarily limited to projects drawing water from storage dams. It can also be used in projects where the supply is limited or fairly predictable as in some run-of-river projects. As indicated earlier, downstream control is a means to simplify main canal operation but is not synonymous to demand irrigation. If necessary, rationing of water can be imposed at the distribution level which, in most cases, is under upstream control.

End of Part IV.
In this part of the program, we will review the operator-oriented and user-oriented approaches to centralized control of canal systems.

In the downstream-controlled systems examined in Part IV, the check structures are operated serially as the hydraulic head increases or decreases along a canal.
With remote centralized control, all canal regulating facilities including pumping plants, buffer reservoirs, and offtakes, can be operated almost simultaneously, from a control center and the requested changes in flow conditions can be made immediately.

A typical centralized control system performs five basic functions in the operation of an irrigation system: acquisition of data, data communication, processing of data, the transmission of orders, and operation of the control facilities.

The first function is acquisition of data on crops and climatic conditions. This also includes monitoring of control facilities such as water levels and gate settings.
The second function is data communications and transmission to an operation center.

The third function is data processing.

The fourth function is transmission of orders.
The fifth function is operation of control facilities.

In its simplest form, operation of a centralized system is relatively straight-forward. All the data are collected and transmitted by voice communication to an operation center. After processing of the data by hand or with the help of mini-computers, a central supervisor decides on the adjustment required in the system.

Orders from the control center for adjustments to the facilities are then transmitted, again by voice, and carried out by field operators.
This simplified form of centralized control requires supervisors with long experience in dealing with canal system response.

This is because of the many factors involved and the complexity of unsteady flows in canals. For more precise water management of a large and complex irrigation project, rapid processing of the large amounts of incoming data is required. Industrial computers have opened up new possibilities for processing data and for determining the complex adjustments of control facilities.

A first step toward centralized control is a remote monitoring system which collects operational data, displays the data at a central location, and activates an alarm should a problem occur. These systems usually provide remote control of a few key structures.
Remote control specialists distinguish between two types of centralized computerized systems. One is an open loop system which requires the intervention of an operator for one of the five functions. The second is a closed loop system which is entirely automatic.

An example of an open loop centralized, computerized system is the Salt River Project in Arizona. This project began in the early 1900s, was modernized in 1950, and the modern control facilities were completed in the mid-1970s. It permits remote operation and monitoring of canal gates and automatic gauging of water levels anywhere in the main canals.

Water orders are entered into the computer which, in turn, determines the need for gate settings to maintain variations of levels within plus or minus 8 centimeters.
The operators then run the system from a master console. The open channel distribution system is operated locally.

As with local control methods, there are two approaches to centralized, computerized control. The first requires an advance schedule of water demand and is operator-oriented. The second responds automatically to any change in hydraulic conditions or water demand, and is user-oriented. We will review both of these approaches beginning with advance scheduling.

Under the first approach, an operator must enter the next day's water orders into a computer, along with current water levels, gate openings, and flow rates. The system is therefore an "open loop."
The control logic depends on the facilities of the distribution system. On the one hand, precise control of water levels is important for open channel laterals or low pressure pipelines.

On the other hand, precise control of the water level is not essential if conveyance sections of canals have no offtakes or if water is then distributed under high gravity pressure or pumping pipelines, as long as the level does not exceed safety limits.

Fully centralized remote control goes much further than simple monitoring. Field data are used as inputs for a computer model referred to as a control logic which simulates the hydraulics of a canal system.
The simulation programs estimate canal reactions to various flow changes and gate movements. However, accurate hydraulic simulation models are cumbersome to use because of the size of the programs, the many hydraulic variables, and the complex mathematics required in unsteady flow analysis.

The accuracy of such programs is limited by the difficulty of correctly estimating hydraulic values in the field. For example, the roughness of a canal may fluctuate widely during an irrigation season due to weed growth.

Old unlined canals are difficult to model because of irregular and variable dimensions.
Accurate hydraulic simulations require the formulation of gate discharge equations. Discharge coefficients must be calibrated in the field for individual gates under a wide range of flows.

A computer program called "Gate Stroking" was developed by the United States Bureau of Reclamation. This model computes a series of gate motions to produce a desired water surface profile in a canal. Water levels are carefully controlled.

Such control does not provide automatic response or dynamic regulation. Gate stroking calculates changes according to a set delivery schedule. Deviations from the schedule require manual intervention or the use of local automatic controllers.
A more advanced approach to canal control using computerized techniques was developed in the 1960s for remote operation of the California Aqueduct. The California Aqueduct is more than 600 kilometers long. It conveys water to agricultural and municipal users through a series of lift stations and more than 60 regulating structures. The maximum design capacity is about 430 cubic meters per second.

The Aqueduct deals directly with irrigation and municipal water districts and not with individual farmers. Most districts must notify the operation center 24 hours in advance of desired deliveries and shut-offs.

Part of the logic used is called the "Controlled Volume" principle. Controlled volume differs from "gate stroking" in that primary attention is paid to controlling the volume of water in each pool rather than maintaining precise water levels.
The computer program calculates the current flow rates and volumes in each pool of the canal. Gate movements and pumping schedules are calculated, based on water orders for the next day, current conditions, and anticipated power availability.

Because the pumps along the aqueduct can consume up to 13 billion kilowatt hours per year, the control logic was designed to vary pool storage in order to maximize off-peak pumping, thereby taking advantage of lower electricity rates.

Calculations are usually updated only once or twice a day. Accurate control is maintained if all the hydraulic variables are correctly evaluated and actual flow rate changes closely follow a schedule agreed in advance with the water users.
By moving all of the gates almost simultaneously, the maximum time lag anywhere in the system is the travel time of a flow rate change in a single pool. The flow change occurs in all the pools at the same time so that downstream users do not have to wait for the change to travel several hundred miles, one structure at a time.

In summary, the controlled volume logic used for the California Aqueduct is reliable but as it is now operated, it does not automatically respond to users' demands. It requires advanced knowledge and input of water orders.

A similar approach is now used for the remote centralized control of the Central Arizona Project, or CAP for short. This project, now partially completed, will deliver Colorado River water in central Arizona in place of existing groundwater used by cities, industries, and farmers. A system of canals, inverted siphons, tunnels and pumping plants, approximately 550 kilometers long, will convey the Colorado River water across Arizona.
From the Colorado River, the water will be lifted nearly 950 meters by 14 pumping plants. The system's initial capacity is 90 cubic meters per second.

The CAP's operating facilities, including pumping plants, check structures and offtake turnouts, will be remotely operated by cable and microwave communications system from the project operations center near Phoenix.

The operators in the control center monitor the system's performance, adjusting it as necessary and correcting any problems that occur. The principle of controlled volume is also used for the control logic. Water levels in each pool can be monitored.
Changes in water demand are entered twice a day. In the future, with minor changes in the control logic, hourly changes will be possible, making the system more responsive to on-farm irrigation system management and variations in urban and industrial water supplies.

The centralized systems like those just discussed require precise delivery schedules. Ideally, an effective control system should be more responsive to user needs as opposed to being accurately but rigidly scheduled.

Now, we will review the second approach to centralized control, which is user-oriented. The control system for this approach responds quickly and automatically to changes rather than requiring an advance schedule. These programs are similar to, but smaller than, gate stroking.
The approach was first implemented in Southern France. Computerized dynamic regulation became operational in part of the Canal de Provence system in 1971.

Since that time, it has been successfully implemented on 260 kilometers of canals. The water delivery system here is a mix of pumping plants, concrete-lined canals and high-pressure distribution pipelines. The system was originally designed for a combination of upstream and downstream control with automatic equipment, but that proved very expensive because of the steep topography. Modern computerized control was adopted instead.

A large canal hydraulic simulation model was formulated but is not used for control. The large program was only used to develop the present short computer program control logic.
Two-thirds of the users are municipal or industrial, with a predictable pattern of water use which is easily evaluated through statistics. The remaining users are irrigators whose agricultural applications are more difficult to predict.

Every seven seconds, measurements are scanned. Every 15 minutes, water use predictions are updated and a small computer program decides if the gates should be moved.

The computer program examines water levels in each pool. Actual flow rates are compared to a statistical prediction of demand. Gate motions are then dictated from the central facility.
Precise hydraulic calculations are avoided because they are so cumbersome. By the time a solution has been obtained, the problem would already have changed.

The combination of statistics, approximations, frequent updating of commands, and proper sequencing of gate motions provides a system which operates completely on demand with high flexibility.

The piped distribution system of The Canal de Provence made system operation easily responsive to users' needs. This was not achieved in any canal system so far. The irrigation districts which will receive the Central Arizona Project water will have this capability at least technically. Operation of the Maricopa district facilities including the Santa Rosa canal branching from the CAP and all lateral canals will be remotely controlled.
The farmers will be able to adjust their turnouts located close to the remotely controlled regulators on the lateral canals.

The farm turnouts are equipped with ultrasonic flow meters.

The meters provide digital readouts of flow rates and total volumes.
We have seen two different approaches to centralized control of canal systems using computers. The California Aqueduct and other programs like gate stroking are safe and reliable, but as currently applied, they require some advance scheduling. Both the Canal de Provence, with a piped distribution system, and the canal system of the Maricopa district, however, offer a complete demand operation to the ultimate users.

Centralized control can be introduced by stages. The degree of sophistication can be progressively increased and the canal system under remote control can also be expanded as has been the case for the Salt River project.

Computers obviously help in the complex modelling of canals under unsteady conditions. However, they must be associated with reliable data acquisition and transmission equipment. Furthermore, software must be carefully selected so that the data processing and instructions are compatible with the system's physical constraints and philosophy of management.
Of course, any system is only as good as the service it provides. Higher water efficiencies can be obtained through automated control, but responsiveness to users' needs is also important.

End of Part V.
Now that we've considered the various concepts of canal and system operation we will review control equipment. Specifically we'll examine the alternatives for local control at various points in an irrigation system. They are: flow division, water level control, combined flow and water level control along canals, flow control at offtakes and a combination of all these.

Then we'll briefly review the features of certain types of equipment used in remote and centralized control.
Some manually-operated devices, whether motorized or not, require frequent adjustments by operators. Some simple but ingenious hydraulic devices function automatically and require no external source of energy. And, finally, other devices may be automatically controlled by local or centralized electrical controllers.

The origin of some equipment used in irrigation is buried in the mists of history. Some devices such as the Persian wheel have spread around the world through technology transfer.

The performance of any irrigation system depends upon its control system. Many countries, however, have placed little emphasis on this factor. Most projects built in the past and even some now under construction require operators to frequently adjust the control system. Let's review some developments in the recent past to provide self-control in irrigation.
In the 19th century, some self-acting water modules were developed in southern Europe, such as this one consisting of a circular weir connected to two floats. Although technically sound, these modules with moving parts were not reliable because of mechanical friction. A number of modular outlets were also developed in the early 1900s in India which were also designed to extract silt from the distributary canals.

A significant advance in canal control technology took place in the early 1940s with the development of automatic hydraulic equipment. Three decades later, advanced communications systems, electro-processors and computers were introduced.

Research on hydraulic equipment was initiated by the "Laboratoire Dauphinois d'Hydraulique" located in Grenoble, France to assist irrigation projects in North Africa in the late 1930s. The most important objective of the program was simplification of operations through hydraulic automation.
Fifty years later, the hydraulic equipment developed at Grenoble is still being manufactured. It is used in about 20 countries, mostly in the Mediterranean basin and Western Asia.

Research on remote and centralized control systems began in the United States and France in the mid-1960s when the computer and communications industries had developed technologies which could be applied to water system control.

Before describing control equipment in detail, let us look for a moment at the operational characteristics of the two basic hydraulic devices used in canal control - that is, weirs and orifices, or overflow and underflow devices. Because of their different mathematical equations...
... the responses to changes in flow are different for weirs and orifices as illustrated here. A 20 percent increase of the flow rate over a weir only requires a 12 percent increase in the water depth above its crest - but with an orifice, the required differential level increase is 40 percent.

This means that variations in water level caused by variations of flows would be relatively small in a canal controlled by overflow devices and would not require frequent adjustments. By contrast, operation of a canal equipped with undershot gates requires frequent readjustments to maintain a nearly constant level.

Besides their greater sensitivity to flow variations, undershot gates have another drawback. In most practical cases, discharges through these gates are influenced by the downstream conditions unless these conditions are free flow as in this example. It is therefore difficult to maintain steady flow conditions in canals equipped with undershot gates manually controlled because of the interaction between the pools of canals. Despite this difficulty, manually controlled undershot gates are more often used for cross-regulators than are overshot structures.
Now, we will begin our review of control equipment. First, flow dividers.

Flow dividers are static weir-type structures that ensure automatic flow partition. They are often found in traditional schemes where water rights are well established.

These structures have been used to upgrade traditional schemes in North Africa in order to maintain downstream rights.
The incoming flow can be divided into several channels according to fixed ratios as in this concrete structure.

The flow ratio can be adjusted by maneuvering a vertical dividing flap as in this example in Algeria.

Flow dividing structures are used in the tertiary systems of modern projects to equitably divide a given flow between farm units.
The second type of control equipment is water level regulators.

These control water levels at critical points in a canal. Some structures such as concrete weirs are static, others such as undershot or overflow gates are adjustable, either automatically or manually.

In its most basic form, a weir consists of a simple overspill structure across a canal. Weirs may be adjustable or fixed.
Flashboards are used here to form an adjustable weir. The boards are removed or added for major flow rate changes.

However, handling of flashboards may be risky for the operating staff.

This weir is also manually adjustable but it can be operated safely from the canal bank by use of a gear box.
These two motorized overflow gates installed in a main canal in Malaysia can be easily adjusted by on-site operators using push-buttons to maintain a constant level. They could be operated by remote control in the future if required.

Long crest weirs automatically maintain a nearly constant upstream water level even with relatively large changes in flow. This is an advantage for flow control at offtakes located close to these weirs.

Long crest weirs can be oblique as in this main canal.
Or as in this small-flume tertiary canal.

This is a duckbill weir oriented downstream.

And this one is oriented upstream.
This slide shows a combination of three duckbill weirs once used in the Doukkala main canal in Morocco.

Cross regulators equipped with undershot gates can be manually operated. However, the handling of large and heavy gates is tiring and the number of adjustments is limited by the time needed for each change.

To overcome this limitation, large gates in recent projects have been motorized. They can be locally or remotely controlled.
In a canal equipped with undershot gates, the time lag in water volume transfer can be shortened by opening the gates wide. This flexibility is not offered when static weirs are used alone.

Therefore an attractive solution is to combine weirs and undershot gates. In this way, large changes in flows are accommodated by gate resettings, and smaller changes are accommodated by varying the depth of water over the side weirs.

Here's another example of the combination of gates and weirs.
Another possibility is to install gates which automatically maintain an upstream constant level such as the two gates shown here. The design of these gates is similar to downstream constant level gates.

The third type of equipment that we will review controls both flow and water level together along a canal. This can be done through either electrically-assisted or hydraulic regulation.

First, electrically-assisted regulation. In this case, a conventional gate is motorized and automated with a local independent controller designed to set one of the canal hydraulic parameters at a desired value. The parameters that can be controlled may include upstream or downstream level in the adjacent pools, volume in the downstream pool, head across the gate or any combination of these parameters.
An electromechanical device, known by its nickname "Littleman", was designed by the United States Bureau of Reclamation. In more recent projects, a microprocessor is used in conjunction with a pressure transducer.

This seemingly simple device is actually fairly complex.

Shown here is a schematic of the basic components of a Littleman installation. It displays a deadband, multiple speeds, and an anti-hunt mechanism to prevent over-correction and hydraulic instability.
All the capabilities of an electro-controller can be performed more simply by automatic hydraulic devices ...  

... such as the constant upstream or downstream level gates. They require no electricity and have only one moving part. They work on a principle of balancing forces. The downward force of ballast containers is balanced by the upward force of a float. 

During installation of the gate, the ballast must be precisely adjusted to achieve stability in any position of the gate.
The target water depth is the axis of rotation.

Upstream and downstream gates are produced in various sizes. The systems designer can select the sizes that are most suitable to flow capacities and available head.

In some cases, canal equipment should be able to respond to a more complex set of hydraulic conditions. Different types of so-called composite gates have been developed for this purpose.
This gate, for example, maintains a constant downstream level during normal operation but keeps the upstream level between a maximum and minimum. When the supply suddenly exceeds the demand, the gates will prevent overtopping. On the other hand, when demand exceeds the supply, the canals are no longer in danger of being drained.

Composite gates can also be used to store water in extra deep canals designed for that purpose. In that case, the gates maintain a constant head between upstream and downstream while still avoiding overtopping and draining as discussed earlier.

These gates are especially attractive when there is a hydroelectric power plant along the canal system or when the canal is supplied by a pumping station operated during off-peak hours.
Continuity of automation can also be ensured when short pipelines are incorporated into a canal system. Self-centering disc-valves, as shown here, acting as a balanced float valve and operating under low pressures maintain a constant downstream water level as do the gates in free-flow conditions discussed earlier.

Next, we will turn our attention to flow control at offtakes.

The two options for controlling flow at offtakes, again are hydraulic or electrical equipment. The objective is to deliver a constant flow - or target flow - at offtakes in spite of the water level variations upstream of the control structure.
Offtakes should have an underflow (or orifice) design rather than an overflow (or weir) design when possible. Fluctuations in the supply canal have less effect on orifice discharges than on weir discharges. In this case, flow from a simple offtake located on the canal bottom and discharging into open air will hardly be affected by variations in water depth in the canal.

In some projects, however, offtakes consist of manually adjustable weirs, whereas orifice-type structures would be more appropriate.

The most common offtake consists of a simple adjustable structure associated with a measuring device which has to be manually readjusted as often as necessary.
This is a time consuming process, requiring dedicated and skilled operators qualified to read graphs, charts, and gauges.

To solve the staffing problems of manual adjustment, the structure could be automated if it were motorized. One alternative is to use an electroprocessor to activate the gate to maintain a constant hydraulic parameter such as the target level over a flow-calibrated weir or the differential head over an orifice until the next flow target is set. This adjustment could be controlled locally or remotely.

The second alternative is to use hydraulic distributors, commonly called modules, which are self-flow controllers and not simply measuring devices.
A module consists simply of a sill associated with one or two baffles. The contraction of the fluid vein when the flow changes from a weir—

— to an orifice regime ensures a constant flow, of course within certain limits of the upstream level.

This chart shows the flow variations with the depth of water above the sill for a single baffle module. Modules delivering 20, 50, and 100 liters per second per decimeter with an accuracy of ±10 percent can accept upstream water level variations of 11, 19, and 31 centimeters respectively.
With double baffles, the acceptable variations in upstream level for modules of the same size are 28, 52, and 83 centimeters. This is nearly 3 times the variations acceptable for single baffle modules.

With single or double baffle modules, the discharge can be easily controlled simply by varying the width of the flow section. A distributor therefore consists of a series of modular elements of different widths which are controlled by small gates locked in one of the two positions "on" or "off." In this example, the two central gates deliver 100 and 200 liters per second.

These modules exist in different sizes and widths which can be selected by the designers depending on the flow capacity of the offtakes and the possible upstream water level variations. This is one example.
This is a second example,

and a third one.

The modules are very simple to operate even by unskilled labor. They provide a constant delivery flow plus or minus 5 percent to 10 percent, depending on the upstream water level variations.
They can be used as water meters by simply recording the opening and closing times of the gates.

Farmers appreciate the reliability and the ease with which they can control the flow delivered to their farms by these devices.

Next, we will review how to achieve flow and control at offtakes in conjunction with flow and level control in the supply canal.
At the design stage, offtakes and cross-regulators should be located judiciously to make the best use of control equipment.

In a canal under upstream control, offtakes preferably should be located upstream of the regulator to facilitate the delivery of target flows in the branch canals.

Conversely, in a downstream-controlled canal offtakes should be located in the upstream end of the pools.
363. Depending on the variations of water level, single or double baffle modules may be used.

364. When the variations exceed the acceptable limits of the appropriate modules, a constant downstream level gate on the secondary canal could be installed upstream of the module. A slide gate may be added for emergency purposes and for closure of the secondary canal for maintenance.

365. Here are a few example of various arrangements of regulators and offtakes for branching canals. In this picture, an oblique weir controls the water level upstream of a module which delivers 30 liters per second to a farm outlet.
Here, modules serving a lateral canal are diverting water from a main canal under downstream control.

This module is installed on line with a constant downstream level gate operating under a head of a few meters created by an upstream reservoir.

In this picture, a module is associated with a disc-valve which controls the water level at the lower end of a pipe under low pressure.
Last, we will review several aspects of equipment used for remote localized or centralized control.

This equipment evolved quickly with technological advances in communications systems, micro-processors, and computers.

Much of this equipment is standard, such as radio, microwave or satellite communication systems, computers, and associated hardware such as printers and television displays.
Other equipment used for centralized control is tailored to the project, such as this mimic display board.

And this device to measure gate opening.

Some systems use hardwired communication links, while others use radio or microwaves. Successful remote control operations usually have an automatic and independent backup communications system.
Some systems use local microprocessors near each check structure to condense the information which must be sent to a remote control facility.

Automatic and remotely controlled systems must provide for two levels of manual override. Operators at the control center must be able to intervene manually. The capability for manual override in the field is also required.

In addition to duplicate communication systems and command levels, computerized control systems must have emergency power supplies. Emergency generators should be started once a week for a routine check.
Safety precautions at different levels of a computerized control system are necessary because failures of all types can occur. With proper precautions, these failures will not affect the safe operation of the canal system.

Before closing this part of the program, we would like to make two important remarks. It should be noted that in this presentation of modern design equipment, we have not discussed any flow measuring devices. Strictly speaking, flow rates are not measured. Main and distribution canal operations are based on water levels. Flow rates at offtakes of minor canals or of farm turnouts are self-controlled. Like other industrial or domestic devices such as control of room temperatures, the flow rate is set on a controller device which maintains a target flow.
In this part of the program we have reviewed the equipment available to improve water control in surface irrigation systems. It was beyond the scope of this presentation to discuss irrigation pipeline control systems. They are almost as varied as those for canals -- from low-pressure pipeline systems installed by innovative farmers to reinforced concrete pipe systems equipped with pressure regulators and flow control valves.

End of Part VI.
Title Slide. PART VII: Selection of Appropriate Method of Operation

In previous parts of this program, we have seen that there are a variety of approaches to irrigation management and system operation. In this part we will review the various factors that influence the selection of operational concepts and associated technologies for irrigation canal systems.

The selection of appropriate technologies for different cropping patterns under different physical and socio-economic circumstances involve numerous complex and often conflicting considerations. Not all of these considerations are of equal importance in this selection process. We will identify those that are essential in selecting an appropriate method of irrigation system operation.
A critical consideration at the planning stage may be the irrigation national policy. As indicated earlier in this program, adoption of extensive irrigation for the purpose of alleviating rural poverty dictates, together with other factors, the rules of water distribution and design to achieve equity of water allocation.

Besides the country’s socio-economic considerations, water management factors for new projects fall into two broad categories—physical and managerial. In the case of upgrading old projects, existing infrastructure is an additional crucial aspect to consider in the rehabilitation process.

There are at least seven physical factors that pertain to water management: the water supply pattern, the water quality, climate and rainfall pattern, the physical properties of soils, the crop type, the topography, and the project size.
The first and most critical one is the water supply pattern, that is the daily and seasonal variability of the flow. It is the major determinant in the selection of project operational objectives: equity, reliability, timeliness, efficiency, and flexibility.

If the water supply is highly variable and unpredictable, the only practical objective to set is equitable distribution. This may be the case for run-of-river projects, especially those using headwaters where runoff closely follows rainfall variations.

On the other hand, all the desirable objectives of irrigation can be achieved in projects with a fully regulated supply which diverts water directly from a storage reservoir.
This is also the case in diversion projects drawing water from a river with a sustained flow capable of meeting a well-planned demand at any time.

The second physical factor to consider is the quality of water and especially the silt content, as strongly contrasted in this picture of two large rivers. High silt content may considerably increase maintenance costs if canals are operated under variable flow conditions. This aspect is one of the crucial factors in selecting the "on-off" operating mode of some large run-of-river projects in South Asia.

The third physical factor to consider is climate ...
... and the rainfall pattern. The variability and intensity of rainfall require flexibility in irrigation system operations in order to achieve efficiency, especially where there is a scarcity of water.

The system should be able to respond quickly to a sudden fall in demand without wasting too much water into the drainage system.

In cases where the storage reservoir is far upstream of the diversion dam, optimal use of the unregulated flow and rainfall over a large irrigated area requires a communications system for centralized control as well as a storage capacity in the distribution system.
The next factors to consider are soils and crops. The soil-water-plant relationship is a critical consideration in on-farm water management.

Sandy and clay soils have different holding capacities and water intake rates. Coarse soils have a low water holding capacity and a high intake rate. Fine soils have a high water holding capacity and a low intake rate.

For the irrigation engineer, the physical properties of the soils have an influence on design decisions about the flexibility in frequency, flow rate, and duration of irrigation. Soils also have an influence on the method of field application.
Another important factor in designing a system is the type of crop to be irrigated. In East Asian countries, for example, both rice and upland crops are irrigated, but each has quite different water requirements.

In addition crops have variable water requirements depending on their stage of growth and climate factors.

For example, rice requires a substantial flow during land preparation. This can be supplied to farm units in sequence. But during the growing stage continuous irrigation is often preferred. Continuous irrigation is often a more practical way to maintain adequate water depth in the paddy fields.
This simple but ingenious gate used in Malaysia has been developed to meet the two different rates required for rice irrigation.

In rice production, excess supply has no impact on crop yields as long as the water level can be controlled by releases to the farm drain.

On the other hand, upland crop irrigation has a different pattern. Irrigation is provided at variable intervals.
Upland crops have very exacting water requirements for optimal production, and both excesses and deficits in water delivery will affect yields.

Crops and soils together with other requirements for farming practices and economic considerations determine which mode of irrigation to use, either surface methods, as shown here...

... or pressurized methods, such as drip or pivot irrigation.
The important conclusion for the designer is that the system should be able to provide the irrigators with enough flexibility in operation and water delivery. This flexibility is needed to accommodate crop needs and the modes of irrigation adopted, which can vary by time and place.

Topography is another major factor in deciding on the mode of irrigation. For example, undulating lands with shallow soils may be unsuitable for surface methods.

Topography affects the system design in different ways. Downstream control is not economical for canals with slopes of more than about 25 centimeters per kilometer.
The last physical factor is the size of a project. Centralized control is the most practical and effective method for large canals conveying water over hundreds of miles. Simple local static control is suitable for small projects.

Next, we will review the managerial factors to consider.

The most common managerial factors include the effective operation of the system at minimum cost, the ease of operation, farmers' participation and the tradition of irrigation.
In countries where manpower is costly, it is in the interest of water users to minimize operating staff requirements by making system operation as automatic as possible.

In countries where technical skill is limited, operations should be as simple as possible, especially routine tasks of field operators. Frequent resetting of structures and complicated procedures should be avoided.

In both cases, minimal human involvement in canal control in the field should be the objective.
418. For the control method using modern communications systems and computers, well-trained, high-level technical staff are an absolute must, both for operation and maintenance.

419. For example, electricians must be able to make rapid on-site repairs.

420. An institutional aspect often discussed in relation to water management is the need to promote farmer organizations. This is an important factor for water distribution at the farm level.
In areas where there is a long tradition of irrigation, farmers are willing to cooperate and have developed invaluable knowledge about irrigation. However, in new irrigation systems, farmers' cooperation does not develop spontaneously.

A system providing a dependable flow to tertiary units will provide the foundation for an equitable distribution of water to farmers and promote their participation in operating and maintaining the tertiary system.
Provision of a reliable water supply to the tertiary units should be a primary operational objective of a project. This objective was sometimes neglected in the past when emphasis was placed on farmer participation and on-farm water management, without considering possible mismanagement upstream in the system. This picture, for example, shows a tertiary canal which can be served only when the secondary canal is running at nearly full supply which was not the intent at planning stage. Indeed the system was supposed to be operated at variable flows which would have required construction of more cross-regulators.

The farmer's cooperation and knowledge is important to consider when planning a project. This is especially true in selecting the mode of irrigation and cropping pattern, or for example when introducing new on-farm systems and farming methods. How to accommodate established water rights should also be carefully discussed with the water users at the design stage.
Next, we will review the special problems of upgrading infrastructure in existing projects. The principles for upgrading the design and operation of existing projects may be the same as those for new projects. But implementation of actual physical improvements in existing projects is much more difficult.

Built-in constraints and limitations in existing projects have to be identified, evaluated, and removed on a project-by-project basis. For some projects, significant improvement may not be technically or economically feasible.

Research may also be needed to identify the most economical ways of incorporating improved canal control concepts into the vast network of existing systems to meet the higher requirements of modern irrigated agriculture. For example, this structure could be converted into a composite cross-regulator by constructing a duck-bill weir, upstream oriented, across the two central bays and installing gates in the two other bays.
Downstream control may not be economically feasible either because canal slopes are excessive or because it is impractical to raise canal berms which are obstructed by trees, housing, or other facilities.

It also may not be practical or economical to replace the existing major control structures that are equipped with large conventional radial or sluice gates, like the ones shown here, by automatic hydromechanical equipment.

Now for some general recommendations. As we have seen, a great variety of modern concepts and associated technologies are available. But no one concept or technology is appropriate to all the various types of irrigation projects.
In selecting the appropriate technology, the designer should be guided by the search for simplified operations.

Another sound principle is to take maximum advantage of hydraulic regulation in the design process.

Hydraulic regulation provides a safe, and reliable solution to the problem of canal control. It offers great simplicity of operation and a high degree of automation but does not depend on an external source of energy. Furthermore, it requires minimal staff training.
Design of run-of-river projects could be based on partition of water proportional to the areas served by each subsystem. Terminal reservoirs could also be added to provide some flexibility in water application.

For new projects with a reliable water supply, downstream control may be an attractive solution for the main canals, provided that the canal slope is suitable. Upstream control can be judiciously combined with downstream control.

Small hydraulic static structures, providing constant water levels or flow releases, can be used in the design of the secondary and tertiary canals.
For very large and long canals, the most convenient solution is centralized control - either a remote monitoring system or a fully automated computerized system. Hydraulic regulation can be used for control in the branch and minor canals of these very large systems.

For the modernization of existing projects, the only practical solution for improving the main system is usually to motorize the gates and introduce some form of centralized control in addition to conventional repair works and structural improvements.

The distribution system - which often requires massive rehabilitation - can be improved by removing obsolete structures and introducing simple structures to provide hydraulic regulation.
Like other control methods, automated canal operation discussed in this program also has some limitations. Some automatic equipment is more vulnerable to interference and vandalism than the conventional systems with pad-locked gates. As already mentioned, high silt content is a critical constraint to operation of canals at variable flows. In some projects and under certain conditions, use of automation may not be advisable. In other cases automation could be limited to some control structures, for example, when there are small variations in water demand in arid and semi-arid countries, or where canals are operated on the on/off schedule mode.

The design of irrigation systems using the concepts and techniques discussed in this program does require more elaborate hydraulic studies at the design stage and a substantial training program for most designers. It also requires greater care during construction to ensure proper installation of control structures.
442. A question which frequently arises is the cost of these modern systems. An efficient control system typically represents less than 10 percent of the total cost of a project.

443. The additional cost of a modern control system over a conventional one may represent only a small percentage of the total cost.

444. A major reason is that the increased efficiency and improved safety provided by a modern control system usually reduces civil works requirements. This results in savings in construction costs. Smaller canal capacities are required to serve the same cropping program if overall efficiency can be increased from, let's say, 40 percent to 50 percent. Less freeboard is also needed and safety embankments can be eliminated.
This picture, for example, shows a canal under centralized control designed with minimum freeboard and no safety embankment.

The costs of a modern system should be compared with the benefits derived from proper water management. As an example, we will use the Doukkala project in Morocco. Today, system efficiency is usually high, at about 75 percent between the headworks and the farm turnouts.

Management is also quite efficient. The number of operating staff, at about one per 300 hectares, is low compared to some conventionally designed projects with the same average farm size and providing the same service to water users.
A high level of operational efficiency has been achieved while at the same time providing a high level of service to individual farmers. Water charges to farmers are volumetric and, following a recent increase in rates, cover operation and maintenance costs.

The sale of industrial crops to processing industries allows a nearly 100 percent collection rate. This is because the water charges are deducted directly from prices paid to farmers for their crops. This irrigation charge is then passed on by the processing industry to the agency responsible for irrigation.

Modern water control equipment has been a major factor in the success of the project. It allows management to concentrate on aspects of agricultural production like farmer organizations and extension services...
and supplying inputs to farmers in areas where irrigation was recently introduced.

All of the systems described in this program have worked successfully for many years. When they are combined with proper canal management they help provide the ultimate user...

...the farmer - with a manageable and dependable supply of water, and they offer solutions to the problems of irrigated agriculture.