# Modernizing irrigation management – the MASSCOTE approach

Mapping System and Services for Canal Operation Techniques

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➤ Modernisation de la gestion de l'irrigation: L'Approche MASSCOTE cartographie du système et des services en vue de la gestion technique des Canaux.
Version courte composée des 3 premiers chapitres et annexe 2 "Sensibilité et performance de l'infrastructure d'irrigation"

➤ MASSCOTE – *draft version* (Arabic and Chinese).

➤ MASSCOTE Training presentations (Introduction plus the 11 steps)

➤ MASSCOTE – a methodology to modernize irrigation services and operation in canal systems Application to two systems in Nepal Terai: Sunsari Morang Irrigation System and Naryani Irrigation System.

➤ Modernization lectures: a set of presentations

➤ Rapid appraisal procedure –Text and spreadsheet file.
(English, French and Spanish)

➤ Irrigation training manuals for technicians

➤ Strategic planning training modules

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- PC with Intel Pentium® processor and Microsoft® Windows 95 / 98 / 2000 / Me / NT / XP
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- 50 MB of available hard-disk space
- SuperVGA monitor
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Acknowledgements

Preface

The MASSCOTE methodology has been developed to assist technical experts, irrigation managers and irrigation professionals engaged in the difficult task of modernizing or re-engineering the irrigation management of medium-to-large irrigation canal systems.

While most irrigation experts, policy-makers, donor agencies and practitioners recognize the pressing need to bring about drastic changes in irrigation management, few know how to do so in practice. Despite considerable commitments in terms of effort and resources, many modernization projects have failed and irrigation institutional reforms have not yielded expected results because of a lack of attention to detail. In Asia, an FAO regional irrigation modernization programme concerning more than 30 irrigation systems highlighted inadequate attention to canal operation as a major reason for disappointing results and underperformance.

Irrigation has been and will remain instrumental in combating food insecurity in rural areas. However, a significant shift towards more productive agriculture and wealthier farming systems is underway. At the same time, there is a growing focus on the multiple uses of water for improved livelihoods, on the need for conserving the environment for sustainable development and on the use of water resources. With increasing water scarcity and growing competition from different sectors for the water resources available, irrigated agriculture is expected to do "more with less" in terms of both water and funding, thus freeing up resources (water and money) for other uses.

In spite of the increased challenges and changing context in which irrigation takes place, irrigation engineers are still trained in the same traditional manner that only prepares them to design and construct the canals and not to manage irrigation systems. There are very few training centres and universities (and these mostly in the developed countries) that provide training in service-oriented irrigation management and modern canal operation techniques. Usually, irrigation professionals are expected to learn by themselves in the field how to handle issues related to performance improvement, multiple uses of water, environmental needs, low farm-gate prices, conjunctive use, etc. Generally, they are left with limited capacity and resources to deal with the increasing complexity of management.

Irrigation modernization is often misunderstood and associated exclusively with high technology or costly automation. However, modern irrigation management is essentially concerned with responding to the needs of current users with the best use of the available resources and technologies as well as a sense of anticipating the future needs of the scheme. How to convert this into very practical, effective technical solutions is a critical question. As they say, "the devil is in the details", but the paradox is that driving out the devil is not attractive to many. The more water is debated globally, the less managers are provided with practical solutions and tools to address complex situations and requirements.

The MASSCOTE approach is an attempt to overcome this paradox and to help managers address modern needs, issues and challenges in a serious way. The entry point is canal operation, but the scope is modernization and the goal is to promote service-oriented management, with specific identified targets in terms of effectiveness in relation to money, to water and with regard to the environment.

The methodology capitalizes on many modernization programmes in which FAO has been involved in recent years, in particular through associated training (RAP and MASSCOTE training courses). In the last decade, FAO has trained more than 500 engineers in Asia. Therefore, it is fair to say that the approach presented here has

largely been developed in close collaboration with irrigation managers in the field, who are envisaged to be the main users of this product.

MASSCOTE seeks to stimulate the critical sense of engineers in diagnosing and evaluating obstacles, constraints and opportunities, and in developing a consistent modernization strategy. The methodology is developed in a step-by-step approach in order to convert the overall complexity into simple and straightforward elements. These are then explored in a recursive process leading progressively to a new management setup and improvements in canal operation in order to facilitate the move towards more effective water management and improved water delivery service

The English word mascot means an object, person or animal believed to bring good luck, especially one kept as the symbol of an organization such as a sports team, and it comes from the French word *mascotte*. The authors believe that achieving success in bringing about modernization in irrigation through service-oriented management requires good organization, a good team and also some good luck – this is why MASSCOTE is needed.

This publication is accompanied by two CD–ROMs containing training material and technical documents on key topics in water and irrigation management, including some versions of MASSCOTE in Arabic, Chinese and French.

List of acronyms and symbols

BFSL	Below full supply level
CA	Command area
CI	Confidence interval
CMC	Chatra Main Canal
COT	Canal operation technique
CR	Cross-regulator
CV	Coefficient of variation
DBW	Duck-bill weir
DOI	Department of Irrigation
ET	Evapotranspiration
ETc	Crop evapotranspiration
ETo	Reference evapotranspiration
F	Froude number
F	Hydraulic flexibility
FF	Fixed frequency
FSD	Full supply depth
FSL	Full supply level
g	Gravity acceleration
GLBC	Ghataprabha Left Bank Canal
H	Head
h	Water level
IPTRID	International Programme for Technology and Research in Irrigation and Drainage
ITRC	Irrigation Training and Research Center (California Polytechnic University)
IWMI	International Water Management Institute
IWRM	Integrated water resources management
Kc	Crop coefficient
KOISP	Kirindi Oya Irrigation System Project
Ks	Water stress coefficient
LBO	Left Bank Old
LCW	Long-crested weir
M&E	Monitoring and evaluation
MASSCOTE	Mapping System and Services for Canal Operation Techniques
MOM	Management, operation and maintenance
NIS	Narayani Irrigation System
O&M	Operation and maintenance

PRA	Participatory rural appraisal
PTL	Proportional to time lag
Q	Discharge
q	Discharge through offtake
RAP	Rapid Appraisal Process
RBMC	Right Bank Main Canal
RBN	Right Bank New
S	Sensitivity indicator
SBU	Sequential bottom-up
SCADA	Supervisory control and data acquisition
SMIS	Sunsari Morang Irrigation System
SO	Simultaneous operation
SOA	Service-oriented architecture
SOM	Service-oriented management
TLO	Time-lag operation
V	Velocity
WDP	Water distribution plan
WUA	Water users association
WUC	Water Users Committee
WUCC	Water Users Coordination Committee
WUCCC	Water Users Central Coordination Committee
WUG	Water users group

Summary

The performance of many canal irrigation delivery systems is unsatisfactory in terms of: (i) water resources management; (ii) service to irrigated agriculture; and (iii) cost-effectiveness of infrastructure management.

In recent years, participatory approaches and management transfer reforms have been promoted as part of the solution for more cost-effective and sustainable irrigation services. Large agency-managed systems have been turned over partially or completely to various types of management bodies. However, the results have usually been disappointing. Common findings have been: (i) the new management bodies are not up to the task; and (ii) these bodies have inherited dilapidated systems and severe financial constraints.

This FAO Irrigation and Drainage Paper presents a step-by-step methodology for water engineering professionals, managers and practitioners involved in the modernization of medium-scale to large-scale canal irrigation systems from the perspective of improving performance of conjunctive water supplies for multiple stakeholders. While the focus is on canal operation, the scope concerns the modernization of management. The approach consists of a series of steps for diagnosing performance and mapping the way forward in order to improve the service to users and the cost-effectiveness of canal operation techniques.

This paper presents a proposed comprehensive methodology for analysing canal operation modernization, which is based on Mapping System and Services for Canal Operation Techniques (MASSCOTE). It discusses the main elements of canal operation and organization before describing the steps of the MASSCOTE approach in detail. These steps are grouped into two main parts: (i) baseline information; and (ii) a vision of water services and modernization plan for canal operation.

The part relating to baseline information focuses on: the Rapid Appraisal Procedure (RAP); system capacity and behaviour (sensitivity); perturbations; water networks and water balances and the cost of operating the system.

The part relating to the vision of water services and modernization plan focuses on: service to users; re-engineering of management; and options for modernization improvements. The analysis leads on to a consolidated vision of the future of the irrigation system management and a plan for a progressive modernization of irrigation management and canal operation.

Chapter 1
Introduction

PURPOSE

This paper presents a step-by-step methodology for water engineering professionals, managers and practitioners involved in the modernization of medium-scale to large-scale canal irrigation systems from the perspective of improving performance of conjunctive water supplies for multiple stakeholders. The paper does not consider small-scale and/or farmer-managed irrigation systems.

In this paper, while the focus is on canal operation, the scope concerns the modernization of management.

A major part of the 250 million ha irrigated worldwide is served by surface canal systems. In many cases, their performance is low to mediocre. There is a critical need for improvements in:

➤ water resources management;
➤ the service to irrigated agriculture;
➤ the cost-effectiveness of infrastructure management.

Managing canal irrigation systems to achieve efficiency, equity and sustainability is a difficult task. Participatory approaches and management transfer reforms have been promoted widely as part of the solution for more cost-effective and sustainable irrigation services. In recent years, large agency-managed systems have been turned over partially or completely to various types of management bodies, which have had to struggle to improve service to users. Although many important lessons have been learned, the results have usually been below expectations. Common diagosis have identified that: (i) the farmer-oriented new management bodies have been inadequately prepared/trained/resourced, or just inexperienced; and (ii) these bodies have inherited dilapidated systems and have had to operate under severe financial constraints.

The methodology presented in this paper is an attempt to help those confronted with such situations to engage stakeholders and improve modernization planning with the goal of providing improved services to users at a more appropriate cost. It is termed the MASSCOTE approach, this being an acronym that stands for Mapping System and Services for Canal Operation Techniques (Figure 1). The term mapping is used in two senses: (i) spatial survey, and (ii) planning.

Chapter 2 introduces the proposed comprehensive methodology for analysing canal operation modernization, based on: Mapping System and Services for Canal Operation TEchniques (MASSCOTE). Chapter 3 discusses the main elements of canal operation and the related organizational features. Subsequent chapters then describe in more detail the various steps of the MASSCOTE approach, which are grouped into two main parts:

FIGURE 1
MASSCOTE: mapping systems and services for canal operation techniques

Ultimate goal of MASSCOTE = Mapping the entire serviced area into manageable cost-effective units to better serve users

FROM
Service to users
Perturbations
Opportunities for water management
Costs

TO
Strategy for:
Water management
Service delivery
Canal operation
Modernization
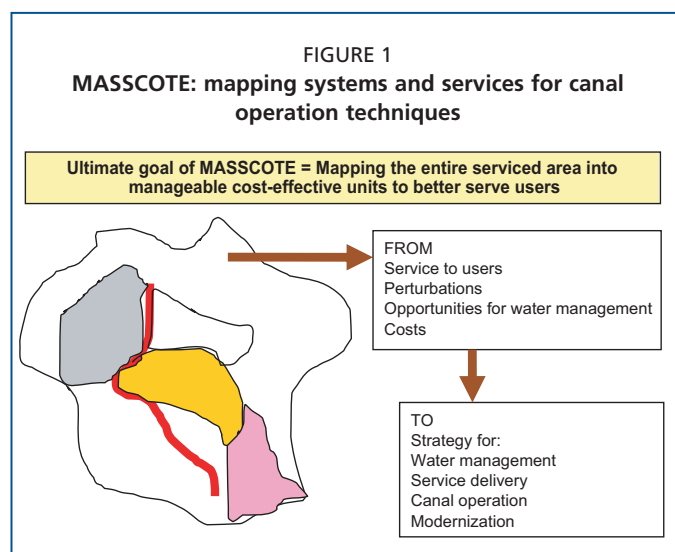
➢ Baseline information:
- The Rapid Appraisal Procedure (RAP): An introduction to the diagnostic tools for a process and performance assessment in order to increase knowledge about the constraints and opportunities that the system management has to consider.
- System capacity and behaviour (sensitivity): This knowledge is critical for operation. The focus is on the hydraulic aspects of canal operation (capacity and reactivity) and on some physical and organizational characteristics.
- The perturbations that are likely to occur along the irrigation canal systems.
- The water networks and water balances, which have a considerable influence on water management in the command area (CA).
- The cost of operating the system.

➢ A vision of water services and modernization plan for canal operation:
- The service to users: This is the main purpose of the system management, and canal operation is the primary element in determining the service provided to end users. Service-oriented management (SOM) is the key for modern management; it does not necessarily imply a high level of service but the one that is best adapted to user demand. A clear vision of the water services should be the starting point from which others steps are carried out.
- The re-engineering of management: This includes reorganizing the management setup and defining spatial units (partitioning management units) with the objective of favouring professionalism and cost-effective management.
- Options for modernization improvements: This part of the paper deals with the methodological development that can be used for developing a consistent strategy for improving canal operation and the project life cycle, in which managers and users need to engage progressively. It examines: analysis of the canal operation demands for the different units, the design of canal operation improvements, and a project to consolidate the improvements.
- A consolidated vision of the future of the irrigation system management and a plan for a progressive modernization of irrigation management and canal operation.

THE NEED TO IMPROVE PERFORMANCE AND ADDRESS THE COMPLEXITY OF MODERN CANAL OPERATION

As mentioned above, many canal irrigation systems perform well below their potential and improvements are needed urgently in water resources management, irrigated agriculture and asset management. In the last decades of the twentieth century, the emphasis was on performance outcomes and institutional reforms. This resulted in the management transfer of numerous irrigation systems and subsystems to water users associations (WUAs) and other farmer-oriented organizations. However, these new management bodies, formed as part of irrigation management reforms, often inherited dysfunctional infrastructure and severe financial limitations. In addition, they were often ill-prepared and too inexperienced to operate and manage these complex systems. Furthermore, insufficient attention was given to canal operation in previous management reforms.

While documentation on the concepts and benchmarking of irrigation performance abounds, there are few manuals on canal operation techniques and ways to improve the water delivery service achieved by operators. Therefore, both public agencies and newly created water management bodies (e.g. WUAs) are often ill-equipped to deal with the complexity of irrigation service delivery to users. In addition, they often lack adequate training and proper mandates, and many do not know where to start and what with.

According to many studies carried out by the FAO Water Development and Management Unit (NRLW) of the Land and Water Division, substandard canal operation is among the major causes of underperformance of irrigation systems.

This finding motivates the initiative to revisit canal operation and develop basic methodologies that can enable management bodies and all the professionals involved to tackle this complex issue.

SEPARATING OPERATION AND MAINTENANCE

In 1976, Taylor and Wickham stated: "Separating operations and maintenance: although a certain degree of coordination between operations and maintenance is important to the smooth functioning of each, …. distinctions between the two must be made." This statement is still valid today. However, most of the time, an inadequate distinction is made between operation and maintenance (O&M) in terms of budget or responsibilities.

Although they are quite different in nature, operation and maintenance have long been closely associated in irrigation management. While both apply to the physical infrastructure, operation differs fundamentally from maintenance. Operation is concerned with adjusting the setting of structures, whereas maintenance is about maintaining the capacity of the structures. Therefore, it is important not to mix operation with maintenance. However, recognizing and diagnosing trends or changes in the hydraulic properties of a canal (caused by siltation, weed infestation, tampering, etc.) form an intrinsic part of operations. The proper diagnosis should result in: (i) an operational mitigation strategy (i.e. cope with the changes temporarily); and (ii) hydraulic maintenance requirements/specifications to restore hydraulic and operational capacity.

COMMON MISCONCEPTIONS ABOUT CANAL OPERATION

There is a common misconception that canal operation is a well-understood and widely known technique, one that is well taught in engineering school and well mastered on the ground. Furthermore, there is the mistaken belief among many that the issues of poor irrigation performance are not related to engineering but more to do with the socio-economic context. However, many surveys carried out by FAO show that canal operation is not well mastered and that it is very often the origin of the vicious cycle of poor service, poor fee recovery, leading to poor maintenance, and resulting in the physical deterioration of the irrigation infrastructure and services provided.

There is also a misunderstanding that the hydraulics and control techniques of canal systems are highly complex and always require the inputs of high-level experts, computers and a complex information system in order to achieve a reasonable level of performance.

The truth lies somewhere in between. This paper does not propose that canal operation is not complex, nor does it say that only highly skilled experts can master it. Rather, this paper explains concepts and makes clear the complexity in order to enable the best service possible to users.

MASTERING THE INCREASED COMPLEXITY OF CANAL MANAGEMENT

As a general trend, the complexity of irrigation management and canal operation has increased since the 1970s, mainly for three reasons:

 ➢ Service to users is more diversified. Improving the performance of irrigated agriculture requires more flexibility in water delivery for modern on-farm irrigation methods such as drip irrigation. Irrigation managers are increasingly confronted with a spatially diversified and dynamic service demand.
 ➢ Water management is more demanding. Increasing competition for water requires water management to be more effective and efficient. Complexities increase further where management evolves towards integrated water resources management (IWRM).

FIGURE 2
Complexity of different control strategies at design construction and operation stages

Source: After Plusquellec (2002).
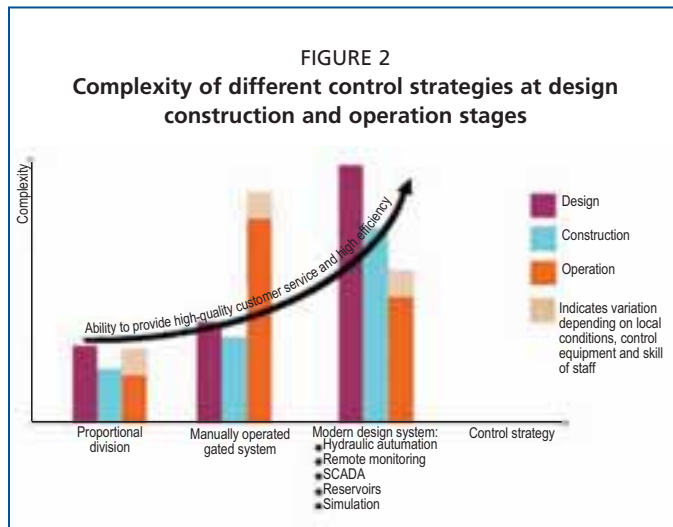
> Cost-effective management. Over time, it is becoming more difficult for governments to continue to subsidize irrigation management. The period when direct and indirect inputs covered by government agencies were not really accounted for belongs to the past. Investments in irrigation infrastructure, state-owned or user-group-owned, need to be economically sustainable, and cost-effective management is now imperative.

The complexity of operating an irrigation system depends on its physical nature (topography, water source, farm size, etc.) and on the service expected. For open-channel delivery and distribution systems, which are the focus of the technical approach in MASSCOTE, the least complex types are those based on proportional division with few structures to be operated (also called "structured systems"), but where the service to the end user is minimum, inflexible and not differentiated. Gated systems are more demanding in terms of operation but also provide a better range of service (Figure 2). One way to reduce the required manual efforts for delivering water is to introduce automation, which can be achieved through simple or very sophisticated techniques, and may or may not increase overall operational complexity.

The operation of open-channel infrastructure is a complex task requiring numerous simultaneous or timely sequenced and coordinated actions along the canal network. It is demanding in terms of effort (staff, coordination, transport, communication, means, etc.).

The nature of the efforts needed to operate an irrigation system is often, and it should be, adjusted according to the local technical and socio-economic context. For example, in countries where labour costs are high and where most of the irrigation cost has to be borne by the users, many canal systems that were initially manually operated have been progressively automated to some degree.

Automatic and self-acting structures performing with no or minimum direct human intervention should be based on sophisticated design techniques. However, the resulting structures can be simple. For example, a long-crested weir regulator does not require any computers in order to work.

In most countries, manual, labour-intensive operation of canal systems is still the prevailing method, but this manual operation can be improved and made more efficient and cost-effective.

Thus, the choice for managers is not one of either "very expensive high technology" or "no change at all" but somewhere in between, and the necessity is to implement modernization at an appropriate pace. Modernization is a continuing process that requires step-by-step implementation and it must be driven by the demand and resources of users. Indeed, FAO (1997) has defined modernization as: "a process of technical and managerial upgrading (as opposed to mere rehabilitation) of irrigation schemes with the objective to improve resource utilization (labour, water, economics, environmental) and water delivery service to farms."

There is growing evidence that failure in specifically addressing canal operation and service-oriented management (SOM) in practical terms is a main reason for

the lack of success in donor-funded modernization programmes, management transfer and other irrigation sector reforms.

The bottom line is that engineering aspects, and in particular the specific skills needed for effective canal operation, are prerequisites for successful and cost-effective irrigation management.

SERVICE-ORIENTED MANAGEMENT

The primary goal of the operation of a canal system is to convey and deliver irrigation water to users according to an agreed level of service that is well adapted to their requirements for water use and cropping systems. This approach is embedded in the concept of SOM (Box 1), which substitutes previous more top-down and rigid approaches.

Service-oriented management can be modelled at the interface of agency–user (or supplier–receiver), as shown in Figure 3. In simple terms, the agency and the user first agree upon the specific details of the service of water (where, when, how, how much, etc.). The agency provides the service to the user, who in return remunerates the agency. It is generally considered that the effectiveness of a system in responding to user demands depends on its operational flexibility. Ideally, the users should be able to select and change the level of service corresponding to their demand, and the service provider should be able to control the delivered service to each user, and, if necessary, cut off the

> **BOX 1**
> **A definition of service-oriented management**
>
> In the business sector Service-oriented management (SOM) is the operational management of service delivery within a service-oriented architecture (SOA). The primary objective of SOM is to provide a differentiated service delivery capability during operation, using business objectives to drive system behaviour.
>
> An SOM solution supervises and controls the delivery of a service from a service provider to a service requester. (It can also be seen as supervising and controlling the consumption of services by a requestor from a number of providers.) An SOM solution should be able to manage any service from any technology without requiring code changes, special deployment, or special development environments. SOM solutions are runtime solutions rather than development or deployment solutions.

FIGURE 3
The service-oriented management approach
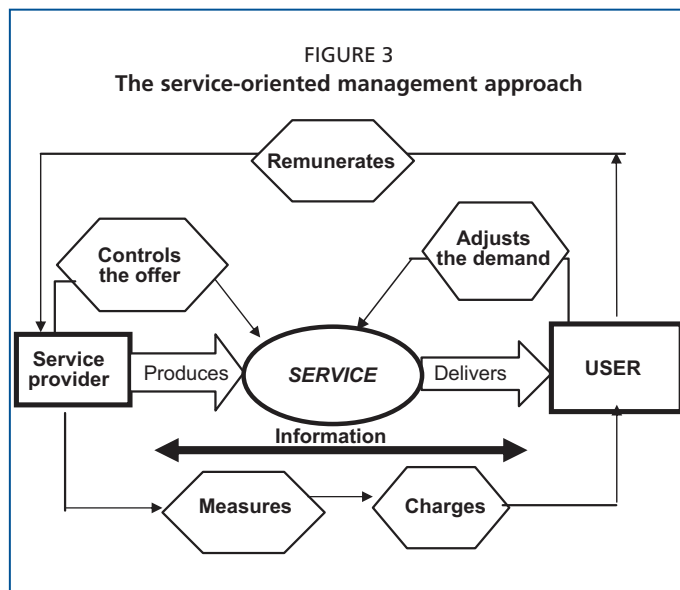
Source: Renault and Montginoul, 2003.

service in the event of non-payment. This means that a key element in the concept of service is the information between the provider and the receivers, as well as among the receivers. Information is required in order to:

➢ predict the services that can be offered;
➢ assess the demand for services;
➢ correct the demand in real time during the season;
➢ adjust actual service to the demand;
➢ measure and charge for the services provided.

As regards to the service that should be remunerated, there are three basic flows in this SOM approach that must be considered: (i) water; (ii) information; and (iii) money.

While canal operation is centred on water flows, it would be a mistake not to give full consideration to the other two elemental flows in developing new and/or improved canal operation strategies.

The service of irrigation water also requires information flowing between the service provider and the users. Information is needed beforehand in order to agree upon a type of service, and then on a regular basis during the process of water delivery planning. All this depends much on the type of service. Where access to the service is free, the information flow needed for water delivery is minimal, if not nil. With an on-demand-type service, the information must flow constantly in both directions. The request from the user goes up to the agency, then the service provider processes the demand, and a response goes down to the user.

Similarly, the service provided needs to be remunerated by the users. Thus, it needs to be measured or assessed/evaluated in a reliable and transparent manner. Information on the service should be shared and checked on both sides wherever conflict arises. This paper focuses mainly on water and information flows. Another volume in the series on irrigation modernization is planned to deal with money flows (water charging and cost recovery).

Chapter 2
MASSCOTE

A METHODOLOGY FOR DEVELOPING A MODERNIZATION PLAN FOR IRRIGATION MANAGEMENT

MASSCOTE seeks to generate a solution for irrigation management and operation that works better and that serves the users better.

Canal operation is at the heart of the MASSCOTE approach for two main reasons:

➢ In the diagnosis phase: The critical examination of the canal state and the way it is operated yields significant physical evidence on the ground of what is really happening in terms of management organization and service to users.

➢ In the development of the modernization plan, canal operation is critical as the intervention aims to achieve the agreed upon and/or upgraded service. Many irrigation reforms have shown how important canal operation is the hard way, by neglecting it in the design.

Users are central to this SOM-based approach. The way the various steps of MASSCOTE are developed aims to generate solutions for service and operations on which the users will have to decide.

Therefore, it is fair to say that canal operation is the focus of MASSCOTE, while its overall goal is modernization of management and the users as central actors.

Talking of modern irrigation management, it is always risky to bring forward a definition as there is then the possibility of not capturing all aspects of the problem, of being misunderstood, or of becoming rapidly obsolete or irrelevant in some context. Nonetheless, this paper proposes the following:

Modern irrigation management is an SOM with a cost-effective institutional and technical setup to govern the scheme and operate the system for producing the agreed-upon services.

Canal operation is a complex set of tasks involving many critical activities that have to be carried out in a consistent and timely manner for good irrigation management. Among the numerous aspects of management, the following need to be considered:

➢ service to users;

➢ cost and resources dedicated for O&M;

➢ performance monitoring and evaluation (M&E);

➢ constraints on the timing and amount of water resources;

➢ physical constraints and opportunities relating to topography, geography, climate, etc.

There is no single answer as to how to integrate all the elements into an effective and sustainable framework for improving canal operation. However, the new MASSCOTE approach has been developed on the basis of extensive experience with irrigation modernization programmes in Asia between 1998 and 2006.

A STEP-BY-STEP FRAMEWORK

MASSCOTE aims to organize the development of modernization programmes through a step-by-step methodology:

➢ mapping various system characteristics;

➢ delimiting institutionally and spatially manageable subunits;

➢ defining the strategy for service and operation for each unit.

The first steps outlined in Table 1 and Figure 4 are to be conducted for the entire CA. The goal is to identify uniform managerial units for which specific options for

TABLE 1
The MASSCOTE framework

Mapping	Phase A – baseline information
1. The performance (RAP)	Initial rapid system diagnosis and performance assessment through the RAP. The primary objective of the RAP is to allow qualified personnel to determine systematically and quickly key indicators of the system in order to identify and prioritize modernization improvements. The second objective is to start mobilizing the energy of the actors (managers and users) for modernization. The third objective is to generate a baseline assessment, against which progress can be measured.
2. The capacity & sensitivity of the system	The assessment of the physical capacity of irrigation structures to perform their function of conveyance, control, measurement, etc.
	The assessment of the sensitivity of irrigation structures (offtakes and cross-regulators), identification of singular points. Mapping the sensitivity of the system.
3. The perturbations	Perturbations analysis: causes, magnitudes, frequency and options for coping.
4. The networks & water balances	This step consists of assessing the hierarchical structure and the main features of the irrigation and drainage networks, on the basis of which water balances at system and subsystem levels can be determined. Surface water and groundwater mapping of the opportunities and constraints.
5. The cost of O&M	Mapping the costs associated with current operational techniques and resulting services, disaggregating the different cost elements; cost analysis of options for various levels of services with current techniques and with improved techniques.
Mapping	Phase B – Vision of SOM & modernization of canal operation
6. The service to users	Mapping and economic analysis of the potential range of services to be provided to users. Mapping a vision of the irrigation scheme.
7. The management units	The irrigation system and the service area should be divided into subunits (subsystems and/or unit areas for service) that are uniform and/or separate from one another with well-defined boundaries.
8. The demand for operation	Assessing the resources, opportunities and demand for improved canal operation. A spatial analysis of the entire service area, with preliminary identification of subsystem units (management, service, O&M, etc.).
9. The options for canal operation improvements / units	Identifying improvement options (service and economic feasibility) for each management unit for: (i) water management, (ii) water control, and (iii) canal operation.
10. The integration of SOM options	Integration of the preferred options at the system level, and functional cohesiveness check.
	Consolidation and design of an overall information management system for supporting operation.
11. A consolidated vision & a plan for modernization and M&E	Consolidating the vision for the Irrigation scheme.
	Finalizing a modernization strategy and progressive capacity development.
	Selecting/choosing/deciding/phasing the options for improvements.
	A plan for M&E of the project inputs and outcomes.

FIGURE 4
The steps in the MASSCOTE approach
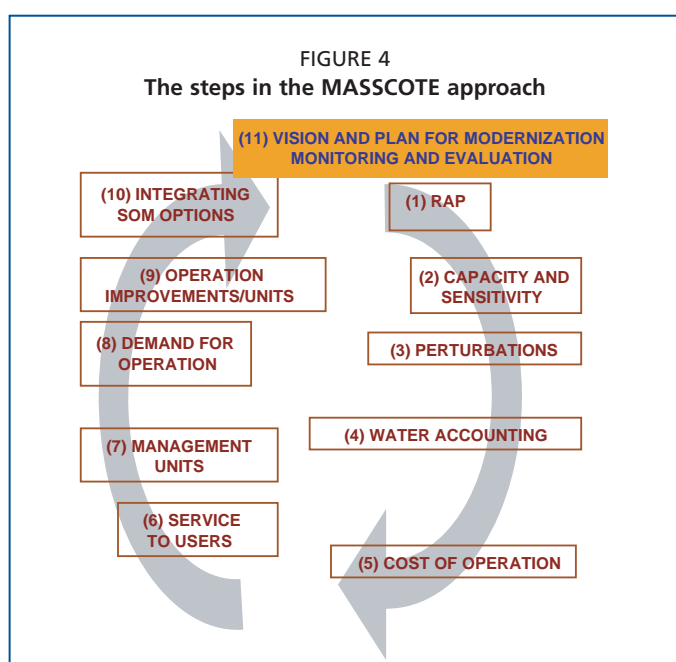
canal operation can be designed and implemented.

THE STEPS IN THE MASSCOTE APPROACH
Step 1: Mapping the performance: the Rapid Appraisal Procedure (RAP)
An initial rapid appraisal is the essential first step of the MASSCOTE approach. The RAP consists of a systematic set of procedures for diagnosing the bottlenecks of performance within an irrigation system.

The RAP internal indicators assess quantitatively the internal processes, i.e. the inputs (resources used) and the outputs (services to downstream users), of an irrigation project. Internal indicators are related to operational

procedures, management and institutional setup, hardware of the system, water delivery service, etc. They enable a comprehensive understanding of the processes that influence water delivery service and overall performance of a system. Thus, they provide insight into what could or should be done in order to improve water delivery service and overall performance (the external indicators).

The RAP external indicators compare input and output of an irrigation system in order to describe overall performance. These indicators are expressions of various forms of efficiency, e.g. water-use efficiency, crop yield, and budget. They do not provide any detail on what internal processes lead to these outputs and what should be done to improve the performance. However, they could be used for comparing the performance of different irrigation projects, nationally or internationally. Once these external indicators have been computed, they could be used as a benchmark for monitoring the impacts of modernization on improvements in overall performance.

Step 2: Mapping the system capacity and sensitivity

Mapping the system capacity and sensitivity deals with features of the physical infrastructure including the function of structures for conveyance, water level or flow control, measurement, and safety. Irrigation structures are intended to perform a particular function. How they are designed, installed, calibrated and maintained results in specific performance characteristics – some designs are better than others depending on the situation – and actual conditions may change with time owing to various phenomena, such as erosion, siltation and rusting.

It is important to have a reasonable assessment of the existing status of the system in performing the basic functions. Specifically, it is critical to identify any weak points, bottlenecks and/or areas with particular deficiencies. The mapping assessment of the flow capacity of infrastructure is necessary in order to compare with the design, but more importantly to ensure that the whole system is consistent with the operations plan to be developed.

Any major structural deficiencies need to be addressed as part of the planning process of modernization. Modernization improvements cannot be carried out successfully without dealing with the impacts of severely degraded or dysfunctional infrastructure.

Mapping the physical characteristics of the system is done in this step, and in particular the sensitivity of irrigation structures (offtakes and cross-regulators) is determined. Mapping of the sensitivity at key locations is crucial in managing perturbations (Chapters 6 and 7).

The basic idea is to know where the sensitive offtakes and regulators are located, and which subsystems are propagating the perturbations and which ones are having to absorb them. Thus, in terms of mapping:

➢ mapping of structures: sensitive regulators and sensitive offtakes;
➢ mapping of subsystems: average characteristics per subsystem – sensitive for flow control and water-level control.

This step gives rise to the following operational requirements and management options relating to sensitive structures/subsystems:

➢ sensitive structures must be checked and operated more frequently;
➢ sensitive structures can be used to detect fluctuations (part of information management);
➢ sensitive subsystems can divert perturbations into subareas which are less vulnerable to lack or excess water.

Step 3: Mapping perturbations

Perturbations of water variables (level and discharge) along an open-channel network are the norm not the exception. Despite being a target for canal operation, steady state along a canal is rarely found in practice. Thus, perturbation is a permanent feature

of irrigation canals caused by upstream setting of structures, and compounded by intended or unpredicted changes in inflows/outflows at key nodes.

Thus, if perturbations are unavoidable, then the only option for managers is to have a reliable knowledge of their origins, and to know how to detect and manage them. Managing a canal also deals with uncertainties and instabilities.

The types of perturbations that need to be mapped are:
➢ positive perturbations:
  • nature (inflow-outflow – internal),
  • magnitude (water-level fluctuation – relative discharge variation),
  • frequency;
➢ negative perturbations:
  • nature (inflow-outflow – internal),
  • magnitude (water-level fluctuation – relative discharge variation),
  • frequency.
With positive perturbations, the management options are:
➢ share the surplus proportionally among users;
➢ divert and store the surplus into storage capacity.
With negative perturbations, the management options are:
➢ compensate from storage;
➢ check for immediate correction;
➢ reduce delivery to some offtakes, with compensation later on (less sensitive/ vulnerable areas, delivery points with storage facilities, with alternatives source of water).

Step 4: Mapping the water networks and water balances
In this step, the concept is to map the surface water network including irrigation and drainage layout, but also any natural channels if they interact or may interact in the future with the canal system and/or storage facilities. The objective is to know where and when all the inflow points to and outflow points from the service area occur in terms of flow rates, volumes and timing. This mapping includes all safety structures built to evacuate surplus water to the drainage network.

Managers must have accurate knowledge about all the paths of water (surface and groundwater) – where it is coming from and where is it flowing to, and in what volume. Knowing the water balance of the system is important not only for achieving high efficiencies but also for tackling environmental issues such as waterlogging and salinity buildup. It is also a good management tool for transparent water distribution within and among subareas of a system.

Step 5: Mapping the cost of O&M
In this step, mapping is done of the costs for current O&M. It also involves disaggregating the elements entering into the cost and developing costing options for various levels of services with current techniques and with improved techniques.

In order to produce the service that has been decided/agreed upon with users, managers need to mobilize a set of various resources or inputs, such as water, staff, energy, office, communication, and transport. All of these entail a cost. This step aims at clarifying the issue of inputs and costs for operation as part of the overall management activities and as fundamental elements of the modernization process.

Investigating inputs and costs is important for:
➢ setting the service levels, in particular in exploring options for different types of services and associated costs;
➢ water pricing to users, in order to propose a set of charging procedures that takes into account the real cost of service production;

➢improving performance and cost-effectiveness, by investigating technical options for maximizing operational effectiveness (better allocation of existing resources, automation, etc.).

Step 6: Mapping the service to users

From the previous steps, a preliminary vision of the future of the scheme can be proposed for the future, from which initial features of the water services in the CA are derived:

➢How many categories of service are considered, and how are these spatially distributed?

➢How are the services evolving with time throughout the year?

➢What is the service for crops with respect to the different seasons?

➢What is the flexibility in defining the services with respect to the resources constraints?

➢What are the features of allocation, scheduling and water deliveries that define the overall service?

Assessing all the different services provided to different users and their related costs are what need to be mapped in this step. Mapping of service is required for further analysis of modernization opportunities and economic analyses to be done in later steps. This specific mapping exercise of services leads de facto to crafting a preliminary vision of the irrigation scheme which should be made explicit before carrying out the next steps.

Step 7: Mapping the management units – a subunit approach

Canal irrigation systems serving large areas are usually divided into smaller manageable units called tracks, blocks or subsystems. In the past (and particularly for new systems), these management units have often been based on the hierarchy of the canal network (main, secondary, tertiary, etc). Today, with the increasing complexity of management and operation needed to provide higher levels of service, this partitioning might be less relevant than it was when the systems were originally constructed. There are more relevant operational criteria on which subunits should be based (Table 2), for example:

➢participatory management;

➢spatial variation of water services;

➢conjunctive water management;

➢multiple users of water;

TABLE 2
Subunits – criteria and options

	Options
Criteria for division into subunits	Managerial/institutional: the subunits should correspond to the institutional partition of the service area among the users (farmer groups, users associations, etc.).
	Homogeneity of the conditions for the desired level of service.
	Sensible limits *vis-à-vis* available water resources – both the surface water and groundwater networks.
	Drainage conditions that physically partition the service area between recycled and non-recycled.
	Cost efficiency (too many units may prove unfeasible).
	Scale and the sense of ownership.
Singular points of interest for partitioning	Highly sensitive regulators that detect upstream changes in the water balance (even low changes) are good points at which to check the downstream of the subunit.
	Well-measured points.
	Well-controlled points.
	Major physical partition points.
	Storage allows smoothing discharge fluctuations and re-starting flows for downstream subunits.

➢drainage conditions.

Subunits of operation/management should define an area for which a certain level of service is agreed upon and provided, and for which the water balance is to be managed as a single unit. A workable compromise has to be found between the physical/hydraulic system and the institutional/managerial resources in each subunit.

The grounds on which subunits should be based are multiple. However, the setting up of too many units should be avoided, keeping in mind the baseline costs associated with the management of individual units.

Step 8: Mapping the demand for operation

This step involves assessing the resources, opportunity and demand for improved canal operation. It entails a spatial analysis of the entire service area, with preliminary identification of subsystem units (management, service, O&M, etc.).

Assessing the requirements for canal operation needs to be done alongside and in combination with the definition of the service by users and stakeholders. However, canal operation requirements cannot be derived only from service demands. The system presents opportunities and constraints that set the boundaries for possible modes of operation. In short, the requirements for operation will depend on three domains: (i) the service will specify the targets; (ii) the perturbation will specify the constraints in which the system operates; and (iii) the sensitivity will specify how fast the system reacts to changes and produces changes.

The rationale is straightforward: the higher the sensitivity, perturbations and service demand, the higher the demand for canal operation. This can be expressed in the relationship: demand for operation = service × perturbation × sensitivity.

Step 9: Mapping options for canal operation improvements / units

This step entails identifying options for improvements to canal operations. Improvements should aim at specific objectives such as:

➢improving water delivery services to agriculture users;
➢optimizing the cost of operation;
➢maximizing the conjunctive use of water;
➢integrating the multiple uses of water (IWRM).

It is necessary to develop modernization improvement options for each subunit based on: (i) water management; (ii) water control; and (iii) canal operation (service and cost-effectiveness).

The improvements are to be sought through one or a combination of the following options:

➢allocating existing resources and inputs in a more cost-effective and responsive way;
➢optimizing the organization and the operational modes;
➢changing the operational strategy;
➢investing in improved techniques and infrastructure.

For water management, the improvements aim to increase productivity and/or storage by: (i) minimizing losses; (ii) maximizing harvest; and (iii) re-regulating storage.

For water control, the improvements concern the hydraulic configuration of the operations. This entails a sequence of: (i) fine-tuning the hydraulic heads of canal structures in relation to each other; (ii) creating a specific hydraulic property of the canal (section) so that it performs as intended; and (iii) choosing the option that will minimize manual operational interventions/regulations for a specific period.

Step 10: Integrating service-oriented management options

Improvement options for the subunits are finalized together with the associated costs for every option. These are then aggregated for the entire command area in line with

the improvement option at the main canal level. A modernization strategy is laid out with objectives and proposed achievements/improvements.

Step 11: Consolidated vision and plan for modernization and M&E

The carrying out of the previous steps with some reiterative cycle is the process by which, progressively, a vision of the future for the irrigation scheme is crafted and consolidated.

FIGURE 5
Embedded nature of the RAP and MASSCOTE

MODERNIZATION PROJECT

RAP | MASSCOTE

This vision must then be converted into a plan that should aim at implementing the vision. Modernization improvements must be implemented in order to keep expectations and potential achievements at a realistic and practical level. A decision about the options to pursue is taken through extensive participation of the users. The solutions that are easiest and most cost-effective to implement are to be selected to start the process of modernization.

Monitoring and evaluation of the improved operations are necessary in order to ensure that achievements are maintained, and to provide a basis for comparison of the situation before and after the improvements.

IMPORTANT FEATURES OF MASSCOTE

There are four important features to bear in mind about MASSCOTE.

The first is the embedded nature of the RAP and MASSCOTE within a modernization project (Figure 5).

The second feature concerns the different time frames of the interventions:
- RAP = week;
- MASSCOTE = month;
- modernization project = year.

The third feature concerns the revolving nature of MASSCOTE. This might imply iterative circles before reaching a consolidated stage of analysis and project – several rounds of MASSCOTE at given levels before integrating at the upper level and going back at lower level.

The fourth feature is that a major entry point of the MASSCOTE methodology is canal operation, for diagnosis and for designing improvements. However, the overall objective in carrying out a MASSCOTE exercise is modernization of management. Canal operation is a critical entry point because: (i) it is the activity that puts management decisions into tangible outputs; and (ii) it is there that the current management performance is sanctioned and expressed in the most obvious manner (its symptoms). Field survey along a canal system is the most effective and reliable way of identifying management problems. MASSCOTE evolves from canal operation to management options (institutional partitioning, organization, and SOM).

MASSCOTE, THE RAP AND BENCHMARKING

The MASSCOTE approach needs to be seen in the context of other irrigation management and modernization tools and methodologies that have been developed in the last decade, in particular, the RAP and benchmarking.

These approaches are developed in the same three-dimensional space of impact (external indicators), process (internal indictors) and solution (option for improvements). The focus might be different, and some approaches are more inclusive. Benchmarking allows monitoring and checking of the performance of the management compared with other similar systems elsewhere, or after having introduced some improvements in the techniques and procedures. It is an essential component of a modernization project development.
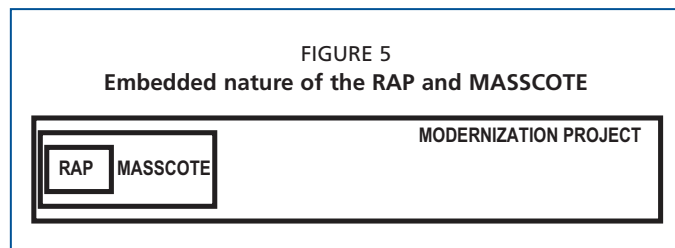
The MASSCOTE approach adds value to benchmarking and the RAP by focusing on the development of solutions that are derived from a thorough diagnosis of the impacts and processes that the other two tools provide. Therefore, it is logical that the first step in the MASSCOTE approach is the RAP.

Chapter 3
Canal operation – objectives and organization

This chapter sets the scene for canal operation by reviewing: (i) the main types of open-channel irrigation systems; (ii) the usual modes of operation and regulation techniques; and (iii) how operation should be organized and coordinated at the system level. It discusses scheduled and unscheduled operation techniques, and proposes various options. It also addresses the importance of defining the right partitioning of the serviced area for more effective operation. Therefore, readers already familiar with these notions can go directly to Chapter 4.

Irrigation canal operation depends on various factors related to the types of:
➢ systems (gated and ungated);
➢ control (mainly upstream control and downstream control);
➢ operation (manual, motorized and automatic);
➢ service delivered to users (rotation, arranged, free access, etc.).

Operating an irrigation system consists of carrying out a specific set of actions at the control and measurement structures (hardware) of an irrigation infrastructure network in order to:
➢ convey, deliver and monitor water to meet a pre-defined irrigation service to end users/clients, according to the schedule and the allocation agreed upon;
➢ ensure efficient water management within the gross command area;
➢ maintain the infrastructure/hardware.

Thus, operation is not limited only to physical interventions at major structures. It also includes:
➢ information collection from users for water orders and water charges;
➢ regular observations on the status of the system;
➢ decision-making procedures with user participation;
➢ M&E of the effectiveness of implementation.

PURPOSES OF OPERATION
The purpose of canal operation is manyfold:
➢ Scheduled operation for planned setting changes according to updated water distribution plans. Actions at this level aim to provide the targeted water delivery service. This mode of operation is also called predictive operation (USBR. 1995).
➢ Routine operation to deal with stabilizing perturbations by making changes in the settings of control structures for water supply and delivery. The perturbations are caused by illegal/unforeseen interventions, or difficulties in predicting natural causes (floods, winds, rainfall, and increased return flows). Actions at this level are undertaken in order to react to unplanned changes, with the overall objective of maintaining the quality of service as well as ensuring the safety of the system. This mode is also called reactive operation.
➢ Emergency operations. When unexpected surplus water in the canal system creates the risk of breaches, emergency spill structures have to be activated (where they are not automatic).
➢ M&E of the process at regular intervals is necessary for sound decision-making by the operators, and it is essential for evaluating the service to the users. Therefore, M&E deals with the status of the system structures (intended vs actual) and flows

TABLE 3
Types of operation, related activities goal, and objectives

Type of operation	Targets	Goal	Possible objectives
Scheduled operations	Targeted service at delivery points	Service to users	Produce the required service. Ensure high performance and efficiency.
Routine operations (unscheduled)	Unscheduled changes in inflows/outflows	Service to users	Manage perturbations and maintain a good service to users.
		Water management	Take advantage of surplus water, and compensate for water deficit.
Emergency operations	Sudden changes in the system creating high risk	Safety	Ensure safety of the canal under all circumstances.
Monitoring and evaluation (information)	Status of key variables (flow, water level, structure setting)	Service to users	Monitor, evaluate and improve performance and efficiency levels.
		Water management – decision for operation	Decision-making for better water management.

at key points, as well as the service provided to users. Actions target frequent monitoring of the internal physical variables (water levels, discharges, and gate settings) and the service (deliveries to intermediate and/or end users).

Table 3 provides detail on the type of operations, related activities goals and objectives.

In the category of scheduled operation, different types of interventions can be distinguished:

➢ re-start of irrigation deliveries (filling the canals at the start of the season or between rotation cycles);
➢ regular water distribution changes;
➢ de-watering at the end of the season (canal closure).

For each type of canal operation, a specific procedure (or set of procedures) needs to be established as part of an operations plan.

In practice, each category of operation aims to achieve a specific objective. For example, the targeted service to users defines a water distribution plan (WDP), which basically specifies the flow rate at each key location of the system as a function of time (e.g. major canal bifurcations and service area turnouts). In other words, the operation plan is designed in order to implement the WDP.

FUNCTIONS OF CANAL STRUCTURES

Operation is a set of actions at irrigation structures to perform specific functions. A hydraulic infrastructure network is a set of interconnected structures, each one ensuring one or several specific functions. The structures of a network serve the following functions:

➢ storage,
➢ conveyance,
➢ diversion,
➢ distribution,
➢ control,
➢ measurement,
➢ safety,
➢ transmission.

The storage function

The storage function consists of storing excess water at a given point in time and space (runoff, and discharge in rivers or canals) in order to deliver it at a more convenient time and place according to users' requirements. The lag time between storage and distribution may have different time steps, ranging from a few hours (night/day) up to some years for reservoirs that ensure several years of regulation.

The storage function is often ensured by surface reservoirs behind a dam. A distinction can be made between storage reservoirs situated upstream of the service area and inline or intermediate regulating reservoirs. Proper use of the storage function results from the coordinated release of water in relation to the capacities of canal system.

Finally, the storage function today cannot ignore the utmost importance and great vulnerability of groundwater. Aquifers sometimes represent an important and usable storage but may be equally limited in recharge. Today, the protection and management of underground aquifers (control of withdrawals, and recharge of the groundwater) are a critical part of the issues facing water resources managers.

The conveyance function

In most irrigation systems worldwide, conveyance is made through open channels. However, there are also buried pressurized pipe networks, and buried gravity networks (as in the traditional systems of piedmont groundwater abstraction, such as Khetarras in northern Africa). Natural systems (rivers) are also used to convey water between storage and the place where it is diverted to be distributed through the irrigation network.

The diversion function

This is the function by which irrigation water is diverted to be conveyed to the area where it will be used (irrigation scheme or subscheme). Diversion works are installed either on rivers or on large conveyance canals. Where the withdrawal is made on a dam, it is typically called an "offtake" structure. On rivers, the structure is often called a "diversion dam", but it usually has a very limited storage function; its essential function is to raise the natural water depth in order to supply water to the intake canal by gravity.

The distribution function

Distribution consists of delivering the required discharge to key points in the network (head of secondary, tertiary and quaternary canals). This function is typically accomplished through gated structures that divert a regulated discharge from one canal level to the next lower level.

The division function (proportional)

In proportional irrigation systems, the flow is divided proportionally at key points in order to allow a pre-set share of the available water to be distributed to downstream branches (Plate 1).

The control function

In order to ensure the good operation of a conveyance and distribution network, some intermediate variables need to be controlled. For example, on a pressurized network, the pressure is controlled at different points. In the case of an open structure, the water depth is controlled in the canals, in particular, close to the offtakes. Control structures are equally called regulators, cross-regulators (Plate 2), level regulators and check structures.

Plate 1
Proportional fixed divider structure seen from upstream, SMIS, Nepal.

Plate 2
Slide gated cross-regulators, SMIS, Nepal.

Plate 3
Side-gated structure (escape), SMIS, Nepal.

Plate 4
Fixed side-weir with cross-deflector, Maharashtra, India.

The safety function

The infrastructure in a canal system branches as it goes downstream and the conveyance capacity of individual structures is reduced. Owing to the nature of unsteady flow, it is necessary to ensure the safe disposal of spill water. In an upstream control canal system, such an overload can exceed the capacity of the conveyance structures. It is then a matter of performing, at some critical points, the disposal of all the additional discharge in order to prevent any damage to the canal and the areas it passes through (risk of breach in the canal, and flood hazard for riparian areas).

The safety function can be performed with side-gated structures (escapes) as shown in Plate 3, or through automatic structures made of a cross-deflector device (Plate 4) that limits the flow on the cross-weir, and a lateral side weir that evacuates the surplus when the flow hits the deflector. For automatic structures, no decision is needed nor any transport and operation, while these are all needed for a gated structure, which may limit the safety efficiency.

The measurement function

Management of canal systems entails regular decision-making with respect to the known status of the system. Therefore, it is necessary to obtain information on the state of the system in order to organize a proper response. Thus, monitoring at key points in the system through appropriately designed and situated measurement structures is essential to the manager (Plate 5). These structures have to quantify accurately relevant parameters that are important for management (discharge, water depth, etc.).

The information transmission function

This function aims to ensure that information collected in the field is available in real-time or near real-time at the decision-making

centres. This function is being performed increasingly by wireless communication devices. Supervisory control and data acquisition (SCADA) is the system often referred to in relation to information and control along an irrigation system.

The information management function

Although not a part of physical canal system compiling, processing, displaying and archiving are the basic functions of information management.

MAIN TYPES OF CANAL SYSTEMS: GATED AND UNGATED

Irrigation systems are composed of numerous reaches – conveying flows – and nodes that are division or diversion points. A node (also called a bifurcation point) is a particular point where:

Plate 5
A measurement station with remote terminal unit, Morocco.

- ➢ the flow in a canal is subdivided into two or more flows according to a pre-set pattern or to a specific, controllable target;
- ➢ the error/deviation from targets is also subdivided into the different dependent canals.

Thus, a node is defined with the specific flow targets of each branch, but also by the way deviations are shared. The node can be proportional, overproportional or underproportional.

There are two basic categories of nodes: gated or ungated, and this corresponds to the two main types of systems: gated, and ungated. The latter are often based on a fixed proportional division of the inflow, typically called a proportional system. The former are equipped with adjustable gates that are used to adjust the outflow from zero to the maximum value.

DEFINING THE CONTROLLED WATER VARIABLE

Operation consists of manipulating gates and structures in order to produce the agreed service and deliver it to the users. There are various types of control logic for canal operation, depending on several features, which are presented briefly in this chapter. One important aspect is to define the control variable.

Discharge control is the most common control procedure whereby inflows from the main inlets are adjusted to match the discharge demand along the infrastructure, or the deliveries are adjusted to match the net availability (inflows minus losses). This technique of "discharge control" goes together with the control of water depth in the canal to ensure a steady head at the outlets.

Other systems are designed and operated to control volume in canal reaches. This technique requires the availability of storage, either inline storage capacity in the canal itself or in intermediate reservoirs. Available storage is dependent on variations in the water depth in the system. Therefore, offtake discharge should be somewhat independent of upstream water level, i.e. outlet structures (the delivery structures in this analogy) should have a low sensitivity to the changes in water level in the parent canal.

FIGURE 6
Sketch of upstream and downstream control principles
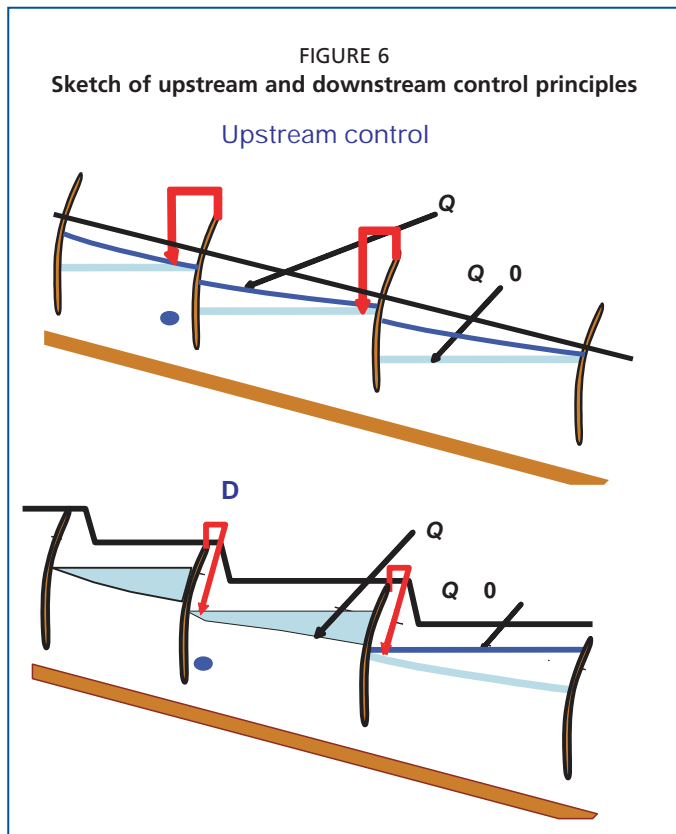
TYPE OF CONTROL: UPSTREAM AND DOWNSTREAM

Most gravity irrigation systems are based on upstream water-level control (Figure 6). With this technique, cross-regulators in the canal have to be adjusted on a timely basis in order to maintain the water level immediately upstream owing to variations that arise from changes at the headworks, considering the time lag for water transfer and changes to the flow diverted by upstream canals or turnouts or entering the canal. The objective is to maintain the water level upstream of each cross-regulator in order to control the backwater profile in the upstream reach. The backwater profile determines the head at offtakes in the upstream reach.

The alternative technique, i.e. downstream control, has attracted the attention of engineers and irrigation managers mainly because of the potential advantage of responding automatically to varying downstream demands from users. However, the technique is expensive as it usually requires horizontal canal banks and automated control structures.

TYPES OF OPERATION
Manually operated systems

For a manually operated gated system, irrigation staff have to manipulate every offtake and control regulator when a change in the flow regime is scheduled or occurs because of an unscheduled perturbation. This task has to be carried out at least once per day. The difficulty in operating these systems results from the numerous structures to be adjusted when the flow regime is changing. This large number of structures implies the mobilization of correspondingly large amounts of resources (human and/or transport) for adjusting and monitoring control settings. The greater is the density and sensitivity of structures, the greater is the difficulty of the control task resulting from unsteady-flow conditions.

Ungated systems are easier to operate from the standpoint of the system operators as they do not require numerous and frequent interventions for regular operation. In the commonly known systems originally developed in India, Pakistan and Nepal (Shanan, 1992), typically termed "structured systems", water delivery is organized around releases of constant discharge with a varied frequency. Distribution is proportional below the structured point, and structures are permanently fixed at the construction stage (no adjustable parts). The non-adjustable section of structured systems is limited to secondary/minor canals with the main/branch canals remaining fully adjustable. The savings in resources for manipulation of structures can be large. These systems were developed mainly for conservative irrigation and famine protection, with the goal of serving an average of one-third of the water needs for the entire CA. At the time of their construction, they were modern in the sense that they were responding to the urgent needs and matching the resources of their time. Today, with increasing demand for crop

diversification and with rapid growth in cropping intensity, they are often no longer able to satisfy user demand.

Automatic/semi-automatic gated systems

Automated systems are equipped with structures that control the water levels in canals over a full range of discharge. These structures may be either downstream or upstream control devices.

The control of water level is achieved by mechanical movements of regulator gates, slide gates, radial gates, and flap gates.

Plate 6
A self-acting upstream control gate (AMIL gate).

Automated systems differ by the way gates are operated. Generally speaking, there are: (i) energy-driven gated systems; and (ii) gates driven by hydraulic forces without an external source of energy or human intervention.

In many Mediterranean countries, several modernized systems are equipped with hydraulic driven gates. In the United States of America, the gates are more often motorized, with a local programmer controlling the water level.

The hydraulic-driven gates include AMIL (Plate 6), AVIS/AVIO (Goussard, 1987), DACL (Clemmens and Replogle, 1987) and Danaidean gates (Burt and Plusquellec, 1990). Variations in water level must still be expected to occur at locations remote from the control regulator. Hence, hydraulically automatic cross-regulator structures are frequently associated with constant discharge distributors, such as baffles (Burt and Plusquellec, 1990), in order to enhance overall performance.

Fixed ungated systems

Some cross-structures can ensure good control of the water level without gates. They use a simple long-crested weir (LCW), which minimizes drastically the variation in water level upstream caused by discharge changes to the extent that this variation is acceptable for the nearby offtakes.

One category of LCW is the well-known duck-bill weir (DBW). In these systems, the water level upstream of the LCW structures is controlled when the canal flow varies. Therefore, the discharge variation through the nearby offtake is minimized by selection of low-sensitivity offtake structures.

Simple pipes in the bottom bed between the parent canal and the dependent canal are also simple ungated offtaking structures, whose performance depends on the head exercised.

STRUCTURES OF GATED SYSTEMS
Offtakes and regulators

The most common structures in gated systems are: (i) offtakes (diverting structures), to control water diversion at a given point (Plate 7, Figure 7); and (ii) regulators (water-level control structure), to minimize water-level fluctuations at a given point (Figure 8).

If the offtake is not sensitive to water depth variation in the parent canal, then there is no need to install a cross-regulator. This is the case for some specific structures such as the baffles, but also for some orifice-type offtake when they are fed with sufficient head (H), say 1 m or more (meaning they are "low sensitive").

Plate 7
Diversion control structure (offtake).

FIGURE 7
A diversion offtake opening controls diverted discharge

Figure 8
A regulator gate controls the water level upstream
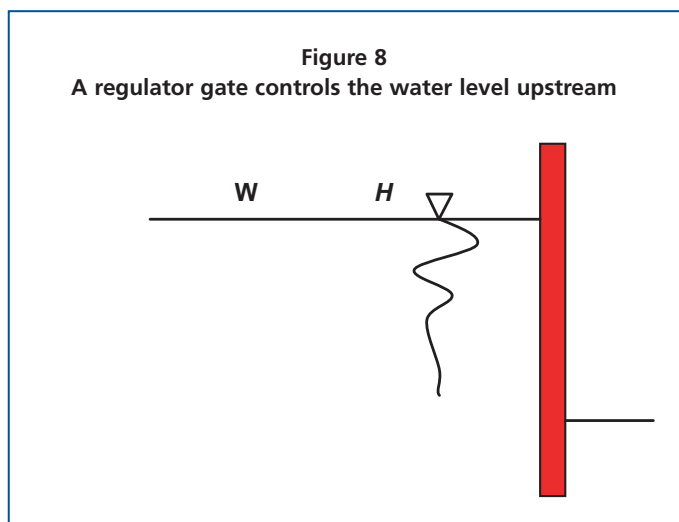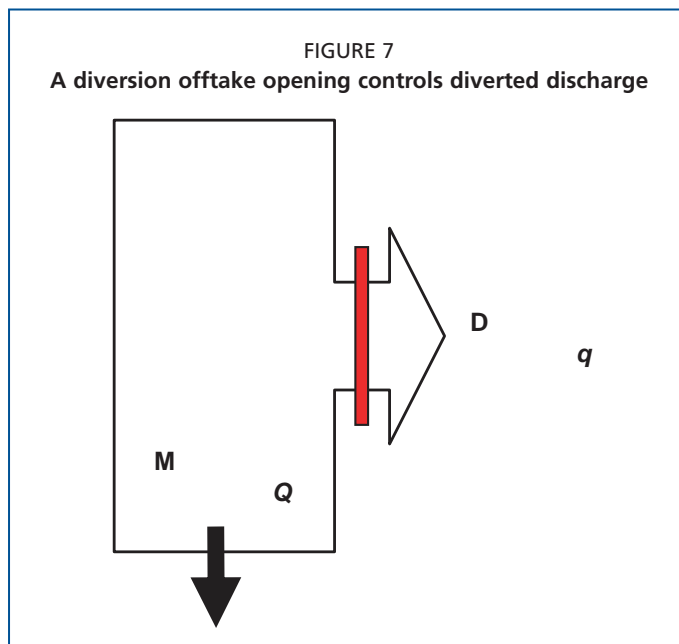
Where offtakes are sensitive to water-level fluctuations, it is often necessary to control the level at this node by installing a control structure.

Adjustment of irrigation structures

The adjustment properties of irrigation structures are: (i) the freedom and precision that can be exerted in the adjustment of the structure; (ii) the effort required for manipulation and control; and (iii) the hydraulic stability based on the sensitivity of the structure. These properties lead to the identification of the criteria for operation.

The properties freedom of adjustment and precision of control can be analysed through the classification of structures as proposed by Horst (1983):

➢ Fixed: no adjustment is possible, e.g. weirs, orifices and dividers.
➢ Open/closed: generally gates for minor canals, either fully open or closed.
➢ Step-by-step: regulation by steps, modules or stoplogs (Plate 8).
➢ Gradual adjustment: gated orifices, and movable weirs.
➢ Automatic: hydraulically adjusted gates.

For fixed structures, freedom of adjustment is nil as output is imposed directly by ongoing discharge (input), and precision is meaningless. For open/closed structures, freedom and precision are not relevant. For step-by-step adjustment, freedom and precision are limited by the number of discrete steps in the adjustment between zero and full capacity. For gradually adjustable structures, the degree of freedom is intrinsically high in that it is generally possible to choose any setting between zero and the maximum value. Precision will depend on the increment of the mechanical adjustment. For hydraulically automatic structures (self-acting), flow conditions are the governing factors. In general, these

structures cannot be adjusted in normal use and, therefore, the degree of freedom is zero. However, the operational objective is to maintain constant output, and precision is determined by the range of variation in output resulting from variations in input.

Finally, for all types of structures, it is necessary to distinguish between manually, hydraulically, and motorized control structures.

ORGANIZING THE OPERATION OF IRRIGATION STRUCTURES

There are two critical steps in organizing the operation of a canal:

Plate 8
A step-by-step regulator, Sri Lanka.

➢ defining the specification of operation for each structure (considered as independent);
➢ defining the sequencing of interventions: operation plan for scheduled change and for routine interventions.

Operating a structure means a cycle of various activities: (i) decision to operate; (ii) modalities of operation; (iii) intervention in the structure; and (iv) monitoring of the structure, which can then again trigger a decision to operate, etc. The specific function of the structure can be to control the diversion flow, regulate a target water level, measure key variables, or record information. Different types of structures are used to perform these different tasks. For each type of structure, managers must define clear targets to be achieved and establish clear sets of instructions for operators on how to proceed.

SINGLE STRUCTURE: OFFTAKE

Operating a delivery point (offtake) means achieving a time-bounded change in the discharge at this point. Where it is a single end-user outlet, it can be on and off, with or without the possibility for adjusting discharge. Where it is an intermediate node serving a large group of users, it can entail adjustments to allow a range of flows.

Operating a delivery point entails a set of physical interventions that are:

➢ manipulating the structure: opening and closing of the gate;
➢ adjusting for the targeted discharge: setting the gate opening;
➢ checking and reacting.

For each offtaking structure, clear operation instructions should be given, as in the example in Table 4.

Manual operation implies that an operator must be present at the structure in order to manipulate the gate (open and close) according to the distribution plan and also in order to perform routine operation. Thus, "operation" mobilizes various types of resources: staff, transport, communication, capacity and instructions.

Given the numerous structures along a canal system, the physical operation of one single structure has to be put into the context of:

TABLE 4
Example of an operation structure sheet

Structure X	Instructions
Function:	Diversion
Target:	From 0 to *Q* max. 100 litre/s
Tolerance:	+/-10%
Frequency of checking:	Twice a day
Modalities of checking:	Measure water level at the gauge of the downstream weir
Modalities of decision:	Centralized and/or localized
Modalities of interventions:	Opening and closing according to the operation plan by adjusting the gate opening after checking

> ➢ The decision-making at the management level. Specific schedules and targets have to be decided according to the water distribution plans and water balance of all inflows and outflows (canal and management losses).
> ➢ The infrastructure network, where interactions among structures, time lags between action and effects have to be taken into consideration in order to minimize the requirements for interventions (or stated another way, to maximize their effectiveness).
> ➢ The coordination of resources allocated/available to operate the system. A single-structure operation is simple to perform where means are sufficient, e.g. staff can be deployed at each structure or group of nearby structures. However, complexity arises where there are many structures within the CA. This requires a well-structured organization to coordinate and optimize operations while minimizing O&M costs.

SINGLE REGULATOR

In upstream-control systems, the objective is to control the water depth upstream of the regulators within a specified variation (tolerance) around the target. This target has usually been set to allow offtakes under the influence of the regulator to be fed properly.

Cross-regulators can be fixed (LCW), automatic (AMIL gate) or adjustable, consisting of one or more gates. Apart from a few exceptions on modern systems, cross-regulators are often equipped with undershot gates (slides or radials).

Plate 9
Cross-regulator equipped with central radial gates and side weirs, Mahaweli B, Sri Lanka.

A significant improvement is obtained with undershot gated regulators where they are equipped with dual side weirs (Plate 9). In this case, the objective for operation is to keep the water surface slightly overtopping at the spill level of the side weirs. A target below the crest provides the worst control because there is no operational benefit derived from the flow over the weirs.

The gates of adjustable regulators must be operated with specific rules (reaction to a measured deviation of water depth, to the pace of changes, etc.) in order to enable good control of water depth without generating too many oscillations of the water profile along the canal (Table 5). In a manually operated system, specific rules, although much simpler, must also be worked out.

The operation of a regulator consists of mainly two elements: the timing (when to operate); and the mode of adjustment (how to adjust).

In manual operation, it is common, for routine operations that the correction applied by the operator to the gate setting is proportional to the observed deviation of water level from

TABLE 5
Example of rules for an adjustable regulator

Structure	Regulator (i)
Function:	Water-level control
Target:	Specific water level
Tolerance:	Plus or minus X cm around target
Frequency of checking:	To be defined
Modalities of checking:	Deviation from target
Modalities of decision:	According to predefined changes
Modalities of interventions:	Adjusting the regulator gates with specific rules (adjustment and changes)

the target, which corresponds to full supply depth (FSD).

In describing an operational procedure, it is necessary to distinguish between: (i) scheduled changes in flow rates or predictive operation (which require direct adjustment of the regulator gate settings to allow the expected discharge at this point after the water surface profile has stabilized); and (ii) routine operation or reactive operation.

Operations for emergencies and M&E are quite different by nature, and they are not considered here. With a frequently operated system (often automated), there is no need to distinguish between scheduled and routine operation; each cross-regulator

Plate 10
Adjusting the opening of a radial gate at a cross-regulator, Pakistan.

is operated according to the measured variations by sensors. With manual operation (Plate 10), it is important to make the distinction between scheduled and unscheduled operations.

OPERATIONS AT SYSTEM LEVEL

In large canal systems, structures are highly interactive. Operations are not merely the addition of independent actions. Rather, they must be a coordinated set of actions aimed at maximizing the service to users and minimizing losses.

With medium to large systems, the implementation of canal operations is not done solely by one person or one group but split into multiple operational units. These units are defined in several ways:

➢ partitioning into clear-cut separate water management units;
➢ administrative district/sectors;
➢ groups of major canal structures that can be handled by one operator.

Clear-cut defined separate water management units are intended to allow for independent water management and canal operations in a defined zone. For the latter two, managment and operation are more dependent on what is happening upstream.

Distribution plan – communication and planning

Before the operation of a scheduled delivery on a weekly/daily basis, planning has to be done based on demand analysis, possibly emanating directly from the users (water ordering) and some aggregation, in order to ensure the balance of available water supplies. An operation plan is also necessary in order to ensure proper allocation of means (transport, staff communications, etc.) and hydraulic smoothness of the planned change (e.g. taking into account the time lag along the infrastructure).

Scheduling of deliveries and flows at main points and nodes

The scheduling of deliveries and flows requires an operation plan (a consistent sequence of interventions on the structures).

A typical motivation for scheduled adjustments to the cross-regulator structures along a canal is when there is a change in the distribution pattern (e.g. every week or fortnight). For example, this happens when the rotation of water deliveries is changed, implying an increase in flow at some delivery points, and elsewhere a decrease or a cutoff (if on rotation). The whole balance of water flows has to be moved from one stage to another.

FIGURE 9
From water demand to distribution plan down to operation plan
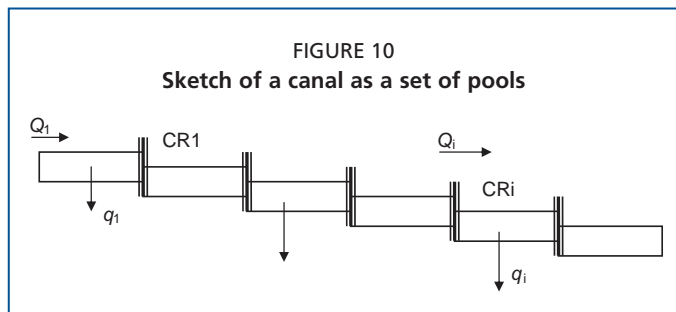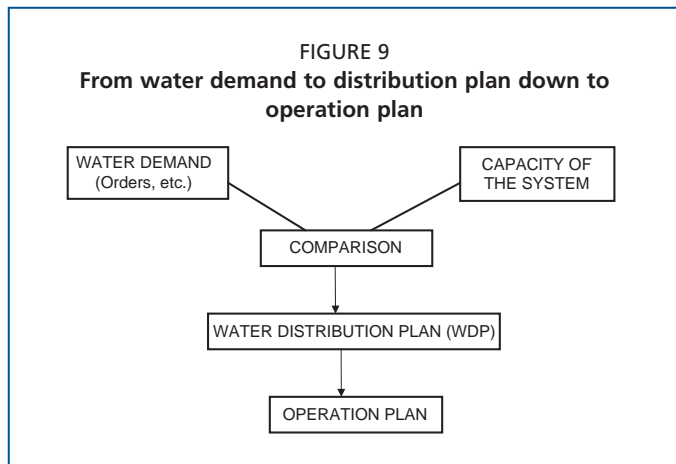
This implies numerous changes on control and delivery structures. Such changes need to be organized in a coordinated and effective way.

FROM WATER DISTRIBUTION TO OPERATION PLAN

There are many ways of operating a system depending on the water management constraints and opportunities, the techniques in use, the physical conditions of the system, etc. However, all gated upstream controlled systems follow the same basic steps from the comparison between the demand and the capacity, down to the operation plan via the water distribution plan (WDP), as illustrated in Figure 9.

The WDP is the first step in developing a canal operation plan. It is constructed around matching the users' requests with the constraints of the available water resources, as well as with the capacity of the infrastructure for conveyance and distribution:

FIGURE 10
Sketch of a canal as a set of pools

➢ Collection of water orders from users and demand analysis for water services.
➢ WDP (per day, per week and or longer [ten days or monthly]): a time-based and location-based allocation of water flows and volumes within the service area, and throughout the canal system, considering constraints on water availability, and physical constraints of conveyance.

The operation plan aims to implement the WDP while considering three important features:

➢ the scheduling of water deliveries at delivery points according to the WDP;
➢ the necessity of dealing with errors and uncertainties;
➢ accommodating unscheduled changes.

As a result, an operation plan must have a consistent system-wide procedure/organization/sequence in order to: (i) implement scheduled changes; (ii) deal with uncertainties; (iii) have local instructions that can take care of unscheduled changes.

Figure 10 shows a sketch of a canal as a set of pools. With this as an example, the following questions may be posed:

➢ How to organize the sequence of operation at cross-regulators to allow a change in withdrawal in the reach "i", for example by openning a new offtake discharge from 0 to q_i at a given time t_i?
➢ When should operators change the main discharge at the headworks?
➢ What is the sequence of operations at the cross-regulators between the headworks and the reach "i" that should be implemented in order to put the new distribution pattern in place?

Several options for the sequencing of operations are discussed below.

OPTIONS FOR SCHEDULED/PREDICTIVE OPERATIONS

For a simple cross-regulator along a canal, the literature mentions several procedures for scheduled or predictive operations (USBR,1995). The main ones are:

> ➢ sequential downward, which includes: time-lag operation (TLO), or any variation of TLO, such as proportional to time lag (PTL);
> ➢ sequential bottom-up (SBU);
> ➢ simultaneous operation (SO).

Sequential downward TLO

FIGURE 11
Downward wave propagation along a canal

The sequential downward regulator operation is particularly compatible with manual operations as the operator can adjust the gates sequentially while travelling down the canal.

The sequential TLO requires gate operators to adjust gate settings as the transient wave front arrives at the cross-regulator in response to upstream operations. With this technique, the anticipation of the passage of the transient wave is zero. Changes in withdrawals must wait for the passage of the wave.

The transit times of changes can be relatively long in canals. It is not rare that a change in supply to a long canal takes more than 24 hours to become apparent at the downstream end of the network. In order to operate structures and meet demand on time, it is crucial for managers to know how the waves are propagated through the system (Figure 11).

Transfer time from the main reservoir to any point along the infrastructure can be estimated from past experience or from evaluation using a non-permanent model. Detailed knowledge of the transit time along a canal system can be translated into a management strategy of structures and, in particular, it serves to prevent established management rules from giving rise to amplification of perturbations along the canal (oscillations).

The difficulty with this method arises when the time lag extends beyond 12 hours, which is the case for most medium to large systems. This means that, somewhere, operations may have to be carried out at night – which may sometimes be socially difficult and not easy.

When the time lag to reach the tail-end exceeds one day, then this method creates large delays in enabling delivery changes, which may or may not be compatible with the water schedule. Where these delays are not acceptable, the managers should proceed with anticipation of the deliveries by issuing in advance the flow changes required for the tail-end; hence, the time-lag change is no longer applicable.

Bottom-up per block

The bottom-up operation consists of implementing gate adjustments starting from the tail-end of the system. In practice, each gate operator is responsible for the operation of several cross-regulators (termed here as one block). Therefore, the operators start adjustments at the same time at the most downstream of the regulators under their individual control. After setting the required gate position, the operators move to the next regulator upstream (Figure 12). In general, the delay between operations of successive regulators is about 60 minutes. Finally, the main intake regulator is adjusted, and the change in the supply propagates through the system. Anticipation of

FIGURE 12
Illustration of bottom-up operation per block

FIGURE 13
Operating options
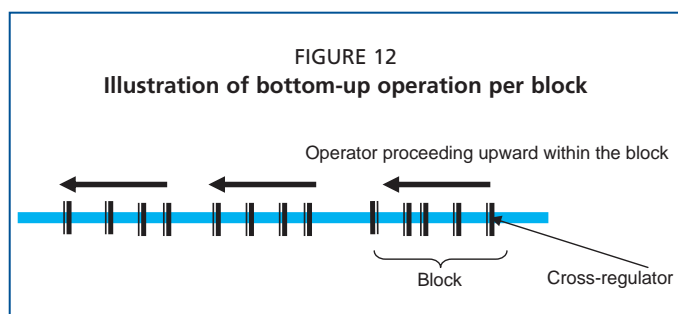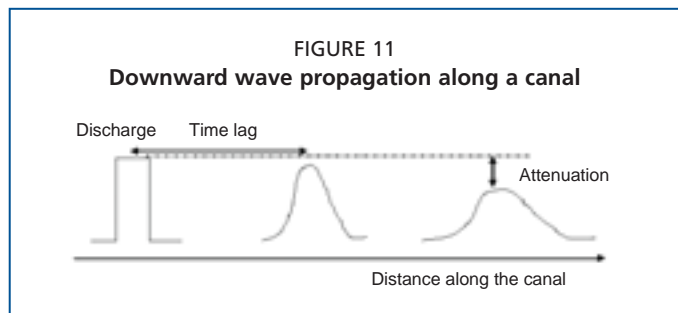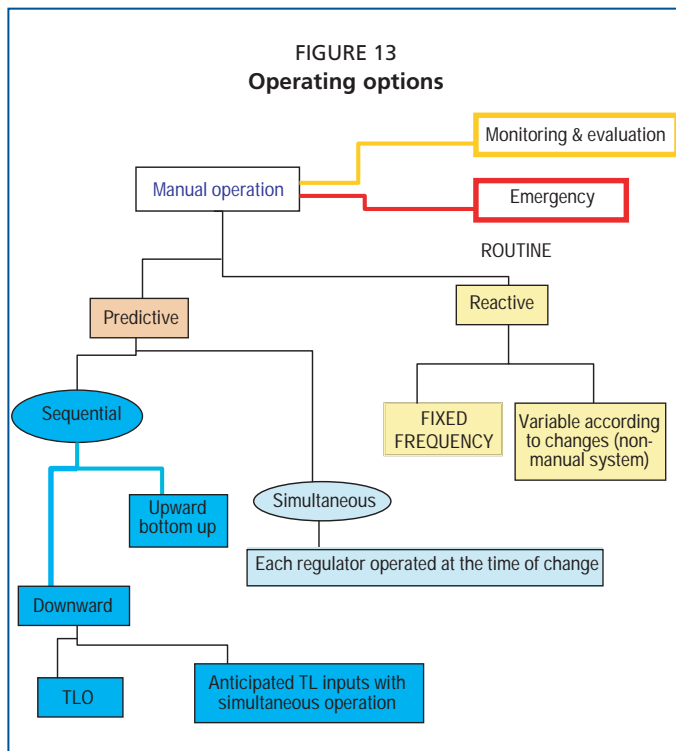
the wave is maximum in bottom-up operation.

Simultaneous operation

Simultaneous operation (SO) requires that all structures be adjusted at the same time. This enables a new steady state to be established rapidly along the canal. When operated, regulators generate both positive and negative waves in the adjoining reaches. These waves cancel each other at the pivot point of the pool and establish a new steady profile. This is possible only where an operator is available at every structure. In practice, operators have to move from one regulator to the next. Anticipation of the transient wave is intermediate between time-lag and bottom-up operations.

Anticipated time-lag inputs with simultaneous operation

When a delivery change has to take place at the same time of the week from a long canal, then a TLO cannot be applied as described earlier. The time lag has to be considered by anticipation. Incremental anticipated inputs changes from the main supply can set the system to the right status with the right flows at the time of the change. For example, an increment increase of 10 m^3 is made 12 hours in advance at the main supply if the time lag to reach the point of this particular delivery increase is about 12 hours. While the incremental inflow changes (waves) are passing through the canal, upstream regulators are operated on a routine basis.

Other methods

Proportional to time-lag (PTL) operations are a compromise between TLO and SO. Gates are operated at a specified proportion of the time lag (between 0 and 1). The degree of anticipation is variable. Implementation of PTL operation requires operators to have a rough estimate of the usual time lag. This can be obtained experimentally by observing the propagation of a flow change along the canal. These estimates can thereafter be used to identify approximate values for the PTL at each cross-regulator of the canal.

Figure 13 summarizes all the operating options.

FIXED-FREQUENCY OPERATIONAL PROCEDURE FOR ROUTINE OPERATION

Routine operations are carried out at cross-regulators only and they occur at a fixed frequency (FF). For example, in Sri Lanka, the frequency of operation is often generally twice per day, one operation taking place between 7 and 9 a.m. and the other between 4 and 6 p.m. This pattern corresponds to a nominal 12-hour frequency of operation. Exchanges of operational information between gate operators and the system manager are limited to one exchange per day, usually in the morning.

With the FF procedure, no specific operations are identified for response to unscheduled flow changes; routine adjustments at a frequency of 12 hours are considered sufficient response. For instance under the usual mode of operation – with

target set at full supply level (FSL) – no attempt is made to manage positive flow changes, for example, by storing additional flow volumes either in the canal section or in inline reservoirs. In that case the basic management objectives are to minimize the impact of flow changes on deliveries in progress and to dissipate peak flows without structural damage to the canal.

EMERGENCY OPERATIONS

The aim of emergency operations is to prevent serious failures in the canal system caused by unexpected flooding, structural failures, etc. They do so by channelling or storing water surplus in natural streams and storage basins.

MONITORING AND EVALUATION

Monitoring and evaluation are required in order to enable sound decision-making for operations, and are essential for evaluating the actual service provided to the users. Therefore, M&E targets the status of the system structures and flows as well as the service to users. Actions here target monitoring of the internal physical variables (water levels, discharges, and gate settings) and the service (deliveries to intermediate and/or end users).

Performance analysis is an intrinsic part of management. It is needed in order to target and monitor actual achievements in operation. Performance should be looked at from three perspectives: (i) the service to the users; (ii) the efficiency in managing the resources; and (iii) the cost of managing the infrastructure.

Operation has its own, very specific, information requirements (collection, transmission and processing) and, thus, operation plans have to include specific "operational information management systems".

REFILLING CANALS AT THE START OF THE IRRIGATION SEASON

When operations start at the beginning of the season, the system must be cleaned and all accumulated trash removed. This is particularly important in systems in urban areas. Some pre-cleaning must be carried out in order to remove most of the buildup. However, it is often not sufficient, and when the canals are filled with water it is probable that there will be a lot of floating debris at the front of the wave. Where nothing is done to remove the floating debris at key locations, the system runs the risk of creating some plugs and spills.

The requirements for this type of operation depend on the duration of the non-flowing period – the longer is the period, so the greater is the need for resources and pre-season actions.

CANAL CLOSURE AT THE END OF THE SEASON

The closure of a canal must always be progressive. A too rapid drop in water level in an earthen canal is likely to generate scourges in the banks. The literature indicates some maximum recommended decreases in canal velocity (USBR, 1995).

REFILLING CANALS AFTER A SHORT BREAK DURING THE SEASON

The refilling of canals after a short break caused by a short-term event such as rainfall must be handled carefully as the demand for water may be uncertain. There is a need to carefully monitor water delivery *vs* any changes in the demand in order not to have to spill excessive volumes of water. There is also the risk that widespread and heavy precipitation will contribute to more uniform (or near-uniform) soil moisture levels in the service area and generate a new pattern of the demand with all the requests coming at the same time instead of in rotation as before.

PARTITIONING INTO UNITS OF MANAGEMENT/OPERATION

Medium-sized and large canal systems are often organized for operations through the partitioning of units of management/operation. In some cases, these units may be defined according to administrative boundaries, or for other practical reasons, such as the capacity of one operator to handle a certain number of canal structures with the available communications and transportation.

While partitioning into clear-cut separate water management units is always the best choice, conditions do not always allow it. A clear-cut management partition point can be defined as a point where discharge can be controlled (fluctuations compensated). An independent (to a certain extent only) unit is a subcommand area for which the inflow is controlled (up to a certain extent) and not totally dependent on the upstream operation. A simple way of partitioning an irrigation system into smaller units is to have a single authority controlling the main canal, whereas second-level and third-level canals (individual canals or groups of canals depending on the lengths of these canals and/or other conditions) may form distinct units.

Given the interconnectedness of canal systems, full operational independence is rarely achieved (only a CA with a single reservoir can enjoy this). However, relative independence is found more often, which brings some benefits in terms of management.

In practice, there are three cases where the inflow to a service area can be controlled:

➢ where there is a large storage reservoir;
➢ where a water-abundant system is run with continuous spills to evacuate the surplus;
➢ where an alternative water resource is readily available to smooth out the variations in flow generated by upstream operations.

The use of intermediate reservoir storage

Intermediate reservoir storage within a canal system is a major asset for management. It provides an opportunity to re-start the management of the system with a controlled and measured discharge which can match downstream demand.

The different types of reservoirs include:

➢ inline of the main canal;
➢ off-line but connected directly to the same canal.

Reservoirs can be useful not only for the management of the entire branch on which they are installed but also for other canals branching out upstream of the reservoir.

Alternative sources of water

Where an alternative source of water is readily available, some of the variations in main canal flows can be compensated for through the additional supply. This additional water supply may have various origins:

➢ additional natural surface streams that can be tapped;
➢ recycling of drainage water;
➢ groundwater.

The management of spills

Managing spills is one of the operational elements in upstream-controlled irrigation systems. In particular, this technique is adapted to run-of-the-river systems when and where discharge availability in the river is not a major constraint. It consists of diverting surplus water and organizing the canal system into units separated by spills (Figure 14). Each unit runs with a surplus of water and the operator in each unit is responsible for managing the upstream spill to adjust to the demand (e.g. opening the spill when demand within the unit decreases).

The spill discharge (Q_{spill1}) is adjusted regularly in order to balance flows in the downstream unit (Q_{spill1} = Q_{MC1} - Q_1 - Q_{MC1}). Whenever there is a variation in this balance, the operator will adjust the spill accordingly. This system allows adjustments at any time to the downstream demand and can be considered as a sort of downstream control management.

FIGURE 14
Layout of canal equipped with spills
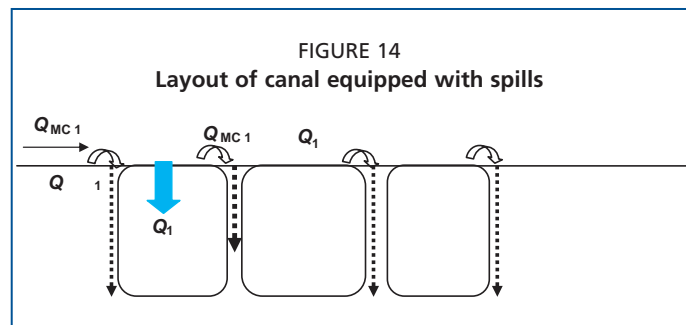
Chapter 4
The RAP evaluation

A sound diagnosis of the current performance situation is often the most important phase in the modernization process. It gives a good indication of the constraints and problem areas in the system. Although system performance could be assessed in different ways, FAO recommends using the RAP, which has been developed by FAO and the Irrigation Training and Research Center (ITRC) of California Polytechnic State University to enable managers to proceed with the initial stage of modernization together with user group leaders.

The RAP is a systematic set of procedures for diagnosing the bottlenecks and the performance and service levels within an irrigation system. It provides qualified personnel with a clear picture of where conditions must be improved and assists in prioritizing the steps for improvement. Furthermore, it also provides initial indicators that can be used as benchmarks in order to compare improvements in performance once modernization plans are implemented. Annex 3 provides detailed information on the RAP and how to conduct it.

BASIC ELEMENTS OF DIAGNOSIS AND EVALUATION

The diagnosis or appraisal of project performance provides the fundamental basis for designing modernization strategies and plans. Thus, if it is not done properly, the whole modernization process will probably be flawed and fail to yield the intended results. Appraisal of irrigation system performance should help in the identification of short-term, medium-term and long-term actions needed to improve its performance. An appraisal or evaluation must be:

➢ systematic: conducted using clear, step-by-step procedures, well planned, and precise;
➢ objective: if done by different professionals, the results should not differ;
➢ timely and cost-effective (not taking too much time, and not too expensive);
➢ based on a minimum of data required for a thorough evaluation.

It should cover:

➢ all aspects that could influence actual water delivery service, including the physical infrastructure, water management practices, roles and responsibilities governing WUAs, budgets, and maintenance;
➢ all levels of the system.

A proper diagnosis or appraisal process should be based on a combination of:

➢ field inspections, for evaluating physical system and operations;
➢ interviews with the operators, managers and users, for evaluating management aspects;
➢ data analysis, for evaluating a water balance, service indicators and physical characteristics.

A systematic evaluation of the current situation should be able to provide answers to the following questions:

➢ What level of water delivery service does the system currently provide?
➢ What hardware (infrastructure) and software (operational procedures, institutional setup, etc.) features affect this level of service?
➢ What are the specific weaknesses in system operation, management, resources, and infrastructure/hardware?

TABLE 6
Examples of internal and external indicators

Internal indicator	External indicator
Flow rate capacities	Command area efficiency
Reliability	Field irrigation efficiency
Flexibility	Production per unit of land (US$/ha)
Equity	Production per unit of water (US$/m³)

➢ What simple improvements in various components could make a significant difference in service delivery to users?
➢ What long-term actions could be taken to improve water delivery service significantly?

Conventionally, appraisals of irrigation systems often look at the big or overall picture and consider the inputs (water, labour, overall cost, etc.) and outputs (yield, cost recovery, etc.) of a system. While the overall picture is important, it does not provide any insight into what parts or components of a system should be improved or changed in order to improve the service in a cost-effective manner. Therefore, a sound diagnosis should provide insights into the internal processes as well as outputs. In other words, it should integrate internal and external indicators.

Internal indicators

The internal indicators assess quantitatively the internal processes (the inputs [resources used] and the outputs [services to downstream users]) of an irrigation project. Internal indicators are related to operational procedures, the management and institutional setup, hardware of the system, water delivery service, etc. (Table 6). These indicators are necessary in order to have a comprehensive understanding of the processes that influence water delivery service and the overall performance of a system. Thus, they provide insight into what could or should be done in order to improve water delivery service and overall performance (the external indicators).

External indicators

The external indicators compare the inputs and outputs of an irrigation system in order to describe overall performance. These indicators are expressions of various forms of efficiency, e.g. water-use efficiency, crop yield, and budget. They do not provide any detail on what internal processes lead to these outputs and what should be done in order to improve performance. However, they could be used for comparing the performance of different irrigation projects both nationally and internationally. Once these external indicators have been computed, they can be used as a benchmark for monitoring the impacts of modernization on improvements in overall performance.

EVALUATING IRRIGATION PROJECTS – METHODS, TOOLS AND PROCEDURES

An irrigation project can be appraised in many different ways incorporating all or some of the elements described above. The methodologies commonly used by researchers and evaluators of the system make use of checklists, detailed data collection and analysis, participatory rural appraisal (PRA) techniques, and detailed surveys. However, the use of these tools depends on the perspective with which diagnostic analysis is performed. For example, researchers often opt for data collection and detailed analysis, which requires time and other resources. PRA is often used to incorporate local knowledge and perspective on the irrigation system performance into the diagnosis.

Traditionally, diagnostic procedures have focused on only one or two of components, e.g. equity in water delivery or institutional reforms, and only covered part of the system, e.g. one lateral. These limited-purpose diagnostic studies have usually been based on the collection of substantial field data and, thus, are time-consuming and expensive. Field data collection is feasible for long-term research projects. However, for project appraisals and diagnosis for modernization improvements, it is often necessary to evaluate the situation rapidly with whatever data are available. The lesson learned is that where data are not readily available at a project, it is usually not realistic to expect project staff to gather them.

The FAO approach to irrigation system appraisal

Experience has shown (FAO, 1999) that a rapid and focused examination of irrigation projects can give a reasonably accurate and pragmatic description of the current status of an irrigation system, and of the processes and hardware/infrastructure that in turn result in the present condition. It is on this basis, that FAO, together with the ITRC and the World Bank, developed a methodology/tool called the RAP with well-defined procedures for the rapid assessment of the performance of irrigation schemes.

The RAP allows for the identification of major actions that can be taken quickly in order to improve water delivery service (especially where the diagnosis is made in cooperation with the local irrigation authorities). It also helps in identifying long-term actions and the steps to be implemented in a modernization plan.

Although irrigation systems can be evaluated and appraised using any or combinations of the above-mentioned methods, FAO recommends using the RAP because of its rapid nature, systematic procedures, and comprehensive approach, as it covers all the different components (physical, management and institutional) of an irrigation system. The following sections describe the concept of the RAP while Annex 3 details its procedures.

THE RAPID APPRAISAL PROCEDURE

The RAP was developed originally by the ITRC in the mid-1990s for a research programme financed by the World Bank on the evaluation of the impact on performance of the introduction of modern control and management practices in irrigation (FAO, 1999). Since its introduction, the RAP has been used successfully by FAO, the World Bank and other irrigation professionals for appraising projects in Asia, Latin America, and North Africa.

The conceptual framework of the RAP (Figure 15) for the analysis of the performance of irrigation systems is based on the understanding that irrigation systems operate under a set of physical and institutional constraints and with a certain resource base. Systems are analysed as a series of management levels, each level providing water delivery service through the internal management and control processes of the system to the next lower level, from the bulk water supply to the main canals down to the individual farm or field. The service quality delivered at the interface between the management levels can be appraised in terms of its components (equity, flexibility and reliability) and accuracy of control and measurement, and it depends on a number of factors

FIGURE 15
Conceptual framework of the Rapid Appraisal Procedure

RESULTS
• Cropping Intensity
• Average crop Y\yields (tonnes/ha)
• Yield/unit of water consumed
• Downstream environmental impacts

SYMPTOMS
• % collection of water fees
• Viability of water user associations
• Condition of structures and canals
• Water theft

SERVICE
• Actual level and quality of service delivered
 - To fields
 - From one level of canal to another

FACTORS INFLUENCING SERVICE QUALITY

Hardware design
• Turnout design
• Check structure design
• Flow rate measurement
• Communications system
• Remote monitoring
• Availability of spill sites
• Flow rate control structures
• Regulating reservoir sites
• Density of turnouts

Management
• Instructions for operating check structures
• Frequency of communication
• Maintenance schedules
• Understanding of the service concept
• Frequency of making flow changes
• Quality and types of training programs
• Monitoring and evaluation by successive levels of management
• Existence of Performance Objectives

CONSTRAINTS

Physical Constraints
• Dependability of water supply
• Adequacy of water supply
• Availability of groundwater
• Climate
• Silt load in the water
• Geometric pattern of fields
• Size of fields
• Quality of seed varieties
• Field conditions
 - Land levelling
 - Appropriate irrigation method for the soil type

Institutional Constraints
• Adequacy of budget
• Size of water user association
• Existence of and type of law enforcement
• Purpose and organizational structure of WUA
• Destination of budget
• Method of collecting and assessing water fees
• Ownership of water and facilities
• Ability to dismiss inept employees
• Staffing policies, salaries
• Availability of farm credit
• Crop prices

related to hardware design and management. With a certain level of service provided to the farm, and under economic and agronomic constraints, farm management can achieve certain results (crop yields, irrigation intensity, water-use efficiency, etc.).

Symptoms of poor system performance and institutional constraints are manifested as social chaos (water thefts, and vandalism), poor maintenance of infrastructure, inadequate cost recovery and weak WUAs.

The basic aims of the RAP are:
➢ assess the current performance and provide key indicators;
➢ analyse the O&M procedures;
➢ identify the bottlenecks and constraints in the system;
➢ identify options for improvements in performance.

The RAP can generally be completed within two weeks or less of fieldwork and desk work if some data are made available in advance by the system managers. A set of Excel spreadsheets in a workbook is developed in order to conduct the RAP (Annex 3). These spreadsheets provide the evaluators with a range of questions related to the physical, management and water systems of an irrigation project that the evaluator has to answer. Based on the data and information input, a set of internal and external indicators is computed automatically.

The RAP has also been used as a foundation for benchmarking. The International Programme for Technology and Research in Irrigation and Drainage (IPTRID) defines benchmarking as a systematic process for achieving continued improvement in the irrigation sector through comparisons with relevant and achievable internal or external goals, norms and standards (IPTRID, 2001). The overall aim of benchmarking is to improve the performance within an irrigation scheme by measuring it against desired targets and own mission and objectives. The benchmarking process should be a continuous series of measurement, analysis and changes to improve the performance of the schemes. Thus, the RAP becomes a tool for regular M&E of an irrigation project.

APPRAISING THE PHYSICAL INFRASTRUCTURE

The physical infrastructure or hardware (reservoirs, canals, diversion and distribution structures, etc.) of an irrigation system is the major physical asset of an irrigation authority or water service provider. Keeping the infrastructure/hardware in reasonable shape and operating it properly is the only way to achieve water delivery targets, provided that the delivery targets are set realistically (based on the available water resources and the capacity of the system). The main items to examine while appraising the physical characteristics of a system are:
➢ assets: conveyance, diversion, control and other structures per kilometre;
➢ capacities: canals and other structures;
➢ maintenance levels;
➢ ease of operation of control structures;
➢ accuracy of water measurement structures;
➢ drainage infrastructure;
➢ communications infrastructure.

APPRAISING PROJECT MANAGEMENT

The management arrangements, procedures, incentives, etc. of any irrigation system play a vital role in how it is operated. The ways in which decisions are made, communicated and implemented influence not only the way the system is managed but also the perceptions of users about how the performance of the system meets their needs.

Often, operations, and thus water delivery service, could be improved significantly without much monetary investment by improving operational procedures, including for example the way control structures are manipulated. However, this often requires

capacity development and appropriate targeted training of the office personnel and operators.

In order to identify improvements in the management of a project, it is necessary to appraise the following items (as a minimum):

➢ operation:
  - water allocation and distribution rules,
  - rules and procedures for operation,
  - stated vs actual policies and procedures,
  - the way structures are manipulated and operated – how changes are managed,
  - communication,
  - skills and resources of the staff at all levels;
➢ budget:
  - how realistic the budget is for the system operation to achieve set targets,
  - cost recovery – whether the system is able to pay for itself and invest in improvements as needed;
➢ institutional:
  - user satisfaction,
  - user involvement in decision-making – WUA.

APPRAISING WATER MANAGEMENT
Water delivery service

Irrigation systems are composed of hydraulic layers, where each layer or level provides service to the next, lower level (water supply → main → secondary → tertiary → user). Therefore, it is necessary to evaluate water delivery service at all levels (Figure 16).

At each level in general and for water users in particular, it is very important to receive the required volume of water at the right time, thus adequacy, reliability and timeliness are crucial. However equity of water deliveries is also a critical target for managers. Therefore, adequacy. reliability and equity indicators are often used for assessing water delivery service. Other important indicators, particularly for modernization, are flexibility (frequency, rate and duration) and measurement of volumes. Farmers can strategize and plan their cultivation and irrigation activities better where they can choose or at least predict the frequency, rate and duration of water delivery. Thus, the RAP computes the following indicators for assessing water delivery service at each level of an irrigation system:

➢ reliability,
➢ equity,
➢ flexibility,
➢ measurement of volumes.

As mentioned above, irrigation systems are often under increasing pressure to provide water for uses

FIGURE 16
Water service functions at basin and scheme levels

Hydraulic levels	Management functions
Reservoir / Dam	Water collection and storage
	Abstraction by irrigation scheme
Inflow	
Main canal	Conveyance
Inflow	
Distributary canal network	Distribution
Field channel network	Delivery to farms
Farms	Water application
Drainage & return flow	Water disposal
	Regulation and monitoring of water quality
Seepage / Outfall	
Abstractions by other Users	Intersector water allocation

other than irrigation. In such cases, it is also necessary to evaluate the level of service required for these other uses.

Water balance

A water balance provides an accounting of all the inflows and outflows within a defined boundary, as well as information about different water efficiencies (e.g. conveyance efficiency and application efficiency). Thus, it provides a good assessment of existing constraints and opportunities for improvement. It helps set the stage for determining the level of water delivery service to be achieved and for designing appropriate allocation strategies. The RAP includes a water balance at the system/project level for the rapid assessment of the external indicators and identification of the potential for water conservation. However, for regular monitoring and water management decision-making, a more detailed water balance is required (Chapter 8).

CAPACITY DEVELOPMENT FOR DIAGNOSIS AND EVALUATION

Managers, engineers and national experts are not usually equipped to systematically evaluate the performance of irrigation projects and appraise modernization improvements. Therefore, international experts are brought in at the initial phase for project appraisal. However, there is the risk that, once the project has been implemented and the international experts have gone, everyone can go back to "business as usual" and the project can return to its routine cycle of operation without any M&E of service. Moreover, changing the mindsets of irrigation authorities from supply-oriented management to SOM requires substantial investment in the capacity building of managers, engineers, national experts and water users.

Even the well-documented procedures of the RAP require the adequate training of an experienced water resources professional. Experience has shown that successful application of the RAP requires:

➢ prior training and field experience in irrigation and drainage;
➢ specific training in the RAP techniques;
➢ follow-up support by trained experts when the evaluators begin their fieldwork.

Without investing in capacity building, modernization projects will not yield the desired results. There is a need to raise the capacity of irrigation personnel in order to enable them to evaluate critically their own system and be able to appraise conditions objectively, and to propose and undertake improvements in consultation with the users. Thus, it is critical to have capacity development programmes at project and national level with a view to promoting the adoption of effective irrigation modernization strategies in support of agricultural development, increases in water productivity and IWRM. Any modernization programme undertaken without adequate associated capacity development programmes may fail to produce real improvements and may result in considerable amounts of money being wasted.

AN RAP CASE STUDY
Description

The Sunsari Morang Irrigation System (SMIS) is the largest irrigation system in Nepal. It is located in the southeast Terai, a continuation of the Gangetic Plain. Figure 17 shows the layout map of the SMIS project. The gross command area exceeds 100 000 ha, with an irrigated area of about 64 000 ha. The SMIS is served by the Chatra Main Canal (CMC), which extends 53 km from the left bank of the Koshi River in a general west to east direction, with a maximum capacity of 60 m^3/s. A series of secondary, subsecondary and tertiary canals runs in a southerly direction nearly 20 km to the Indian border.

The system was designed originally for supplementary irrigation of paddy rice during the monsoon (kharif) season based on 80-percent rainfall. Thus, the capacity

of the system is not sufficient by itself to supply the full crop water requirement to the entire command area. Similar to large irrigation projects in India, the SMIS was intended to provide drought protection and deliver irrigation water to as many farmers as possible. However, demand for irrigation water on a year-round basis has increased steadily. After construction of the system in the mid-1970s, farmers began to utilize the system for a winter wheat crop in the rabi season (November–March). Later, spring season (April–July) crops were introduced in portions of the system.

The main physical constraint identified by the project authorities is that the flow of the Koshi River in winter and spring can only provide 15–20 m³/s (as low as 5 m³/s). In low-flow conditions with the present control strategy and infrastructure, it is very difficult to supply irrigation water equitably to different areas of the project. Historically, tail-enders have suffered the most from water shortages, with many receiving no irrigation water from the canal system. As a result, there is rising conjunctive use of groundwater and low-lift pumping of drainage water, particularly towards the tail-end of the system. There is also evidence of a lack of coordination between farmers and project engineers, indicated by the planting of rainfed crops adjacent to the canals while spring paddy may be at the end of watercourses.

The major crops grown in the CA include: paddy rice in the summer; wheat, pulses (lentil, soybean, other local varieties), oilseed crops (mustard, linseed), and vegetables (cauliflower, cabbage, eggplant, onion, tomato, etc.) in the winter; and jute, mung bean, maize, vegetables and spring paddy in the spring. The average landholding per household is 0.5–1 ha, which is significantly less than when the project was initially designed and constructed. The mean annual rainfall is 1 840 mm, most of which falls between May and September.

Since the completion of the original project, consisting of service down to 200-ha blocks in the mid-1970s, the SMIS has evolved through three phased implementations of command area development initiatives and construction activities (Stages I, II and III – described below). Phase 1 of Stage III had just been completed at the time of the RAP. Phases 2 and 3 of Stage III are planned for the areas in the project that are now termed "undeveloped". About 60 percent (40 000 ha) of the total command area has already been rehabilitated through the construction of unlined canals down to the watercourse level as part of Stages I, II and III. The major innovation in Stages II and III was the introduction of proportional flow dividers at the tertiary canal level and below.

Step 1. RAP

Objective

The primary objective of the initial rapid diagnosis was to obtain an initial sense of what and where the problems were, how to prioritize them, etc. The second objective was to start mobilizing the energy of the actors (managers and users) for modernization. The third was to generate a baseline assessment, against which progress would have to be measured. The RAP was conducted in May 2003 (FAO, 2006). The following sections are from the executive summary.

The SMIS has received substantial technical and financial assistance from various donor agencies for infrastructure rehabilitation and institutional development. It is an unlined, manually operated canal system. The system is characterized by:

➤ seasonally variable water supplies, which may reduce by 50–70 percent in the winter and spring (15–60 m³/s);

➤ lack of accurate flow control into secondary and tertiary canals associated with severe water-level fluctuations in the CMC;

➤ rotation schedules that are not enforced rigorously;

➤ institutionally weak WUAs with responsibility for O&M of substantial portions of the project, but which have only minimal budgets;

➤ severe inequity (tail-ender problems);

FIGURE 17

Layout of the SMIS project, Nepal
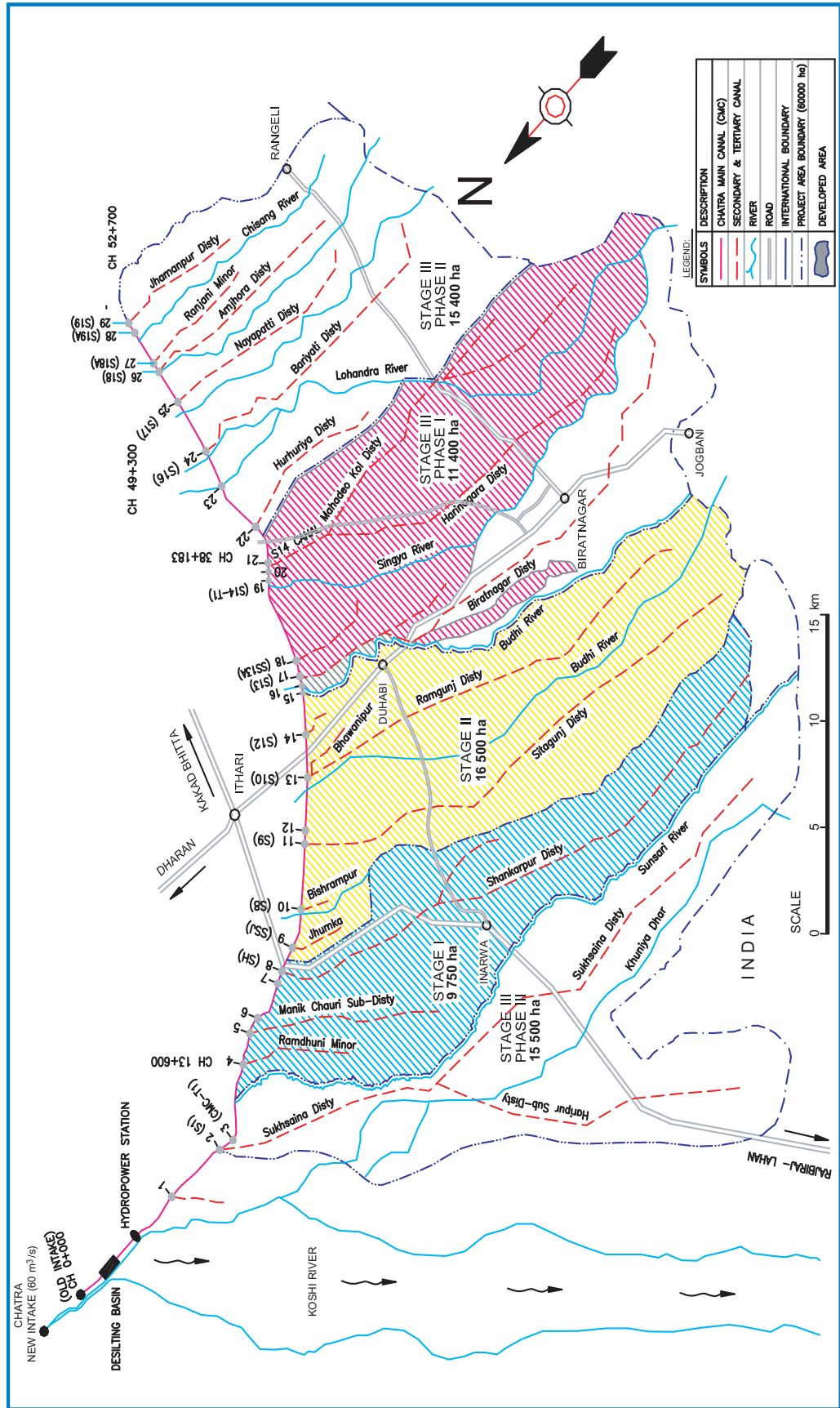
> low collection rates for an irrigation service fee that is set well below actual costs;
> phased implementation rehabilitation efforts, which have resulted in a mixture of different water control strategies and hardware (fully gated vs proportional flow division).

An RAP diagnostic evaluation was performed in different parts of the SMIS in two and a half days of intensive fieldwork. The results of the RAP quantified the performance of the SMIS in terms of the quality of water delivery service at each canal level in the system (Table 7). Internal indicators showed that only marginal improvements have been made in the most recent command area development (Stage III – Phase 1). However, they demonstrated clearly that the design concept of proportional flow division does not provide the operational flexibility required for meeting demand variations (owing to rainfall, crop diversification, etc.). In addition, a major deficiency of this design is the inequity that results from less than the full design capacity being achieved as a consequence of either low-flow conditions in the main canal or changes in the hydraulic characteristics of various canals caused by siltation, weed growth, etc. Although the new system has been in operation for one year, operators have already reacted by installing steel gates at proportional structures in order to regulate the flow in some tertiary canals.

Key points from the RAP conducted at the SMIS

The phased implementation of construction activities and institutional development in different stages of the SMIS has resulted in relatively better service in some parts of the project. However, it has also resulted indirectly in not enough attention being paid to overall issues such as how water is controlled in the main canal. One lesson of the SMIS RAP is that it is critical to ensure that the technical/engineering details are correct before expecting any success in participatory management schemes.

The present operation of the CMC results in severe inequities in the "undeveloped" areas of the project. The design of the main canal cross-regulators (manually operated, vertical steel gates with no side weirs) makes it difficult to maintain constant upstream water levels, which is compounded by the operation of the secondary canal offtakes.

Water delivery service is relatively poor at all levels of the SMIS but worsens at the tertiary canal level, which is the interface where water users groups (WUGs) are supposed to take over O&M from the staff of the Department of Irrigation (DOI).

TABLE 7
Internal indicators: variation from RAP in the SMIS

Sunsari Morang Irrigation System	Value
Actual water delivery service to individual ownership units (e.g. field or farm)	1.1
Stated water delivery service to individual ownership units (e.g. field or farm)	1.8
Actual water delivery service at the most downstream point in the system operated by a paid employee	0.7
Stated water delivery service at the most downstream point in the system operated by a paid employee	1.5
Actual water delivery service by the main canals to the second-level canals	1.7
Stated water delivery service by the main canals to the second-level canals	2.0
Social "order" in the canal system operated by paid employees	1.0
Main canal	
Cross-regulator hardware (main canal)	1.2
Turnouts from the main canal	2.0
Regulating reservoirs in the main canal	0.0
Communications for the main canal	1.3
General conditions for the main canal	1.6
Operation of the main canal	2.4
Second-level canals	
Cross-regulator hardware (second-level canals)	1.5
Turnouts from the second-level canals	1.7
Regulating reservoirs in the second-level canals	0.0
Communications for the second-level canals	1.1
General conditions for the second-level canals	1.6
Operation of the second-level canals	2.1
Third-level canals	
Cross-regulator hardware (third-level canals)	1.7
Turnouts from the third-level canals	0.7
Regulating reservoirs in the third-level canals	0.0
Communications for the third-level canals	0.9
General conditions for the third-level canals	1.4
Operation of the third-level canals	1.8

Note: Maximum possible value = 4.0; minimum possible value = 0.0.

Part of the reason for the inadequate quality of service is related to the hydraulic characteristics of the cross-regulators (manual undershot gates) in secondary and subsecondary canals. In addition, in low-flow conditions, which occur regularly in winter and spring, the structured design (proportional flow division) in the tertiary canal system in Stage III – Phase 1 is not compatible with providing good service.

There was only a marginal improvement in the service provided by the tertiary canals in the most recent command area development (Stage III – Phase 1), even though substantial investment was made in training farmers and promoting the use of proportional flow dividers. The future planning for the next phases of Stage III must address the constraints associated with the structured design at low-flow conditions.

Most of the water measurement structures in the project are relatively inaccurate, and the current monitoring activities have not been integrated into an effective operation plan. For example, operators in some areas are recording measurements for rated cross-regulators even though they should be concerned only about maintaining constant water levels.

Chapter 5
Mapping the capacity of a canal system

This chapter focuses on the characteristics of the canal system that are of operational importance with respect to their various functions: hydraulic properties, such as conveyance capacity, water-level control (regulator), diversion capacity (offtake) and division capacity (proportional dividers), and storage capacity. It also discusses the functions of some specific structures, including drops, syphons, and escapes/spills. Flow conditions and hydraulic principles for irrigation canals and structures are reviewed briefly in Annex 1.

For effective operation of any irrigation system, managers must know the capacity of the structures within their CA. Therefore, system capacity needs to be assessed (or re-assessed) properly at each main structure, considering the main functions (storage, transport, diversion, etc.).

The RAP evaluates the canal capacities of structures in the system in general and it provides a first indication of where capacity problems may exist. However, the system manager requires a greater and in-depth understanding and knowledge of all the structures and their capacities in order to enable improvements in routine operation and management.

THE MAIN ELEMENTS OF SYSTEM CAPACITY AND FUNCTIONALITY

System capacity and functionality is assessed for the infrastructure as a whole and for each of the physical structures with respect to four main features:
- functionality: whether the infrastructure/structure is functional or not;
- capacity: if functional, what the actual flow capacity of the structure is with regard to its function (possibly compare with design and/or ideal target);
- ease of operation: how easy the structure is to operate;
- interference: whether the structure has adverse impact on the behaviour of other structures (specifically for hydraulic structures).

Table 8 presents an example of the criteria that can be used to assess these elements of system capacity and functionality.

Functionality

This indicator is straightforward and expresses the ability of a structure in fulfilling its intended function. This intended function could be either the original, current targeted one or for improved services. The idea here is that rehabilitating everything back to the original design may neither be the best solution nor a desired one. Therefore, it is best to assess the functionality of a structure according to its intended use. It is often a question of yes or no.

Too many dysfunctional (Plates 11 and 12) or broken structures may indicate a problem of bad maintenance and budgetary and institutional constraints. Thus, provision for maintenance of the structures is a critical issue for modernization plans.

TABLE 8
Criteria related to system capacity and functionality

Criteria	Characteristics
Functional	yes – no
Capacity	nil – reduced – as design – not matching current needs
Ease of operation	easy – difficult – cumbersome – costly
Interference	yes – no

Plate 11
Dysfunctional cross-regulator along a main canal in Sindh, Pakistan – radial gates are blocked fully open as they cannot be closed because of design problems.

Plate 12
Dysfunctional cross-regulator (spindle missing) along a secondary canal, SMIS, Nepal.

Capacity

System capacity needs to be analysed by examining the actual situation compared with current needs, and, additionally, by evaluating them against design assumptions and the as-built condition. Problems with system capacity may be related to the following aspects:

➤ The needs of users may have changed since the construction phase. For example, in the SMIS (Nepal), the intake flow to the service area has increased from 45 m³/s to 60 m³/s, and, therefore, the conveyance required along the main canal has increased, creating localized capacity problems. The desired, but not yet achieved, level of service may have evolved as users wish to move away from crops such as rice that are suitable under proportional division to diversified crops requiring more flexible water deliveries.

➤ Some physical interventions may have modified, intentionally or otherwise, the capacity of structures in the canal system. For example, the construction of measuring weirs downstream of offtakes may have created a reduction in their diversion capacity, especially where the parent canal is run at low levels, which further exacerbates their operational sensitivity.

➤ Erosion and/or sedimentation may have generated a degradation of the physical capacity where maintenance has not been regular and adequate.

➤ Some interventions (illicit operation and vandalism) may have generated a degradation of the physical capacity of the structure, such as missing or broken gates.

Ease of operation

Ease of operation can be described by two factors:

➤ Access: structures that are remote or difficult to access require more time (travel) and resources in order to make adjustments or to maintain.

➤ Ease of operation: some structures may be physically difficult (Plate 13) or impossible to operate either by design or by lack of proper maintenance (rust, missing parts, etc.).

The RAP (Chapter 4 and Annex 3) provides a good assessment of the ease of operation of cross-regulators and offtakes.

Interference

Hydraulic interactions between irrigation structures are normal. In fact, some structures are set by design to interact in order to produce the expected effect on water flows. However, an issue arises where undesirable hydraulic disturbances affect the performance of other structures.

This undesirable interference can occur for several reasons:

➤ by design (the wrong type of structure or the wrong size/setting);
➤ by lack of maintenance (modifying water-level conditions at peak discharge);
➤ by changes in flow conditions;
➤ by construction of new structures (adding measurement structures).

ASSESSING SYSTEM CAPACITY

There are three ways of assessing the physical capacity of a canal system:

➤ inspection of the canal by a qualified evaluator (visual assessment);
➤ measurement/assessment of the capacity;
➤ interviews with managers and local operators.

Visual assessment, interviews with managers and local operators, and checking the existing records usually give a good indication of the system capacity. However, where needed, measurements could also be made at selected points for verification purposes and for establishing correct values and magnitudes.

Plate 13
A gated structure that is extremely difficult to operate – two operators are required to make any gate adjustment – Sindh, Pakistan.

Plate 14
Conveyance capacity stretched beyond the limit, Tadla, Morocco.

CONVEYANCE CAPACITY

Deferred maintenance and lack of desilting of canals is the most common cause of their reduced carrying capacity. In addition, canals are sometimes used as dumping sites for rubbish, particularly where they cross cities and urban settlements. Plates 14 and 15 present some cases where the conveyance capacity of the canals and drains has been compromised for different reasons.

The conveyance capacity of canals can be assessed readily through inspection, as in the RAP (Chapter 4). In order to obtain estimates of the magnitude of changes in carrying capacity, the checking of existing records and interviews with the managers and local operators should be of help.

Plate 15
Reduced carrying capacity of a canal because of sedimentation, Fuleli, Pakistan.
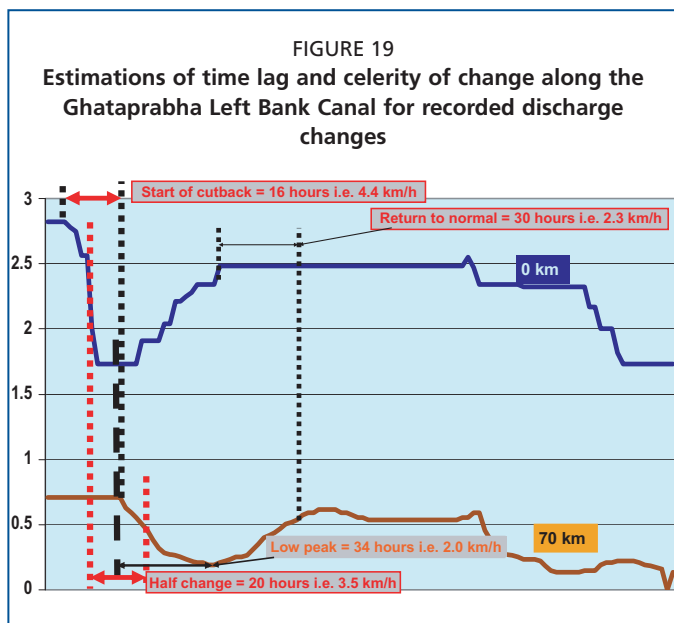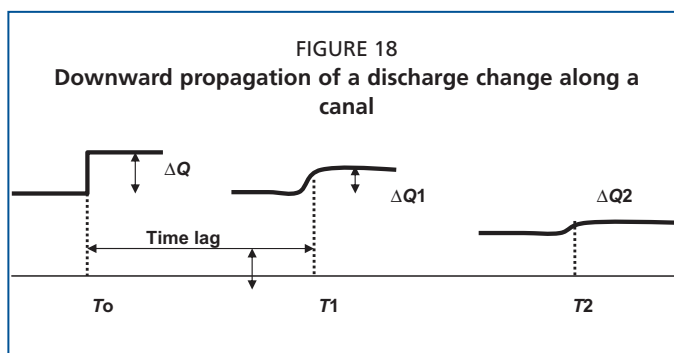
FIGURE 18
Downward propagation of a discharge change along a canal

FIGURE 19
Estimations of time lag and celerity of change along the Ghataprabha Left Bank Canal for recorded discharge changes

TRANSFER CAPACITY AND TIME LAG

As seen previously for the options for operation (Chapter 3), the time lag between a change upstream of the canal and its conversion at a downstream point of the canal is a critical feature of an open-channel network.

The celerity of discharge transfers along a canal is an important feature of the infrastructure capacity that should be known by the manager in order to design appropriate operation plan.

The relevant characteristics of discharge transfer are:

➢ time lag for each location, or the celerity of transfer of changes (kilometres/hour);

➢ the attenuation factor expressing the way the discharge change is modified or not when moving downward (Figure 18) – this characteristic is linked to the sensitivity of the structures, and it is discussed in Chapter 6.

Assessing time lag or celerity of change propagation can be done through the analysis of discharge records along a system in the absence of manipulation of cross-regulators. Figure 19 presents such an analysis for the Ghataprabha Left Bank Canal (GLBC) in Karnataka, India, between headworks and km 70. Estimations vary from 2 to 4.4 km/hour depending on the nature of changes considered (reduction or increase) and the criteria used for assessment (starting point of the change, low peak of change, or mid-term change).

The cut-off starts travel faster than the return to normal (increase).

SUBMERGENCE

Where irrigation structures are submerged (Plate 16), the flow through the structure is also controlled by the flowing conditions downstream of the structure. This happens because of the subcritical flow conditions (Box 2) downstream of the structure.

Submergence is not necessary undesirable, but it is necessary to know the consequences of submerging a structure. These can be:

BOX 2
Flow definitions

Froude number: The Froude number is a dimensionless parameter that measures the ratio of inertia force to the gravity force. It determines the "flow regime", also called the flow condition. The Froude number can be calculated as:

$$F = \frac{V}{\sqrt{gh_m}}$$

where: F = Froude number; V = velocity (m/s); g = gravity acceleration (9.8 m/s^2); and h_m = hydraulic mean depth (m).

Critical flow: Critical flow occurs when F = 1. Critical-flow condition occurs when the energy of the flow velocity is at its minimum. It does not occur naturally, and it is a transition point from supercritical flow to subcritical flow, at which point a hydraulic jump occurs.

Supercritical flow: Supercritical flow occurs when F > 1. It is characterized by high velocities and low water depths, and is also called shooting flow. Supercritical flow basically means that the waves cannot travel upstream.

Subcritical flow: Subcritical flow occurs when F < 1. It is characterized by relatively slow velocities and high depths, which implies that it can be influenced by the downstream flow or "tail-water". In general, unlined canals are designed for subcritical flow in order to prevent scouring.

Free flow: A condition of flow through or over a structure where such flow is not affected by the tail-water. The flow is governed only by the upstream conditions. This flow condition corresponds to supercritical flow, when F > 1.

Submerged flow: A condition of flow through or over a structure where such flow is affected by existence of tail-water and the structure is drowned. This flow corresponds to subcritical flow when F < 1.0. The flow is governed by upstream and downstream conditions.

Head (over a structure): The elevation of the hydraulic grade line at the structure (plus the velocity head). The energy head may be referred to any datum: bed bottom for open channel flow; weir crest for overflow structures; or level of orifice axis for undershot gates. In submerged conditions, head is approximated as the difference between upstream and downstream water level

➢ Reduction in the flow capacity as a result of the reduced head at the structure.
➢ Modification of the behaviour of the structure. Flow becomes dependent on both upstream and downstream water level; discharge perturbations are propagated downward, water-level perturbations are propagated upward.
➢ In some cases, such as a proportional division box, submergence can change the hydraulic properties of the structure and practically make it dysfunctional.

The water level downstream of a gate depends on the flow rate, the

Plate 16
Offtake with downstream submerged conditions.

Plate 17
Offtake with free-flow downstream conditions.

FIGURE 20
Undershot and overshot flow conditions in an irrigation structure

downstream conditions, and any adjustments to the nearby downstream structure.

Structures that are affected by submergence in different conditions are:

➤ Offtakes equipped with measuring devices (weir or flume) downstream of the structure at the entrance of the dependent canal. The submergence for these structures depends on the available head across the headgate.

➤ Offtakes serving a dependant canal under the influence of a backwater effect from a downstream structure.

➤ Offtakes or regulators for which the submergence is locally caused by normal flow conditions.

➤ Regulators under the influence of the next downstream regulator.

DIVERSION CAPACITY

The diversion capacity is the capacity to divert from the main canal to a dependent canal or to a delivery point a specific targeted flow, which can range from zero when the diversion structure is closed to the maximum discharge capacity at this point.

Individual structures of canal systems can be classified into two main hydraulic categories: the orifice type (also called undershot); and the overshot type (Figure 20). For both categories, two types of flows can be distinguished with different hydraulic laws and consequent operational demands. Table 9 provides an overview of undershot and overshot structures, examples and basic hydraulic characteristics.

The flow is said to be free when it passes through a supercritical flow stage that dissociates the downstream and the upstream of the structure (Plate 17). Only the water head exerted by the supply level on the axis of the gate controls the discharge through the structure. These structures are called semi-modular.

The flow is said to be submerged when the downstream water level is above the elevation of a designated point (sill or other). Under this condition, the head downstream of the gate also affects the flow passing through the structure. These structures are called non-modular.

TABLE 9
Typology of water control and discharge regulation structures according to hydraulic characteristic in irrigation systems

Hydraulic category	Examples	Type of flow	Modularity	Discharge determined by
Undershot/orifice	Sluice gates, radial gates, baffle distributors	Free flow	Semi-modular	$H_{US} - H_{Orifice}$
		Submerged	Non-modular	H_{US} & H_{DS}
Overshot	Broad-crested weirs, sharp crested weirs, duck-bill weirs, flumes	Free flow	Semi-modular	$H_{US} - H_{Crest}$
		Submerged	Non-modular	H_{US} & H_{DS}

Modular structures, providing a constant delivery at an offtake irrespective of the water level in either the parent or the dependent canal, have caught the imagination of engineers for centuries. There are no practical manual examples of these structures. However, some automated structures, e.g. step-by-step distributors ("module a masque" by Neyrpic distributors) have been developed approximating modular flow within a certain range and limitations. This means that for non-proportional systems water-level control is one of the most important targets of canal operation. The hydraulic laws governing the most common discharge regulation structures are outlined below.

Plate 18
Dysfunctional proportional divider (Nepal) with different downstream conditions: free-flow (main branch left) and submerged (small branch right). The capacity of the structure with respect to proportional division is at stake.

FLOW DIVISION IN PROPORTIONAL DISTRIBUTION

Proportional-flow division structures distribute the total flow proportionally over a number of downstream outlets, according to the command area. The proportional structures do not need to be operated if the incoming flow changes; the flow in the downstream canals/outlets will also change. The flow is governed by the upstream head in the canal as long as the flow condition downstream is free flow. However, the downstream cross-section affects the flow division if the structure is submerged (Plate 18).

When a drop in water level occurs, proportional division structures can be highly accurate in distributing the flow proportionally and are not manipulated easily. Proportional division is always more reliable when free-flow conditions occur downstream. However, ungated proportional structures are not flexible in operation.

In most canal systems, division structures are supplemented with gated diversion structures. This requires more attention but can cater for more flexible or rotational operation.

Division capacity is assessed against proportionality through the indicators of hydraulic flexibility, which is defined as the ratio between the relative change in offtake flow to the relative change in ongoing flow:

$$F = \frac{\Delta q / q}{\Delta Q / Q}$$

where: F = hydraulic flexibility; q = offtake flow, or flow in dependent canal at offtake structure; and Q = ongoing flow, or flow in parent canal.

The flow is proportional if $F = 1$. Hydraulic flexibility is discussed further in Chapter 6.

WATER-LEVEL CONTROL

The main function of water-level control structures, also called check-structures or cross-regulators, is to maintain a stable water level. In an upstream controlled canal, these structures are located just downstream of offtakes and could be of the "overflow"

or "undershot" type. The, *Q-h* relationship of water-level regulators is similar to those of discharge regulators. Overshot structures are more suitable for water-level control because they are less sensitive to variations in water levels as compared with undershot structures. The reason that makes overshot structures less suitable for discharge control.

Given that the demand for irrigation water is not constant over time, and because of other reasons described above, canal flows fluctuate throughout a canal system in terms of both time and space. The consequence in terms of operations and for providing good service is that without well-designed water-level control structures situated at the correct place, water depths along canals vary considerably and so does the available head at diversion points. As the discharge through an offtake is related to the available head in the parent canal, which is dependent on the water level, water-level control is important to guaranteeing good service.

STORAGE CAPACITY

An important capacity feature of canals is storage. For dynamic operation, the bulk of the water in canal reaches can be used for rapid variation of delivery within these reaches. Canal storage capacity increases with the size of the canal (wetted cross-section multiplied by the length of the canal section before the regulator at the end of the pool/canal reach). Canal reaches can also be used to store rainwater to be delivered later. Where the canal system is designed with large channels and sufficient freeboard, this capacity can be used in an optimal fashion. However, variation in water levels will occur. Storage in canals or in microreservoirs located strategically within the network can be used to fade out turbulence and variations in water levels. In paddy systems, the water levels in the rice fields can also be used as temporary storage for water. However, canals cannot replace proper regulating reservoirs, and their capacities are considerably below the capacities of properly sized regulating reservoirs.

The extent to which canal storage capacity can respond better to variations in supply/needs depends on:

➢ the ability to encroach on freeboard without jeopardizing the canal, which depends entirely on how responsive the water-level and flow control structures are (plus pool hydraulics);

➢ the ability to accommodate high variations in head at critical turnouts (plus or minus normal water level);

➢ the slope of the canal that gives the effective length of the canal reach on which the volume of extra storage depends (high slope means small length and low volume). The effective volume is a prism with the base as the extra sectional area at the cross-regulator;

➢ the density of cross-regulators (high density means more pools to be accounted for).

Generally speaking, the storage capacity within the canal is limited to cover the needs for storing surplus or accommodating deficit for a short period, e.g. a few hours.

CANAL FLOW MEASUREMENT

Often neglected as a critical hydraulic faculty of canal systems, the ability to measure accurately and reliably flows at key locations is critical to providing good service. Water measurement could play an important role in improving operation, service delivery, and water management. It helps improve transparency in water delivery service, thus can lead to better equity in water allocation and distribution.

Similarly to the other structures that convey and distribute canal flows, measurement structures at selected points enable the operator to control the canal system. As with all aspects of canal operation, measurement is about hydraulics as well as management.

The measurement capability of an irrigation system is a combination of good measurement devices and the location of these structures at strategic points within

the system, i.e. at critical branches and service outlets. Identification of important points where water measurement could make a difference in water delivery service and/or operation, e.g. at a point of management change, is critical to the water measurement plan of an irrigation system.

Flow measurement structures must be designed in such a way that *Q–H* relations are clear and that even small changes in discharge are reflected clearly in the changes in the head (this is why a Duck Bill Weir cannot be used as a measurement device – overshot curve in Figure 21). Although the structures and canal hydraulics described above link discharge to head as the most important parameter, regulation devices are almost never designed for or accurate enough for proper flow measurement. In combination with measurement errors (water level/head, gate opening, and hydraulic coefficient of the flow), this means that these formulae can give useful estimates but not great accuracy. Plate 19 shows an extreme example of inaccuracy in assessing water level with a staff gauge in the middle of a canal, far from the canal banks, and unreadable. Proper design and construction is required. Care also needs to be taken when proper measuring devices are designed and constructed, as faulty devices may obstruct the flow in addition to give wrong estimates of discharge and volume. The problem is exacerbated when these structures influence normal flow or are submerged (Plate 20).

FIGURE 21
Discharge–head relationship for overshot and undershot structures

Plate 19
Reading capacity at stake: dysfunctional gauge far from the canal banks and no longer readable, Ghotki Area Water Board, Sindh, Pakistan.

Selection of flow measurement devices

The selection of proper flow measurement devices depends on various project-specific and site-specific factors, such as accuracy requirements, cost, maintenance requirements, range of flow rates, and head loss. One of the most important site-specific technical factors is the head loss as most of the flow measurement devices require a drop in head; such additional head may not always be available, especially in areas with relatively flat topography. Moreover, in some cases, the head used in measuring flow may reduce the capacity of the canal at that point.

Another important consideration in selecting flow measurement devices is the adaptability of these devices to varying operating conditions as most of the irrigation systems deliver water with varying range of flows. The quality of measurement devices

Plate 20
Measurement capacity: submerged flume with no critical section, yielding incorrect measurements GLBC, Karnataka, India.

lies not only in their accuracy, but also in their transparency to operators and users (e.g. a gauge that reads in actual discharges).

Several measuring devices, tools and methods are available. They range from a rough velocity–area method to sophisticated sensors, and they have their advantages and disadvantages. Most flow measuring devices include weirs, flumes, flow meters, current meters, and electronic sensors. All these devices and methods have different accuracy levels (USBR 2001) and corresponding costs and maintenance requirements that must be taken into account when making a decision about the water measurement devices, structure and method. More accurate water measurement devices are needed where these are to be used for billing purposes in order to ensure better equity and transparency. Proper calibration of these devices is critical to achieving reasonable levels of accuracy. The cost of water measurement devices includes not only the initial cost (the price of the device or design, construction and calibration where these devices are permanent structures) but also the O&M cost.

Different flow measurement devices and methods have different maintenance requirements. For example, weirs and flumes require periodic cleaning of the approach channel if the flow contains sediment and debris, and current metering requires not only regular cleaning of the instrument but also of the section of the canal used for measurement. Occasional maintenance of electronic sensors is needed in order to ensure their proper functioning.

The environment in which flow measuring devices operate is critical for their life and operation. This is particularly the case for ones with the moving parts or sensors. For example, acidity and alkalinity in water may corrode metal parts, whereas water contaminants may damage plastic parts. These devices must be compatible with the site environment and should be well protected against vandalism.

MINIMIZING WATER LOSSES

If a canal system were simply a closed network for conveying water (where inflows and outflows are equal), diversions and storage would describe sufficiently the hydraulic parameters for operation. However, canal operators also have to consider water losses in their water management plans. Losses that occur through leaks, seepage and evaporation are important, particularly with earth (unlined) canals. These losses may be in the range of 20–50 percent of total inflow. For example, the design efficiencies considered in the Indus River irrigation system are between 80 to 90 percent along the main and secondary canals and 80 percent along the watercourse, which means losses of 10 – 15 and 20 percent, respectively (Habib, 2004). Although lossess occurring in watercourse was not considerd important at the design stage, field studies show that actual lossess in unlined watercourses are higher – between 20 and 50 percent – than expected (Wahaj 2001).

If these losses are not given adequate consideration, water supplies to downstream users will always be too little, if the water reaches the tail-ends at all. General indications or formulas for water loss cannot be given, and they should be assessed per system. Seepage losses depend on:

➢the characteristics of the soils crossed;
➢the water depth in the canal (load and wetted perimeter);
➢the nature and quality of bed and side-walls (smooth or irregular);
➢the sediment load in the irrigation water;
➢flow velocity;
➢depth to groundwater.

TABLE 10
Seepage loss indications for different soil types

Soil type	Seepage loss (m³/m²/24 hours)
Clay loam	0.15–0.30
Sandy loam	0.30–0.45
Sandy/gravelly	0.45–0.70
Lined/clay	< 0.05

Various methods for measuring specific losses are available:
➢measuring the difference between inflow and outflow for a certain canal section, while keeping the discharge constant;
➢ponding a canal section and measuring the rate of infiltration;
➢using a seepage meter to assess the losses;
➢using an empirical formula with parameters: water depth, infiltration rate, wetted perimeter and length of the canal.

The choice of any of the above-mentioned methods depends on the requirements. For example, where determining the seepage or infiltration in a specific section of the canal is the main objective, then the ponding method is preferable. Where the objective is to establish conveyance losses in a long canal sections, then the inflow–outflow method is better suited. The accuracy of the results also depends on how the tests are carried out.

Seepage losses can be expressed in volume per unit area of wetted perimeter per day or in a percentage for a given canal section (and discharge). Table 10 provides indications of seepage losses for various soil types.

Losses along a canal network do not only result from seepage. They are also the result of management (operation). These losses can be very direct, e.g. operational losses caused by the incorrect setting of gates, lack of gate adjustment over time, etc. They can also be more general, e.g. if the operating organization is not able to target supply to demand. These demands might change gradually (cropping season) or suddenly and locally (owing to precipitation). In proportional and many supply-based systems, the supply cannot be adjusted to specific demands, resulting in spills. Even the canals that supply water with some delivery flexibility need to have spill, which results in some losses, although some of this spilled water could be used downstream. As this concerns management setups rather than hydraulics, this issue is taken up in subsequent chapters.

SEEPAGE ACCOMMODATION / GROUNDWATER RECHARGE

In conjunctive-use systems where groundwater is an important alternative water source for users, the issue of seepage along the canal networks must be considered carefully. Seepage from canals can be a significant problem when too much seepage creates a limitation of the available discharge at the tail-end of the system. However, as far as water management is concerned, seepage might not be a problem in systems where conjunctive use is fully developed.

There are many examples of systems for which groundwater recharge during the peak period of water use is only sustained by seepage and deep percolation. For example, a modernization plan was designed in Cabannes, France, in 1982 specifically considering the seepage and groundwater recharge issue. The upstream part of the scheme was intentionally maintained under surface irrigation, although modernized, whereas the downstream part of the scheme, where orchards were thriving, was converted into a pressurized collective system for drip irrigation, using groundwater. This option was only feasible because of the seepage and percolation from canal water. An accurate water balance was made before engaging the users in the modernization plan.

RECYCLING FACILITIES

Recycling facilities along drainage and streams are key capacity elements that warrant proper consideration in the context of capacity and operation.

SEDIMENT CONTROL

Canal operation should take into account sediment loads in the water. In order to reduce maintenance related to removing excessive sedimentation from canals and structures, two basic strategies can be applied:

➢ collect and dispose of as much as possible of the sediment at the head-end of the system;
➢ convey all or as much as possible of the sediment through the system until the farm level.

The choice between these different strategies depends on many project-specific factors, e.g. sediment amount and type, canal slope, and operation type. The first strategy involves the construction of a sediment trap (stilling basin). Operation requirements are flushing or otherwise emptying the stilling basin at regular intervals.

The second strategy involves maintaining the velocity within certain limits in the entire system. Regime theory and tractive force equations can be helpful in the design stages of an irrigation system. Flexible management of irrigation systems and the maintaining of stable water levels may be problematic in canals with heavy sediment loads. Maintaining a stable water level at different flow rates means that the velocity is highly variable, which may result in sedimentation buildup at control points. Sedimentation problems usually occur just before or after control points, as velocities change at these points.

FIGURE 22
Freeboard in a canal
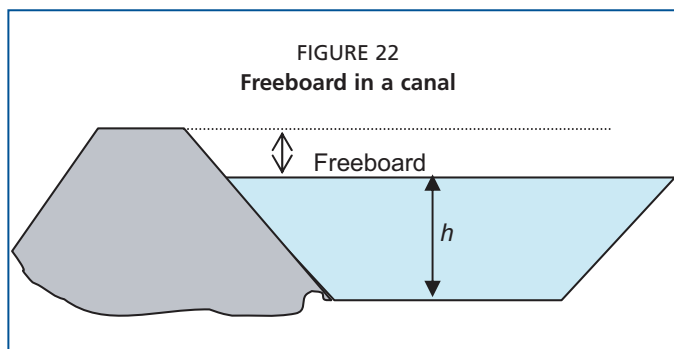
SAFETY

The freeboard is the safety margin between the maximum operational level, defined by the maximum water level at design discharge, and the top level of the canal banks (Figure 22). This freeboard is necessary to prevent overtopping caused by:

➢ temporary excess discharges related to sudden movement of gates (shockwaves);
➢ a strong wind generating waves and a rise in the relative water level;
➢ management/operational errors;
➢ emergencies, such as partial blockage of the canal obstructing normal flow.

As a rule of thumb, the freeboard should be at least 0.15 m or $1/3*h$, whichever is greater. The freeboard should never be used as extra storage as it provides a safety margin for operation.

Plate 21
An operator using an old communications system in the Nara Canal, Sindh, Pakistan.

TRANSPORT AND ROADS

It is critical for irrigation managers to have access to the whole canal infrastructure and not only to the cross-regulators. Generally, an inspection road is built together with the main canal. However, often, the maintenance of these roads is not done properly, the use of these roads by population and for the transport of goods is often intensive, and the capacity of transport is reduced in terms of travel time from one point to the other, and in terms of capacity to dispatch machinery quickly whenever urgent works are required.

COMMUNICATIONS

This is an important aspect of management, which has been often overlooked in the past in many systems (Plate 21). In the past communication was mainly done through telegraph, telephone, and wireless. Today, the situation has improved dramatically as more and more rural areas have become equipped with mobile phone facilities.

Chapter 6
Mapping the behaviour of irrigation systems – sensitivity

How a canal system behaves after the structures have been set for a particular water distribution plan and left without attendance is the central focus of sensitivity analysis. It is important to know how structures react or behave under perturbation (Box 3) in order to be able to plan for adequate actions/responses.

Steady-state water profiles along a canal are a management target. However, they are rarely achieved in practice. Perturbations are permanent features of irrigation canals as a result of upstream operation itself or of changes in inflows/outflows at key nodes.

This chapter analyses the behaviour of irrigation structures through the assessment of their sensitivity: (i) for each main type of structure taken in isolation; (ii) for a combination of associated structures; and (iii) at the reach and subsystems levels.

Finally, the sensitivity of subsystems is linked to the performance achieved with respect to the control of the water depth.

SYSTEM BEHAVIOUR UNDER PERTURBATION

> **BOX 3**
> **Definitions of terms used in sensitivity analysis**
>
> **Perturbation:** A significant change in the flows occurring along a canal network as a result of external variations in inflows or outflows, changes or adjustments in the settings of structures, or transient flow during distribution changes. Perturbations can be either positive or negative, representing an increase or decrease in discharge, respectively.
>
> **Structure sensitivity:** The ratio that a rate of change in output of a structure bears to the rate of change in the input. Input and output are either water level or discharge, depending on the function of the structure. Sensitivity is not a static hydraulic parameter of a structure. It varies with time (through wear and tear) and with the exerted head.
>
> **Hydraulic flexibility:** The ratio that the rate of change in discharge from the outlet bears to the rate of change in discharge of the parent canal.
>
> **Head (over a structure):** The elevation of the hydraulic gradeline at the structure (plus the velocity head). The energy head may be referred to any datum: bed bottom for open-channel flow; weir crest for overflow structures; or level of orifice axis for undershot gates. In submerged conditions, head is approximated as the difference between upstream and downstream water level.

Perturbations of discharge and of water levels along a canal are the norm rather than the exception. Perturbations are propagated and transformed downstream. Therefore, what appear to be minor differences at the head-end may result in serious deviations from the planned operation or even chaos through overtopping of canals, while others fall dry. The hydraulic analysis of an irrigation system cannot be limited to a summing-up of all static design capacities, it should also deal with the behaviour of the system towards perturbations, causing inaccuracy and unequal distribution that is compounded at all levels.

Predicting the behaviour of structures under perturbation is necessary in order to be able to implement adequate responses. The behaviour of the main types of irrigation structures is analysed through assessment of their sensitivity. In short, sensitivity tells how a structure reacts to a variation in input.

Studies on sensitivity and hydraulic flexibility analysis were initiated a long time ago with the emphasis on delivery structures by Mabub and Gulati (1951), and further

FIGURE 23
Input–output analysis

work has been carried out by Horst (1983), Albinson (1986), Ankum (1993) and Renault (1999).

SENSITIVITY ANALYSIS

Sensitivity analysis offers a practical method for analysing fluctuations in irrigation systems without having to resort to the difficulty of unsteady-flow hydraulics. It focuses on the behaviour of system elements (structures, nodes, canal reaches, and subsystems) under various inputs. Basically, it is a simple "what if" analysis, i.e. "what would be the change in output if the input change were such?" (Figure 23).

Thus, a sensitivity approach considers two different steady states, each of them corresponding to a slightly different value of the input. The sensitivity of an irrigation structure or a system is then defined as the ratio of the relative or absolute variation in output to the relative or absolute variation in the input follows:

$$\text{Sensitivity} = \frac{\text{Variation in output}}{\text{Variation in input}} \qquad (1)$$

Hence, structures and systems with a high sensitivity show a large variation in output to a small variation in input and vice versa.

The sensitivity of a given structure gives an idea of how it will react when the conditions change, for example:
  ➢ What will be the change in discharge through an offtake when the water level in the parent canal changes by 10 cm?
  ➢ What will be the change in water level at a cross-regulator when a variation of 10 percent in the canal flow rate occurs?

At the system level, knowledge of the sensitivity of irrigation structures is fundamental to answering the following questions:
  ➢ What is the propensity of the system to be affected by fluctuations?
  ➢ What is the propensity of the system to create fluctuations?
  ➢ How is performance affected by the sensitivity of the system?
  ➢ How can more appropriate and simplified operational procedures be developed?
  ➢ Where should managers concentrate efforts to ensure that no unpredictable deviation affects the water balance?
  ➢ Where should managers focus data collection?
  ➢ How can sensitive sections of the infrastructure be used to store unexpected surpluses of water (regulate perturbations)?
  ➢ What are the places where water scarcity is likely to be experienced first?

Highly sensitive structures, generating or amplifying fluctuations, are more difficult to manage than less sensitive structures. They require more frequent and detailed attention. On the other hand, they might be useful for information collection as they react to and can detect small variations. In addition, as regards the management of surplus water, they can help to identify possible locations to divert positive perturbations to.

Sensitivity is introduced in a step-by-step manner. The following sections each focus on a different level of sensitivity analysis: structures, nodes, reaches and subsystems (see also appendix 2 for more details). Analysis at the reach and subsystem level is important as structures interact and convey their behaviour downstream or upstream. However, analysis of single diversion points gives important insights in local performance and operation requirements of specific structures.

OFFTAKE SENSITIVITY
Sensitivity indicator for diversion

The sensitivity of any structure must be defined with respect to its function. Thus, the sensitivity of a diversion structure, an offtake, refers to the function of generating an assured discharge in a dependent canal from a certain water level in the parent canal (Figure 24).

A variation in output refers to the relative variation in discharge through the offtake ($\Delta q/q$), depending on the input, i.e. the variation in water level (Box 4) in the parent canal (Δh):

$$S_{Offtake} = \frac{\Delta q / q}{\Delta h} \quad \text{(unit: m}^{-1}\text{)} \quad (2)$$

where q refers to discharge through offtakes.

For example, a sensitivity indicator of 1 m^{-1} indicates that a change of 0.1 m in water level in the parent canal generates a discharge variation (q) through the structure of 0.1, or 10 percent.

Use of the offtake sensitivity indicator
Estimating discharge change for a given water-level control

Sensitivity indicators can be used to estimate the reaction of an offtake when the water depth (Δh) in the parent canal varies (Figure 25).

Where the sensitivity of an offtake is known, the relative variation in discharge experienced at a diversion structure (offtake) can be computed as equal to the sensitivity indicator multiplied by the variation in water level (Equation 2).

$$\Delta q / q = S_{Offtake} \cdot \Delta h \quad (3)$$

For example, for a diversion structure with a sensitivity = 2, a variation of 10 cm in the water level upstream of the offtake will be translated into 20-percent variation in discharge through the offtake. Further indicative figures are given in Table 11.

A structure with a sensitivity indicator $S < 1$ is considered low, while $S > 2$ indicates a highly sensitive structure. A sensitivity of 0 is rare as it would refer to modular structures (i.e. not influenced by variations in upstream water level). Offtakes equipped

FIGURE 24
Input and output for offtake structures

Water level (h) → Offtake funtion: Translate water level in parent canal into dicharge in dependent canal. → Discharge (q)
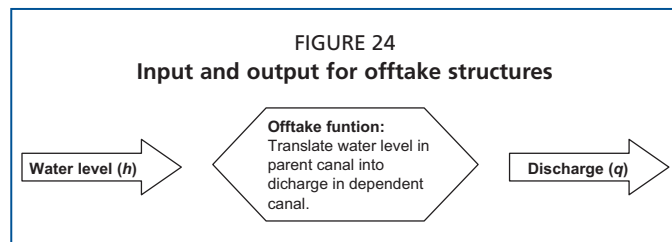
BOX 4
The issue of relative or absolute variation of water level

The question often arises why it is suggested here to use (Δh) in previous equations of sensitivity instead of the relative value ($\Delta h/h$), which would make the indicator dimensionless (an advantage).

However, while mathematicians may like relative values, managers prefer the absolute variation for h for practical reasons. Most of the time, the management variable that is used to define the target for control is (Δh), and rarely ($\Delta h/h$).

For example, an instruction from a manager to a gate operator would probably be: "You should operate the regulator when the deviation in water level (Δh) from the local nominal target exceeds 10 cm." This instruction is straightforward. The instruction would be much more difficult to handle in relative terms: "You should operate the regulator if the relative deviation of water level from target exceeds 5 percent."
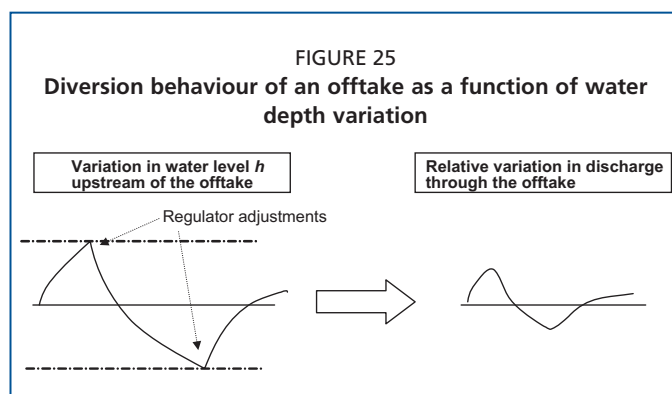
FIGURE 25
Diversion behaviour of an offtake as a function of water depth variation

Variation in water level h upstream of the offtake

Regulator adjustments

Relative variation in discharge through the offtake

Water-level variation in parent canal	Sensitivity indicator ($S_{Offtake}$)		
	0.5 m^{-1} **Low**	1 m^{-1} **Medium**	2 m^{-1} **High**
	(%)		
+/-0.05 m	2.5	5	10
+/-0.10 m	5	10	20
+/-0.20 m	10	20	40

with pumping/lifting devices are somewhat insensitive to water-level fluctuations.

Estimating tolerance on water control

Offtake sensitivity is not only used for assessing the discharge variations for different water levels. It could also be used to set water-level control requirements for appropriate service delivery. On the basis of Equation 2, the permissible variation in water level can be derived:

$$\Delta h_{permissible} = \frac{\left(\Delta q / q\right)_{set}}{S_{Offtake}} \quad \text{(unit: m)} \tag{4}$$

For example, in a hypothetical system, the agreed service discharge is q ±10 percent. With a known $S_{Offtake}$, this requirement can be translated into operational requirements concerning the water level in the parent canal. If $S_{Offtake}$ is 2, the permissible variation in water level (Δh) is $\Delta q/q$ divided by $S_{Offtake}$ = 0.1/2 = 0.05 m. In order to guarantee a good service to users, water levels in the parent canal should not exceed this margin of h ±5 cm.

Sensitivity indicator for conveyance at a diversion point

An important effect of the variation in diverted discharge through the offtake is the resulting variation in discharge in the parent canal. In other words, a fluctuation in water level Δh generates a variation in the diverted discharge (Δq), which in turns provokes an equivalent opposite variation in the parent canal discharge ($-\Delta q$). Depending on the ratio q/Q (Q refers to the discharg in the parent canal), this perturbation might or might not be noticeable in the parent canal downstream of this diversion point. This is why high discharge offtakes even with low sensitivity can have a large impact on perturbation along the main canal. This aspect can be formalized through a sensitivity indicator for conveyance, expressing the relative variation in the main canal discharge as a function of variation in water level:

$$S_{Conveyance} = \frac{\Delta Q / Q}{\Delta h} \quad \text{(unit: m}^{-1}\text{)} \tag{5}$$

As $\Delta q = \Delta Q$, this equation can be rewritten as:

$$S_{Conveyance} = \frac{\Delta q / Q}{\Delta h} = \frac{\left(\Delta q / q\right) \cdot \left(q / Q\right)}{\Delta h} \quad \text{(unit: m}^{-1}\text{)} \tag{6}$$

which is simplified after replacing the sensitivity indicator of the offtake:

$$S_{Conveyance} = S_{Offtake} \, q / Q \quad \text{(unit: m}^{-1}\text{)} \tag{7}$$

Where $S_{Offtake}$ is used to determine the impact of perturbations to the offtaking canal (high $S_{Offtake}$ means high impact), the indicator for $S_{Conveyance}$ is used to determine the impact of the fluctuations in the offtaking canal on the main system.

For example, at a diversion node, the ratio of q/Q is 1/3 (high). An offtake sensitivity of 1 (average) gives a 10-percent offtake discharge variation for 10 cm of fluctuation in water level. The main canal, carrying two-thirds of the discharge experiences a 5-percent discharge variation downstream of the offtake. This is an important fluctuation

TABLE 12
Sensitivity for conveyance – figures and indicators

$S_{Offtake}$ (m^{-1})	Different values of q/Q				
	1/100	1/50	1/20	1/6	1/3
0.5	0.005	0.01	0.03	0.08	0.17
1	0.01	0.02	0.05	0.17	0.33
2	0.02	0.04	0.10	0.33	0.67
Sensitivity for conveyance		Low	Medium	High	
Indicator		< 0.05	0.05–0.1	> 0.1	

for a main canal. The opposite is true, i.e. highly sensitive offtakes diverting only a small fraction of the discharge will have little influence on the main canal.

The impact of the behaviour on the main system is related both to the sensitivity indicator for diversion and to the relative magnitude of the diversion (*q/Q*). Some indicative figures and indicators are given in Table 12.

Assessing offtake sensitivity indicators

There are three ways to assess the sensitivity of irrigation structures:
- ➢ on-site measurements;
- ➢ analysis of historical data;
- ➢ use of hydraulic formulae together with geometrical data.

On-site measurements

Direct measurement of the sensitivity indicator for an offtake can be achieved by generating a variation in head (Δh) in the parent canal and measuring the corresponding variation of discharge (Δq) through the offtake. The sensitivity indicator is then derived directly from Equation 2.

Analysis of historical data

In situations where water-level, setting and discharge data are available for a long period of time, it is worth conducting a data analysis in order to determine the variation in discharge (Δq) generated by water-level changes only (Δh). Again, the indicator is then given by Equation 2.

Sensitivity from hydraulic formulae

The value of the indicator given by Equation 2 can be computed from the equation of the flow through the structure. A generic equation of the flow through the structure of the following form is assumed:

$$q = M (\text{head})^{\alpha} \tag{8}$$

where:
- ➢ *M* is a value independent of the head exercised on the structure. *M* depends on the shape, size and hydraulic coefficients of the flow through the structure.
- ➢ head is the head exercised on the structure (water level upstream minus the water level downstream if the structure is submerged, or minus a level of reference taken as the crest level for overshot structure or the orifice axis for undershot if the structure is not submerged).
- ➢ α is the exponent in the relevant hydraulic equation for flow; α equals 1.5 for overshot flow and 0.5 for undershot flow.

Taking the logarithm derivative of Equation 8 yields:

$$\Delta q / q = \alpha \frac{\Delta \text{head}}{\text{head}} \tag{9}$$

TABLE 13
Overview of offtake sensitivity indicators

Structure	Variable studied	Definition	Geometrical formulation	Approximate formula (ignoring submergence)
Offtake (orifice)	Offtake discharge q as a function of the fluctuation in the supply water level (Δh)	$S = \dfrac{\Delta q / q}{\Delta h}$	$S = \dfrac{0.5}{h_E}$ h_E (head equivalent) includes effect of submergence	$S = \dfrac{0.5}{head}$ The "head" variable is the difference in head exerted on the structure ($h_{US} - h_{DS}$)
Offtake (overshot)			$S = \dfrac{1.5}{head}$	Overshot offtakes are not frequent because they are highly sensitive

FIGURE 26
Sensitivity for a diversion structure as a function of head for two types of flows (overshot and undershot)
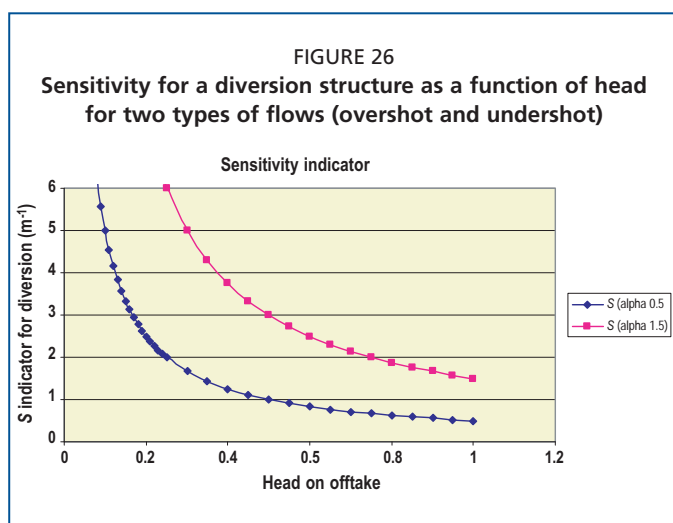
from which the value of the sensitivity indicator is identified as:

$$S = \frac{\alpha}{head} \quad \text{(unit: m}^{-1}) \quad (10)$$

When the structure is submerged, the derivative of Equation 8 cannot be made as simple as presented here. However, the generic approach captured through Equation 10 is sufficient to give a rough estimate of the sensitivity. One decimal precision is not required here, it is necessary to know whether the sensitivity is about 0.5, 1, 2 or 4.

The sensitivity indicator (Table 13) is basically dependent on two factors:

➢ the head exercised on the structure: difference between water levels upstream and downstream of the offtake;

➢ the nature of the flow through the structure expressed: at equal head, overshot structures are three times more sensitive ($\alpha = 1.5$) than undershot structures ($\alpha = 0.5$) to changes in water level (Figure 26).

It should be remembered that sensitivity is not a static hydraulic characteristic of a specific structure. Operation at different heads gives different sensitivity indicators.

REGULATOR SENSITIVITY
Sensitivity indicator for water-level control

The water-level sensitivity along the canal, at a cross-regulator or at any other section, is expressed as the variation in water level (output) resulting from a relative discharge variation (input), as shown in Figure 27.

FIGURE 27
Input and output for a cross-regulator

Discharge (Q) → **Regulator:** Translate a range of discharges into a relatively stable water level. → Water level (h)
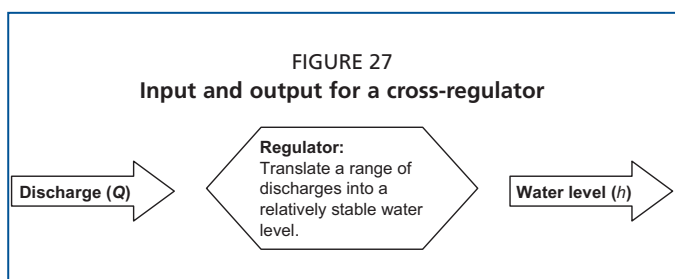
As the function of cross-regulators is conceptually the opposite of the function of offtakes (maintaining a constant water level for varying discharges vs maintaining a constant discharge for varying water levels), the expression for sensitivity of a cross-regulator is the inverse of the expression for an offtake (Equation 2):

$$S_{Regulator} = \frac{\Delta h}{\Delta Q / Q} \quad (unit: m) \quad (11)$$

In summary, the focus of sensitivity analysis for an offtake is on how a fluctuation in water level is transformed into a variation in discharge. Conversely, the focus of sensitivity analysis for a cross-regulator is on how a variation in main discharge is converted into water-level fluctuation.

FIGURE 28

Variation in discharge in main canal and in water level

Relative variation of discharge (Δ Q/Q) in the main canal	$\Rightarrow$	Variation in water level (Δ h) upstream the regulator

TABLE 14

Water-level variation for various values of sensitivity and discharge perturbations

Relative variation in canal discharge	Sensitivity indicator ($S_{Regulator}$)		
	0.5 Low	1	2 High
	(m)		
+/-0.05 (or 5%)	0.025	0.05	0.10
+/-0.10 (or 10%)	0.05	0.10	0.20
+/-0.20 (or 20%)	0.10	0.20	0.40

Use of the cross-regulator sensitivity indicator

Estimating variation in water level with discharge

Indicators of cross-regulator sensitivity can be used to estimate the change in water level at a cross-regulator (Δh) when main discharge in the parent canal varies (ΔQ) and the regulator is not operated (Figure 28).

When the sensitivity of a cross-regulator is known, the fluctuation in water level is computed as equal to the sensitivity indicator multiplied by the relative variation in main discharge.

$$\Delta h = S_{Regulator} \cdot \frac{\Delta Q}{Q} \quad (unit = m) \quad (12)$$

Thus, a cross-regulator with a sensitivity of 2 will generate a fluctuation of 0.1 m in the water level upstream when a 5-percent variation in canal flow rate occurs. Table 14 presents further indicative figures.

Estimating variation in discharge for a fixed regulator

Cross-regulator sensitivity can be used to determine a permissible range beyond which the regulator should be adjusted. With a set ratio of $\Delta Q/Q$, the permissible Δh can be determined. This Δh can be predicted for a Q_{min} and Q_{max}, giving the range of discharges within which the regulator behaves within acceptable limits.

For example, at the offtake of the hypothetical system from a previous example, the permissible Δh was set at 0.05 m. It is the cross-regulator that should keep water levels within the range $h \pm 5$ cm. For a cross-regulator with $S_{Regulator} = 0.5$, this means that the regulator should be operated when discharge in the main canal varies by more than 10 percent. In this system, variations in discharge of more than 10 percent are rare and, thus, this regulator does not need careful monitoring. However, if the regulator had an S of 4, adjustments would be required for ±1-percent variation in discharge, and it would have to be monitored continuously.

Estimating the frequency of adjustment for a gated regulator

The tolerance to discharge variations can be translated into operational requirements. Highly sensitive cross-regulators (Plate 22) need to be adjusted more frequently than do low-sensitive regulators of the same system. Thus, frequency of operation depends not only on the perturbation experienced by the system, but also on the sensitivity of the structure. In practice, this can be translated into an arrangement in which highly sensitive regulators are checked frequently, e.g. every few hours, while less sensitive regulators can be left without checking for a day.

Plate 22
Example of a highly sensitive cross-regulator – the head is about 2 m, hence the sensitivity indicator is equal to 4.

Detecting variation in discharge
Although highly sensitive cross-regulators are generally to be avoided, they can fulfil a positive function as a control point as well. A sensitive cross-regulator generates relatively large fluctuations in water level for small discharge variations. This feature of the structure can be used to detect relatively small perturbations in discharge along the irrigation canal. Information from this detection point can be used in real-time operational strategies downstream in the system.

Assessing cross-regulator sensitivity

Assessing sensitivity for regulators can be achieved through: (i) direct measurement; (ii) analysis of records; and (iii) hydraulic formulae.

The assessment principles for cross-regulators are the same as those for the assessment of sensitivity for offtakes; the difference lies in the input and output to be measured. Starting with a similar generic equation of the flow (Equation 8) and of the derivative (Equation 9), the indicator is calculated by:

$$S = \frac{head}{\alpha} \tag{13}$$

Table 15 gives an overview of sensitivity indicator.

Overshot structures are less sensitive than undershot structures to variation in discharge, therefore are better suited for water-level control. This is exactly the opposite of sensitivity for diversion. Inversely to offtake, submergence downstream of the regulator tends to increase the sensitivity.

Differential variation on mixed cross-regulators

Some cross-regulators include orifice-type gates in the middle part and overshot weirs on the sides. The crest of these weirs generally defines the target level to be controlled at this point. Thus, these structures differ in their behaviour with the spill. For water level below the weir crest the sensitivity is governed by the central gates (orifice type)

TABLE 15
Overview of regulator sensitivity indicators

Structure	Variable studied	Definition	Geometric formulation	Approximate formula (ignoring submergence
Regulator (orifice)			$S = 2 \, h_c$	$S = 2 \cdot head$ The "head" variable is the difference in head exerted on the structure ($h_{US} - h_{DS}$)
Regulator (weir)	Water level as a function of the relative variation in discharge Q	$S = \dfrac{\Delta h}{\Delta Q / Q}$	$S = \dfrac{head}{\left(\frac{3}{2}\right)}$	$S = 0.66 \cdot head$ Head is equal to water height above weir crest if not submerged

whereas for water level above the crest the sensitivity depends mainly on the effect of the weirs which are much less sensitive. For this type of mixed structure, the sensitivity above crest level is reduced considerably compare to that of below level. Two sensitivity indicators should be defined for a composite structure, depending on whether there is a spill or not (*S+* and *S-*).

The mixed cross-regulator shown in Plate 23, and charted in Figure 29, has a very different sensitivity: for water levels below the crests, the regulator is highly sensitive; *S* is greater than 4 (with the head estimated at more than 2 m) and for water levels above the crests, the sensitivity drops dramatically to very low. This type of cross-regulator should always have water flowing over the weirs in order to minimize the negative consequences of the very sensitive middle gates.

Plate 23
Mixed cross-regulator with undershot middle gates and side weirs, Thailand. The functioning of the regulator is not appropriate – water should spill over the crest.

ACCURACY IN ASSESSING SENSITIVITIES

Canal engineers are often geared towards high accuracy in measurements. Indeed, accuracy is necessary for many aspects of canal operation. For example, for the proper assessment of the conveyance capacity, high accuracy is required. However, for analysing the non-static characteristics, such as the sensitivity of control structures, an indicative figure is sufficient. For adequate

management, the canal operator has to know whether the part of the system under consideration has either very low, low, medium, high or very high sensitivity. An understanding of the principle of sensitivity will already give guidelines for operation improvements. Knowing the exact indicators to ±25 percent is usually acceptable.

THE USE OF SENSITIVITY INDICATORS

In the example shown in Figure 30, sensitivity varies significantly from one cross-regulator to another. In the first section up to CR7, sensitivity is high for both offtakes and cross-regulators. Downstream of CR7, both indicators are rather low.

If the degree of water-level control exercised on the cross-regulators in this system is uniform, then for a fluctuation equal to 0.1 m (±10 cm), the water diverted at each offtake would vary as per Table 16.

The range of discharge variation at the offtake is wide – from 3.5 percent (very precise) to 43 percent (low precision). This should trigger different rules for operating the system.

FIGURE 30
Sensitivity of cross-regulators along the SMIS, Nepal
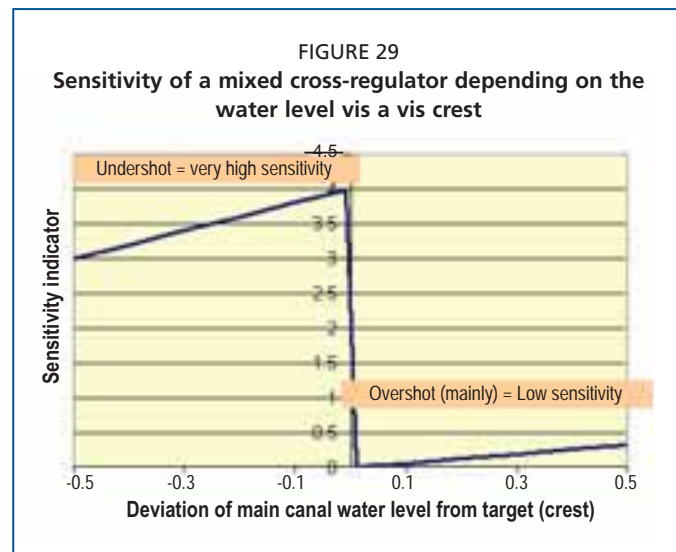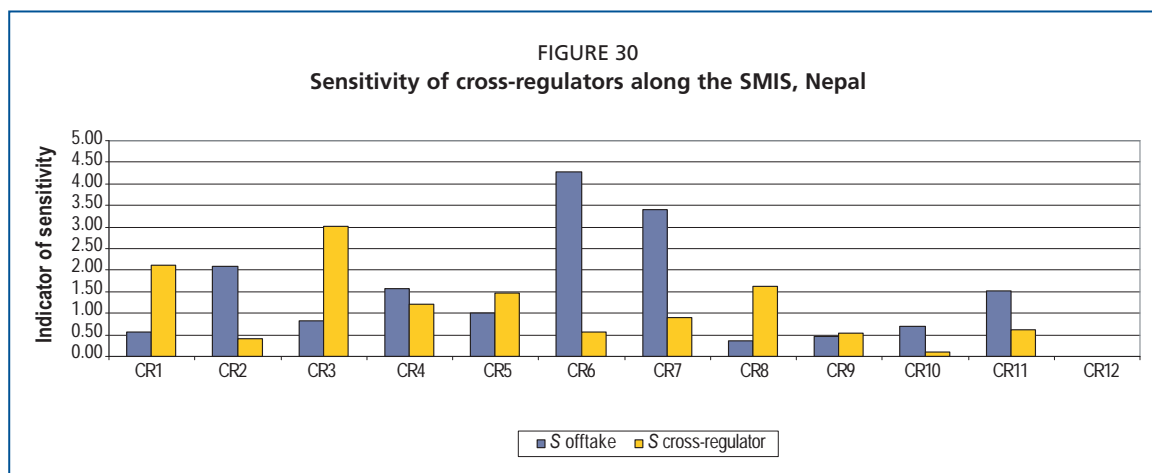
TABLE 16
Variations in discharge experienced by the offtakes along the SMIS main canal for a water level change of 0.1 m

CR	1	2	3	4	5	6	7	8	9	10	11
S offtake	0.6	2.0	0.8	1.6	1	4.3	3.4	0.35	0.5	0.7	1.5
						(%)					
Variation in discharge (+ or - initial setting value)	6	20	8	16	10	43	34	3.5	5	7	15

TABLE 17
Operational rules for tolerance and frequency of adjustment as a function of the sensitivity at the cross-regulator along the SMIS main canal, Nepal

Cross-regulator	Features	Tolerance on water-level control	Frequency of adjustment of the CR
CR1	*S* regulator high (2)	Tolerance 0.1 acceptable	More frequent adjustment
	S offtake low		
CR2	*S* regulator low (0.4)	Reduced tolerance should be sought (±5 cm)	Low frequency sufficient
	S offtake high (2)		
CR3	*S* regulator very high (3)	Tolerance 0.1 acceptable	More frequent adjustment
	S offtake low (0.8)		
CR4 & CR5	*S* regulator average (< 1.5)	Tolerance 0.1 acceptable	Average frequency adjustment
	S offtake average (< 1.5)		
CR6 & CR7	*S* regulator low (< 1)	Reduced tolerance should be sought (±5 cm or below)	Average frequency adjustment
	S offtake high (>3.5)		
CR8–CR11	*S* regulator average or below	Tolerance 0.1 acceptable	Average frequency adjustment
	S offtake average or below		

As a minimum, cross-regulators 6 and 7 should be operated with a tighter tolerance on water-level fluctuations than the others. A reduced target of ±5 cm would reduce the discharge variations at nearby offtakes to 21.5 and 17 percent, respectively.

When looking at cross-regulator sensitivity, CR1 and CR3, with sensitivity indicators of 2 and 3 respectively (Table 17), should also be monitored more carefully.

NODE SENSITIVITY OR HYDRAULIC FLEXIBILITY

Irrigation structures are permanently interacting, influencing one another. Therefore, knowledge of the behaviour of an individual structure through sensitivity indicators is not sufficient for understanding the behaviour of nodes, reaches and subsystems when numerous structures are interfering.

Earlier sections of this chapter examined the sensitivity of independent structures. A first step towards aggregating sensitivities is to look at the nodes in irrigation systems. The flexibility indicator aims to characterize the relative variations in discharge in the dependent and parent canals at diversion or division nodes. Hydraulic flexibility is especially well adapted to ungated systems, which have been developed largely in India, Pakistan and Nepal on the principle of proportionality and which are also in use in the North African oases, spate

FIGURE 31
Hydraulic flexibility along the SMIS main canal, Nepal

irrigation systems and mountain systems fed by unregulated springs. In all systems, hydraulic flexibility analysis provides insight into the distribution and conveyance of perturbations within the system (Figure 31). The flexibility indicator expresses the link between the relative variations in discharge in the parent and dependent canals, and it is equal to:
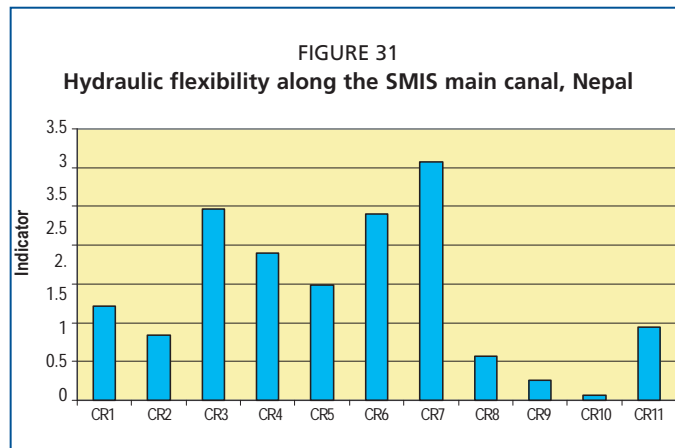
$$F = \frac{\Delta q / q}{\Delta Q / Q} \tag{14}$$

where: Q is the discharge in the parent canal; and q is the discharge in the dependent canal.

Dividing both the numerator and the denominator by the variation in water depth in the parent canal leads to the multiplication of the two sensitivity indicators, i.e. the sensitivity for discharge through the offtake ($S_{Offtake}$) and the sensitivity of the regulator in the parent canal ($S_{Regulator}$):

$$F = \left(\frac{\Delta q / q}{\Delta h_{US}} \right)\left(\frac{\Delta h_{US}}{\Delta Q / Q} \right) = S_{Offtake} \cdot S_{Regulator} \tag{15}$$

For any node in the irrigation system, this hydraulic flexibility indicator can be calculated or assessed. Using the typology of Horst (1983):

➤ $F < 1$ (underproportional): a relative change in discharge in the parent canal generates a smaller relative change in the offtaking canal. Fluctuations are diminished in the offtaking canal.

➤ $F = 1$ (proportional): a relative change in discharge in the parent canal generates an equal relative change in the offtaking canal. Fluctuations are divided uniformly.

➤ $F > 1$ (hyperproportional): a relative change in discharge in the parent canal generates a larger relative change in the offtaking canal. Fluctuations are exacerbated in the offtaking canal.

A comprehensive analysis of various types of configurations of parent and dependent canals and of the resulting flexibility indicators can be found in Albinson (1986).

The ideal value of the flexibility indicator for ungated systems is unity ($F = 1$). In this situation, the discharge, whatever it may be, is divided proportionally over the canals, and a high level of equity is obtained.

In gated systems, proportionality approaches unity when the sensitivity indicators of the offtakes and the cross-regulators are inverse (Equation 15). As a gated

FIGURE 32
Propagation of waves for different flexibilities
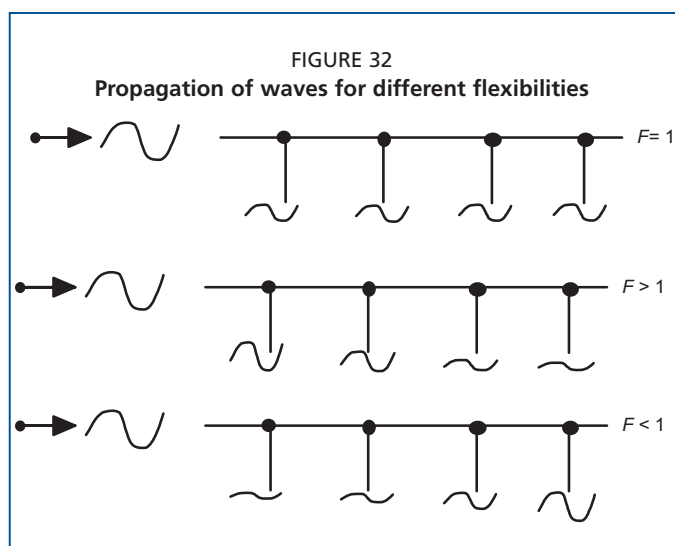
system allows multiple strategies of perturbation management through gate settings, proportional distribution of perturbations is not necessarily the target of canal operation in such a system. Desired delivery flexibility should be discussed in the service agreement and operation plans. Decisions on desired flexibility indicators for gated systems should be taken up at system level as flexibilities at main, secondary, tertiary and quaternary level can add to one another.

REACH SENSITIVITY
Subsystem flexibility analysis

In all systems, nodes can be seen as points of division or diversion, whether the node is equipped with structures regulating the flow or not.

In many gated systems, it is more fruitful to look at reaches, aggregating several offtakes under a cross-regulator influence.

A qualitative global approach to flexibility, studying the propagation of perturbations through a canal or subsystem, has been synthesized by Horst (1983). Aggregation of node flexibilities shows that perturbations (excess water or shortages) will be spread evenly throughout the system for flexibility $F = 1$, will be felt most strongly at the upper end of the system when $F > 1$, or at the lower end of the system when $F < 1$ (Figure 32).

Constant discharge offtakes, such as baffles, present a flexibility almost equal to zero; perturbations are propagated all the way down for a canal equipped with these delivery structures. While the absolute perturbation is propagated downstream, the relative perturbation is amplified downstream, causing either waterlogging/overtopping of canals or severe water shortages where there is no strategy to cope with these waves. Inversely, overshot offtakes have high values for flexibility, and perturbations are flattened in the upper part of a canal equipped with this type of offtakes. The result is that upstream offtakes have highly variable discharges and that downstream offtakes are relatively stable. This situation raises serious operational issues. The flexibility approach is useful for gaining a general idea of the global behaviour of the system. However, it does not provide quantitative insights in aggregated sensitivities at reach level. This is discussed in more detail in the following section.

Use of sensitivity indicators for reaches
Predicting propagation of perturbation
Better than single-structure sensitivity for system analysis, the reach sensitivity indicators show how the perturbation is distributed through the canal/system. Reaches with high sensitivity indicator (see Appendix 2 for computation) will absorb a large part of the perturbation through their offtakes. This means that these reaches will experience overdraft or water scarcity depending on the sign of the perturbation. Inversely, reaches with low sensitivity indicator will convey most of the perturbation downstream to the next reach. This analysis will show how the benefits and burdens of perturbations will be shared in the system and can inform decisions on targeting operations to specific sensitive reaches.

Determining the freeboard of reaches

Reaches with a high sensitivity for water depth should be equipped with sufficient freeboard or safety structures; whereas in reaches of low sensitivity for water depth, the freeboard can be lower.

Increasing the efficiency of canal storage

Where the sensitivity for water depth in the reach is high (i.e. aggregated sensitivities of offtakes are low and those of the regulators are high), a large part of the perturbation will be experienced in the reach through water-level fluctuation. This will result in a significant drop in water level

FIGURE 33
Performance, control and sensitivity

Perf = 0.75
Perf = 0.85
Perf = 0.95

(negative perturbation) or a rise in the water level (positive perturbation). Much depends on the geometry of the canal. The understanding of this behavioural characteristic of a specific reach and the advance knowledge of an incoming perturbation can be used in operation plans in order to buffer out the perturbation or transport the water to a place in the system where it can be used beneficially.
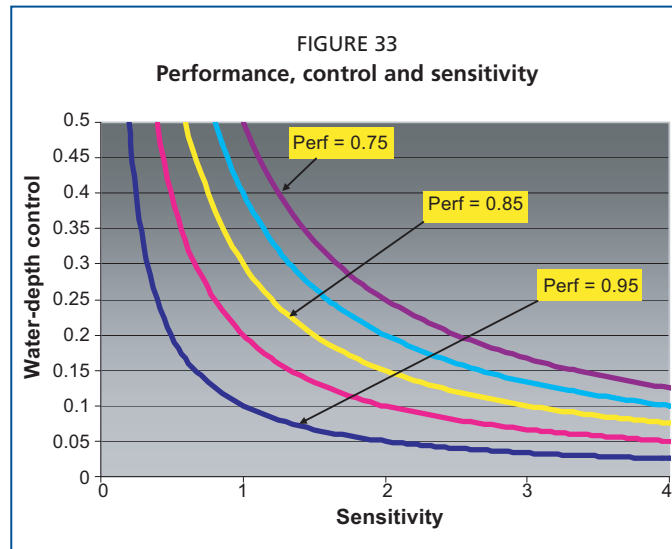
Performance and sensitivity

The performance expected from an irrigation system is the product of two terms: water-level control capability, and system sensitivity (Figure 33). This allows managers to estimate the degree of control to exercise [tol.(H) or ΔH_R] given the performance required for the service and the physical properties of the system. Different global sensitivity indicators at the system level have been developed for adequacy, efficiency and equity performance.

The performance for adequacy and efficiency is related to the precision and influence of control. A formulation of the performance indicator along the canal can be proposed as follows:

$$P = 1 - \frac{1}{2} \Delta H_R S_S \tag{16}$$

where S_s is a system sensitivity indicator, aggregating structure sensitivity indicators and ΔH_R the control exercised over water level.

Inversely, the control on water level that operators should exercise can be derived from the sensitivity of the systems (given) and the performance targeted through the following formula:

$$\Delta H_R = 2 \left(\frac{1-P}{S_S} \right) \tag{17}$$

MAPPING THE SENSITIVITY OF IRRIGATION STRUCTURES

MASSCOTE is a step-by-step process, yet there is no intention to carry out sensitivity analysis on each and every structure (regulator and offtake). The MASSCOTE approach starts with the main-canal level and then proceeds with the identification of lower units of management for which another round of MASSCOTE should be run.

TABLE 18
Example of information required, SMIS, Nepal

Structure	CR1	Offtake 1	CR2	Offtake 2	Offtake 3	CR3...	CR11
Alpha (exponent)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Head (m)	1.05	0.90	0.2	0.25	0.60	1.50	0.30

Mapping the sensitivity of the main-canal structures

Mapping of regulator sensitivity along a main canal, requires a flow parameter (the exponent of the flow equation) and knowledge of the value of head (H upstream minus H downstream).

The flow parameter is known from the type of structure (1/2 for undershot, or 3/2 for overshot –with a mixture of the two for some regulators). The head can be obtained from records of water level, or from a quick survey when the canal is underwater with direct measurement of head using a topographic level. This information can be obtained readily through a quick survey – about one hour for each node (cross-regulator and nearby offtakes). The example shown in Table 18 should then be covered in less than two days.

Mapping the sensitivity of structure along main, branch and secondary canals, SMIS, Nepal

The following example refers to the third measurement campaign (September 2006) for the SMIS, Nepal.

The behaviour of the system appeared to be different from that stated in 2003. The main features were:
 ➢ most of the main-canal cross-regulators were all fully open and acting as weirs;
 ➢ cross-regulators along the secondary canal were fully open;
 ➢ offtakes along the secondary canals were mostly fully open.

This situation reflects a loss of control of operation and flows by managers along the SMIS infrastructure. No serious attempt was being made to control the flows and ensure that all offtakes along the distributaries were receiving enough water.

There was a false belief that the system was basically proportional at FSL, which somehow justified the absence of operation. This was not reflected by the behaviour of the structures. Moreover, the managers were of the opinion that, as the canal was flowing full and water requirement was not at its peak, there was no real need for operating the cross-regulators. Figure 34 shows the flexibility along the main canal, with structures that were significantly either underproportional (F< 0.5) or hyperproportional (F> 1.5).

Figure 35 summarizes a simulation of the propagation of a perturbation generated upstream of the main canal (intake discharge variation set at 5 percent of the total, i.e. 2 740 litres/s), showing several stages:
 ➢ an upstream plateau until CR3;

FIGURE 34
Proportionality along the main canal at main division points, SMIS, Nepal

FIGURE 35
Simulation of perturbation along the SMIS main canal at main division points
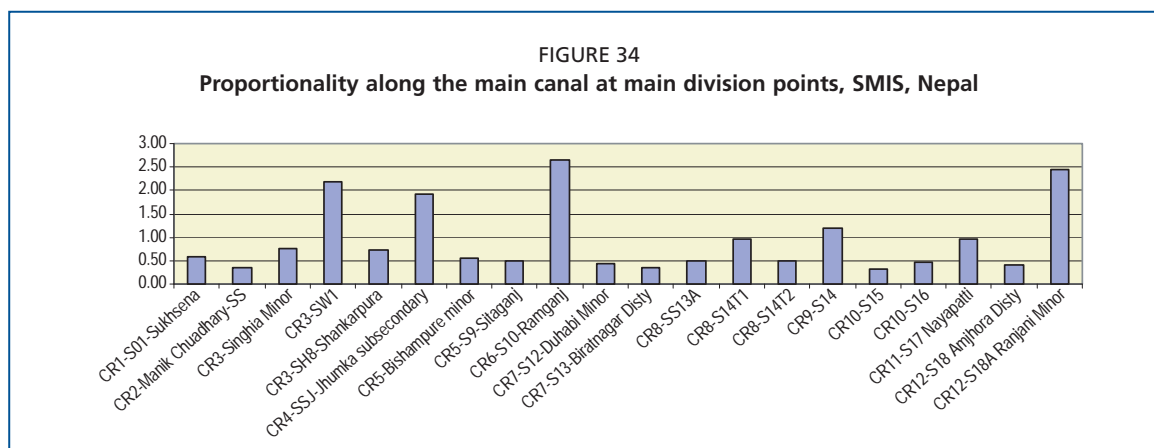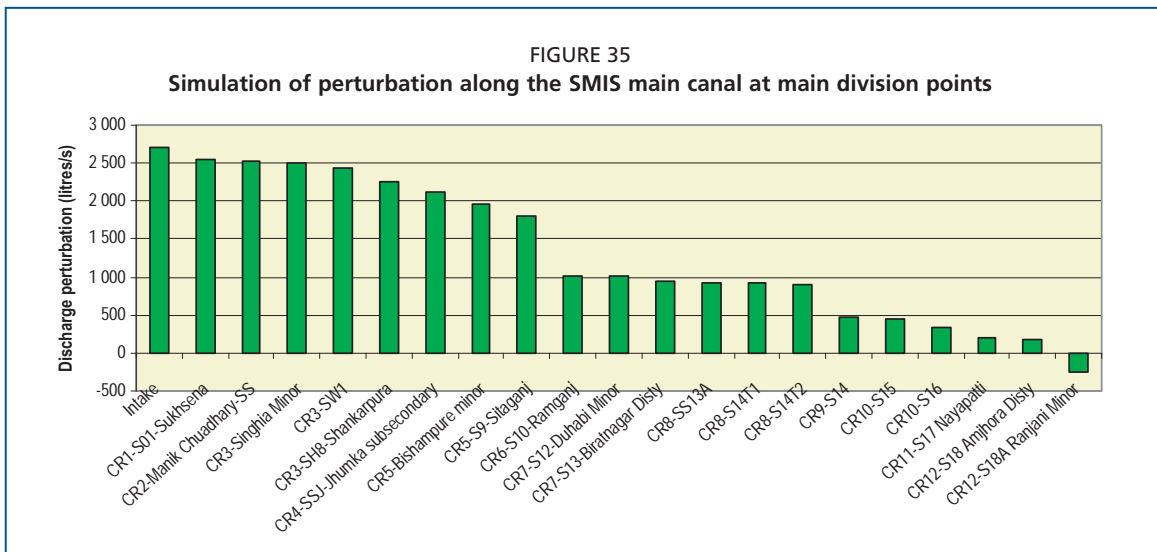
> a proportional decline from CR3 to CR5;
> a drop at CR6;
> a plateau from CR6 to CR8;
> a drop at CR9;
> a proportional decline further down.

This simulation shows that CR6 Ramganj was absorbing 30 percent of the perturbation (826 litres/s) whereas its share was less than 10 percent.

With the operational mode adopted by the managers (no operation of the main regulators and offtakes along main canal), it can be seen that it would be difficult to convey changes downstream; after CR6 (half of the system), only one-third of the upstream change remained, and, after CR9, only 10 percent.

FIGURE 36
Proportionality along the Ramganj secondary canal, SMIS

A similar situation occurred along secondary canals. The sensitivity of the structures was mostly high owing to the full opening of the gates. The flows at offtakes were no longer undershot but overshot, thus making them more sensitive to water-level changes. This was the main cause of upstream downstream differences in water supply/availability observed in the field. Figure 36 shows an example of hydraulic flexibility of a secondary canal in the SMIS.
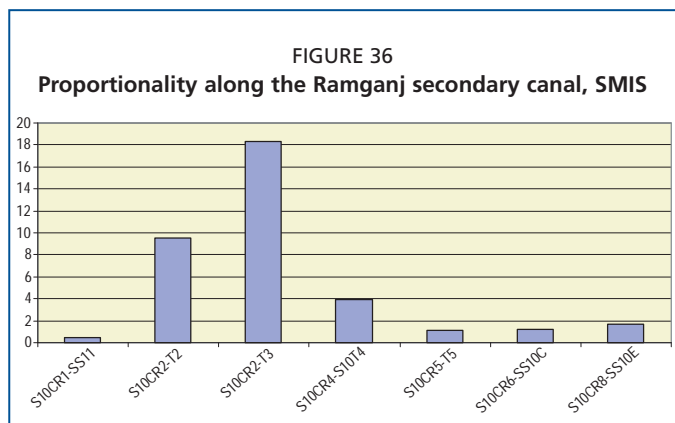
Chapter 7
Mapping perturbations

CANAL OPERATION FOR CONTAINING INSTABILITIES

Steady-flow conditions are often the targeted status for canal operation, at least this is quite often the written rule in the plan for O&M. This status may occur in a very well-isolated and well-controlled system. However, in common practice, it is seldom achieved. This is often because, by the time the system is converging after the implementation of major changes and further fine tuning, new changes and numerous perturbations (disturbances) are already beginning to be reflected on flow conditions throughout the system.

The complexity of canal operation stems from the fact that it is necessary to deal with numerous physical components and individuals, and the process is fraught with uncertainties.

During an irrigation period, for example of one week or ten days, canal operation entails thousands of individual actions that have to be coordinated, sequenced (keeping in mind the time lag), checked and adjusted. The time lag, which is the water travel time between any two points, is a key factor that needs to be taken into account when operations are coordinated and implemented.

Therefore, it is much safer to consider permanent unsteady-flow conditions rather than a hypothetical steady flow.

The focus on steady flow also generates confusion in management interventions. It is quite common to see managers trying to stabilize both water levels and discharges through the operation of regulators, which is practically impossible. This confusion leads to chaos and increasing instability. It is preferable to consider unsteady conditions (variation in discharge) for canal operation and to focus the control of water levels at controlled points.

HOW INSTABILITY INCREASES DOWNWARDS

Perturbations of water variables (level and discharge) along an open-channel network are the norm not the exception. Thus, perturbation is a permanent feature of irrigation canals owing to the upstream setting of structures and compounded by intended or unpredicted changes in inflows/outflows at key nodes.

An example of amplification of discharge variation has been reported along the GLBC (Karnataka, India), as shown in Figure 37. Discharge is recorded every two hours at different locations along the main canal, and the graph displays the average variation recorded between two measurements, showing a sharp increase in variability reaching a high value of 3 percent of change every two hours at km 100. The bihourly increasing variation in discharge moving downwards also comes with variations and deficits in a longer period (Figure 38). This is an

FIGURE 37
Average variation in discharge every two hours along the GLBC, kharif 2006

FIGURE 38
Hydrograph at various locations along the GLBC, kharif 2006 (July–October)
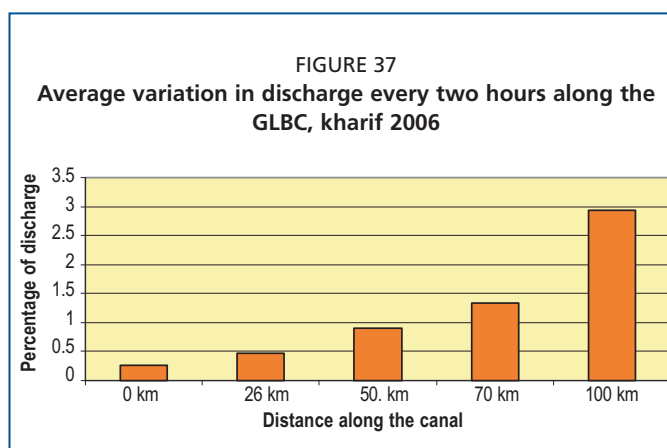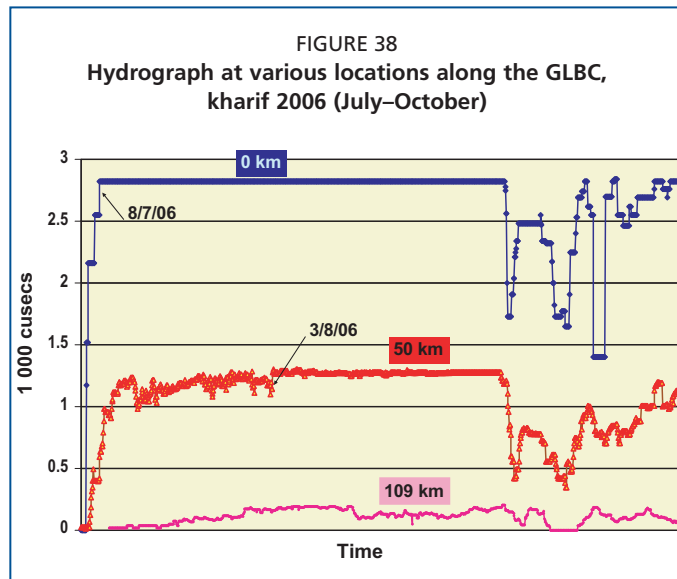
example of the well-known situation of increased instability penalizing downstream users.

THE CHALLENGES OF INACCURACY, UNCERTAINTY AND INSTABILITY

Imprecision and uncertainty plague the process of canal operation. The main issues that exacerbate imprecision, and thus contribute to the complexity of canal operations, are:

➢ Accuracy:
  • inaccuracy of data for water demand and main sources of water (inflows);
  • imprecision in anticipating the impact of the downward propagation of waves caused by operation itself;
  • imprecision in action or gate settings.
➢ Interventions:
  • inappropriate reactions to scheduled and unscheduled perturbations;
  • incorrect operation procedures;
  • illicit interventions.
➢ Unscheduled external perturbations:
  • from the source upstream – or unexpected runoff along the canal;
  • unexpected rainfall causing perturbations – may require closure of canals and disposal of additional water.

THE UNAVOIDABLE NATURE OF PERTURBATIONS

In many contexts especially in tropical areas, variability in both inflows and outflows is often a major characteristic of irrigation systems. For example, in the MUDA Scheme, Malaysia, the regulated supply accounts for only 35 percent (controlled supply from a remote reservoir [29 percent] and recycled drainage water [6 percent]) of the annual total water supply to the area (ITIS, 1996). Other components are direct rainfall (52 percent) and uncontrolled river flows (13 percent). In this context, fluctuations in inflows are as important as fluctuations in the demand as far as operational decisions are concerned.

In general irrigation systems might experience inflow fluctuations caused by:

➢ Return flow: overflows from distributary channels or from fields that return to the irrigation system – these vary over time.
➢ River diversion supply: run-of-the-river systems are subjected to greater variability in inflows than are reservoir types.
➢ Upstream canal operations: for a canal branching out of a main canal there is a certain control on the supply rate, whereas for a serial diversion – section of the main canal fed by the upstream reaches – control is low, i.e. the flow from upstream must be accepted at the supplied rate. Fluctuations at this point are the consequences of upstream operations.
➢ Single-bank: single-bank canals, i.e. canals without a built bank on the uphill side, also called contour canals, are quite common in slightly undulating topography. Large inflow fluctuations are the results of unregulated runoff entering the canal system during rainfall events (Plate 24).

Some systems however are not so much concerned by inflow perturbations, these are in particular the ones fed by a well regulated reservoir and serving a double bank canal network where intrusion is limited if not nil.

Features that are worth considering for inflow variations management are

- ➢ Localized storage: the presence of an intermediate reservoir within the system is an opportunity to damp perturbations.
- ➢ Return flow: diverting positive perturbations towards areas with return flow enables implementation of efficient reactions.
- ➢ Reuse system: positive perturbations can be diverted preferentially towards areas where it is known that water can be recycled downstream.

Plate 24
Single-bank canal experiencing runoff during wet season, KOISP, Sri Lanka.

OPERATION FOR SCHEDULED CHANGES AND UNSCHEDULED PERTURBATIONS

The strategy of management and canal operation is a twofold one: a strategy for implementing the scheduled changes (known and planned); and a strategy for dealing with perturbations resulting from imprecision and unscheduled changes.

In facing and managing scheduled changes and the imponderables (perturbations), a logical sequence would be to:

- ➢ implement, in the best way possible, the scheduled operation and distribution plan;
- ➢ deal with perturbations, both external and internal, generated by imprecision in the water plan and by the operations themselves.

If a perturbation is to be managed, it must first be detected in order to trigger a sequence of interventions that operators must be ready to implement. In the case of unscheduled perturbations, this implies that the managers and operators have to:

- ➢ check water variables (water levels, discharges, water demand, inflow, outflow, etc.) and compensate;
- ➢ manage the perturbation or let the system react without any intervention (diversion);
- ➢ increase the flow of information, both upwards and downwards.

WHERE UNAVOIDABLE ERRORS GO

Even with the better controlled gated system using modules (baffles), the best flow control that can be achieved is ±5 percent of the set value. Therefore, on a branch canal with 1 m³/s at head, serving 10 modules of 100 litres/s each, the discharge can vary as follows:

- ➢ at the head: between 950 and 1 050 litres/s;
- ➢ at each offtake: between 95 and 105 litres/s.

As a consequence, the first nine offtakes of the branch withdraw a total flow varying between 855 and 945 litres/s. Hence, the remaining flow for the downstream offtake may vary between 55 and 145 litres/s. Consequently, the last offtake may face

Plate 25
*Tail-end spill on a canal equipped with rigid offtakes (baffles),
Tadla, Morocco.*

Plate 26
*Uncontrolled direct outlets on the main canal as sources of
perturbations, Sindh, Pakistan.*

a high shortage of water (-45 litres/s) or a high surplus (+45 litres/s). For the latter, a spill is needed in order to evacuate the water in excess (Plate 25). This illustrates the tail-ender concept in irrigation systems – the last offtakes have to compensate for the errors further upstream in the system.

OTHER SOURCES OF PERTURBATIONS
Illicit operations
Operations carried out by users without permission/authorization are an important source of perturbations in a CA. Illicit operations are usually attempts by users to divert more discharge than they are entitled to or that the running conditions allowed. This phenomenon aggravates rapidly further downstream as more people try to compensate for the propagating deficit. It ultimately results in large portions of the downstream CA receiving little if any supply.

Illicit operation can also be a problem during the intermediate season in the event of unexpected rain. The unauthorized closure of offtakes can generate a surplus of flow within the system that may create some physical damage if the canal is not well protected.

Direct outlets
Errors are not all generated by operation and management or by external variation in flows. Outlets offtaking directly from the main canal without any effective control mechanism (Plate 26) are common in many irrigation systems.

The issue of direct outlets is socially critical because it always results in extra pressure on irrigation managers. The consequence is that sometimes a large fraction of the available flow entering the system cannot be managed effectively by operators. In one system in Pakistan, about 40 percent of the flow was not under the control of the managers. This is not only an issue of equity. Uncontrolled outlets on the main canal can generate high discharge variations. This has consequences on the performance and resulting service to users served by the controlled outlets.

PROPORTIONAL SYSTEMS
In proportional systems, the service is proportional by design and this is achieved no matter what the inflows are and what the variation in internal flows are (where the structures are properly set and installed). This is why the proportional systems, also called structured systems, are easy to operate, they have the lowest O&M costs.

However, these systems have other constraints, in particular with regard to service to users. Historically, they have been widely used in traditional irrigation systems, e.g. in Indonesia, and in more structured multilayered irrigation systems, e.g. in the Indo-Gangetic Plains, as an inexpensive technique for distributing water to the maximum numbers of farmers and area of land. The proportional system is reliable where the sharing of the flow is ensured by a single proportional division structure. Where proportionality results from two separate structures, then there is a high risk of seeing the proportionality "drifting" because of changes in hydraulic conditions (sedimentation and erosion).

DIMENSIONS OF PERTURBATIONS

As mentioned above, perturbations have different origins. For mapping perturbations, it is important to know their origin, timing or frequency of occurrence, amplitude, and then how the system reacts to them. It is important to know whether the system is self-reacting or whether specific interventions need to be carried out.

LINKING SENSITIVITY AND PERTURBATIONS IN A CONSISTENT WAY

Sensitive regulators are good points at which to detect perturbations. A small variation in discharge will generate a noticeable variation in water level at these structures.

At the subsystem or reach level, it is critical to know whether the system absorbs or propagates the perturbations. Figure 39 presents two different systems in terms of their capacity in propagating/absorbing perturbations. A discharge change was generated at the head of each canal (Regulator 1 in Figure 39). Then, measurements were made at each reach in order to estimate how much of the change was retrieved downstream when no operation was carried out to change the setting of the irrigation structures.

The two systems presented indicate very different behaviours. The Kirindi Oya Irrigation System Project (KOISP) propagates the change regularly. In absolute terms, it declines regularly, but in relative terms the change remains steady. This means that the system is more or less proportional.

The Mahaweli-B system is heterogeneous, either fully propagating or highly absorbing. The initial change is absorbed significantly in two reaches (the first reach downstream of Regulator 1, and the reach downstream of Regulator 5). Reaches 2, 3 and 4 propagate the full change downstream. After Reach 5, only 20 percent of the initial perturbation remains in the main canal, 80 percent of the water surplus being diverted through sensitive offtakes.

The strategy for canal operation and water management will differ in these two systems. Without going into great detail:

- ➢The KOISP propagates and shares the perturbations: For scheduled changes, it is necessary to operate all the regulators with the same care. No specific action is required in the event of unscheduled perturbations.
- ➢Mahaweli-B either propagates or absorbs perturbations. Operation for scheduled changes should focus primarily on Reaches 2 and 6 in order to ensure that they do not divert the input variation. For unscheduled changes, the offtakes

FIGURE 39
Analysis of perturbation absorption along two canal systems
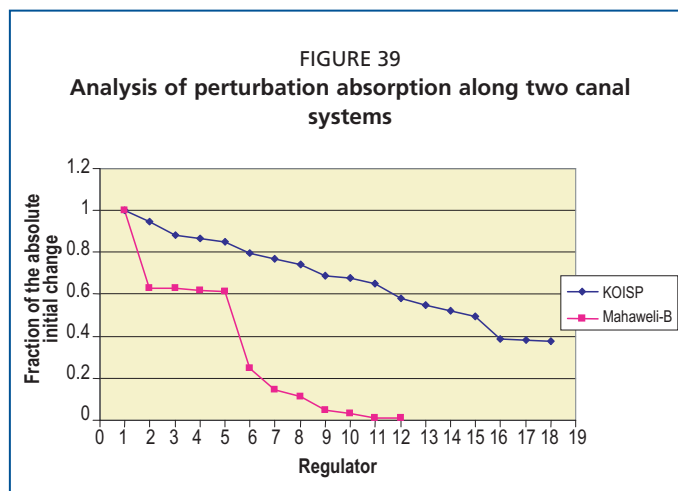
TABLE 19
Perturbations – summary of meaningful characteristics for operation and possible responses

Type of perturbations	Solutions (options for managing perturbations)
Positive perturbations:	Share the surplus among users, particularly relevant where the system is proportional. Divert and store the surplus into storage capacity.
Nature (inflow-outflow – internal)	
Magnitude (water-level fluctuation – relative discharge variation)	
Frequency	
Negative perturbations:	Compensate from storage.
Nature (inflow–outflow – internal)	Check for immediate correction.
Magnitude (water-level fluctuation – relative discharge variation)	Reduce delivery to some offtakes with compensation later on (less sensitive/vulnerable areas, delivery points with storage facilities, with alternatives source of water).
Frequency	

of these reaches have to be operated carefully in order to distribute equitably the changes in the inflows.

An illustration of how this information can be used to organize control at subsystem level in Mahaweli-B is as follows:

 ➢ Downstream of Reach 1, the precision of flow control for a scheduled operation depends considerably on upstream headworks setting, but also on the first reach setting. If Regulator 2 is not properly adjusted, then the scheduled change in flow implemented at the headworks will be reduced significantly within the first reach (40 percent).
 ➢ Unscheduled perturbations in the first reaches are mostly absorbed in Reaches 1 and 5, after Regulator 6 only 20 percent of the perturbation remains in the main canal.
 ➢ Between Regulators 2 and 5, perturbations are transferred without change. Therefore, Point 5 should receive a lot of attention and should be checked very often in order to control the three upstream reaches.

MAPPING AND MANAGING PERTURBATIONS

Mapping perturbations means identifying and characterizing their dimensions (Table 19) as described previously:

 ➢ origin;
 ➢ frequency and timing;
 ➢ location;
 ➢ sign and amplitude;
 ➢ options for coping.

Example from the SMIS – Step 3. Perturbation
Main supply

There is only one source of surface supply, the Koshi River. The supply ranges from 60 m³/s in the monsoon period to 15–25 m³/s in winter and spring. However, the supply is stable on a weekly basis. Variations in the supply are generated by the necessity to close the intake and flush out the sediment trap upstream at monsoon time. This can take two hours a day during periods of high sediment load in the river. This generates perturbations at the main intake.

The hydropower plant downstream of the trap reach is also a potential source of perturbation of the flow during the low-peak season, when the main entrance flow is cut in order to raise the water level in the desilting basin, and when discharge is reduced as a consequence of this.

FIGURE 40
Variation in water level at CR4, Jhumka Minor, monsoon season

Water level recorded daily at 52 RD between 25 March and 2 October 1999

FIGURE 41
Variation in water level at CR4, Jhumka Minor, winter season

Water level recorded daily at 52 RD between 2 October 1999 and 25 March 2000
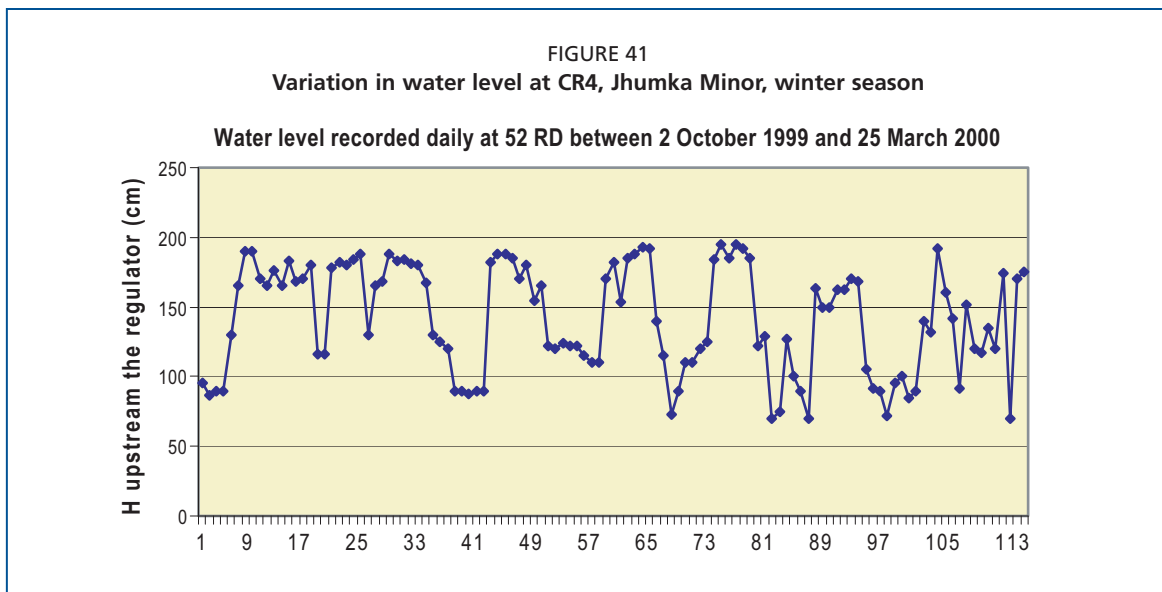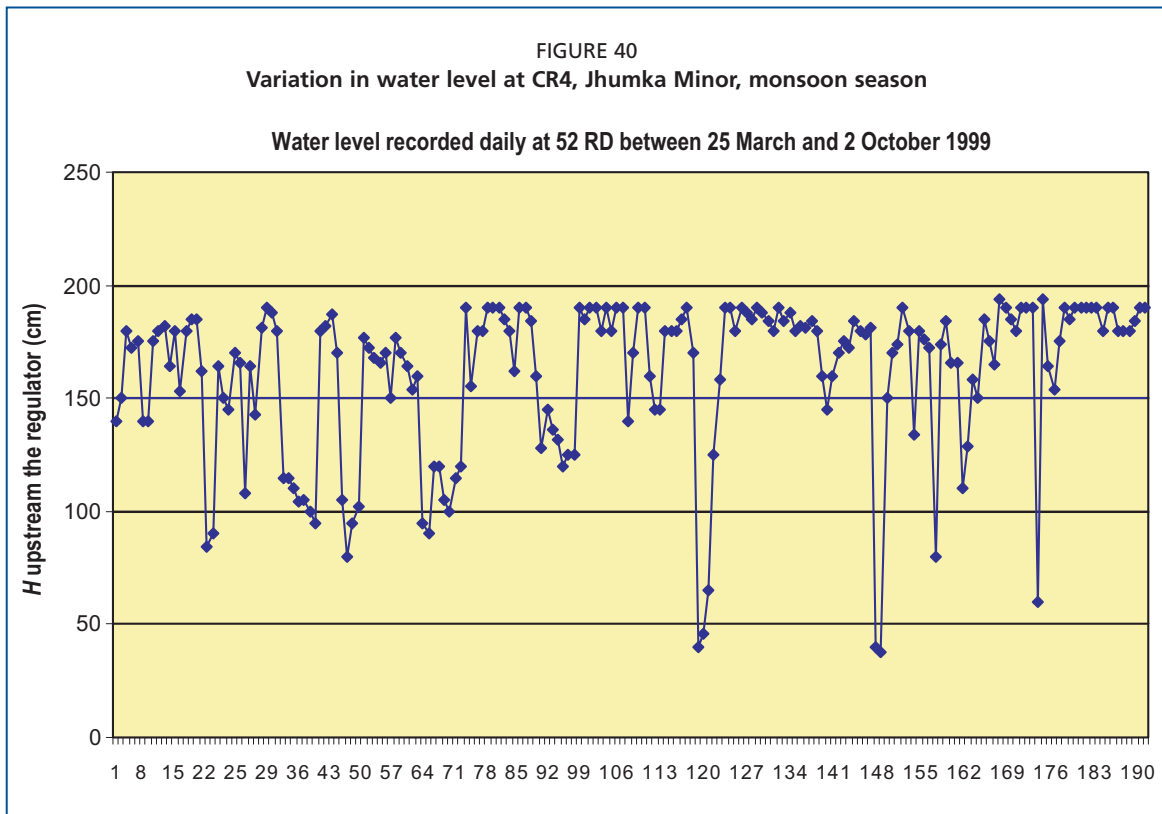
Supply to secondary canals

The supply to secondary systems has been reported as varying significantly (Figures 40 and 41). This may be the consequence of the low control on water level. Throughout the year, water-level variations of up to 25–30 cm occur on a regular basis. Although lower, daily variations can reach 9–17 cm. These variations, associated with sensitive diversion structures offtaking at CR2, CR4, CR6 and CR7, are one of the two main causes of the significant variation in supply (the other being illegal direct interventions on diversion structures).

TABLE 20
Recorded precision of control along the CMC and related discharge variation

Cross-regulator	Day-to-day average variation in water level upstream the CR (not including major changes) (cm)	Sensitivity of the CR	Sensitivity of the offtake (head of secondary canal)	Discharge variation at secondary canal intake, in ± target (%)
CR1		2.0	0.60	
CR2	12	0.5	2.00	± 24.0
CR3	15	3.0	0.80	± 12.0
CR4	17	1.0	1.60	± 27.0
CR5	9	1.5	1.00	± 9.0
CR6	11	0.5	4.30	± 47.0
CR7		1.0	3.40	
CR8		1.5	0.35	
CR9	13	0.5	0.50	± 6.5
CR10		0.1	0.70	
CR11	11	0.5	1.50	± 16.5
CR12		n.a.	n.a.	

However, even with the existing structures, the control of the water flow can be improved easily. The physical condition of the cross-regulators is fine, and each secondary canal is equipped with a measurement weir. This all allows for good control of supply to the secondary canals. Therefore, the issue is one of organization of operation rather than being about the physical infrastructure itself.

Table 20 shows measured daily variations in water level (day-to-day difference after having excluded the high variation corresponding to a temporary disruption or closure of the canal) for 7 of the 12 regulators. The values express the precision (or tolerance) with which the control is exercised. Multiplying the value by the sensitivity of the nearby offtakes leads to an estimation of the control on discharge exercised.

The higher variation in water level recorded at CR4 is not explained. CR3 has a higher sensitivity than CR4 and still exhibits a much lower variation.

The high variation at CR11, having a low sensitivity indicator (0.5), results from the high variation in discharge reaching the end of the system.

The records on water-level variation do not show any particular trend. This means that there is no increase in perturbations along the CMC.

Three of the six secondary canals evaluated have discharge variations of more than 20 percent as a consequence of the variation in water level.

Chapter 8

Water networks and water accounting

The canal and drainage systems within the service area need to be properly understood in order to develop appropriate and workable water management and operational strategies, ones that fully consider constraints as well as opportunities. In order to achieve this objective, it is necessary to map the flow routes (network) and specify (as much as possible) the flows in terms of timing, flow rates and volumes (water balance).

Water accounting, also called water balance, refers to the accounting of all the influxes and outfluxes of water in a given space and time. It must consider all water (surface water and groundwater streams, conjunctive use, storage and recharge, etc.) that enters and leaves a defined area in a particular span of time. Thus any recycled water within the spatial boundaries is not included in the water balance. It should take into account quantity and also water quality aspects, the use of lower quality water, and the impacts of agriculture practices on water resources.

Although the concept of conjunctive use of irrigation water has been around for many decades, it is only in the last decade or so that systematic and comprehensive water balances have been carried out in major canal systems in order to gain a better understanding of the flows and water resources.

This chapter briefly describes mapping of water network and then introduces the concept of water accounting and its use as a powerful decision-making tool for the operation and management of an irrigation system at different levels of management setup. The RAP includes a water balance at the project or scheme level, which is done with the available data and is useful for making decision about water conservation. In addition to the water balance done as part of the RAP, MASSCOTE recommends making water accounting a part of routine management.

MAPPING WATER NETWORKS

A thorough knowledge of all existing and potential sources of inflows and outflows in service area is required for efficient canal operation and good water management practices. This is done, in MASSCOTE, by assessing the hierarchical structure and the main features of the irrigation and drainage networks, natural surface streams and groundwater, and the mapping of the opportunities and constraints, including drainage and recycling facilities. Thus mapping of water network includes not only irrigation canal and drainage network but also any stream and/or natural channel and drain that crosses the service area and which interacts (or may interact in future) with the canal and drainage network and storage facilities. This also includes escapes that evacuate water to the drainage network.

The geographical distribution of the canal system and infrastructure within the service area is usually quite well known. However, this is often not the case for the drainage system, which typically has not been developed fully or has been developed in various phases, often with no reliable record of precise locations and of what has been maintained and is functional. Information on where and how much water is drained may help managers and decision makers in assessing the potential of recycling this water.

Also information regarding the layout and the (dry) discharges of streams that could be used for irrigation, if the topography allows, in water short system is often

Figure 42
The water accounting system approach and the physical scales at which accounting might apply
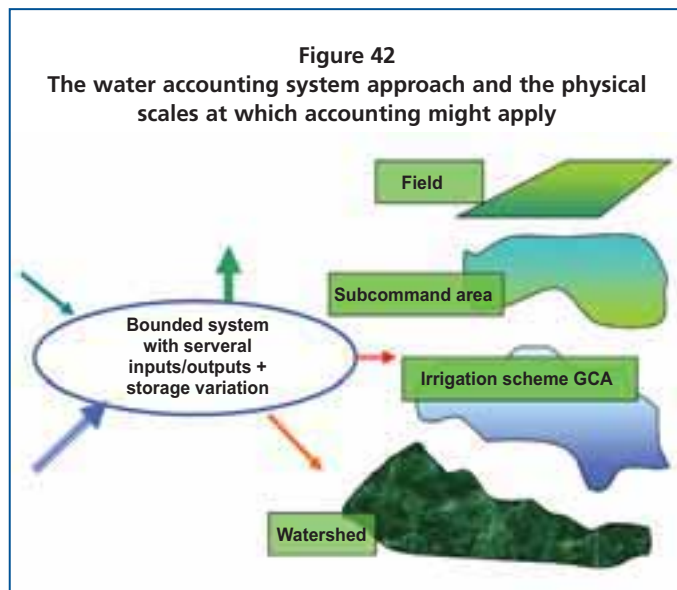
not available, thus managers do not consider water from these streams in allocation and distribution plan.

Mapping of water network is particularly important for developing practical water management strategies and effective water resource allocation, in particular in (seasonal) water short system.

WATER ACCOUNTING FOR WATER MANAGEMENT

Water accounting should be considered as the foundation of water management and operation in the sense that it defines the requirements (demand) for surface water service. Through a spatially disaggregated water balance it is possible to identify: (i) various flows within the service area; (ii) the needs that the managers must satisfy; and (iii) opportunities for sharing the cost of operation among more users than only the farmers. It also gives a good indication of the efficiencies of water management and allows the identification of environmental problems, such as waterlogging.

Where done properly, a water balance can be used by managers to assess the conditions under which canal operations take place.

A comprehensive water balance is critical:

➢ at the initial project stage, for setting water services, designing appropriate management strategies and operational procedures;
➢ later, for appraising modernization strategies to achieving updated performance targets.

Three important features for water balances are:

➢ Delineation of the physical boundaries: upper limit, lower limit and horizontal limit. Figure 42 presents the components of the water balance for spatial boundaries.
➢ Time frame: year, season, month, fortnight or ten-day period.
➢ Focus: water quantity and water quality.

Water quantities must account for all inflows and outflows, plus changes in internal storage. For water quality, the process is more complex and depends considerably on the biochemical and physical properties with time of the parameter under consideration. Along their paths through the water cycle, chemicals are absorbed, degraded, transformed, lost through aerial reaction, etc. Therefore, mass conservation applies to water but does not always apply easily to chemical constituents.

Depending on the purpose, water accounting could be done on a seasonal or yearly basis at the entire scheme level and for submanagement units in order to facilitate management decisions.

DELINEATION OF THE PHYSICAL UNITS WITHIN THE SERVICE AREA

There are many criteria to consider in defining the physical boundaries for an irrigation water balance. A water balance can be conducted for a field, a farm, a submanagement unit, an entire irrigation service area, and a river basin. Whatever the unit of evaluation, it is necessary to define upper, lower and horizontal boundaries of space. Table 21 presents an example of defining spatial limits for water balance. It shows that

TABLE 21
Spatial boundaries of various areas

Space	Upper boundary	Lower boundary	Horizontal boundary
Farm	Crop canopy	Bottom of rootzone	Farm fields
Conveyance system	Water surface	Canal bottom	All diversions, spills and discharge points
Water district without groundwater pumping	Crop canopy	Bottom of rootzone	District
Water district with groundwater pumping	Crop canopy	Bottom of aquifer	District
Water district without groundwater pumping, but with a high water table	Crop canopy	Bottom of aquifer that is tied into the high water table	District

Source: Burt, 1999.

groundwater use or a high water table can have a significant influence on the lower limits of the water balance.

Spatial boundaries for a water balance to assist decisions regarding system management and operation would include:

➢ the gross service area of the project: often used as the first approach to examine a global water balance;

➢ canal hierarchy: main, secondary, tertiary and quaternary;

➢ institutional management: federation of WUAs, WUA, farmers organization.

The above criteria can be included in the definition of the water balance. However, one of the more important aspects is pragmatism. Units for the water balance should be based on realistic boundaries for which flows can be either measured or estimated with reasonable accuracy. In an ideal situation, a water balance is conducted for the entire irrigation service area and each management subunit in order to allow the managers and operators to make decisions within their own subunits as well as at the entire project/system level. However, whatever unit is chosen for the analysis, the boundaries must be clearly set and understood.

Setting the spatial as well as the temporal boundaries for a water balance is very important. The failure to set these limits properly is often a main reason for errors made in computing water balances.

SETTING TEMPORAL BOUNDARIES

Temporal boundaries are critical when computing a water balance. Depending on the objectives for which the water balance is conducted, temporal limits can be set as multiple years, one year, six months, an irrigation season, monthly or fortnightly. For example, making long-term recommendations on the basis of only a one-year water balance is not recommended because such data are often not representative of normal conditions. The values of most of the water balance inputs, such as rain, surface allocations, and evapotranspiration vary from year to year. For the purpose of making long-term recommendations, 4–5-year average values from water balances done on a yearly basis must be considered.

For the purpose of evaluating modernization strategies, a time frame of a year, six months or a single irrigation season is advisable. Monthly or fortnightly water balances are required where the objective is to use the values for real-time management decisions. However, it is often difficult to assess changes in the groundwater storage on a scale smaller than one year. Nevertheless, it is necessary for managers and operators of the irrigation system to keep an account of where water is coming from and where is it going to within the management units in order to be able to make efficient decisions regarding water conservation, allocation and distribution.

WATER BALANCE TERMS

Whatever the spatial unit under consideration, a number of basic flow parameters need to be evaluated (Figure 43):

FIGURE 43
Water flows relevant for water accounting in agriculture
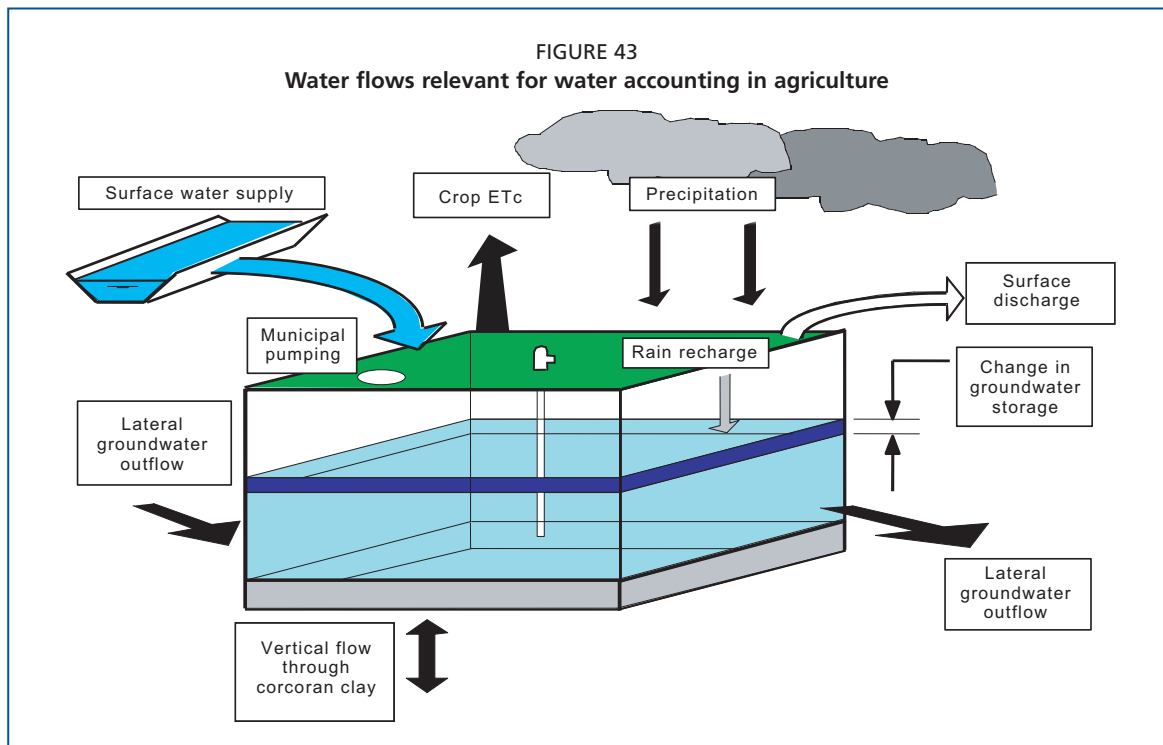
Source: Style and Burt, 1999.

> ➢ irrigation diversions;
> ➢ surface runoff into and out of the spatial boundary;
> ➢ evapotranspiration (ET) from fields and other areas such as canals, drains and other non-irrigated areas;
> ➢ rainfall within the spatial boundaries;
> ➢ surface drainage, lateral groundwater flows and vertical drainage within the lower boundary limit.

Irrigation Diversions
Irrigation diversions are often measured through measurement devices at bifurcations. For a water balance, irrigation diversions entering the spatial boundary must be known.

Rainfall
Rainfall should be measured with sufficient density of points to account for the spatial variability of precipitation, especially if the time frame of events is short. It is common to see large irrigation projects covering dozens of square kilometres that have only one rainfall gauge despite a high variability of rainfall during storm episodes. In practice, the number of rainfall gauges should be adjusted to the local spatial variability of the precipitation. A reasonable distribution is one gauge every 5 km in a medium-size system, and one every 10 km in a large system.

Evapotranspiration
Evapotranspiration or crop water use is usually the largest and the most important component of water balance. It is obtained as the product of crop area and the estimation of crop evapotranspiration (ETc). However, where non-crop vegetation (trees, bushes, etc.) covers a non negligible part of the CA, its evapotranspiration also constitute a significant part of the water balance.

Crop evapotranspiration or crop water requirement can be assessed by multiplying the reference evapotranspiration and the crop coefficient: ETc = $Kc \times$ ETo; where: ETc is crop evapotranspiration; ETo is the reference evapotranspiration; and Kc is the crop coefficient.

The reference crop evapotranspiration represents the evapotranspiration from a standardized vegetated surface. The only factors affecting ETo are climate parameters. Thus, ETo can be computed from weather data. There are a number of methods for calculating ETo, but FAO recommends using the FAO Penman-Monteith method (FAO, 1998). Alternatively, the FAO CROPWAT program can be used to assess both ETo and Etc (see CD-ROM attached).

Some weather data (temperature, solar radiation, relative humidity, and wind speed) are required in order to calculate ETo irrespective of the method used for its calculation. However, it is not always easy to obtain these data from the nearest meteorological station. Where no data are readily available, climate databases such as CLIMWAT (FAO) or the Climate Atlas of the International Water Management Institute (IWMI) provides values for weather parameters needed for ETo calculations. These source also provide good estimates of ETo.

The crop coefficient, Kc, is basically the ratio of ETc to ETo, and it depends mainly on the crop variety and the growth stages of the crop. FAO (1998) provides Kc values for different crops and their growth stages, which are used widely throughout the world for estimating ETc.

The ETc calculated through above equation is the evapotranspiration from crops grown under optimal management and environmental conditions, with good water availability and no limitations of any other input. In most cases, actual crop water use differs from this potential ETc because of non-optimal conditions, such as the presence of soil salinity, water shortage, waterlogging, pests, etc. These conditions may reduce the evapotranspiration rate below ETc. In order to address this problem, a water stress coefficient, Ks, is introduced into the equation (Figure 44). Ks is dependent on the available soil moisture and ranges between 0 and 1. When the rootzone depletion is lower than water that is readily available to the crop, $Ks = 1$, meaning that water uptake to plants is equal to ETc where the soil is wet: ETc adj = $Ks \times Kc \times$ ETo.

FAO (1998) and Annex 3 provide more information on evapotranspiration calculations.

FIGURE 44
Reference ET, crop evaporation under standard (ETc) and non-standard (ETc adj) conditions

Source: FAO, 1998.

Drainage

Drainage should be measured at key points, particularly when it leaves the spatial boundary set for water balance, and possibly monitored for water quality if necessary. Water quality monitoring of drainage water from

FIGURE 45
Example of use of hydromodelling to simulate groundwater flows (right) after calibration with water-table levels (left), Tarascon, France
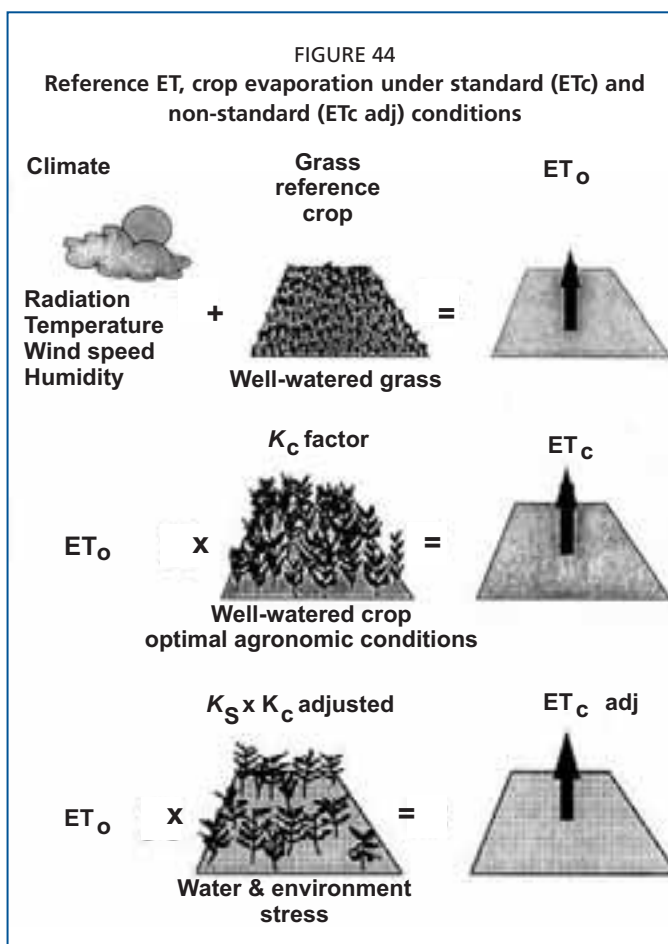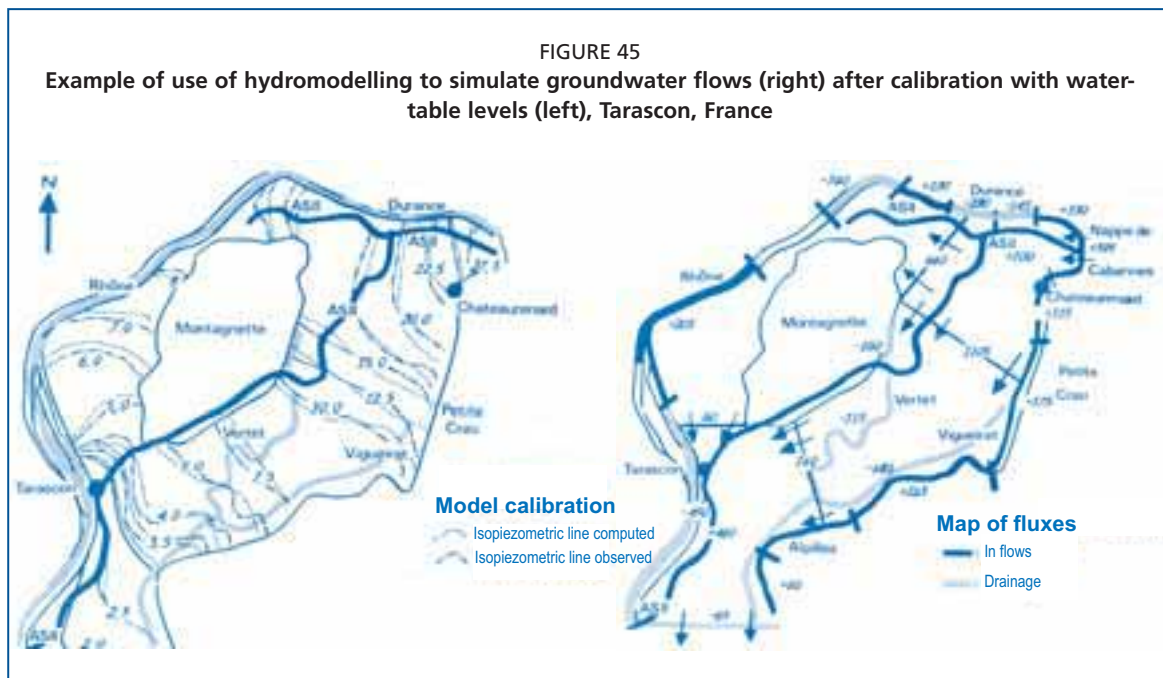
irrigated areas is important, in particular where this water is to be used for irrigation downstream, in order to keep a check on the safe levels of agrochemical loads.

Groundwater

Groundwater fluxes, i.e. lateral flows and vertical drainage, are often the most difficult aspects to handle in a water balance. While direct measurements of groundwater flows are not possible, water-table levels can be measured, and groundwater or hydrological modelling (Figure 45) can be used to reconstruct the flows using trial and error and comparison with field data. However, it is not always easy to calibrate these models owing to a lack of empirical data. An easier way of monitoring the changes in groundwater is to install monitoring wells, which could be made locally.

Groundwater is an important component of water accounting. The setting of the lower spatial boundary usually determines whether the use of (shallow and/or deep) groundwater is considered a supply or a mere recirculation of surface water supply and rainfall. However, a distinction between shallow groundwater and deep groundwater should be made in the water accounting procedures if they are to be conducted for assisting in management decisions, particularly in semi-arid and arid regions.

In case shallow groundwater (less than 20 m) is incorporated in the lower spatial limits of the water accounting system, there is no need to take account of additional water supply from the tubewells fed by the shallow groundwater. Only lateral sub-surface flows entering and leaving the limits of the system should be considered.

Generally, water extracted from deep groundwater (more than 20 m), is considered beyond the limits of the system. Therefore, the specific water supply from deep ground water is usually added to the inflow.

In order to avoid double-counting of water entering into the spatial boundary of the water balance area, it is necessary to clearly identify the groundwater that is pumped within the spatial boundary and which may be considered as the recirculation of surface water and rainwater entering the spatial boundary. This groundwater should not be accounted for whereas groundwater that is pumped outside the spatial boundary but is used for irrigation within the boundaries of water balance should be taken into account as inflow/supply.

CONFIDENCE INTERVALS

A certain amount of error or uncertainty is inherent in all measurement or estimation processes. Therefore, the true or correct values for the water volumes needed to calculate terms such as "irrigation efficiency" are unknown. Estimates must be made of the component volumes, based on measurements or calculations.

One method of expressing the uncertainty (Annex 3) is to specify the confidence interval (CI) that is associated to the estimate of one value. If it is believed that a reasonable evaluation of data indicates that the correct value lies within 5 units of 70, then it should be stated that the quantity equals 70±5. More specifically, when discussing an estimated quantity, the meaning of a CI should be illustrated, e.g.: "The investigators are 95-percent confident that their estimate of the irrigated area in the project is within ±7 percent of 500 000 ha (between 465 000 ha and 535 000 ha)."

Statistically, a CI is related to the coefficient of variation (CV), where: CV = (mean) / (standard deviation); CV has no units. In addition, CI = ±2 × CV, where the CI is expressed as a fraction (%/100) of the estimated value. Stated differently, if the CI is declared to be 0.10, this means that the ±2 standard deviations cover a range of ±10 percent of the stated value.

Assuming a normal distribution of data, then in about 68 percent of cases the true value is found within plus or minus one standard deviation of the estimated value. Similarly, in about 95 percent of cases (from which comes the "95-percent confident" statement), the true value is found within plus or minus two standard deviations of the estimated value.

Combination of independent parameters

Many terms in a water balance are the result of the addition or multiplication of individual terms and parameters. There are methods for calculating the CI of such aggregated parameters, such as $m = m_1 + m_2$ or $m = m_1 \times m_2$ when these parameters and terms are independent.

Clemmens and Burt (1997) provide more detail on CIs.

HIGH UNCERTAINTY ON THE CLOSURE OF WATER BALANCE

The closure of a water balance is a term or a set of terms of the balance that cannot be measured but have to be estimated from the assessment of the other terms. The closure of water balance is always computed with a high uncertainty because it accumulates all the uncertainties of the other terms. This aspect can be illustrated with three cases: perennial vegetation, groundwater, and seepages.

Non-crop vegetation of the gross command area

Non-crop vegetation in the CA might be an important term of the water balance as many trees thrive on water made available from surface irrigation. This phenomenon can be assessed visually by looking at areas within and outside the CA. In dry zones of the tropics, there is often a clear difference in terms of type of vegetation and foliar development, and, as a consequence, in terms of water consumption. However, it is not easy to estimate the areas covered and the unit consumption.

The value of the perennial vegetation water consumption can be computed as the closure of the balance after having estimated all the other terms.

Net lateral groundwater contribution

The lateral net contribution of groundwater (not including recharge from the canals and surface of the CAs) can be estimated as the closure of the other terms, and as such known with high uncertainty.

In the case of the GLBC (Figure 46), with high inaccuracy on the other terms of the balance, the initial estimation is that the closure is probably known at ±55 percent.

FIGURE 46
Closure of the balance for lateral groundwater in the gross command area of the GLBC
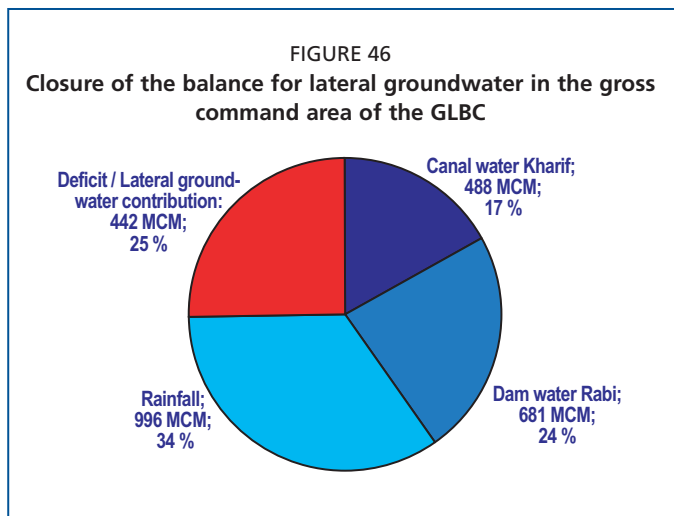
Thus, the groundwater lateral flows might be between 238 MCM and 732 MCM per year. Some further investigations need to be made in order to reduce this uncertainty by improving the assessment of the other terms.

Seepage measurement

Seepage measurement is also a good example of how a closure of a water balance is fraught with uncertainty. Most experts recommend measuring seepage using ponding tests, from the records of drop in water level in an isolated reach (no inflow and no outflow) taking into account the evaporation.

The other possible method, the inflow–outflow method is much less precise. It consists of measuring the flow in the canal at two locations and deducting all the inflows and outflows occurring between the two sections considered: Seepage = Inflow - Outflow.

In order to provide an accurate estimate of seepage, the water lost should be significantly greater than the error in measuring the flows.

The problem of accuracy can be illustrated through the case of the main canal in the GLBC project. A measurement campaign was done to assess the seepage. Discharge was measured at 0 km and 50 km in order to estimate the losses through seepage. Inflow was 78.90 m³/s, total outflow was 73.36 m³/s, leading to a seepage estimate of 5.6 m³/s for 50 km, i.e. 0.11 litres/s/ml. The problem is that the uncertainty about the inflows and outflows is such that this result is probably known plus or minus 200 percent.

Even with an ideal situation where inflows and outflows are known in the field at 2.5-percent accuracy, the inflow is known thus ±1.97 m³/s and the outflow ±1.83 m³/s. In these circumstances, the seepage estimator is know at ±3.8 m³/s, and thus lies between 1.8 m³/s and 9.4 m³/s. This kind of figure cannot be conclusive on seepage losses and related water savings from canal lining.

THE RISK OF DOUBLE-COUNTING

The risk of double-counting in a water balance is real and it is always necessary to ensure that only the fluxes through the boundary of the system are accounted for.

A typical example of this is groundwater pumping or recycling from drainage. While it is important to have an estimate of their value, they should not be counted in the water balance if this water has already been accounted for as inputs either from the rain or from the irrigation supply. Only external water to the system should be counted, which can be deep groundwater and lateral water from aquifers. The same applies for the surface recycling facilities.

USE OF WATER BALANCES AT MANAGEMENT LEVEL

The rationale behind water balances may differ depending on whether the goal is to use the overall water balance within the gross service area or to evaluate the management and operations of potential modernization strategies. Water balances can be useful to the management of a canal system in several ways:

➢ to set up an efficient and user-oriented water management strategy;
➢ to manage water in real time during the season and operate the system accordingly;

➢ to assess performance in water management as well as in delivering the service by providing an estimate of external indicators.

Water balances for assessing water management strategies

Water balances are vital to understanding issues such as the potential for improvement (e.g. water savings), the different uses of water within the service area, and, particularly, non-crop water use.

In Cabannes, France, a modernization project early in the 1980s was designed explicitly on the basis of a water balance. The scheme was divided into two sections:

➢ The upstream part, devoted mainly to cereals and field crops, was modernized using modern surface irrigation technologies (mainly furrow irrigation) to maintain high the recharge of groundwater for the downstream part of the system as well as for some domestic supply.

➢ The downstream part, devoted mainly to orchards, was modernized with drip irrigation using shallow groundwater pumping stations.

The water balance of the whole system was checked carefully in order to ensure a sustainable supply for both sections, in the knowledge that the modernized downstream part would need to divert much less water with localized irrigation technique compared with the earlier surface techniques.

Water accounting for institutional arrangements among users

In many cases, canal systems provide water services to different types of users, regardless of the fact that the main objective is to supply water to crops. Multiple uses of water are the common rule and not an exception.

Water for crop use and water for other uses

Although most irrigation systems have been built solely to supply water to crops during dry periods, in practice some of them have been feeding other uses of water, from the management losses or natural seepages. This is often the case for rice systems, where water ponding generates high shallow groundwater flows that might be tapped by others users.

In old, gravity-fed systems in southeast France, figures of less than 25 percent of annual surface water supply for irrigated crops are not unusual, the remaining fraction being shared by groundwater recharge and surface-stream supply. This phenomenon is not well documented in the irrigation systems in developing countries. However, one such example is the Kirindi Oya irrigation system in Sri Lanka, where water for natural vegetation and homestead gardens in tropical humid areas takes an important fraction of the irrigation water input (Figure 47).

In these types of systems, water accounting may have a strong impact on the identification of different uses of water, and to a lesser extent on the qualification of users or beneficiaries that take advantage of water

FIGURE 47
Water balance in the Kirindi Oya Project, Sri Lanka

Negative externality (excess drainage in the lagoons) 3 %

Real losses (no possibility of reuse) 16 %

Tank evaporation 6%

Fallow evapotranspiration 8%

Rice water consumption (evapotranspiration) 23 %

Perennial vegetation (coconut trees - homestead gardening) 44 %
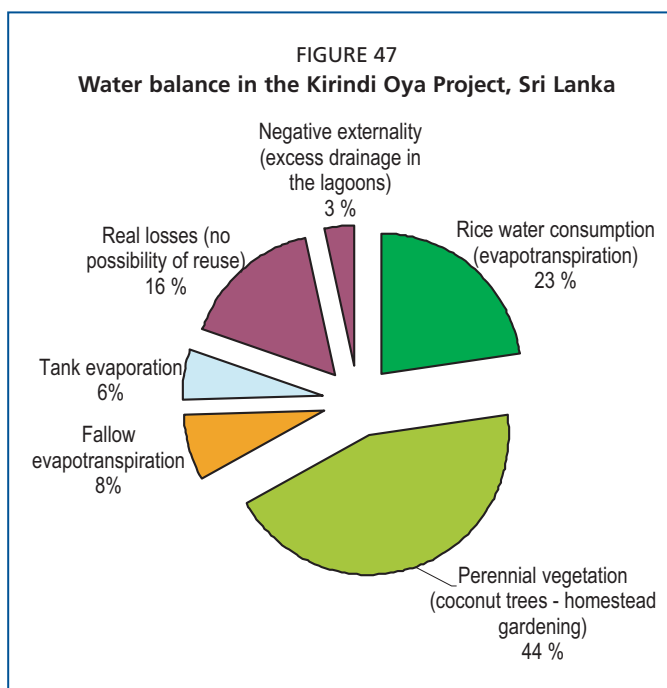
Source: Renault *et al.*2000.

management. It is the basis on which managers, users and beneficiaries can discuss management strategies within the project. This can assist in initiating a discussion on how the cost of operating the system should be borne by all stakeholders and not only irrigators.

Water accounting for performance assessment

Water accounting for canal operation is also useful for performance assessment within a period of time (ten days, month, season and year). In particular, it is useful in comparing water deliveries with water uses. Figure 47 shows the water balance of the Kirindi Oya system (for one full year (1998), considering the two crop seasons as well as the fallow period. This water balance was carried out because of the presumed poor performance of irrigation management. The fact was that the water duty (water delivered for irrigation from the main reservoirs divided by the CA) was dramatically high, values of 3 000–4 000 mm/season were not unusual, this was the initial motivation for investigating the matter.

The water balance has changed completely the way of looking at performance in this project. The striking facts that were brought to light in 1998 were:

➢ Crop evapotranspiration accounts only for 23 percent of the total water supply (irrigation plus rainfall).

➢ The bulk of the consumption lies in homestead gardens and coconut trees, fed mostly by lateral flows from the irrigated areas, and which are very beneficial for the people.

➢ Other users are those who fish in the tanks, and cattle growers for their use of the fallow period on paddy-fields.

➢ A win–win situation was identified for the lagoon, where excessive freshwater from irrigated areas are generating negative impacts for a total of 3 percent of the total water volume.

➢ The real water losses (at the sea mouth, where no more value can be assigned to freshwater in the project) account for 16 percent.

➢ The potential for water savings (16 percent + 3 percent) is significant compared with crop use (23 percent) although it is necessary to consider that part of these water losses occur at flood times and would be difficult to value.

A water balance can also provide estimates of external indicators, such as irrigation efficiencies, ratio of relative water supply (water required vs total water available), and crop yield per unit of water supplied (Chapter 4 and Annex 3).

Water accounting for canal operation

Water accounting can also be important for real-time decision-making for adjusting operation and upstream deliveries. On this short time scale, it is more a combination of indicator assessment and water accounting.

For example, the presence of excessive drainage flows downstream from a subarea can indicate that there is too much water entering the CA compared with the current use. Observing this can be a trigger for action. The managers need to know: (i) by how much to reduce the inflow to the CA in order to reduce significantly the drainage without creating a water shortage in the downstream part of the CA; and (ii) how long it takes for an inflow change to be reflected in the drainage flow. These parameters of the reaction to the presence of drainage flow can be adjusted by trial and error, and simple water accounting.

IMPROVING THE WATER ACCOUNTING PROCESS

The uncertainty relating to water accounting within a gross command area can be reduced progressively with time. The compilation of data over long periods of time allows the uncertainty on some parameters to be reduced, and some inconsistencies to

be detected and corrected. This improves water balance data and helps to narrow the gap between estimations and actual values.

Improvements in water balance data require good measurement devices and efficient information management systems, which cost resources in terms of time and money.

The intelligent use of the memory of water accounting enables improved decision-taking in the followings seasons and years.

WATER QUALITY

The quality of water in irrigation is also an important issue for the environment, resource management, and the health of the local population. A separate account of quality of water entering into and leaving out of a physical boundary helps in identifying water related environmental hazards. This information then could lead to the identification of appropriate mitigation strategies. The main issues of water quality in an irrigation system are related to:

➢ salinity – reduced crop yield, reduced soil quality;
➢ environmental pollution – disposal of industrial and municipal wastes into irrigation canals;
➢ drainage water from irrigated area with agrochemical loads;
➢ health – water related diseases, arsenic and heavy-metal contamination.

Use of marginal quality water in irrigation

There are various impacts to consider in relation to the use of marginal quality irrigation water.

➢ Soil pollution/contamination: Marginal quality irrigation water can affect crop yields severely and damage soils. In particular, in semi-arid and arid countries (e.g. Egypt and Pakistan), soil salinity and sodicity are major problems that have been exacerbated by irrigation from saline groundwater because of unreliable surface water supplies. High levels of heavy metals in the water are likely to accumulate in the topsoil and then enter the food chain.
➢ Conflict with other uses: Wastewater from small industries as well as municipal waste is frequently discharged into the canals and surface water streams. This creates pollution and health hazards as these canals often provide water for drinking purposes and domestic use. Moreover, use of un-treated waste water for irrigation in urban and peri-urban agriculture is a major source of concern to human health.

Urban areas

Canals running through settlements, villages and urban areas are also frequently used as dumping grounds for refuse. This creates pollution and health hazards for the adjacent communities. It also causes problems of water conveyance by blocking the canals, and eventually disrupts water distribution downstream.

Health issues

While water-borne diseases are caused by consuming contaminated water, stagnant water in waterbodies, canals and fields are major sources of vector-borne diseases as they become breeding grounds for insect vectors, especially mosquitoes.

The uptake by plants of heavy metals and arsenic through direct contact with irrigation water or through accumulation in the soil also poses a threat to human health as these elements can enter the food chain.

Monitoring and evaluation of water quality

Water quality requires its own M&E system, which is not always possible for irrigation managers to organize and handle because of the lack of technical and financial resources.

However, a minimum dataset of water quality indicators needs to be developed and monitored in canal systems, in particular for those providing water for multiple uses and where water quality is a major issue, e.g. where the water is known to be saline/sodic, or contaminated with high levels of arsenic and/or heavy metals.

Chapter 9
Mapping the cost of operation against services

In order to produce the service that has been decided/agreed upon with users, managers need to mobilize a set of various resources or inputs (water, staff, energy, office, communication and transport). These resources/inputs all have a cost. This chapter clarifies the issue of inputs/costs for operation vs outputs/services as part of the overall management activities and as a fundamental element of the elaboration of a modernization process.

On the one hand, analysing the current cost of operation provides a clear idea about the cost-effectiveness of current operation and, thus, helps in identifying changes in different inputs (increases or decreases) for improving the cost-effectiveness of operation. On the other hand, it provides a good basis for a cost analysis of any improvements. Thus investigating inputs and costs is important for:

> setting the service levels, in particular in exploring options for different types of services and associated costs;

> water pricing to users, in order to propose a set of charging procedures that takes into account the real cost of service production;

> improving performance and cost-effectiveness, by investigating technical options for maximizing operation effectiveness (better allocation of existing resources, automation, etc.).

MAPPING THE INPUT–OUTPUT CHARACTERISTIC

The objective of this step of MASSCOTE (i.e. mapping the cost of operation/service) is to provide some meaningful information about the input–output relationship even in an approximate format. Figure 48 presents nominal service-cost curve. It is assumed that this theoretical curve linking service (outputs) and cost (inputs) is of the general shape, with an initial fixed cost at service nil (point O) and a progressively increasing cost (inputs) with the quality of service provided to users.

In Figure 48:

> Point O corresponds to no service at all for any reason, such as lack of water in the reservoir. However, there are always operating costs as some maintenance, safety and financial costs are incompressible. Thus, even if users do not ask for a service, or ask for it and do not receive it, costs are incurred.

> Point A refers to the situation where the quality of service to users is low, e.g. inadequate or unreliable or inflexible deliveries.

FIGURE 48
The nominal service–cost curve (input–output)

For example, point A could be a service based on fixed rotation of irrigation and proportional deliveries.

➢ Point B indicates that with a limited increase in inputs the service is much improved. This could be the typical situation for many large-scale irrigation systems in the world. Inputs are low, and a medium level of service should theoretically be expected.

➢ Point C could correspond to a highly reliable and flexible service of water on a gated system. Moving towards better service (C) becomes increasingly costly with the same system, and the stage may be reached (D) where the service can no longer be reasonably improved with the same physical system. Any further improvement would have to be obtained by drastically changing the type of system, e.g. shifting towards downstream controlled canals or to a pressurized system or utilizing another source of water (groundwater supply) from a shallow groundwater well (highly reliable, flexible, adequate, timely, etc.).

➢ Point E corresponds to a performance of management below nominal; actual performance is below what could be obtained with the same level of inputs (resources) when the management of resources is more focused. Many large irrigation systems in the world are "point E" type.

This curve is central in SOM when there are discussions with users about deciding on the irrigation service that managers should target and that the users are willing to pay for. Users need to have a good knowledge of what the cost should be for the service they want. They need to know:

➢ what a low-service cost is (point A of the curve), what a high-service cost (point C) or any intermediate type of service (B) is;

➢ what the expected potential gains in service quality are by refocusing inputs (from E to B);

➢ what the expected reductions in costs are by reducing inputs for the same level of service S_E (from E to E').

CHALLENGES IN MAPPING THE COST OF OPERATION

The inputs and costs of a canal system are seldom transparent to the users. Indeed, they are sometimes not transparent to the management either. For many reasons, there is a dramatic lack of references on the real cost of irrigation services, although the concept of water charging has been debated thoroughly in the water sector in recent years.

Information and knowledge about the costs of management and O&M are usually fragmentary and often not enough to estimate cost of operation. Further analysis is mostly required in order to produce reliable figures on what should be considered a reasonable cost for a given service, and what the maintenance should entail.

The challenges are manifold:

➢ a basic lack of information;

➢ difficulties in interpreting the information where it is available;

➢ difficulties in separating operation from the other activities;

➢ identifying the proportionality between services and inputs.

Critical issues

The critical question here is about the proportionality of management, operation and maintenance (MOM) to the service. This can be captured through a set of questions, and ultimately it is necessary to document the proportionality, as shown in Table 22. Some specific questions are:

➢ What are the fixed costs of MOM?

➢ What part of maintenance is proportional to the service? What part is fixed?

➢ What part of management is proportional to the service?

> What is needed in terms of input changes in order to modify the service to users?
> What will be the cost (gain or additional) associated with this change?
> What are the options for reducing input yet with the same level of service?

This chapter does not attempt to provide references but to give some directions that should be investigated by managers, as well as local and national stakeholders, in order to determine more reliable, locally specific information about the cost of operation as a function of service.

TABLE 22
Proportionality of MOM with services, indicative values

| Activity | Fraction of the activity that is: | |
	fixed or independent of service	proportional to service
	(%)	
Management	80	20
Maintenance	100[1]	0
Operation	0	100

[1] Assuming that 100 percent of maintenance is fixed or not proportional to service is an extreme assumption. In many cases, it might be correct but not in all. In canal systems, the nature of maintenance work might change with the level of service but the total cost might remain the same. With a lift system, maintenance is related more closely to the service (volume and pressure).

Sources of information
Where clear information on cost of operation is lacking, other available sources should be utilised to acquire cost estimates. Some such sources of information and knowledge on the input–output relationship are listed in Table 23.

TARIFF ANALYSIS
The assumption here is that the tariff for services should normally reflect the intensity of efforts deployed to produce the service. This assumption is not always nor fully verified on the ground as other considerations engender some explicit and/or implicit distortions.

Crop-based tariff
Irrigation fees are often crop-based. As water needs (volume, frequency, and season duration) vary with the crop, the service to users and, therefore, the fees they should pay are different. To a certain extent, the set fees recognize the fact that the service is different for each crop. However, part of the tariff may also reflect the added value of the crops. This is the case in Maharashtra (India), where the fees for perennial cash crops (e.g. sugar cane and bananas), are much higher than for any other sequence of three crops throughout the year (Table 24). Thus, a crop-based tariff is one source of information about service cost as a function of crop, but it is necessary to double-check what is really reflected in the composition of the fees.

Energy-based tariff
In irrigation systems where energy is an important component of the cost, a differentiation is to be expected depending on the energy input in the service. This

TABLE 23
Sources of information and knowledge on the input–output relationship

Sources of information	Assumption	Outcomes
Tariff analysis	Tariffs are based on service	General shape
Survey of actual service and fees	Fees are related to actual delivery of service	General shape
Budget analysis of the management agency	Breakdown between operation and maintenance	One point of the curve
Cost analysis (macro)	Breakdown between operation and maintenance	One point of the curve
Groundwater services	Groundwater individual services provides the best service	One point along the curve and the general shape

TABLE 24
Irrigation fees according to crops, Maharashtra, India, 2004–05

Crop	Surface canal water (US$/ha)
Kharif	
Seasonals & paddy	5.2
Groundnut, hy. seeds, etc..	10.4
Rabi	
Seasonals (except wheat and groundnut)	7.8
Wheat	10.4
Cotton, groundnut, paddy, etc.	15.8
Hot-weather season	
Seasonals	15.8
Perennial	
Sugar cane and banana	137.0

is the case for surface and pressurized irrigation services. Figure 49 presents water charges in three different situations in Morocco: surface irrigation in Tadla; sprinkler irrigation in Massa; and disaggregated surface irrigation lift and sprinkler systems in the Gharb irrigation projects. The figure shows water prices per cubic metre of water based on the Agricultural Investment Code. This code provides the legal and institutional framework for significant recovery of both investment and operating costs in irrigation (full recovery of O&M costs and up to 40 percent of initial investment costs).
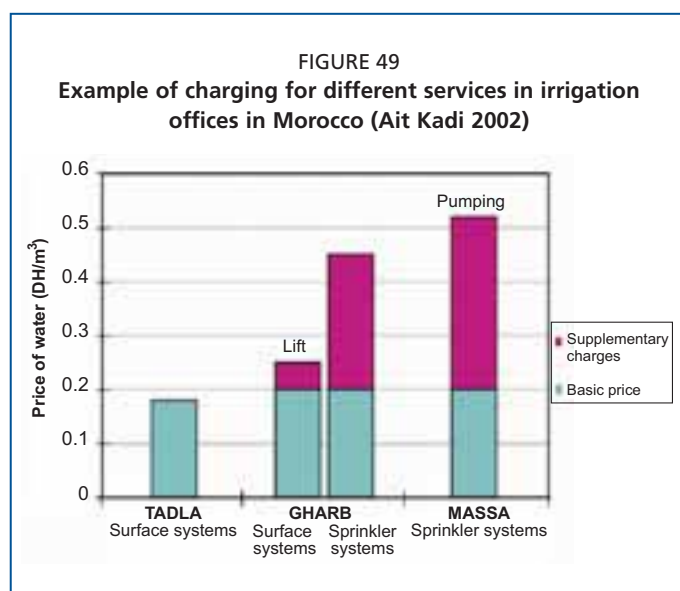
SERVICE–FEE RELATIONSHIPS FROM VARIOUS RAPS IN ASIA

Water charges reflect both the level of service provided and the constraints influencing the costs associated with it. This is illustrated in Figure 50, which plots the irrigation service fee of 11 irrigation projects against the overall service indicator (which embedded in itself individual service indicators of flexibility, equity and adequacy) from RAPs conducted of these projects between 1995 and 2005.

Figure 50 shows that, although the O&M of most of these irrigation systems are subsidized (especially the ones at the lower end of the service indicators), the overall service indicator increases with the irrigation service fee or water charges. Lower water charges are mainly in the irrigation systems, which are designed for staple crops such as rice and wheat as major crops. Systems with high water charges are designed more for cash crops such as cotton and tobacco. The main reasons for low water delivery service indicators included deferred maintenance and improper operations, which in turn were related to the budget constraints. This shows that considerable increases in water charges (and improvements in their collection) are required in order to improve overall water delivery service. For

FIGURE 49
Example of charging for different services in irrigation offices in Morocco (Ait Kadi 2002)

FIGURE 50
Irrigation service fee vs water delivery service in different irrigation projects
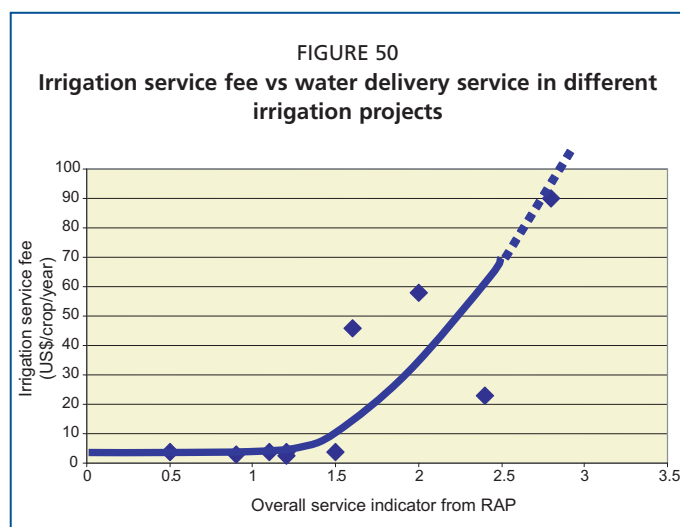
water users, improved water delivery service (meaning improved reliability, adequacy and flexibility) would result not only in better yields and in improved planning and undertaking of on-farm irrigation activities, but also in more freedom to choose which crops to grow. Thus, their decisions on investing in improved water delivery service (one or more components) will depend on their choice of crops to cultivate. For example, rice growers may well opt only for improved reliability rather than flexibility, whereas farmers who want to diversify would opt for improvements in all components of the water delivery service.

Even within the same basic type of canal system, the inputs for operation will depend on the land distribution pattern, planting/harvest schedules, frequency of changes, etc. Another factor that influences input cost is the water charging method (not discussed in detail in this paper). For example, if a WUA (or water user) is charged on the basis of volume delivered during a season instead of a fixed charge depending on the area and crop irrigated, then: (i) the volume of water delivered must be known for billing, which requires good measurement structures at the point of delivery; (ii) better planning and very careful operations (gate settings, perturbation management, etc.) are required; and (iii) better communication and mobility of the personnel is also required. All these factors have implications for the inputs and, thus, for the cost.

Although fee analysis and general tariffs provide indications about inputs and costs, they are too approximate and vague to yield useful insights such as to enable full understanding of the elements contributing to the cost of services.

BUDGET ANALYSIS OF MANAGEMENT AGENCIES

The analysis of the budget of the management agency is a source of information on cost associated to operation. The budget information of irrigation projects collected in the RAP (MASSCOTE Step 1) gives a first indication of the cost of operation. However, detailed information on different inputs is required in order to evaluate the cost of different options for improvements. For example, in systems where labour is expensive, the number of staff can be reduced and vehicles provided to the remaining staff in order to increase mobility. In such a case, it is important to know the unit cost of keeping a vehicle (price, insurance, fuel, maintenance, etc.).

For proposing improvements and analysing the cost-effectiveness of operation, it is useful to disaggregate the total budget into activities related to MOM. The cost of O&M often refers to the sum of all costs related to distribution of water and maintenance of irrigation infrastructures. However, some differences exist in different projects about what is included in the irrigation (and drainage) infrastructure and O&M activities. Disaggregating this cost into operation and maintenance (and other relevant components) is important when making decisions regarding the improvements and cost-effectiveness of both operation and maintenance activities.

Personnel cost is usually by far the largest component of operations as staff is a main input for canal operation. Staff costs are rarely less than 50 percent of the total annual cost, often as high as 70 percent (FAO, 1986). The cost of equipment is usually the lowest item. However, some of the costs related to equipment use, e.g. of the staff who operate it, are included in personnel and salaries. Table 25 presents an example of

TABLE 25
Breakdown of the annual budget, Canal St. Julien, France, 2004

Item	Budget allocation (EUR)
Electricity	35 460
Small equipment, stationery, clothing	12 906
Contracts for canal maintenance	193 926
Vehicles (insurances, fuel & maintenance)	26 191
Communication (post & telephone)	13 306
Land tax	7 720
Water agency (tax)	46 508
Personnel (salary, charges & training)	646 605
Miscellaneous	113 620
Total	1 096 242

Note: EUR1 = US$1.28.

FIGURE 51
Budget breakdown for the Cu Chi Irrigation Management Company, Viet Nam
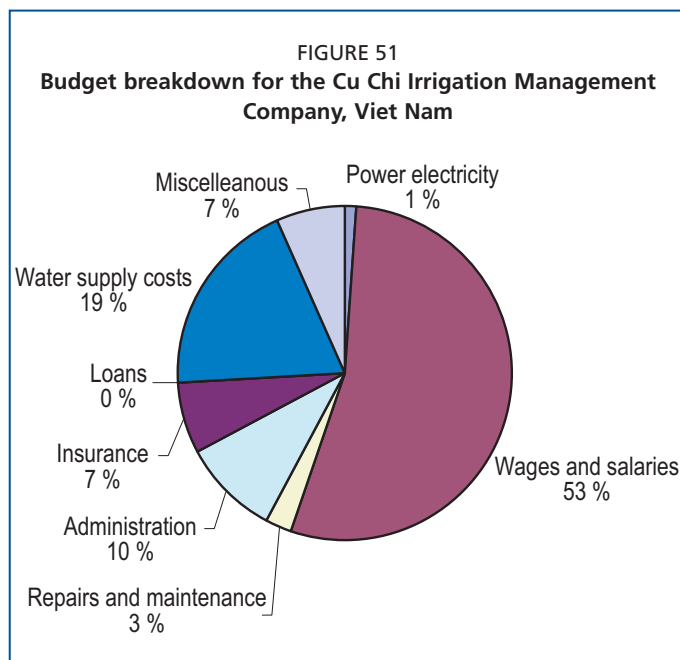
Source: Davidson, Malano and George, 2004.

budget breakdown from the Canal St Julien system in France (5000 ha). The personnel costs represented about 60 percent of the annual budget of the association in 2004. In the past, this cost was even higher when all maintenance was done by the staff instead of being subcontracted (as is done now).

The Canal St Julien system is managed by an irrigation bureau or WUA with some degree of state control. The WUA provides water and collects the water fee from individual owners. The O&M is covered by the water charges. The 2004 budget was EUR1.096 million (about US$1.4 million) with salaries and contracts for canal maintenance as the two major items in terms of budget allocation (Table 25). In 2006, the O&M budget of the WUA was EUR1.2 million, about EUR250 (about US$300) per hectare per year payable by the water users. The investment budget of the WUA for 2006 was EUR1.4 million, to be paid by state subsidies, the river basin agency, and some loans taken out by the WUA.

Figure 51 shows a similar budget breakdown for the Cu Chi Irrigation Management Company in Viet Nam. The annual MOM cost of the company is about US$38/ha for a scheme area of 8 500 ha. Again, wages and salaries represent more than 50 percent of the total budget.

The cases of the Canal St Julien system and Cu Chi Irrigation Management Company are examples and these in no way suggest that every irrigation project or WUA needs to have the same categories for budget allocation. However, it is important for a WUA to have different categories and a detailed account of the budget, rather than putting everything under O&M. The minimum information required for a cost analysis of operation is:

  ➢ salaries and personnel benefits;
  ➢ energy cost for pumps (if there are pumps in the project);
  ➢ communication – telephone bills, etc.;
  ➢ transport, including fuel, insurance and maintenance of the vehicles;
  ➢ equipment – depreciation, operating cost, and repairs;
  ➢ miscellaneous/others (operators' quarters, administrative costs, etc).
  ➢ investments

GENERIC ANALYSIS OF THE COST OF MOM

Another source of information about cost and service is the national or project surveys that are sometimes produced by the national irrigation departments. This generally provides figures for one of the two complementary sources of information about cost analysis:

  ➢ national and/or regional references on costing of operation;
  ➢ accounts of the project.

The ideal case is where both sources can be tapped, combining local figures with national references. However, the information on project accounts and the budget is

often not readily available for this
analysis, and where it is, it is not
always easy to separate the budget
for operation from other activities.
Moreover, in many cases, the budget
for operation is underestimated, which
is one of the causes of low performance
of many irrigation schemes. Therefore,
it is sometimes important to compare
these costs with the cost of operation
at national and regional level.

TABLE 26

Breakdown of operation costs per level of the infrastructure in the SMIS, Nepal

Component	Operation	Percentage of the total cost for operation
	Nr/ha	(%)
Headworks	35	10
Main canal	50	15
Secondary & subsecondary canals	120	35
Tertiary canals & watercourses	125	40
Total	260	100

Source: S. Sijapati, personal communication, 1999.

Cost of O&M: an example from Nepal

In the 1990s, the Irrigation Department of Nepal estimated that the annual O&M
cost for most large projects in the Terai was more than Nr400/ha (US$1 = Nr72),
with operation costs as per Table 26. At that time, the project operation plan for the
SMIS then assumed an annual maintenance budget of Nr770/ha (DOI, 2001). These
figures have decreased since canals serving less than 1 000 ha were transferred to
users.

In the project operation plan for the Narayani Zone Irrigation Development
Project, the annual incremental O&M cost for surface irrigation schemes was Nr950/
ha (Pradhan *et al.*, 1998).

According to the current managers, the O&M cost in the SMIS should be Nr1 500/
ha, with Nr500 for operation and Nr1 000 for maintenance. This amount would
correspond to about 3.3 percent of the gross product in the CA for 2005. According to
Pradhan *et al.* (1998), it would correspond to about 10 percent of the net income per
hectare provided.

Part of the differences in the figures for O&M costs can be explained by inflation
and by the increase in cropping intensity from one irrigated crop per year (rice) to
more than two on average (the cropping intensity is currently 215 percent). With
year-round irrigation, the service is provided for a much longer period of time and the
cost of O&M increases. Therefore, a figure of Nr1 500/year for irrigation should be
considered for O&M.

This figure should be compared with the cost to individual farmers of pumping
groundwater. The RAP estimated this cost at Nr2 000–3 000 per crop/season, meaning
that two crops per year would cost Nr4 000–6 000 with this type of supply (even more
expensive where the farmer has to rent the equipment).

This O&M cost corresponds to the
current service, which in many regards
is not able to satisfy demand in winter
and spring. Responding to the users'
demand with more flexible service,
assuming that water availability from
the Koshi River has been secured,
would increase the inputs again and,
as a consequence, the cost per year
(Figure 52).

Therefore, it seems reasonable
to consider a cost for an upgraded
service from surface supply allowing
two crops at about Nr1 800/ha/year
(the increase being mainly due to
operation). This cost should be

FIGURE 52

Evaluation of different cost/services, SMIS, Nepal
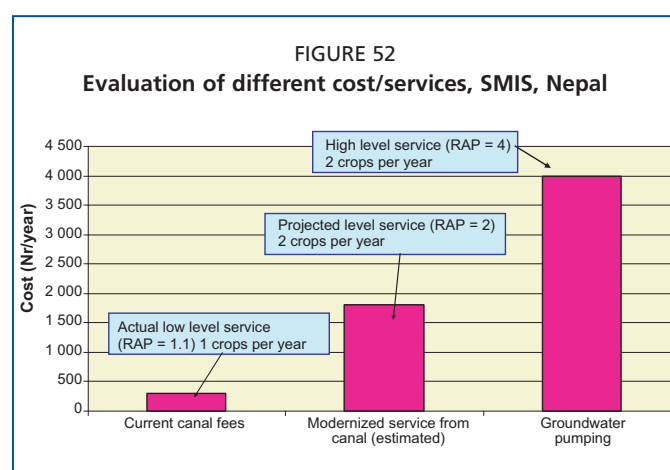
Plate 27
Supplying a paddy-field with shallow groundwater, Nepal.

TABLE 27
Energy requirement when water is supplied by groundwater, Ghataprabha project, India

Crop	Sugar cane
Crop water requirement	2 000 mm as evapotranspiration per year
Field efficiency	66 percent
Water supply at field inlet	30 000 m³/ha
Bore well	80 m, with submersible pump at 40 m
Water lift (head)	24 m (12 m static + 12 m dynamic)
Pump efficiency	75 percent
Energy demand	(Volume × Head)/(367 × Efficiency)
Annual energy demand	2 600 kWh spent for 1 ha sugar cane
Energy per cubic metre	0.086 kWh/m³
Electricity rates	
Agriculture (average)	Rs0.5/kWh
Industrial	Rs7/kWh
Cost of energy for pumping	Rs9 150/ha (at Rs3.5/kWh).

Note: The fixed cost for pumping equipment was estimated at Rs2 000/ha/year. This includes the capital cost for wells and pump equipment, and routine maintenance.

GROUNDWATER SERVICES

Many farmers that have poor service from a canal, or none at all, have moved to groundwater pumping wherever it is accessible at a reasonable cost. Thus, they usually pay a high cost for an adequate, reliable and flexible service. The cost of pumping varies with the context. In Terai, Nepal, farmers spend Nr3 000 per season for rice (Plate 27).

Table 27 summarizes the information on energy requirement and related cost for water extraction from shallow groundwater in Ghataprabha irrigation project in India. The average cost of energy for pumping groundwater to cultivate sugarcane in one hectare is about US$ 210, which is much higher than the canal water fee of sugarcane in the project.

COST ANALYSIS FOR OPTIONS FOR IMPROVEMENTS IN COST-EFFECTIVENESS AND SERVICE

Cost analysis of operations for different options is done for two reasons: (i) to reduce the cost of operation without jeopardizing the existing level of service; and (ii) to improve the level of service. Analysing current costs should allow identification of potential cost-saving items and answer questions such as what the most expensive items are and where money can be saved.

Improving the level of service of an existing irrigation system by taking measures to improve the operation will add a certain cost to the existing operation costs. Being able to estimate the costs associated with such an improvement project is important in order to evaluate whether the expected benefit of a project is reasonable in relation to the expected costs and whether the users can afford these costs.

Estimating costs is commonly done using the standard methods of cost–benefit analysis. These methods help evaluate the financial costs and returns associated with certain projects, and they provide guidance for decisions on the changes in service charges that are needed to recover the costs associated with these projects. In these types of economic analyses, it is important to make a distinction between two different types of costs, each of which is known under different labels:

➢ Capital or fixed costs are the costs that have to be paid, usually at the beginning of a project, in order to buy new equipment and materials, to modify irrigation structures and to set up new information and communication systems. Usually, such capital costs have to be incurred once and then benefits are provided for a long time, 5, 10, 20 years or longer, depending on the equipment or structures.

TABLE 28
Estimation of inputs for operation and for improved service in Narayani Irrigation System, Nepal

		Actual service	Option 1	Option 2
		Blocks 13–15 not served at all. Actual delivery from the main canal 0.4 (Blocks 1–12) (From the RAP)	Operation improvements aim at providing a slightly improved service to all local agencies, including downstream part of the CA	Serving the entire CA with an improved service to all users (2 crops/year).
		Inputs (Nr million)		
Level 1	Staff	1.250	2.000	2.500
Main system	Office	0.250	0.500	0.500
25%	Transport & communication	0.175	0.500	0.500
Level 2	Staff	3.750	4.100	6.000
Secondary and tertiary canals – local agencies	Office	0.750	1.000	2.000
75%	Transport & communication	0.525	1.050	2.000
Total operation		6.700	9.150	13.500
Cost per hectare served		Nr233	Nr244	Nr360

> ➢ Recurrent or variable costs are costs that recur, e.g. on a daily, weekly or monthly basis, and they are the costs associated with providing the service, once all the equipment and infrastructure is in place. They include fuel costs for transportation, labour costs, electricity costs, and general maintenance costs for equipment (e.g. regular servicing for vehicles, pumping stations and diversion structures).

Table 28 shows the breakdown of cost of operation for the Narayani Irrigation System (NIS), Terai, Nepal, with an actual service from the main canal to secondary canals ranked at 0.4 (very low) by the RAP. This value corresponds to water delivery service to 12 blocks (covering about 80 percent of the official CA of the irrigation scheme). The last three blocks do not receive any surface water. With reference to the irrigated area, the cost of operating the system is Nr233/ha.

From the breakdown of the actual cost for different levels and items, a rough estimation of the service cost has been determined for two options.

Option 1 aims mainly at improving water management and deliveries along the main canal through tapping additional water from natural surface streams, an improved information system and better operation. This option does not target much improvement within the secondary CAs. The service (in terms of reliability and equity) to farmers is only slightly improved.

The main system level inputs are increased significantly to face these challenges while some new allocation is made in order to develop the local management capacity in Block 13–15. Under this option, the cost of operating the system would be about Nr244/ha.

Option 2 targets Option 1 plus significant improvements in the service delivery to farmers, which basically means two crops a year and improved reliability and equity. In order to realize this option, an increase in the staff capacity at main canal level and increases in many more inputs at the secondary canal level are required. For this option, the cost of operating the system would be about Nr360/ha.

Chapter 10
Mapping the service to users

Promoting Service Oriented Management (SOM) is the central goal of irrigation modernization. It means that service to users is central at management level and has many implications for the designing, agreeing upon, producing, monitoring and evaluating the service. In irrigation systems, the primary historical focus has been on agriculture. However, consideration also needs to be given to other users. Within an irrigated service area, the provision of different services to multiple users is a constraint for managers; it increases the complexity of the task of controlling and delivering water. However, it is also an opportunity for sharing the cost of management among a larger number of stakeholders.

This chapter attempts to qualify and characterize (mapping) the service to users, starting with the primary service to farmers. In addition, it also seeks to map the services to other types of users.

A preliminary vision for the future of irrigation scheme should emerge at the end of this step of MASSCOTE.

FEATURES OF SERVICE-ORIENTED MANAGEMENT

As stated in the definition of SOM (Box 1): An SOM solution supervises and controls the delivery of a service from a service provider to a service requester. In irrigation management, the latter is called a service receiver. The three pillars of SOM are the service itself and the two actors – the provider and the receiver (or user or beneficiary) – as illustrated in Figure 3.

The actors of the service

In business language, receivers are considered customers or clients. In an irrigation system, receivers are these but also actors or stakeholders of the management through effective participation in the governance of the scheme. For example, in a WUA, farmers are not only the customers of the service, they also are involved in making the decisions about it. In this sense, the farmers are also actors.

The elements of the service

The first element is the water. Water delivery is central in the service, but it is not the only important component. Information is also an important flow of the water service. Information flows in both directions, from providers to receivers and vice versa. Users need to have information about the allocation of water, the scheduling of supply, and about measurements of deliveries.

Indeed, the service consists of three main flows: service = water + information + money (Table 29). These three flows are intrinsically linked to each other, and this can be captured through the following phrases:
- No water, no money.
- Water needs information.
- Information is money for the users.
- Money needs information.
- Money must pay for water, information and money.

TABLE 29
Service flows

Provider	Service	Receiver
Operates the system to produce water deliveries.	Water flows	
Should inform receivers beforehand about the service they can anticipate for a given period of time (season, year), about the scheduling of deliveries.	Information flows	Information on the demand for services from the receiver should be conveyed to the provider.
Information on actual service must be collected.		Information on actual service must be checked/collected.
Should charge for the actual service and ensure the long-term sustainability of the infrastructure.	Money	Should pay the service according to the volume used or benefit obtained.

Information and services

Information is a critical part of the service in SOM. Reliable and accurate information about the service of water is crucial for farmers when they need to make strategic decision about their cropping pattern and cropping calendar. They need to know in advance if the amount of water will be enough for the crops they are planning to grow, and if this water will be available at the water-sensitive growth stages of these crops.

Information on the demand for water services is critical for the managers before and during a season.

Information is also needed in order to assess the actual service and charge the users accordingly.

Money and services

Money is essential for the sustainability of the scheme. Numerous irrigation systems were and still are underfunded by the state, whereas the management transfer to users has not been completed (or even started) in many cases.

The bill for the irrigation management services has to be paid by someone, now or later, for own use and for someone else. It is common to see the taxpayer paying part of the entire bill for irrigation management at the investment. It is also common to see the taxpayer paying for MOM, but this modus operandi cannot last for long.

Therefore, it is a major responsibility of the management to organize effectively the flows of money for producing the services (MOM).

Defining services to users

Irrigation systems were originally built to supply farmers with water where crop requirements could not be met by natural precipitations. Thus, service to farmers has been and should still be the central focus of the management. However, with time, it has become more and more apparent that other beneficiaries are taking advantage of irrigation water supplies for other uses, which may penalize irrigated agriculture. In the extended category of services within an irrigation project, the following services can be found:

➢ domestic supply to villages;
➢ recharge to groundwater;
➢ environmental flows;
➢ health;
➢ industrial uses;
➢ fishing;
➢ recreational areas;

➢tourism.

The services to users are today much broader than at the initial stages of irrigation development although water demands by farmers are still central.

The task of defining the service and determining the requirements for operation consists primarily of answering the following questions that address both the definition of the service and the consequent requirements for operation:

➢What services are demanded by the different user groups?

➢How do these relate spatially, in time and in terms of operational requirements?

➢What services can be offered to the users?

➢What is the possible range of services and fees to be considered?

➢What mode of operation can be followed and with what precision?

➢What should be the frequency of checking and intervening?

➢Which setup is required in order to monitor the service?

➢What are the mechanisms to ensure that services are provided and paid for?

Several possible irrigation service arrangements can usually be conceived. Even where the physical infrastructure is pre-set, there can be a number of variations in planning, flexibility and accuracy of operation. It is logical to expect that an increase in inputs (labour and money) will generally result in a higher level of service. However, it is not that simple. A key factor for successful canal operation is targeted improvements that meet a real demand of the users.

In order to meet contemporary irrigation demands on canal operations, it is useful to follow a service-oriented approach. This implies that users and service providers are jointly responsible for designing and defining the best compromise between the level and cost of service, bearing in mind that users will ultimately reap the benefits and bear the costs of operation.

SERVICE TO FARMERS

The quality of service to agricultural users can be specified through indicators similar to those used for performance assessment, e.g. adequacy, flexibility, reliability and timeliness. For other uses of water, such as fishing, environment and heath, service indicators can be very different: presence of water, fluctuations of streams, temperature, etc.

The service to farmers is usually defined with reference to three time-related aspects that are important for farming organizations:

➢allocation of water for the season or year;

➢irrigation delivery scheduling;

➢actual water delivery.

In terms of allocation of water for the season or the year, the service includes not only the quantum (volume) of water but also the flexibility in negotiating variations around that value. This aspect is important in relation to the structural decision in matching water demand and water supply, for example, in adjusting the cropping pattern to whatever water is allocated, or in securing additional water supply to cover the cropping pattern.

Irrigation delivery scheduling is the procedure to establish a roster of irrigation turns or water applications for a specific period of time, for example an irrigation (or crop) season. The quality of service is specified by the frequency with which water will be made available, e.g. every week, fortnight or month, and again the flexibility in modifying the schedule to match unexpected changes. This aspect is important for ensuring that the water supply will prevent moisture deficit at field level, and also for the organization of the human resources and equipment at farm level. Flexibility here means that for a given allocated volume, the scheduling of supply can be adjusted. For example, some farmers may want to reduce the initial scheduled deliveries and reserve the volume for the peak or the end of the season.

FIGURE 53
Dimensions of service: allocation, scheduling and deliveries
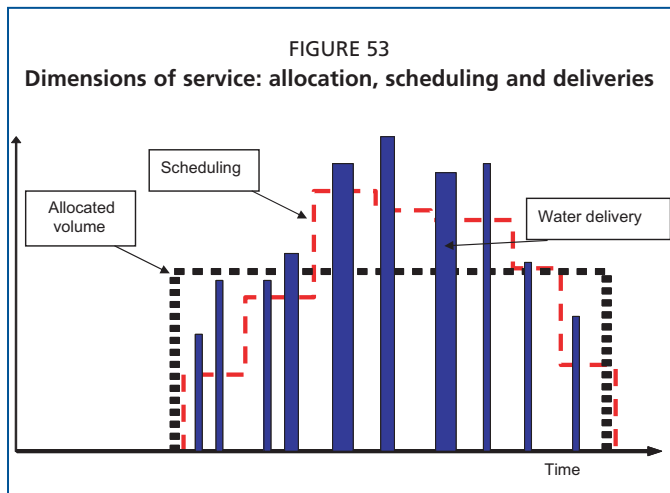
Actual water delivery refers to the water provided to the users. Specifically, it deals primarily with discharge (instantaneous flow) and volume (quantity over a period of time) of water delivered with respect to demand at a given point in time.

Therefore, although the emphasis tends to be on the service in terms of water delivery, it is necessary to bear in mind the three dimensions of the service to farmers (Figure 53).

Water quality is also an important aspect of the service that must be considered by the managers and users. However, it is often not easily controlled, and may be more the result of given conditions.

Sizing the service: target and tolerance

The service can be assessed through hydraulic indicators attached to the deliveries similar to those used for performance assessment, e.g. adequacy, flexibility and reliability. An important indicator of service is the tolerance within which deliveries are allowed to fluctuate. Therefore, it must be specified by two variables: target and tolerance: Service = {Target; Tolerance}. For example:

➤ service = 100 litres/s ± 10 percent;
➤ service = deliveries on time ± 3 days.

The tolerance sets the limits within which the volume is allowed to fluctuate. There is a need to define a tolerance level that is: (i) acceptable to all the stakeholders involved; and (ii) consistent with the accuracy by which service is assessed.

In theory, the previous definition allows identifying without ambiguity when the service is achieved and when it is under default. In practice, it also depends on the accuracy by which it is measured.

Accounting for inaccuracy

The inaccuracy of measurement adds ambiguity to the process. Figure 54 shows how this happens. In this example, the tolerance is set to 10 percent, which for a target of 100 litres/s means that the discharge should vary within the range of 90 to 110 litres/s. Assuming that the measurement device is capable of assessing the true value with a precision of 5 percent, it means that when the reading is 110 litres/s the true value lies between 105 and 115 litres/s. Similarly, for 90 litres/s the true value lies between 85 and 95 litres/s.
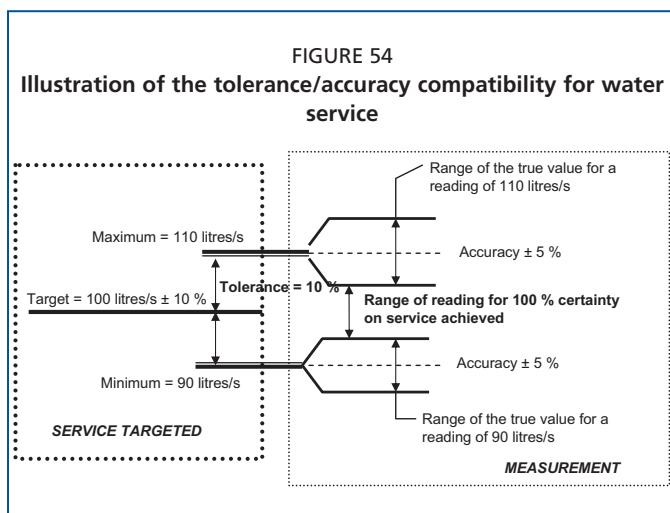
As a result, the range for which there is no ambiguity about the fact that service has been reached is for readings between 95 and 105 litres/s. This range is defined by the tolerance minus the accuracy of measurements. This is why tolerance cannot theoretically be

FIGURE 54
Illustration of the tolerance/accuracy compatibility for water service

equal or lower than the measurement accuracy. It would not be consistent to set a tolerance of 5 percent in discharge with devices that can only be 10 percent accurate.

Plate 28 shows a measurement structure (weir) downstream of an offtake along the SMIS (Nepal). In this structure, the measurement accuracy is very low because of: (i) the imprecision in reading the gauge; (ii) the presence of turbulences; and (iii) the low sensitivity of the weir (too large). It is estimated that accuracy is equal to or greater than 20 percent. Therefore, in this particular case, it is not possible to target service at less than 20-percent discharge.

In short, there is no point in having a narrow tolerance for service on discharge where the measurement accuracy is low.

Plate 28
Head of secondary canal equipped with a measurement device (gauge) of very low accuracy (Nepal).

Types of service

Service targets and indicators for water delivery to farmers (rate, duration and frequency) are to a large extent dependent on the infrastructure/technologies and water-control method. For example, it is not possible to achieve flexibility in delivery rate in a proportional distribution system. The main options for service delivery are:

➤ pre-set;
➤ arranged (on-demand);
➤ free access (full flexibility).

Clemmens and Replogle (1987) reviewed water delivery patterns as far as the target indicators are concerned. Table 30 presents different water delivery targets, their operation parameters and the flow control systems in which these targets are often found or aimed for.

Setting service parameters

The way targets and tolerances are set during the irrigation season results in a certain level of service (Table 31). Service targets and tolerances to variation may be distinct for different users. Some can accommodate a lower service quality than others (access to groundwater); some want very timely water deliveries (vegetables); others want very low discharges over a long period (drip irrigation). Furthermore, demands can change over time. The reliability of irrigation during the transplanting of rice should be very high, whereas some variability is allowed later in the season. Last, the stakes are highest for tail-end users as they will feel the impacts of flawed service the hardest.

Other requirements of service are not so much related to the quantity of individual deliveries but more to the general setup and their influence on the operation system. An important indicator is the flexibility of the system. Delivery flexibility can be defined as the level of freedom to change the variables of water delivery (rate, duration and frequency), e.g. the possibility to request a certain volume of water at a certain discharge at a certain place and time.

In Pakistan, variable tolerances for water deliveries are found in systems managed with rotating priorities for irrigation (particularly during dry or water-short seasons). During one turn (usually a week or ten days), one set of offtakes is given the highest

TABLE 30
Definitions of delivery scheduling methods

Schedule categories / water delivery service targets	Operation parameters			Flow control methods
	Rate	Duration	Frequency	
Free access / on-demand				
Unrestricted	U	U	U	DS-auto, US-auto-cent
Limited rate demand	L	U	U	DS-auto, US-auto-cent
Limited or arranged frequency	L	U	A	DS-auto, US-auto-cent
Limited duration	U	L	U	DS-auto, US-auto-cent
On-request / arranged schedules				
Arranged	A	A	A	DS-auto, US-auto
Limited rate arranged	L	A	A	US-auto, US-man
Restricted arranged	C	C	A	US auto, US-man
Fixed duration arranged	C	F	A	US-auto, US-man
Fixed rate / restricted arranged	F	C	A	US-auto, US-man
Rigid or imposed				
Central system	V	V	V	US-auto-cent; US-man
Fixed amount	F	F	V	US-auto; US-man
Fixed rotation	F	F	F	US-auto; US-man
Varied amount rotation	F(V)	F(V)	F	US-auto; US-man, Prop.
Varied frequency rotation	F	F(V)	F(V)	US-auto; US-man, Prop.
Continuous flow	F(V)	-	-	US-man, Prop.

Note: U: unlimited, no restriction, under user control; L: limited to maximum flow rate, but still arranged; A: arranged between user and water authority; C: constant during irrigation as arranged; F: fixed by central policy; V: varied by central authority, at authority's discretion; (V): varied by central authority, seasonally by policy; DS-auto: downstream automatic; US-auto-cent: upstream automatic central; US-auto: upstream automatic (both central and local); US-man: upstream manual; Prop.: proportional.
Source: After Clemmens and Replogle (1987).

TABLE 31
Example of service targets and tolerances for a delivery to a farmer

Service component	Target	Tolerance
Discharge	100 litres/s	-10 litres/s, +20 litres/s[1]
Timeliness	At the hour	±1 day
Duration	6 hours	±30 minutes
Flow characteristics	Stable flow	20% variation in discharge
Compensation when at fault	Direct compensation in water	Max. 3 days period

[1] The tolerance for discharge might be different under target and over target as a deficit is more penalizing for farmers than is an oversupply.

priority and, therefore, the lowest tolerance of variation from targets, while the other set is fed only if there is some left over, thus with a high tolerance of deviation from target. For the following turn, the priority is reversed.

SERVICE BY TYPE OF CANAL SYSTEM

The concept of a uniform service defined once and forever and for everyone at the design stage is no longer valid. Given the diversification of crop production and marketing strategies, as well as the development of alternative sources of water (e.g. shallow groundwater pumping), the demand for service is increasingly variable within the area of the canal system and throughout the cropping season(s). The question is the extent to which the variety of demands can be accommodated, in the knowledge that more flexibility makes operation more complex and often more costly. Again, a compromise has to be found between meeting the demands of users and keeping complexity and water charges at an acceptable level. Figure 55 shows some examples of flexibility and complexity for various modes of operation and system layouts. The systems plotted in Figure 55 are:

➢ Proportional system:
  • A: Continuous flow (sawah and many hill irrigation systems); low flexibility, but extremely low operational requirements and costs.
➢ Gated system:
  • B: Uniform service: fixed rotational schedule (times, discharges, frequencies, based on shares); flexibility does not increase, but operational complexity does.
  • C: Uniform service, imposed rotational schedule, crop-based on seasonal planning.
  • D: Semi-uniform service, imposed rotational schedule, based on real-time crop demands.
  • E: Diversified service, arranged scheduling and allocation; this is the most flexible situation for gated systems, but can be extremely complex and needs a strong management setup.
➢ Automated or semi-automated system:
  • F: Uniform service, imposed rotational schedule that is crop-based, seasonal planning; the service is similar to the situation under C, but the infrastructure is not designed for this operational mode, and it will be complex to enforce the rotation.
  • G: Diversified service, on-demand, free delivery; this system is rarely found in practice. The dream of many farmers, it resembles the service of domestic water supply. Operational complexity, where well designed, can be low and flexibility is very high.

Figure 55 compares the flexibility of the system with operational complexity and costs incurred. The operational modes are presented as points rather than as curves. Transition from one mode to another is often not a gradual, but a step-by-step or very drastic reform. There is a cloud of possibilities around each point, and many more setups are possible. However, the ones plotted are those most frequently found in practice rather than in the literature. Although complexity and level of service are related, it is not a one-dimensional curve. Infrastructure is a major determining factor in the range of possibilities. For example, point G shows that a semi-automated system can deliver high flexibility at relatively low costs, whereas a traditional gated system can perhaps never attain this level of flexibility and surely at much higher costs. However, the conclusion should not be that all systems should be automated. The reasons for this statement are:

➢ Water-use efficiency is not represented in Figure 55. Where water is scarce, a less uniform but highly efficient system can deliver a better service to the users than a water-consuming flexible system.
➢ Variability in operational modes. Throughout the season, or over the years, the required modes of operation may vary widely. For example, infrastructure and management arrangements should be capable of shifting from a strict to a more *laissez-faire* mode of operation.
➢ Control over the system: Can free-riders be isolated? Is the system

FIGURE 55

Flexibility vs complexity of operation for different modes of operation and system layouts
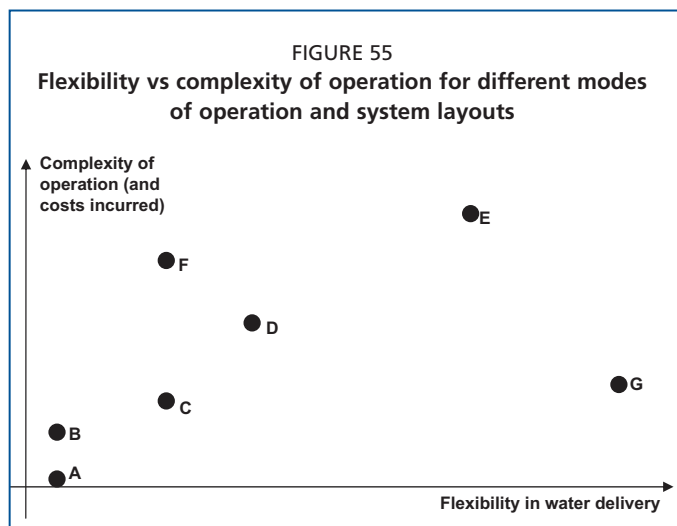
tamperproof? These questions are in the interests of both users and operators, and control can be partly exercised through the choice of infrastructure.

THE MULTIPLE USES OF WATER
Agricultural uses

Primary objective of irrigation systems is to supply water to farmers. Therefore, agricultural demands dominate in debates and negotiations over service. However, agricultural demands are not homogeneous. The demands of an organic farming community, growing vegetables and flowers, will be very different from uniform rice-based smallholder systems, which are again quite different from large cotton or sugar-cane estates. Their irrigation requirements will not only be different in terms of all performance variables, but their water demands will also be based on considerable differences in irrigation techniques, labour requirements, economic returns, vulnerability to service failures, bargaining power, status, gender divisions, etc. Crop water requirements for the different crops and varieties will be the basis of any irrigation service demand, but they are not the only rationale in farmers' irrigation strategies.

In this paper, it is not possible to deal with all considerations and specific service demands that are to be found in projects today. Water users are growing more capable of articulating their demands in debates on service provision. In addition, any debate on irrigation service demand will have to face a mosaic of demands that might be difficult to accommodate, or that may even be mutually incompatible. The final service agreements will reflect different crop water requirements, spatially different irrigation methods, established rights, local power relations, economic interests, etc. that are in line with the water resources available and O&M budgets. They may be different in time and location, with some designated critical periods per year.

In summary, it is important to remember that irrigation service demands:
➤ are heterogeneous in time and space and for different types of use;
➤ deal with delivery parameters as well as with demands on the operation and management setup.

Service to other uses/users and externalities

Water management is not confined to delivering water to crops. Increasingly, irrigation projects are seen within the larger context of basin water management as regards to both the qualitative and quantitative aspects of water. Even within a canal system, "irrigation water" may be used for many other purposes by farmers and other inhabitants of the area (Plate 29). Furthermore, the demands on the operator also include issues in the sphere of mitigation of possible negative side-effects of irrigation, e.g. salinization, waterlogging and the spread of vector-borne diseases. All these issues place more or less stringent requirements on the chosen mode of operation. For example recent studies (IWMI, 2001) have shown the positive effect of intentional water-level fluctuations on vector-borne diseases, e.g. malaria.

Within a canal system, there are several common externalities that managers have to deal with:

Plate 29
Fishing activities in a tank system (Sri Lanka).

➢ domestic water supply to villages (Plate 30);
➢ groundwater recharge;
➢ streams and waterbodies for fishing activities;
➢ water supply for livestock;
➢ environmental needs/impacts (groundwater recharge, waterlogging, salinity, and drainage and return flow from the CA to natural streams);
➢ recreational needs;
➢ health and sanitation.

Energy production is sometimes another important use of water stored in multiple-use reservoirs. The routing and scheduling of water demands for generating energy is most often at the main inflow point to the project. However, in some cases, it may be within the system itself.

Plate 30
Domestic water use, natural streams recharge by the surface canal network (Ghataprabha, India).

Types of service for other uses

The above-mentioned various additional uses and specific needs related to water management require different types of water service, ones that differ from the service for crop production. These extra services are context-specific, sometimes simple and at other times complex; they need to be discussed and tackled locally. The different service issues that managers may have to deal with are outlined in the following sections.

Supplying water to a delivery point

An example might be to provide a specific delivery flow rate at a particular point. In such a case, the service is rather similar to a delivery to farmers. This is particularly the case where water is delivered to a water tank for domestic supply to villages. In this case, the quality of service is mainly about timeliness and adequacy, but it is also about water quality.

An IWMI study (Ensink *et al.*, 2002) in Pakistan showed that a significant part of the CA has unpalatable groundwater and that, therefore, a large fraction of the rural population rely on irrigation surface water for their domestic supply. About 40 million people are estimated to be affected by water quality in the canal system, and this number is likely to double in the next 25 years. With a basic need of 50 litres per person per day, this represents a volume of 2 MCM/day. Some people are heavily dependent on surface irrigation water to fulfil their domestic needs, and they suffer during closure of the canal system for maintenance.

In many countries, water is treated for domestic water use, but there is no guarantee that this is the case for water in canal systems. Few options are available. One is to have water infiltrated in the soil and pump back from the water lenses on brackish water, in which case quantity is as important as quality.

Maintaining flows in local streams and waterbodies

In some low-lying areas, maintaining flows in the local drains, streams and marshes is important for preventing seawater intrusion. In other cases, maintaining water resources in wetlands is equally important for their capacity to sustain wildlife and the environment.

Maintaining water levels in local waterbodies

In some areas, water in the canals is the only source of water not only for drinking but also for other domestic uses such as bathing and for washing clothes. When the canals are closed (e.g. for canal maintenance, or when there is no irrigation demand), people living nearby can suffer owing to poor-quality groundwater – at times, it is impossible for them to access good-quality water. This issue has put pressure on managers to periodically fill portions of the canal systems in order to maintain minimum water levels (e.g. in Pakistan and Sri Lanka).

Maintaining water quality in natural streams

During dry periods, water supplies to natural streams maintain a minimum quality in local streams through the dilution of toxic wastewater drained from urban and peri-urban areas.

Maintaining the capacity for storing water and control floods

In areas and seasons where heavy rains are likely to occur, one objective of water control in the system is to maximize the ability to store precipitation. This has two positive effects: (i) it improves water resource availability; and (ii) it minimizes the impacts of the floods.

Types of operation required for different services

In theory, the basic physical operation of gates in the system is the same for providing any type of service. However, the process of decision-making and planning for these activities may differ from that of farmers and canal managers (Table 32).

An important aspect of operation for these "other uses" is planning and allocation. Canal managers need to know the water demands and requirements, as well as available resources, for these different users in order to be able to allocate water properly for these activities.

The multiple uses can sometimes conflict with one another and there is a need to compromise when the operation requirements are antagonists.

MAPPING THE DEMAND FOR SERVICE

Mapping the demand for service means identifying spatially the type of service, and then quantifying the service itself. More specifically, the demand for water service consists primarily of answering the following questions that address both the definition of the service and the consequent operation requirements:

➢ What type of service is demanded by the different user groups?
➢ What service can be offered to the users?
➢ What is the possible range of service and fees to be considered?

As examined in Chapter 12, service and operation are intrinsically linked. Therefore, mapping the service should not only be done from the perspective of the users but it should also be based on that of the service provider. Thus, an important question concerns how the services contemplated relate spatially, in time and in operational requirements.

The water service from the canal infrastructure has to be placed in the larger context of water management within the CA. In other words, the

TABLE 32
Type of target and service for different uses

Use	Type of service / target
Farmers	A time bound water delivery
	A share of flow
Support to natural surface streams & environment	A specific discharge
	Water quality through water dilution and/or drainage control
Tourism, fishing, groundwater recharge, recreation, wild animals & natural parks	A water presence & a given water level in waterbodies
Control of vector-born diseases in waterbodies	Water-level fluctuations
Flood control	Water storage capacity
Control of drainage return flow	Maximum discharge

BOX 5
Services and users: the case of "energy savings" in a conjunctive-use system

There are cases where considerations about the users and the service are not straightforward. For example, in a well-developed conjunctive-use system, the service from the canal is more about energy than about water.

In a conjunctive-use system, it can be assumed that the destination of canal water is to replenish soil moisture either through direct surface supply, pumping from shallow groundwater, or drainage partially or totally fed from seepages and percolation generated by the irrigation system itself. In a well-managed conjunctive-use system, there are no irrigation water losses, and, therefore, from a strict water management point of view, there is no difference whether the managers succeed in achieving a high delivery service at field level or not. The only major difference is the use of energy and the cost incurred in order to lift the water up again.

In these circumstances, the service of water to fields also comes with the notion of energy. Gravity-fed water at field level is energy saving. The real service for the irrigation system can be divided into two parts: (i) water service as a bulk of water supply to the CA; and (ii) energy savings for water delivered at field/farm level.

Savings depend on the head of the lift, for the example in Table 27, Chapter 9, the savings can be estimated at 3.6 Wh/m³/m lifted.

Users/beneficiaries: Where the farmers pay the full cost of water pumping, they are the users for both water and energy services. Where, as in India, energy is provided almost free of charge to farmers, it is necessary to consider two users/beneficiaries: farmers receive the service of water, and state saves the energy (or funds spend on subsidising energy).

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analysis of the demand for water service needs to consider the individual demand for water service as well as the specific context in which this demand is expressed (Box 5).

Agricultural demand

For agriculture, several criteria influence the nature and the characteristics of service:
- ➢ crop water requirements: function;
- ➢ source of water: rainfall, groundwater, etc.;
- ➢ soil characteristics.

Moreover, it is also necessary to consider different time scales, from the seasonal allocation of water (volume depending on the expected total needs) down to the characteristics of deliveries (discharge and volume, frequency, reliability, etc.).

Within one command, it is probable that the demand for service in irrigated agriculture varies spatially. There are some exceptions to this, for example, a small system with one single crop and no spatial variation in climate (e.g. rice paddy system during the dry season).

THE WATER MANAGEMENT CONTEXT

Irrigation systems, as stated in the previous sections, are increasingly expected to provide services for uses other than irrigation. Hence, service to users must be defined, produced, and assessed in the context of water management. This is considered vital for i) sustainability and enhanced performance of irrigation systems; and ii) mitigating negative impacts of irrigation on health and environment.

Water quality

Modern agricultural practices and the scarcity of freshwater result in some areas having to deal with water containing chemicals (pesticides and nutrients) and other pollutants.

Dealing with the wider causes and effects of water quality is a major challenge for irrigated agriculture, with implications for both surface water and groundwater. Many shallow aquifers are important for domestic supply. These often receive some recharge from dry-season percolation from irrigated areas, representing simultaneously a benefit (supply) and a threat (pollution). In these situations, managers will have to consider both uses and arrive at an effective compromise.

Recycling of irrigation water

Return flows from irrigated areas can be important assets in water management. Losses in one place become inputs for other areas. A good understanding of this cycle can ease the upstream management problem substantially by allowing less precision in distribution, knowing that surpluses will not be lost. Return-flow systems present an opportunity for managers to store positive perturbations, for example to harvest rainfall as both drainage and surplus irrigation are channelled back to the irrigation network itself.

Water harvesting and conjunctive management

Water harvesting during rainfall periods is an important opportunity for water management. Specific operational procedures may be designed to maximize harvesting while preventing canal overtopping. The conjunctive use of water (surface water, groundwater and rainfall) can provide additional flexibility to farmers. Groundwater is frequently used to compensate for rigidity or low performance in the surface-water delivery system. Groundwater recharge can be a target of canal operation. Areas lacking access to additional supplies from groundwater should be considered for greater management attention than areas where pumping facilities can compensate for inadequate or/and unreliable deliveries.

Soil and water salinity and waterlogging

Rising soil and water salinity and the increase in waterlogged areas constitute environmental hazards of great importance in arid regions. They represent a severe threat to many irrigation schemes. The operation of irrigation systems must take into consideration the spatial distribution of these hazards in order to provide a selective and locally adapted water service. In practice, solutions are largely site-specific, and generic guidelines are difficult to derive. However, as a general principle, partitioning of the irrigated area should identify areas where freshwater has to be provided, and areas where excessive percolation should be avoided in order to prevent saline groundwater from rising.

Multiple uses of water

In many irrigation schemes, water is used not only for crops but also for many other purposes (Figure 56). Rules for multipurpose system operations are complex because of potential conflicts in setting targets for the different uses and also, on occasion, because of the lack of suitable accounting procedures. Multiple uses of water may have to be integrated increasingly in management concerns, whether or not these uses were considered at the design stage.

Health impacts

Despite its positive effects on the rural economy and in terms of income for farmers, irrigation has also sometimes led to negative impacts on the health of communities through vector-borne diseases. The maintaining of water in canals for long periods can affect the reproductive cycle of disease vectors. The link between system operations and community health can be strong. The recommendations from health experts are converging towards a requirement for more variability in canal flow regimes in order

FIGURE 56
An example of highly diversified multiple water services with a homogeneous agriculture demand for a rice-based system in Sri Lanka
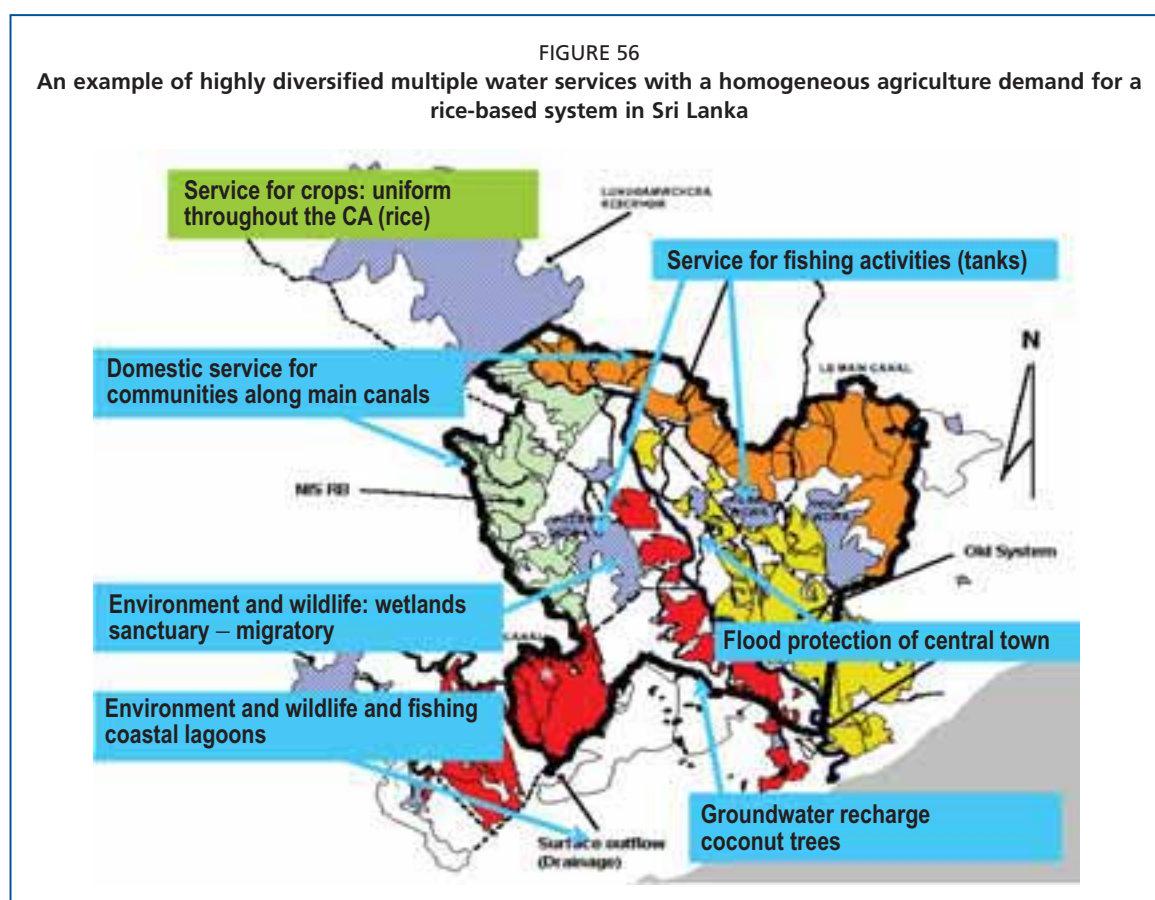
to, for example, reduce the breeding of mosquitoes. However, there is a clear conflict between these requirements for vector control and the irrigation management objective of stable water flows and steady deliveries. New techniques of operation are required in areas where mosquito breeding is related to irrigation practices.

Figure 57 provides an example of how service should be linked to the water context (groundwater management). The downstream part (in red) of the NIS (Nepal) has never been fed properly by canal water and, therefore, has developed extensive pumping from the groundwater. However, this practice has resulted in contamination of irrigation and domestic water supplies by arsenic. An alternative to groundwater must be found through an improvement in canal operations. On the other hand, the upstream part of the system seems to be less vulnerable to arsenic and, therefore, pumping to compensate for reduced canal service is an option that could be considered by the manegers.

MAPPING A VISION FOR THE SCHEME

While mapping all the services, actors, users and beneficiaries of the water scheme a vision of the irrigation infrastructure in the rural society is emerging. At the end of this step it is thus critical to spell out clearly what is this vision as it will be one of the main drivers of the following steps of the MASSCOTE process.

Of course the vision of the future of the system should be agreed upon by the various stakeholders engaged in the process of modernization. Therefore at this point one can only speak of preliminary vision. This vision should cover the agriculture domain as well as the water management domain. Some example of visions that were crafted during previous RAP workshops are:

➢ A lively agriculture sector engaged in high-value cropping based on equity in accessing any water sources, supported by efficient and sustainable operation

FIGURE 57
Map showing three classes of demand for surface water services resulting from arsenic contamination of the Narayani Irrigation System, Nepal
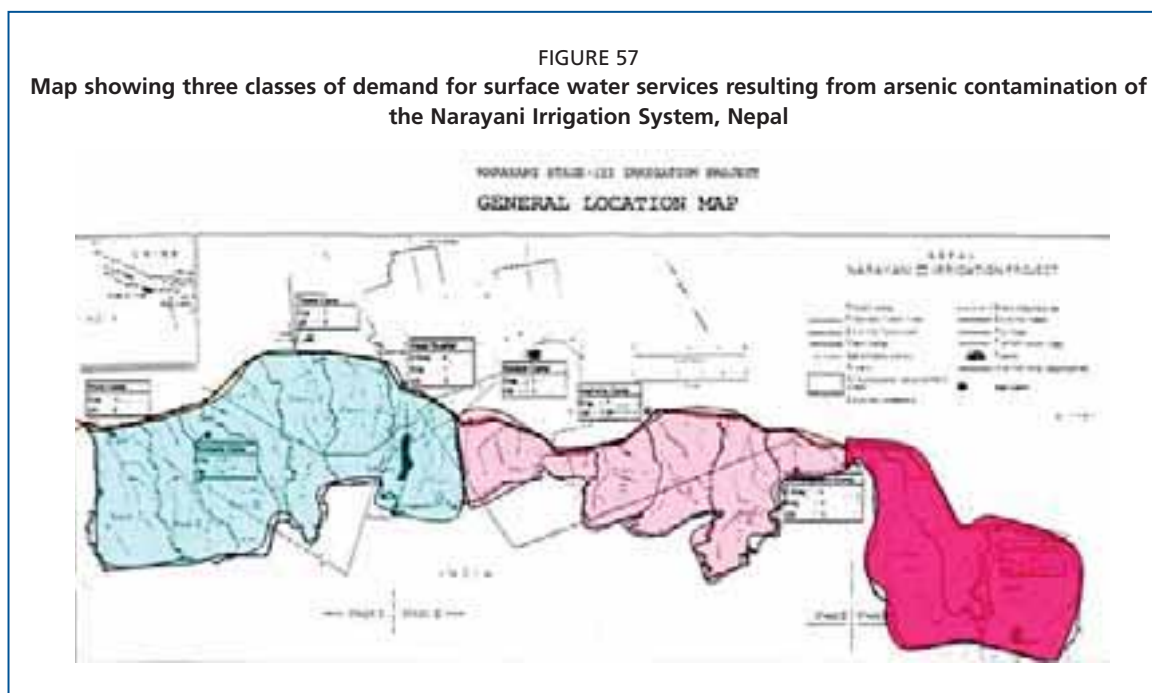
Note: Blue = upstream and low demand.
Red = downstream and high demand.

and management of canal water supply, with users bearing the operational cost coverage at a 10-year horizon.

➢ A staple-food production agriculture supported by low-cost water services.

➢ A project directed towards sustainability through the modernization of hardware and management in order to improve service.

➢ Modernizing the irrigation systems in order to make them more efficient, functional and service-oriented by enhancing the necessary infrastructure and developing the management capacity of the local stakeholders in fulfilling their responsibilities.

➢ Temporal and spatial distribution of adequate, reliable and equitable irrigation water in a flexible manner so as to increase irrigation efficiency for increased agricultural production and, thus, to contribute to poverty alleviation.

➢ Service-oriented water management that provides equitable and reliable deliveries in order to improve the living standards of the community.

Chapter 11
Mapping the management units

Medium to large irrigation systems usually serve thousands of users. Therefore, there needs to be an efficient organization and sharing of responsibility between the central project management unit and the numerous users.

The partitioning of management and of operation must be done on several grounds:

➢ homogeneity in the grouping of users and flexibility in providing service to users;
➢ managerial efficiency, responsibility and professionalism in the definition of the different management levels.

These two rationales can be conflicting and a compromise should be found.

MANAGERIAL APPROACH/MODEL
One of the implicit objectives of irrigation reforms/interventions, such as irrigation management transfer, participatory irrigation management and/or a modernization programme is to identify optimal management units that are likely to yield the best results in terms of performance improvements.

The change is major, from one central management body (an irrigation department) dealing with thousands of individual users, to several layers and units of management with different stakeholders. What is important in this transformation is to make explicit the mission and division of responsibilities among the various actors of the new management setup.

Institutional and water management domains
Irrigation systems can be subdivided into a chain of hydrological water management domains and, thereby, into a chain of water delivery services:

Source – primary canal network – command area water use/demand and allocation
At this level, the water delivery services involved are:

➢ water acquisition (capturing the water source);
➢ water conveyance (operation of primary infrastructure to convey water over the CA and its different uses and users);
➢ water allocation and distribution of the captured water source among the different uses and users (i.e. seasonal water allocations and water rights).

The potential service provider is the irrigation/basin authority, and the potential customers/users are:

➢ irrigation or users authority (secondary network);
➢ irrigators (end users);
➢ nature and nature authorities;
➢ hydroelectric utilities;
➢ water supply utilities;
➢ fisheries, livestock keepers, etc.

Irrigation delivery network (secondary to tertiary)
At this level, the water delivery services involved are:

➢ short-term scheduling;
➢ water delivery and operation;
➢ acquiring water demands (from tertiary level);

TABLE 33
Implicit MASSCOTE managerial model for a large irrigation system

Level and domain	Management unit	Features	Typical size
Water resources management	State responsibility	Regulate water management and ensure that state policy is applied.	Basin
Main system management	Main system agency	A high-level professional agency providing services to local agencies/ users.	20 000 ha and above
	Autonomous multistakeholders body		
Subcommand areas –secondary canals	Local management agency	Professional agency governed by local stakeholders (mostly farmers)	1000–20 000 ha
Local distribution	Farmers and users group	The size of this group is designed to ensure social cohesion within the group.	Fewer than 1000 ha

➢ acquiring water from primary network;

➢ delivering water as per agreed delivery service.

The potential service provider at this level is a professional irrigation agency (preferably farmer-owned) and the clients are WUAs at tertiary level and other sector representatives.

Water-use domain

At this level, the water delivery tasks are:

➢ articulate demand for service and changes therein;

➢ acquire water from network operator;

➢ manage and operate water delivery and distribution and use within tertiary domain.

There are many possible options for this management setup, but it is beyond the scope of this paper to propose an exhaustive review of all of them. The important aspect is to make explicit all the ins and outs of the managerial model. The model presented in Table 33 is the implicit model with which the MASSCOTE approach is carried out. However, it is one approach among several.

SPATIAL DIFFERENTIATION OF SERVICE AND MANAGEMENT

As explained in previous chapters, the MASSCOTE mapping exercise in Phase A consists of first mapping throughout the canal system:

➢ physical features and capacities;

➢ water balance flows and destinations;

➢ the service requirements and requirements for canal operations.

This mapping exercise is done considering that the assumption of heterogeneity within the project is the rule and not the exception. The result is an information database that allows consideration of the whole system consisting of numerous units with homogeneous features.

A central question for the management and the cost-effectiveness of operation concerns how far the differentiation should go.

Too much differentiation of the service requirements can lead to a too high cost of operation (or even impractical and incompatible operational demands), while too little differentiation does not respond to the needs for more adapted service. A compromise has to be found between manageability and differentiated service.

In some types of systems, this principle of differentiation can be applied all the way down to the end users. This is the case with pressurized pipeline systems, where the individual farmers can select the service (pressure, discharge and timing) that they think is best for their production conditions.

However, in canal systems, this principle of differentiation is very often limited for practical reasons and cannot be extended down to the level of users, but more often to a group of users or to a low level of the canal system.

This chapter discusses how the whole service area is partitioned into various levels of spatial and management units in order to devise efficient management and operation procedures and better service to users.

The partitioning should aim to identify management units up to the lowest management unit that will be operated with professional staff. The size of these units depends on the agricultural and economic context, but the order of magnitude ranges from one to several thousand hectares.

The number of canal system levels in the partitioning depends on the size of the whole service area. Very large systems, such as those found in the Indus River Basin in Pakistan (more than 400 000 ha below one single intake along the Indus River), requires several different levels in order to reach down to the lowest management unit with professional staff.

RATIONALE FOR PARTITIONING: GROUPING AND SPLITTING

The partitioning of a canal system into manageable spatial units is required for effective decision-making and management, which contribute to improved water service delivery. The main parameters for partitioning into subunits are:

➢ consistency and responsibility for the main system management;
➢ cost-effectiveness: too many units = too costly and chaotic; too few units = not responsive enough;
➢ critical size of the management unit: to allow for the provision of professional staff for operation;
➢ compactness and sense of ownership for users;
➢ integration of the concepts of IWRM: may need to incorporate multiple uses and multiple sources.

The process of management partitioning is a two-way process, with two rationales:

➢ splitting the CA into small units;
➢ grouping and ensuring a clear responsibility for the main system.

Hence, it is normal that when considering a new partitioning of management it is necessary to consider two actions:

➢ grouping at the main system in order to increase responsiveness (Figures 58 and 59);
➢ splitting the CA into professionals local units.

CRITERIA FOR PARTITIONING

There are many criteria to consider when partitioning a canal system, including social networks and cultural aspects.

Traditionally, canal hierarchy and hydrological units have been used as the basis of partitioning.

FIGURE 58
Options for partitioning: a single agency serving numerous groups and dealing with IWRM

Main canal

Main drainage

FIGURE 59
Options for partitioning: a main system agency serving secondary agencies encompassing several groups

Main canal

Main drainage
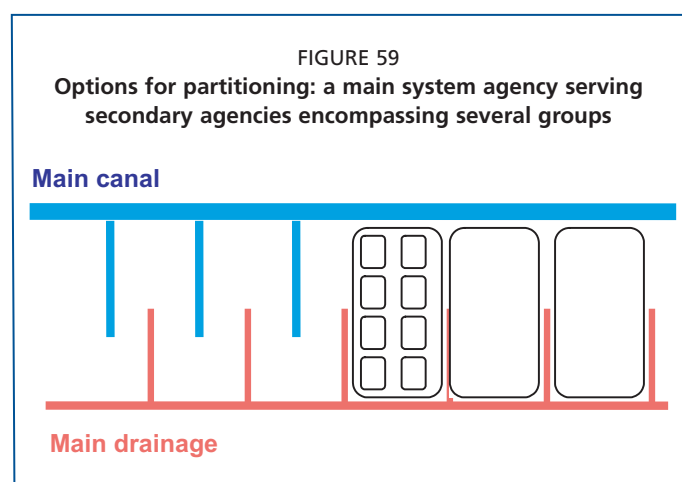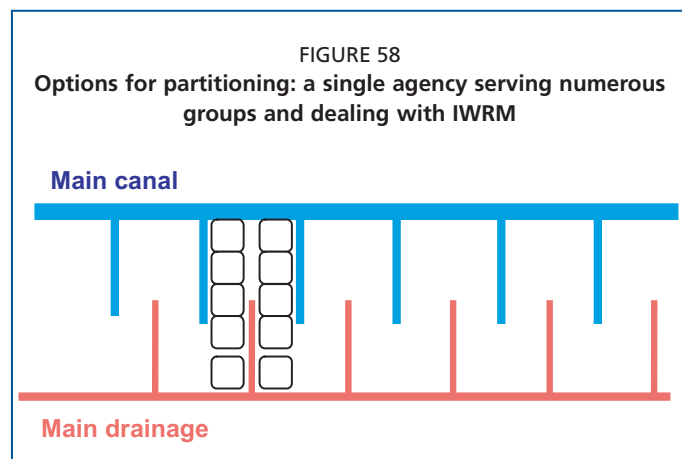
However, there are other relevant criteria on which the subunits should be based:
➢ participatory management and social capital;
➢ spatial variation and requirement for water services;
➢ conjunctive water management;
➢ multiple uses of water;
➢ drainage conditions.

Canal hierarchy

Large irrigation systems are usually divided into smaller management units called tracks, blocks, subsystems and "casiers", often based on the hierarchy of canals (main, secondary, tertiary, etc.). With a single entity in charge of management, this has often been the easiest way to partition a system into subsystems.

Water management partitioning

As seen in Chapter 2, clear-cut separate management units can initially be defined on the basis of major hydraulic control points where discharge can be regulated, i.e. variations in flow can be compensated for.

Where partitioning along institutional lines, managerial subunits should correspond to the wider partitioning of the service area among: (i) the users (farmer groups, WUAs, etc.); and (ii) main system management – federation/WUAs – farmers group – end users.

In partitioning by type of service, it is necessary to consider the homogeneity of the service to be provided. Areas with different types of service should be as separate as possible. An example of partitioning demand by service in a large project is the NIS, NEPAL. In this case, the canal service mapping was done depending on whether or not there was access to safe groundwater. The results of the mapping determined that arsenic-prone areas should receive the best canal service possible (as seen in Figure 57).

Where partitioning by the hydraulic boundaries of subunits, it is necessary to determine sensible limits *vis-à-vis* the interrelationships between the surface water network and groundwater (irrigation and drainage systems, natural streams).

Other potential technical partitioning points are:
➢ well-measured points – these are appropriate for the intake of a subunit as discharge is known accurately;
➢ spills;
➢ main entry point of fluctuations (perturbations);
➢ highly sensitive regulators – these detect upstream changes in the water balance (even small changes) and are good points at which to check the downstream of the subunit;
➢ storage –allows buffering discharge variations and restarting management downstream.

PARTITIONING WITH IRRIGATION SYSTEM TYPOLOGY CRITERIA

When a typology of irrigation systems is available at the national or state level, then it can be worth using the selected criteria of the typology as the main ones for the partitioning, provided that the typology is driven by the same purpose, e.g. canal operation. This reinforces the consistency of the diagnosis and suggested solutions.

This approach was applied in Sri Lanka, where a generic typology (Renault and Godaliyadda, 1998) was developed for the 64 medium to large systems in the country. A total of 21 criteria were initially examined and scrutinized. These were further reduced to four criteria, and the typology identifies four main types of systems:
➢ Reservoir and localized storage system: The main source of supply is a reservoir; it has a localized storage (intermediate reservoirs) at system level, single-bank canals (runoff), and no return flow entering the system.

TABLE 34
Irrigation subsystems identified in the KOISP, and suggested operational strategy (Sri Lanka)

Subunit	Salient features for operations	Suggested operational strategy
LBO	Reservoir – double-bank canal – return flow – non-recycled	Controlled volume strategy by monitoring drainage to the sea and acting on reservoir (intermediate tanks) issues.
RBO	Reservoir – single-bank canal – no return flow – non-recycled	Discharge controlled strategy on each subcommand area by monitoring drainage to the river and acting on offtakes.
		Volume controlled strategy along the main canal.
LBN	Reservoir – single-bank canal – no return flow – recycled into LBO	Volume controlled strategy by monitoring water levels in downstream tanks and acting on issues from the main supply.
RBNT1–2	Reservoir – single-bank canal – no return flow – recycled into RBO – intermediate storage (downstream)	Volume controlled strategy by monitoring water levels in downstream tanks and acting on issues from the main supply.
RBNT5–6	Reservoir – single-bank canal – no return flow – non-recycled – intermediate storage (downstream)	Discharge controlled strategy on each subcommand area (tracts) by monitoring drainage to the sea and acting on offtakes.
		Volume controlled strategy between downstream reservoir and the main upstream reservoir.

> Reservoir without localized storage system: The main source of supply is a reservoir; no localized storage, with single-bank canals, and without any return flow entering the system.
> Diversion river system: The main source of supply is from a river diversion; it has single-bank canals, with or without localized storage and return flows.
> Return flow system: This type regroups irrigation systems with return flows coming back into the system, having single-bank main canals, fed by a reservoir or diversion and with or without localized storage.

This typology approach when applied to the KOISP led to the identification of five subsystems (average size 2 000 ha) within the service area that can be considered as homogeneous with respect to canal operations. The characteristics of these subsystems are summarized in Table 34 together with some identified possible strategies for improved management.

GROUPING AT MAIN SYSTEM AND SPLITTING FOR LOCAL AGENCIES

Creating a new partition of management units implies a complete reorganization of the CA. There should be no attempt to create local management units unless the main system has been reorganized properly.

In the KOISP, the management setup was inherited from the construction phase with three management units at scheme level: one for the old system, one for the right bank of the new canal, and one for the left bank. In a system that is typically a cascade system, where drainage from one unit is used by units downstream, this division of responsibility proved to be inefficient and counterproductive, leading to high water losses.

The first critical step in the modernization process was to reorganize the management into a single unit by looking at the entire scheme in terms of inflows and outflows. The second step was to delimit units according to the recycling and difficulty of operation.

A similar case was found in the GLBC (Karnataka, India), where the main canal system was divided into three divisions. This partitioning has proved to be ineffective in channelling water to the downstream users, and tail-end users face difficulties in knowing who is responsible for this situation and who they should complain to. In this type of situation, partitioning only for local agencies would not yield the expected results. The first recommendation made to the authority in charge of the system was to create a single unit of management for the entire main system (100 km). An example of the proposal made to the project authority is shown in Table 35 and Figure 60.

TABLE 35
Management levels in the GLBC

Existing management setup	Proposed management setup
GLBC management	GLBC management agency Karnataka Neeravari Nigam Limited (KNNL)
3 divisions of 50 000 ha	
3 or 4 subdivisions: 10 000 ha	Local management agencies (stakeholders management) serving water societies where they are active, or directly field group at field channel
Sectors of 5 000 ha	
Distributory subcommittees	
WCs (500 ha)	Water societies serving farmer groups
Field channel groups	Farmer groups

FIGURE 60
Example of combined grouping of main canal into one single unit and splitting into 11 local management agencies, GLBC

FIGURE 61
Managerial units in the Gohtki Area Water Board, Sindh, Pakistan

DILEMMA BETWEEN COMPACTNESS AND CANAL BELONGING

Determining the right size of subunits for effective management is not an easy task. This can be observed at many projects where WUAs have been created through irrigation reforms and entrusted with O&M responsibilities for parts of systems that for many reasons are difficult to manage. An example in Sindh, Pakistan, illustrates this dilemma (Figure 61). In the northwest of the service area, compact units were originally defined with several parallel canals, while in the south and east, very long managerial units were set up along a single canal. During the implementation of the institutional reforms it was found that the very long units were not effective. There were difficulties for farmers to become organized and to meet regularly because of the travel time involved. It was also difficult for the system operators to operate and manage these systems effectively.

Another example of the size dilemma is illustrated by the NIS, Nepal, where if the criteria of canal belonging (secondary) is applied, it would lead to 22 units, most of them too small to be able to hire professionals.

PROCESS OF PARTITIONING

There are different aspects of partitioning to consider in the process of designing management units. A compromise between hydraulic considerations and social coherence needs to be found. As users are central to SOM, compactness and social coherence should be given precedence in the subdivision of a larger system into smaller manageable units.

There is no scientific or technical knowledge that can give the stakeholders the sense of what kind of partitioning units should be best for the management. However, partitioning of the service area into management subunits should be an iterative process that is technically and socially sound. A proposal for partitioning should then be investigated for both aspects and refined as needed before the validation stage. It should be pilot tested within the project or on representative systems.

AN EXAMPLE OF PARTITIONING IN MANAGEMENT UNITS: THE SMIS, NEPAL

The current management is split into five levels (Table 36). It is believed that too many levels are leading to inefficient management. In fact, it would be best to reduce the number of levels to three.

As far as management and operation are concerned, it seems that there is room for two professional levels for the management units. This is what the DOI has adopted in the SMIS with the Water Users Central Coordination Committee (WUCCC) as the professional agency responsible for the CMC supply and for serving the large lower professional agency, the Water Users Coordination Committee (WUCC), one for each secondary canal (Figure 62). In this setup, the WUCCs cover an area of several thousand hectares, and they are responsible for serving smaller units, Water Users Committees (WUCs), of about 300 ha, and they should assume IWRM.

TABLE 36
Existing institutional management setup in the SMIS

	Canal level
Water Users Group	Watercourse
Water Users Committee or Water Users Subcommittee	Tertiary canal
Water Users Committee	Subsecondary canal
Water Users Coordination Committee	Secondary canal
Water Users Central Coordination Committee	System level

FIGURE 62
Management setup in the SMIS

An important issue here concerns the number of second-level agencies (WUCCs).

The partition of the CA into practical management units should be made considering the secondary canals. However, this does not mean that there have to be as many units as there are large or small secondary canals. Other criteria need to be considered, e.g. the size and compactness of the CA.

For the moment, the SMIS managers are considering the partitioning on the basis of all secondary canals, including the small ones. Therefore, there would be 20 WUCCs. For the service interface, it is quite reasonable as each WUCC would then have only one offtake point on the main canal. However, FAO believes that this option is likely to create some small units that would not be viable, while others would have a critical mass (area) that would allow the recruiting of professional staff.

The suggestion by FAO is to consider having only seven WUCCs, with many of them having several offtake points on the main canal, but with each of them being large enough to allow strengthened management. Figure 63 maps out what could be the CAs of the second-level units if the entire system were split in seven units, each averaging 10 000 ha.

When considering a partition with seven units, the downstream unit (WUCC-7) would have four medium-sized secondary canals diverting from the CMC. For the purpose of clarity in management, the proposal is to end the CMC upstream of CR11 and to make the WUCC responsible for, and the operator of, the final sections of the CMC. This option would be accompanied by the construction of a measurement weir upstream of CR11 in order to allow the discharge reaching WUCC-7 to be measured. Operation of the four intakes on the CMC should be the responsibility of WUCC-7.

At the tail-end of the system, it is likely that discharge perturbations will affect the delivery at the entry point of WUCC-7. Therefore, the suggestion is to use the main canal as buffer storage in order to compensate for hourly fluctuations.

FIGURE 63
Proposed partition of the SMIS into seven second-level units

Chapter 12
Mapping the demand for operation

Irrigation project managers allocate and spatially distribute resources, resulting in a quality of service and cost of operation. Constraints affecting the quality and the cost of operation are: human resources availability and skills; transport facilities; and communications. Their current status and likely future scenarios need to be assessed properly before engaging in a modernization programme.

As in other activities, it is critical to adjust as much as possible the inputs to the demand. It is assumed that, in general, operational requirements are not distributed homogeneously throughout a given project.

Defining the demand (requirements) for operation involves answering the following questions:

➢ What service is demanded by the different user groups?
➢ How do these relate spatially, in time and in operational requirements?
➢ What service can be offered to the users?
➢ What is the possible range of service and fees to be considered?
➢ What mode of operation can be followed and with what precision?
➢ What perturbations are likely?
➢ What should be the frequency of checking and intervening?
➢ Which setup is required in order to monitor the service?
➢ What are the mechanisms to ensure services are provided and paid for?

The proposed approach outlined in this chapter aims to define the targets and the level of means to be input in operation with considerations on three main drivers: service demand, perturbation and sensitivity.

THE THREE DRIVERS OF THE DEMAND FOR OPERATION

From an operator's or a manager's point of view, canal operations can be perceived as an industrial process. Inputs are transformed into outputs (water delivery to users) by organizing a complex interaction of production elements (canals, structures, storage, etc.). To manage the inputs effectively, managers have to consider:

➢ The precise service demands and the tolerances allowed by the respective water uses and users – output.
➢ The impact of decision-making on the output – vulnerability of output.
➢ The characteristics of the structures involved in the process. Which modes of operation can be achieved? What are the constraints and opportunities? – system behaviour.
➢ The variability of inputs (water availability and storage) and the frequency and impact of perturbations on the system – input and behaviour.
➢ The organizational and financial resources available or required in order to achieve the required level of performance – management setup, necessary to keep the process going.
➢ Requirements of the process setup – rules, transparency, etc.

Assessing the requirements for canal operation needs to be done alongside and in combination with the definition of the service by users and stakeholders. However, canal operation requirements cannot be derived only directly from service demands. The system presents opportunities and constraints that set the boundaries for possible

modes of operation. In short, the requirements are to be found in three domains: (i) service demand; (ii) perturbation; and (iii) sensitivity.

The service demand domain refers to the articulated and other demands on canal operation. Many of these demands are interrelated; they can add to or be in conflict with one another. Some of the demands can be seemingly autonomous, as some refer to deliveries, others to canal flows, and others to modes of operation of infrastructure. The integration of these demands enables the definition of spatial and temporal operational scenarios that provide adequate deliveries to vulnerable areas in line with key variables in the service demand domain.

Once the scenarios have been articulated in the service demand domain, the perturbation domain gives the boundary conditions from the supply side. The perturbation domain refers to the frequency and magnitude of perturbation events likely to occur in a subsystem, and it enables evaluations of the stability of the service with respect to the demands. As irrigation systems are subject to continuous modification of flow conditions, from both scheduled and unscheduled events, the required service is not achieved easily. This domain determines the mode of observation, measurement and regulation along the system in order to ensure that the water service is achieved.

The sensitivity domain is characterized by the physical properties of the conveyance and distribution system. The behaviour of irrigation systems under operation and affected by perturbation determines the reaction of the system under non-steady flow with respect to the service demands. This domain sets the precision of control required.

The assessment of the requirements for canal operation should include all these overlapping domains. The technical, organizational and financial boundary conditions can be set in this overlay, and compromises will have to be made.

WATER DELIVERY SERVICE, PERFORMANCE AND FLOW CONTROL

Water delivery service, flow control and performance are intrinsically linked. This can be illustrated through the example of a delivery structure (offtake) by looking at the service and operational requirements. For a delivery structure (Figure 64), the water level in the parent canal (H_{us}) conditions the head through the structure (the difference between the upstream and downstream water levels) and, thus, the discharge (q) through the gate once the gate opening is set.

Fluctuations in the water level in the parent canal generate variations in head and discharge through the gate. As described in Chapter 6, for a sensitive offtake, a small fluctuation in water level will generate a high variation in discharge, whereas for a low-sensitive offtake, water levels may vary strongly without significant variations in discharge q. Following Chapter 6 (that showed a clear link between acceptable variation of discharge, sensitivity and control of water depth), the discharge service delivered at this point can be defined by:

$$\text{Service}_{target} = q \quad \mapsto \text{Tolerance}_{(q)} = +y\% \text{ and } -z\%$$

where y and z are tolerance factors considering, respectively, adequacy and efficiency of performance. Adequacy and efficiency are basically opposite to each other – where one is high, the other is low. Values for y and z are not necessarily the same. For example, a high value for y might be tolerated (surplus), while the value for z (deficit) must be kept lower in order not to penalize the user too much (Figure 65).

Assuming there is no adjustment to the setting of the gate, fluctuations result from the variation in the water level in the parent canal. The variation in discharge depends on the sensitivity of the structure and the head variation: Perturbation or Head variation H → Sensitivity → Perturbation of discharge Q.

Where the structure is submerged, the downstream conditions also influence the discharge. A correction for downstream submergence can be brought into

the computation of the sensitivity indicator. However, most of the time, the correction is not needed.

By inverting the equation of sensitivity, the precision required for water-level control in the parent canal (ΔH_{us}) is computed as:

$$\Delta H_{US} = \frac{Tolerance(Q)}{S} \qquad (18)$$

where: S is the sensitivity of the offtake; and tolerance on discharge (Q) is y and z percent (Q is a typical abbreviation for discharge/flow rate).

H_{us} in the parent canal should be controlled in such a way that discharge is maintained within the defined limits of ($Q + y$ percent; $Q - z$ percent). This service objective can then be converted into a control objective at this particular point of the canal.

Equation 18 expresses the tolerance with which the water level in the parent canal at this particular structure is allowed to fluctuate. This in turn has to be converted into control targets at the nearest downstream regulator. Control of water levels along the canal is the result of the combined effects of the hydraulic properties of the canal

FIGURE 64
Linking service and control through a delivery structure

FIGURE 65
Adequacy and efficiency as related to tolerance limits

section, regulator characteristics and periodic operation of cross-regulator structures. The precision with which target water levels are controlled at cross-regulators (ΔH) is an indicator of operational performance directly influenced by management.

THE SERVICE DEMAND DOMAIN

The service demand domain refers to opportunities, constraints and impacts of operation at different scales of space and time. Service demands set by users or other stakeholders can be affected positively or negatively by canal operation. Some demands are more vulnerable to operation than others. Vulnerable periods might be transplanting of rice or flowering of fruit trees. Inversely, areas or periods of low vulnerability are only affected slightly by low-quality operation.

Service demands with high vulnerability need more weight in evaluating scenarios. However, both demands and vulnerabilities have to be considered in the service agreement. Demands and vulnerabilities (and thus levels of tolerance) for the different water uses should have been discussed by the users while defining the service.

The service demand domain refers not to the setting of vulnerabilities but to the responses to these demands. It aims to address which modes of operation can deliver a good service to most of the demands in the area in a cost-effective and efficient manner. Hence, service demands extend beyond the confines of irrigation water for crops and include consideration of larger-scale water management impacts.

Some of the wider aspects of water management that should be mapped as areas of vulnerability include those discussed in Chapter 11:

➢ water quality;
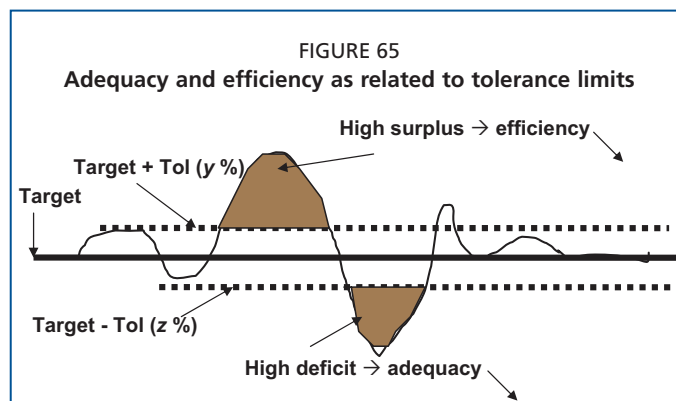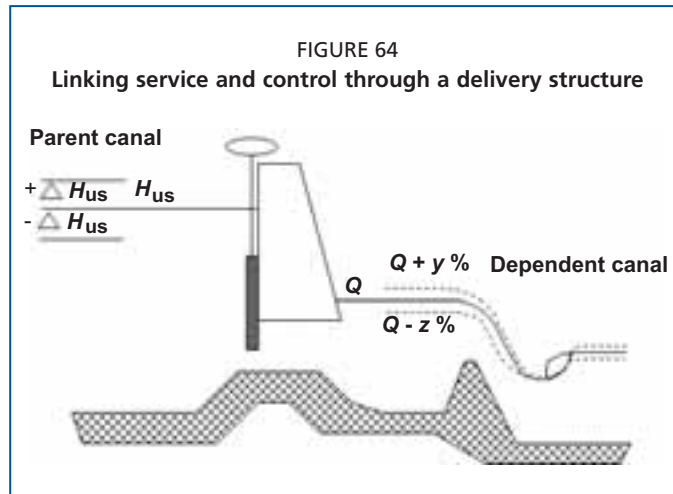
➢ recycling of irrigation water;
➢ water harvesting and conjunctive management;
➢ soil and water salinity and waterlogging;
➢ multiple uses of water;
➢ health impacts.

To these should be added: location within the system. The impact of operations of structures located at the head of the canal system is greater. Therefore, location is included in the vulnerability analysis.

The study of each aspect of the service demand domain leads to an assessment of the aggregate demands for canal operations, as well as areas of vulnerabilities. On the basis of this assessment, the service provider can lay out the contours of an operation plan. The rationale is that highly vulnerable areas require a high-quality water service while a lower quality service may suffice for less vulnerable areas. The spatial and temporal characteristics of the service demand domain can be converted into operational scenarios with specific water service targets that can be measured partly with water supply performance indicators, such as adequacy, efficiency, dependability, timeliness and equity. However, some demands do not relate to deliveries (e.g. health impacts, safety, and canal operation efficiency). They relate more to the mode of operation rather than the quality of delivery.

THE PERTURBATION DOMAIN

Open-channel irrigation systems are hydraulically complex. In general, system operation is reduced to controlling water levels at cross-regulators in an attempt to maintain stable water levels and, hence, discharges at offtake structures. However, steady water-level profiles hardly ever occur in irrigation systems owing to upstream inflow variations and the compounding effects of operational interventions within the system. Hence, even where all the gates are set appropriately, operation is a never-ending challenge, and control structures have to be adjusted continuously in order to meet demands.

A perturbation at a given location is defined as a significant change in the ongoing discharge. Flow changes may originate from planned changes in delivery or arise from unexpected or transient changes. Perturbations of the latter category are more difficult to manage accurately because they cannot be anticipated precisely.

Managing perturbations has two basic objectives:
➢ ensure passing variable flows without adversely affecting deliveries;
➢ ensure that the perturbation is managed properly, by compensating for a deficit of water if the perturbation is negative, or by storing the surplus if it is positive.

To achieve these objectives, there are two options:
➢ Set up an infrastructure in such a way that perturbations are dealt with automatically, e.g. the surplus is diverted automatically towards areas that can store or value the water.
➢ Detect the perturbations and have a proper set of procedures for the operators to react.

For analysis, the perturbation domain is divided into two components: (i) generation; and (ii) propagation. These can also be termed "active" and "reactive" processes (Chapter 3).

The active and reactive processes can be analysed in three constituent parts:
➢ the causes of perturbations, such as return flows, illicit operation of structures, and drift in the setting of regulators;
➢ the frequency of occurrence;
➢ the magnitude of perturbations experienced.

The causes of perturbations are to a large extent determined by the network properties of the canal system. Determining static properties are: the source of supply;

hydraulic layout and variability in discharges; interconnections with other networks, such as drainage; unregulated return flows, etc.; and the number and type of offtakes and regulators. A second cause of perturbation is the operation of the irrigation regulation system itself. The operation of offtakes and regulators generates transient conditions in the network, just as any obstruction of flow, withdrawal and rejection, either planned or illicit. The complexity of the distribution setup and the control mechanisms for diversion and abstraction have a significant influence on the level of perturbation.

The position in the network is a determining factor in frequency and magnitude of occurrence of transients and partially explains the well-known "head/tail" issue in irrigation systems. In general, deviations from planned water deliveries are larger and occur more frequently in the tail-end of a system. This is linked directly to the number and operational characteristics of upstream structures. Slight deviations in the head-end are amplified owing to however minor management errors at all nodes. Furthermore, once the gates have bee set, the sensitivities and flexibilities of structures determine whether perturbations are attenuated or amplified and, thus, spread throughout the system.

Perturbations are expected whenever a change in the distribution takes place. Therefore, the scheduling and distribution policy (on-demand, arranged demand, or rotation) is a key determinant of frequency of occurrence of perturbations. The greater is the flexibility of the service being provided, so the greater the frequency of changes in flows in the canal system will be. Proper consideration of the impacts of service flexibility on the perturbation domain is essential in order to identify the specific operation modes and structure characteristics required for acceptable performance.

THE SENSITIVITY DOMAIN

An important consideration for canal operation is the sensitivity of structures and their impact on the propagation or attenuation of transient flows that enter the canal system. The sensitivity domain analyses the behaviour of structures and subsystems during the propagation of transient conditions. It aggregates sensitivity analyses (Chapter 6). In the absence of operational interventions, the evolution of perturbations through the subsystem shows a decay curve integrating the conveyance sensitivity of the reaches and associated structures.

A QUALITATIVE APPROACH TO MAPPING THE DEMAND FOR CANAL OPERATION

The three domains outlined above must be combined in order to map the demand for canal operations. The rationale is straightforward: the higher the service demand, perturbations and sensitivity, so the higher is the demand for canal operation. This can be captured in the relationship: demand for operation = service × perturbation × sensitivity.

There are some exceptions to this generic equation, e.g. where high criteria do not lead to high demand. This is the case when highly sensitive structures (reach or offtakes) are used to divert high perturbation towards areas that will not be penalized by either a surplus of water or a temporary shortage.

A simple way of aggregating the three domains into canal operation demand is through multiplying primary indicators ranking from 1 to 4, as shown in Table 37.

The service is classified from low to very high (1–4); 1 is for a low service, it could be a service to drought-resistant crops in areas for which an alternative source of water is also available in the

TABLE 37

Adding the primary indicators in order to evaluate canal operation demand

	Service demand	Perturbation	Sensitivity		Product	Canal operation demand
Low	1	1	1		from	1–4
Medium	2	2	2	➔	1	4–16
High	3	3	3		to	16–27
Very high	4	4	4		64	27–64

FIGURE 66
Functional relationships between the vulnerability, sensitivity and characteristics of the service
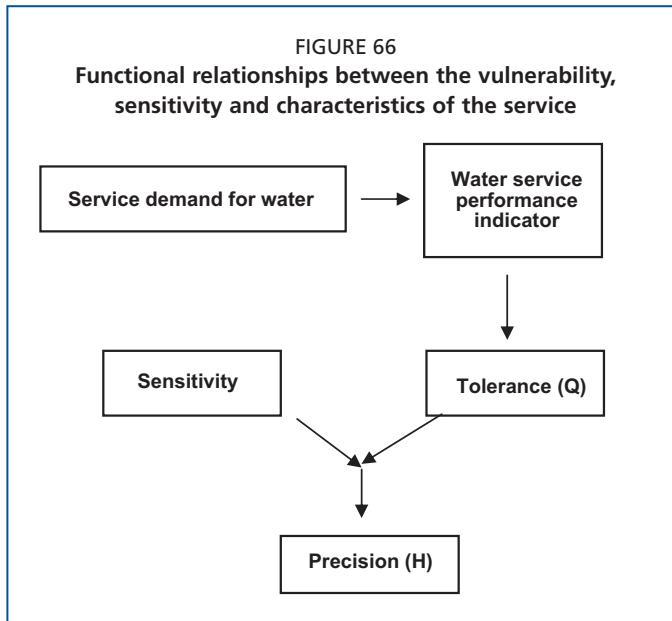
event of emergency, while 4 could be a service to sensitive crops in areas for which there is no alternative source of water. Perturbations are also classified from 1 to 4 according to their frequency and magnitude. For the purpose of consistency with the other primary indicators sensitivity is reclassified as follows, 1 when sensitivity indicator (S) (Chapter 6) is 0.5 or less; 2 when it ranges between 0.5 and 1; 3 for S between 1 and 2 and 4 if S is higher than 2. Similarly the aggregated demand is reclassified as Low for a product between 1-4, medium between 4 and 16, high between 16 and 27 and very high between 27 and 64.

QUANTIFYING CANAL OPERATION REQUIREMENTS

More precise and quantitative indicators for operation can be derived from the service demand domain. The process should consider both water deliveries for irrigated crops and water management in a broad perspective. Here in this analysis, only primary indicators are considered, namely: adequacy, efficiency and timeliness. In order to facilitate analysis, it is preferable to convert performance indicators into tolerance with respect to targets. Thus, irrigation performance for adequacy and efficiency can be summarized by a function expressing that the discharge at a given location should be maintained between target -z percent and target +y percent:

$$\text{Tol}(Q) = \begin{array}{l} +y\% \\ -z\% \end{array} \tag{19}$$

where: z expresses the capacity of the area to accommodate water shortage (z is strictly related to the adequacy indicator and incorporates concerns about the deliveries); and y expresses the capacity of the subsystem to accommodate a surplus of water (positive perturbation). A similar equation can be proposed for timeliness.

The relationship between water service, irrigation performance indicators and operation targets illustrated above for a simple case can be generalized, as shown in Figure 66. This relationship indicates that the required precision of structure operations is the product of the tolerance on delivery and the sensitivity of the structure.

The demand for operation can be derived from the previously outlined relationships by converting the tolerance on discharge to either a tolerance on controlled water depths or some other structure setting. The link between operation and irrigation performance can be established through generic relationships:

$$\text{Service Demand} \left\{ \begin{array}{l} \text{Irrigation requirements} \\ \text{Water management} \end{array} \right\} \Rightarrow \text{Demand} \Rightarrow \text{WSPI} \Rightarrow \left\{ \begin{array}{l} \text{Tol}(Q) \\ \text{Tol}(T) \end{array} \right\} \times \{\text{Sensitivity}\} \Rightarrow \left\{ \begin{array}{l} \text{Tol}(H) \\ \text{Tol}[\text{Setting}] \end{array} \right\} \tag{20}$$

The relationships in Equation 20 express the idea that the water supply indicator is the result of the product of the tolerance in operating the infrastructure and the sensitivity of the structures themselves (Table 38).

PERTURBATION MANAGEMENT

Ultimately, the assessment of the operational requirements is a mixture of both quantitative and qualitative approaches. The objective of a qualitative approach is to

identify the properties of subsystems that influence potential operational strategies significantly. All the above-mentioned properties have to be weighed, and they can be combined to classify the requirements for operation as low, medium or high.

This classification can lead to a more appropriate distribution of efforts for operation within the project. The objective of a quantitative approach (i.e. set targets and tolerance levels) is to specify the service agreement in operational targets so that it can be used for monitoring and control.

TABLE 38

Examples of sensitivity, tolerance and control precision

Sensitivity of the structures (S) (m^{-1})	Tolerance for discharge (α) (%)	Precision of control (ΔH_{us}) (m)
0.5	±10	±0.2
Low sensitive	±20	±0.4
1	±10	±0.1
Medium sensitive	±20	±0.2
2	±10	±0.05
High sensitive	±20	±0.1

An important aspect of canal operation is the management of perturbations (fluctuations of flows). The objective is to increase water management efficiency (e.g. of rainfall harvesting) while minimizing the effect of perturbations on the deliveries. This process combines the opportunities for perturbation management (storage facilities or efficient use of water surplus) and the probability and magnitude of occurrence:

$$\text{Perturbation} \left\{ \begin{array}{c} \text{Opportunities for} \\ \text{perturbation management} \end{array} \right\} \times \left\{ \text{Perturbation} \begin{array}{c} \text{probability} \\ \text{magnitude} \end{array} \right\} \Rightarrow \left\{ \begin{array}{c} \text{Operational modes} \\ \text{Frequency} \end{array} \right\} \tag{21}$$

This allows the determination of the appropriate mode and frequency of operation depending on the expected frequency of perturbations, as illustrated in Figure 67.

The frequency of operation/checks can be summarized as: Frequency (check/operation) = Frequency of perturbation × Magnitude of perturbation × Sensitivity regulator.

MAPPING THE DEMAND FOR OPERATION: AN EXAMPLE

The mapping of the demand for operation can be illustrated through the example of the KOISP, where the methodology led to ultimately four classes of demand for services (Figure 68).

Perturbations

Four subsystems are supplied by a reservoir, hence minor fluctuations in the main inflow are expected. However, three major canals are only single-bank canals and therefore susceptible to perturbations resulting from runoff during rainfall events. One subsystem (Left Bank Old [LBO]) is a return-flow subsystem; hence, discharge within the CA fluctuates with return-flow variations.

Network

Three subsystems do not include recycling and, therefore, should be operated carefully because drainage flows are truly lost to the sea. On the other hand, the Right Bank New (RBN) canal ends in a downstream reservoir, which might compensate for any errors in operation. Thus, for each subsystem an analysis of the impact of the operational performance can be carried out.

FIGURE 67

The functional relationships between the vulnerability, perturbation and operational modes

FIGURE 68
Application of demand approach in mapping canal operation for a rice-based system in Sri Lanka

Note: High demand = red; low demand = green.
Source: Renault and Makin, 1999.

Sensitivity

The sensitivity of offtakes distinguishes the RBN (medium sensitive, average $S = 1.3$) from the LBN and RBO canals, which are classified as highly sensitive (average = 2.4 and 2.2, respectively). This means that the same level of precision in water depth will generate discharge deviations two times greater in the LBN and RBO than in the RBN.

Analysing resources allocations vs demand for operation

As a transitory phase between the approach of the demand for operation and the design of improvement options, it can be a very useful exercise to specifically confront the current allocation of resources and practices throughout the system with the demand for operation. This yields to identify gaps and distortions and allow proposing improvement options by simply reallocating the efforts in operating the system.

This exercise is illustrated through the same example of KOISP, looking more specifically at the main canal of the right bank. The initial allocation of operators along the Right Bank Main Canal (RBMC) was made on a tract basis: 4 operators for tracts 1 and 2; 5 operators for tracts 5; and 3 operators for tracts 6 and 7 considered as a single unit (Table 39). The area served by each tract appears to be rather similar (850–1 000 ha), while the area served by a single operator varies (213–300 ha). The density of structures per operator is also quite constant. These figures show that the current mobilization of efforts is somewhat homogeneous with respect to the area served and the structure density.

Figure 69 plots the number of gate operations at cross-regulators. It shows that, although not constant, variation is limited. For tracts 1 and 2, the variation is between

TABLE 39
Allocation of resource and efforts along the RBMC, KOISP, Sri Lanka

Tract	No. of gate operators	Area served	Area per operator	Number of regulators	Number of offtakes	Structures per operator	Class of demand for operation
		(ha)	(ha)				
1	4	851	213	3	10	3.25	Low
2	4	868	217	6	10	4.00	Low
5	5	1 005	200	5	14	3.80	Very high
6–7	3	896	300	4	8	4.00	Very high

30 and 38 per season. For tract 5, it is higher (mean = 44) and more variable (33–52). For tract 6–7, the mean is 38 but the range of variation is high (20–60).

The average number of operations per offtake is more variable, it decreases from 60 per season for tract 1, to 34 for tract 5 (Figure 70). This reflects a significant variation in the quality of operation, which is confirmed by the analysis of the variation in water depth variation upstream of each offtake and the resulting discharge variation (Figures 71 and 72).

The paradox of the then practice along the RBMC was that operation was more frequent where the flow was more stable than in the upstream reaches.

FIGURE 69
Number of gate operations at cross-regulators, average for 6 seasons, RBMC, KOISP

FIGURE 70
Number of operations per offtake, average for 6 seasons, RBMC, KOISP

FIGURE 71
Seasonal standard deviation of upstream water level at offtakes, maximum, minimum and average for 6 seasons, RBMC, KOISP

FIGURE 72
Discharge variation along the RBMC, KOISP, coefficient of variation

The analysis of the human allocation and of the interventions along the RBMC shows that the density of staff and interventions should be reversed in order to take into account the decreasing quality of the services downward. The need for re-allocating the resources is further reinforced when considerations on the demand are included (see Table 40). Upstream reaches are low-demanding whereas downstream reaches are high-demanding for operation mainly because they do not have recycling facilities, and the surplus/drainage is lost or even has a negative impact on some coastal lagoons.

TABLE 40
Classification of the demand level for operation in the KOISP, Sri Lanka

Subsystem	Tracts 1 & 2 of RBN	LBO	LBN	RBO	Tracts 5 & 6–7 of RBN
Vulnerability	Low	Low	Low	Very high	Very high
Water service at secondary/tertiary canal headworks	Recycled Low Tol $Q = \pm20\%$	Return-flow RF Low Tol $Q = \pm20\%$	Recycled Low Tol $Q = \pm20\%$	Non-recycled Very high Tol $Q = \pm5\%$	Non-recycled Very high Option PA (3) Tol $Q = \pm5\%$ High Option RO (4) Tol $Q = \pm10\%$
Sensitivity of SC/TC headworks structures	High 1.3	Very high (not measured)	Very high 2.4	Very high 2.2	High 1.3
Precision	Low ±15 cm	High 10 cm as an indication	High ±10 cm	Extremely high ±2.2 cm Unrealistic	High ±4 cm for Option PA (3) Medium ±8 cm for Option RO (4)
Perturbations	Low probability Low magnitude	Low probability Low magnitude	Medium probability (high-sensitive offtakes & single-bank canal sections)	High probability & magnitude (no water depth control; single-bank; improved operational procedures)	High probability & magnitude (improved operational procedures)
Operation mode and frequency	Low frequency FBC(2) from downstream tank	Medium frequency FBC(2) from drainage outlets	High frequency checking of sensitive offtakes Low frequency FBC from downstream tanks	Note: a specific control project will have to be designed for RBO, including some rehabilitation and/ or modernization works.	High frequency FBC(2) from drainage outlets Precise control of level Improved operational procedures
Class of demand	D1 Low	D2 Medium	D3 High	D4 Very high	D4 Very high

Chapter 13
Improving subunit operation

Once the management and operation partitioning have been defined, the next stage is to identify modernization improvement options for each subunit (Figure 73) based on: (i) water management; (ii) water control; and (iii) canal operation (service and cost-effectiveness).

FIGURE 73
Sketch of a subunit within the CA

A comprehensive approach needs to be carried out at each unit in order to ensure that the constraints and opportunities have been identified properly.

Improvement in canal operation is carried out for the purpose of cost-effectiveness in servicing users. The objective might be to better serve users according to their demand and at a reasonable cost.

In theory, modernization does not necessarily means improved water delivery service to users, but rather the best compromise between service and cost that has been agreed upon with the users. In practice, modernization often goes with improving the service, but this is more the result of remedying the previously poor management performance in delivering services.

ANOTHER ROUND OF MASSCOTE FOR EACH MANAGEMENT UNIT

Each subunit defined previously must be considered as a separate system for which, ideally, another round of MASSCOTE analysis should be made in order to focus on the specific constraints and opportunities of the subunit. The idea is to specify and produce for each subunit:

➢ A water management strategy: What is the rationale for water management in the CA of this particular subunit? What are the procedures to deal with all the scheduled and unscheduled water fluxes (rainfall, runoff, drainage, groundwater, canal water surplus, etc.)?

➢ A service strategy (allocation – scheduling – delivery): What are the specific rules of services to downstream users, considering the constraints of the resources and services provided by the upper level (main system)?

➢ An operation strategy: What are the main rules used to convert the WDP into operation plans and to deal with perturbations?

➢ Operational procedures for ensuring scheduled deliveries and addressing unscheduled interventions.

Ideally, at the subunit level, the MASSCOTE approach should lead to the proposing of several technical options to the users. The users should decide on the targets and techniques.
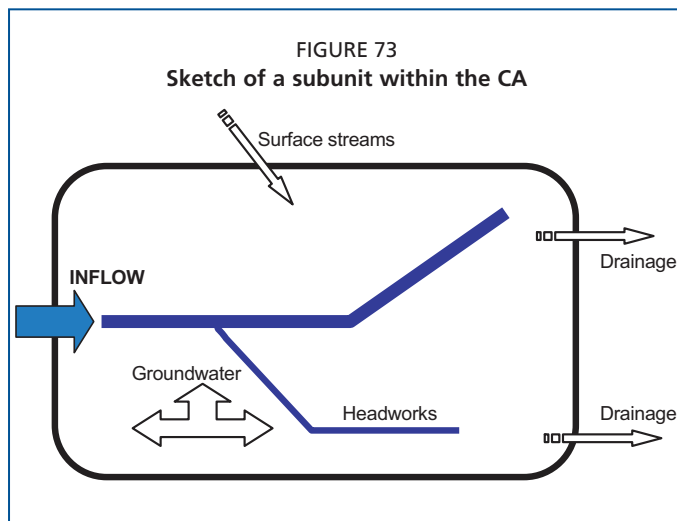
TYPES OF IMPROVEMENTS

Improvements in canal operation techniques can result from different types of interventions. The two major types are:

➢ Adjusting operation to the demand: Within a management CA (served area) and considering one canal operation technique, this consists in better adjusting inputs for operation to the demand for services and to the constraints for operation. Used alone, this should be considered as a "minor change".

➢ Improved canal operation techniques: This consists of significant changes in the techniques in order to respond better to the current demand for service.

OBJECTIVES OF IMPROVEMENTS

Operational improvements should aim at specific objectives such as:

➢ improve water delivery services to agriculture users;
➢ raise the performance of operation in delivering services from one level to the next lower level, with a particular focus on the indicators that ranked low in the RAP exercise;
➢ optimize the cost of operation;
➢ raise the cost-effectiveness of existing procedures.
➢ improve water management and water productivity (maximize the conjunctive use of water);
➢ integrate the multiple uses of water (IWRM).

The overall goal of implementing a MASSCOTE approach is to enhance current operational practices (making them more efficient or cost-effective) or to implement a new and improved strategy.

These improvements are to be sought through one or a combination of the following options:

➢ allocating existing resources and inputs in a more cost-effective and responsive way;
➢ optimizing the organization and the operational modes;
➢ changing the operational strategy;
➢ investing in improved techniques and infrastructure.

MODES OF IMPROVEMENT

Addressing the capacity issues

The first option for the technical interventions is to plan specific interventions to reduce or eliminate the capacity problems identified in Step 4. This can result in a long list of issues and possible interventions and may not lead to a consistent framework. It is necessary to prioritize the interventions. In addition, it is also necessary to check that these interventions are consistent with the overall operation strategy. However, this is also an opportunity to identify simple interventions that can yield significant results without major investments and without major changes in the procedures. As such, this kind of intervention can be "visible" and help restore trust between managers and users.

Table 41 provides an example of the issues and options identified for a main canal system in India.

Improving the current operation strategy

The objective of improving canal operation procedures is not to change the strategy but to improve the efficiency by setting new targets, refocusing operators on specific tasks, and optimizing the use of resources for operation, considering all aspects and functions of operation:

➢ scheduled, unscheduled, safety and information;
➢ transport, control, diversion, storage, etc.

TABLE 41
Capacity issues and proposed options along GLBC main canal

Capacity along the main canal	Issues	Options
Carrying capacity of the system	Localized reduced section.	Restore the sections.
Measurements at the border between management units.	Rating curve calibration not made.	Regular calibration.
Measurement skills	OK, but too frequent manual recording.	
Functioning of CRs	Not operated.	
Remote monitoring (including rainfall data in the command) along main canal	Density of rain gauges insufficient.	Add automatic rain gauges.
Escape capacity / recycling and measurements	Purposely leaking. No measurements.	
Buffer storage in, along and off the canal	No buffer storage.	Investigate online and offline storage to improve water supply downstream.
Sensitivity of the cross-regulators and offtakes	CR not operated (low sensitive). Offtakes low sensitive with few exception.	Special treatment of the sensitive offtakes: physical changes where possible or specific operational procedures.
Seepage accommodation	Quantification of seepage is inaccurate. Accommodation is quite OK throughout the CA except downstream along the Biligi branch.	
Special structures	One syphon with reduced capacity.	
Communication system (road and telecommunication)		
Regulating capacity of Dhupdal weir		

These types of changes can include modifications regarding the frequency of monitoring and adjustments of cross-regulators. For example, in the KOISP system in Sri Lanka, different practices (derived from those currently in use) have been investigated. The current practice is a fixed frequency of operation at twice per day (interval of 12 hours) at the cross-regulators with the aim of maintaining water at FSL. Most cross-regulators in canals in Sri Lanka are mixed-type, i.e. composed of a central undershot gate (or gates) and side weirs. The crest of the weir defines the FSL. Results of the simulations carried out showed that the current practice is not far from the optimal for the conditions of this system. A slight improvement can be expected if the frequency of operation is increased, reducing the interval to six hours during daytime hours.

Changing/optimizing the strategy and organization of operation

Changing the operational strategy can be a way to improve performance sometimes without major physical changes in the infrastructure. In this context the strategy can be simply defined as a structured way to set objectives for water services and practical ways to achieve them. For instance there are many systems in Asia which are set for dry conditions targeting water deliveries to users only but not geared for wet conditions. This strategy is obviously leading to loosing lots of water during the rainy season. Another strategy would then be to target both the water service to users while harvesting and storing as much as possible rainwater within the command area. This strategy change is illustrated below through some examples.

Example of a volume-controlled strategy for managing inflow changes

Operational strategies to integrate the management of water-level fluctuations along a canal with the objective of providing stable deliveries and being able to store the positive fluctuations have been investigated in Sri Lanka. Different strategies for operation, based on the salient physical features identified in the irrigation subsystems of Sri Lanka were tested for various techniques of volume control, targeting the optimal management of possible storage or the effective use of water (Renault, Godaliyadda and Makin, 1999).

These strategies were:

➢ Systematic oversupply some offtakes serving return-flow or re-use subsystems to be used as a "compensation storage" in case of temporary shortage downstream;

➢ undersupplying some offtakes to create on a rotation basis a capacity to absorb water surplus;

➢ wedge storage management by lowering the water level below full supply level to allow runoff to be stored along the canal in case of rainfall events.

The potential for improving the performance of water management using these techniques was first evaluated successfully in hydraulic simulations based on the right-bank main canal of the KOISP. All the options were presented and discussed with the users. Ultimately, they decided to select the on/off option.

IMPROVEMENT IN WATER MANAGEMENT

Using the RAP external indicators as a basis, the goal is to increase water productivity and water uses by: (i) maximizing water harvest; (ii) minimizing losses; (iii) managing perturbations (management of surplus); and/or (iv) by consolidating the control of flows throughout the service area. Although this final aspect is both critical and challenging, it should be a major goal to incorporating (or re-incorporate) into the management and operation all withdrawals that are either legal or illegal but tolerated, such as water lifting from the canals through pumps and illegal outlets along the main canal.

Canal pool storage (wedge) management can also in some circumstances compensate for small volume (time × amplitude) fluctuations.

Water measurement at key points plays an important role in improving canal operation, service delivery, and water management. A sound water measurement programme in the project helps in the following ways:

➢ improving transparency in water delivery service in terms of discharge and volume to an individual farmer or a group of farmers;

➢ ensuring equitable water allocation and distribution;

➢ accounting for water (water balance) in order to minimize adverse environmental impacts, such as waterlogging and salinity;

➢ negotiating service contracts;

➢ conserving water by restricting oversupply, which in turn can prevent deep percolation and runoff;

➢ providing the farmers with good information, on the basis of which they can take important farm decisions about cropping patterns, cropping intensities, irrigation scheduling and frequency, fertilizer use, labour, etc.;

➢ enabling proper billing for water usage (where water charges are based on the volume of water used, or where managers want to introduce volumetric pricing).

IMPROVEMENT IN WATER CONTROL

Based on the diagnosis provided by the internal indicators of the RAP, the goal would be to improve the control of water levels and discharges. This can be achieved by putting in place appropriate water control structures and setting proper operational procedures. Revised operational procedures should take into account improved modalities of operation (targets and modes) through reduced tolerance on H and reduced tolerance on discharge variation.

The first step is to set new achievable performance targets, and the second step is to define technical options for achieving these targets.

IMPROVEMENT FOR COST-EFFECTIVENESS

Operation accounts for a major share of the total cost of irrigation management. Some options for improving the cost-effectiveness of canal systems are:

> reduce the frequency of adjustment (where labour is expensive);
> reduce the sensitivity – upgrade sensitive structures (offtakes and regulators) (Plate 31);
> automate some structures (where labour is expensive);
> develop an effective information management system (for targeted interventions);
> replace gated regulators by automatic or fixed regulators.

Plate 31 shows an example where side weirs could beneficially replace gates of sensitive regulators – reducing the sensitivity and the needs for adjustment.

Plate 31
Building side weirs on gated regulators.

CONJUNCTIVE USE OF WATER

Conjunctive use of surface water and groundwater is important for:

> improving overall water resource management, maximizing the use of water for both quantity and quality;
> improving the service to users by buffering the fluctuations of one source by another one.

INTEGRATED WATER RESOURCE MANAGEMENT

Agriculture and ecosystems are often the two main users of water (be it rainwater or irrigation water). Often, within an irrigation project, water contributes significantly to uses other than evapotranspiration of field crops. For example, in the KOISP, water consumption from rice evapotranspiration accounts less than one-quarter of the mobilized water (Chapter 8). Provision of multiple services in the context of integrated water resource management could, for the operation of irrigation systems be considered both a constraint and an opportunity. It is a constraint because the services are diverse, sometimes conflicting and this made more complex the task of operating the infrastructure. At the same time it is an opportunity to share the cost among various users/beneficiaries and therefore alleviate the burden of farmers in sustaining the irrigation system.

Chapter 14
Integrating service-oriented management options

Improvements in the management and operation of a canal system cannot be investigated only in one way (e.g. from the main canal down to the lowest management unit). What is required is an iterative approach with overlapping facets.

MASSCOTE is first applied within the entire CA without considering specific units. The CA is then partitioned into subunits, and MASSCOTE is applied again at the each of the management units. This phase defines the main characteristics of the service required for each subunit from the upper level.

The main issues that need to be fully evaluated at this point are:

➢ Is the upper level capable of providing the desired level of service?
➢ If so, at what cost?
➢ What are the constraints with the other subunits that need to be considered?

Therefore, the integration as a double sweep of aggregation and disaggregation is fundamental in the development of management and technical options for the re-engineering of the whole system. This double sweep has to be performed several times, and it needs time to allow ideas to mature among the decision-makers.

In this aggregation process, improvement options for the subunits are identified together with the associated costs for each option. These are then aggregated at the system level. A modernization strategy is developed, according to the vision that has been developed as part of STEP 6, with objectives and proposed achievements/improvements.

Solutions that are developed at the management unit level need to be aggregated at the upper system level in order to check for consistency and to see how feasible they are when the upper-level management and operation is considered (Figure 74). Some constraints at the upper level might prevent implementing requested services to the lower level.

Again this aggregation and consolidation process is a two-way process, moving up and down, and converging progressively towards a solution that can be tested on the ground.

Figure 74
Checking for consistency of the water management, services to subunits and main system operation (including drainage)

AGGREGATING THE RATIONALE OF SUBUNITS AT UPPER LEVEL

Once the rationale of water management, services and operation has been investigated at the level of the local management unit, there is a need to aggregate all this at the upper level (e.g. the main system) in order to check for consistency and possibly return back to the lower level in order for any required change to be accommodated.

FIGURE 75
The process of determining a compromise on service

Users defining a desired service	Managers exploring constraints and opportunities
Targets, tolerances vulnerabilities	Operational planning scenarios

Compromising on cost, flexibility, and quality: Service agreement

The rationale for water management, services and operation, how main water management is performed, and whether it is consistent with the lower-level options, how perturbations or unscheduled changes will be accommodated along the main system, etc.

REACHING A COMPROMISE BETWEEN COSTS AND SERVICE

In order to agree upon an irrigation service, a compromise has to be reached jointly by the users and the management and operation agency. For a given system layout, it is a compromise between technical opportunities and constraints, farmers' desires influenced by the agricultural system, and the costs of operation incurred (Figure 75). Decision-making can be seen as comparing what is desirable with what is possible, which then leads to what is affordable.

This process of arriving at a compromise can be summarized as:

1. The agriculture and water management systems determine what particular water service is desirable by the users (farmers or others).
2. The physical water resource and irrigation system in essence determine what is physically/hydraulically possible in terms of implementing a particular water delivery services as a function of various inputs in operation. This leads to a range of possible water delivery services.
3. Comparing the above two items will lead to the specific service that users can afford.

This compromise cannot be reached instantly. It is a progressive process that implies going iteratively back and forth between what is desirable and what is possible (and within the desirable, between individual and collective interests). There should be no illusions that achieving a compromise will be either simple or straightforward. On the contrary, it will often be the case that what is desired by the users is not technically possible, or that the irrigation service provider is too self-assured about its command and control and it does not study seriously possibilities to accommodate farmers' requests. How to guide this process through its different stages and feedback loops merits a paper for itself and, therefore, falls outside the scope of this paper.

Distinguishing between linear and non-linear changes

When considering improvements in canal operation, it is necessary to distinguish between:

➢ improving existing system and managerial procedures by incremental steps (linear approach);
➢ abrupt changes either in the systems and/or in the procedures – this type of change is relevant for full modernization or re-engineering interventions (non-linear approach).

SERVICE AGREEMENTS

The decisions taken as a result of all the above-mentioned negotiations and discussions are to be included in the service agreements between the service providers and the users. The service agreements describe:

➢the service to be delivered;
➢the obligations of the service providers;
➢the rights and obligations of the users;
➢the designated procedures in the event of failure to fulfil the obligations.

A service agreement can be formal and legally binding or informal. In both cases, it can serve as the basis for performance evaluation and accountability of both the service providers and the water users – for the former, in the event of failure to provide the agreed service; and for the latter, in the event of failure to pay for the services received.

In order to increase transparency in the obligations and targets for water delivery, service agreements should include clear information on:
➢point of water delivery;
➢quantity (discharge, volume, etc.);
➢quality (timing, etc.);
➢tolerance levels;
➢flexibility;
➢penalties;
➢compensation in the event of failure.

Although water delivery is the primary concern of canal operation, the water service agreement will encompass more than the timing, reliability and volumes of water deliveries. The quality of service is also measured in terms of organizational capacity and accountability. Whether the operational setup allows for local control and flexibility will be important to many water users, and so are rigidity and transparency of rules for them and other actors. Irrigation service provision and performance of delivery can often be improved significantly by examining:
➢how reliable the management institution is;
➢what the governance mechanisms are to ensure that the service is actually provided.

In collective systems, the irrigation service level cannot be determined at the individual level in a practical way. There are some demands that are incompatible with others, and not all demands can be accommodated. This should be discussed, and it is essential to have coherence at all levels of the system. The irrigation system can be disaggregated to the smallest units for which differentiation is technically possible. These are not necessarily tertiary units as some decisions will have to be made at a higher level. Thus, service agreements can be decided collectively, depending on the physical ability of the system to accommodate "subsystem management" units.

Chapter 15
Towards a plan for modernization and for monitoring and evaluation

It is important to phase the implementation of modernization improvements in order to keep expectations and achievements at a realistic and practical level. A decision about what options and strategies are to be pursued has to be taken. The most cost-effective and easy-to-implement options are selected to start the process of modernization. However, it is necessary to realize that modernization is a long process that needs to start with an agreed-upon vision of the irrigation system and of the irrigated agriculture in the CA. The modernization plan can then be designed as a consistent set of interventions focused on realizing that vision.

A PLAN FOR MODERNIZATION

The RAP and MASSCOTE are tools – methodologies useful for diagnosing current performance and for laying the foundations for embarking upon a modernization plan. Implementing a plan for modernization is a long and iterative process. The RAP is rapid (a matter of days). MASSCOTE is fast (a matter of weeks). A modernization plan is much slower, probably taking months to formulate in all its aspects (Figure 76). Finally, implementation of this plan is a matter of years. An examination of irrigation agencies that are performing well today reveals that most of them have started a modernization process many years ago that is still continuing.

In a context characterized by rapid change in agriculture markets, water management, energy, labour costs, etc., modernization should be perceived as an ongoing activity that allows managers to adjust their performance at any moment of time to the conditions and opportunities.

The process of canal operation improvement is a long-term undertaking that needs to be phased into a proper time frame (which is also important for the financing of projects). The investment capacity of users and other stakeholders (state, local bodies, etc.) is usually limited. Therefore, establishing a realistic time frame is a key factor in the success of a project. Progress that is too slow may result in overly expensive improvements, while progress that is too fast may result in erroneous and expensive interventions.

The development of real, innovative solutions and the adjustment of people's lives to technical solutions takes time (at least several seasons). Even well-tested and reliable solutions need some time for adaptation and adoption, even in the best circumstances.

In summary, time is a key factor in planning for canal operation improvements. There needs to be a valid compromise between hurrying and going too slowly. Moreover, time frames should be defined clearly when embarking upon canal operation improvement projects.

MONITORING AND EVALUATION

Monitoring and evaluation of improved canal operations is a must in order to ensure achievements, take correct action, and compare conditions before and after investment. In any case,

FIGURE 76
Time-related interventions in canal systems on the path to modernization

M&E should form part of the regular activities to monitor key points for operation and water management and periodically evaluate service to users.

The M&E of irrigation and drainage projects is usually meant to provide information on two important flows – water and money – and to evaluate the current level of performance of water delivery service and the cost-effectiveness. A good M&E system should be able to provide the managers with information on the available resources (water and money), output produced (water delivery service), and performance achieved (reliability, adequacy, flexibility, etc.), in order to determine the corrective action that should be taken.

The evaluation of water delivery service is done in order to assess objectively and systematically the realization of targets and objectives. It is a task that should be undertaken periodically. Seasonal (crop seasons, rainy and dry, summer and winter, etc.) or yearly evaluations of water delivery service are common. They provide a basis for discussion among the managers and water users and their representatives on any changes in operation, infrastructure and targets for water delivery.

Monitoring refers to the systematic collection of information and its use to help managers make decisions regarding: (i) day-to-day operation and management; (ii) asset management; and (iii) medium-term to long-term planning for improvements.

It is a task of operation that, where done properly, can make a difference between good and poor performance, particularly in systems subject to variable inflows and perturbations. For example, without monitoring, it is almost impossible to detect any unscheduled perturbation and related action. A "smart" information system is a must for effective operation.

Canal operation has its own, very specific, information requirements (collection, transmission and processing) and, thus, operational plans have to include specific "information management systems".

The main elements of monitoring for operation include:
➢ water levels at cross-regulators;
➢ discharges at the start of management units and offtakes;
➢ the condition of the canal sections and hardware – specifically, at the vulnerable points.

The monitoring of every structure and canal section is expensive and not necessary. Therefore, it is important to identify key monitoring points within the system based on the following criteria:
➢ sensitivity of the structure;
➢ vulnerable points within the system;
➢ service definition and criteria.

Sensitive cross-regulators and offtakes require frequent monitoring as compared with structures that are not sensitive to changes in water level and/or discharge. As shown in Chapter 6, sensitive cross-regulators are good points at which to detect perturbations, and sensitive offtakes may create a perturbation downstream. The monitoring of sensitive structures is necessary for enabling proper action to be taken and operational targets to be achieved.

Vulnerable or weak sections or reaches of the canal network need to be monitored frequently in order to ensure the safety of the infrastructure in the event of a sudden increase in discharge as a result of inflow or rainfall that may result in some damage, e.g. eroding the banks or causing a breach in the canal.

Service definitions and service agreements also define what should be monitored. For example, if the service agreement requires delivery of a certain discharge at certain delivery points, then the discharge at these delivery points should also be monitored.

Operations plans should include regular monitoring priorities, procedures and frequencies. The frequency of monitoring depends on various elements, including:
➢ changes in scheduled operation;

> ➢ variations in inflow – perturbations;
> ➢ changes in the gate setting of the key control structures;
> ➢ special cases (heavy rainfall, floods, etc.).

Conventionally, monitoring is done using human resources (gate operators and other field staff). However, with improvements in technology, it is now possible to have remote monitoring systems at a reasonable cost, e.g. an electronic sensor that sends information to the operator based on real-time conditions. These technologies are particularly useful in facilitating operations where operators are not based along the canals and where flow deliveries to the farmers are more demand oriented. However, some technologies are expensive and have very specific requirements (physical infrastructure, staff capacity and level of water delivery service) for installation and functioning.

There is no point in monitoring and collecting information if it is not analysed and used for making effective water management decisions. The information gathered through M&E is also used to determine the water balances (a must for good water management) and to assess achieved water delivery performance.

Chapter 14
Integrating service-oriented management options

Improvements in the management and operation of a canal system cannot be investigated only in one way (e.g. from the main canal down to the lowest management unit). What is required is an iterative approach with overlapping facets.

MASSCOTE is first applied within the entire CA without considering specific units. The CA is then partitioned into subunits, and MASSCOTE is applied again at the each of the management units. This phase defines the main characteristics of the service required for each subunit from the upper level.

The main issues that need to be fully evaluated at this point are:

➢ Is the upper level capable of providing the desired level of service?
➢ If so, at what cost?
➢ What are the constraints with the other subunits that need to be considered?

Figure 74
Checking for consistency of the water management, services to subunits and main system operation (including drainage)

Therefore, the integration as a double sweep of aggregation and disaggregation is fundamental in the development of management and technical options for the re-engineering of the whole system. This double sweep has to be performed several times, and it needs time to allow ideas to mature among the decision-makers.

In this aggregation process, improvement options for the subunits are identified together with the associated costs for each option. These are then aggregated at the system level. A modernization strategy is developed, according to the vision that has been developed as part of STEP 6, with objectives and proposed achievements/improvements.

Solutions that are developed at the management unit level need to be aggregated at the upper system level in order to check for consistency and to see how feasible they are when the upper-level management and operation is considered (Figure 74). Some constraints at the upper level might prevent implementing requested services to the lower level.

Again this aggregation and consolidation process is a two-way process, moving up and down, and converging progressively towards a solution that can be tested on the ground.

AGGREGATING THE RATIONALE OF SUBUNITS AT UPPER LEVEL

Once the rationale of water management, services and operation has been investigated at the level of the local management unit, there is a need to aggregate all this at the upper level (e.g. the main system) in order to check for consistency and possibly return back to the lower level in order for any required change to be accommodated.

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Users defining a desired service ↔ Managers exploring constraints and opportunities

Targets, tolerances vulnerabilities ↔ Operational planning scenarios

Compromising on cost, flexibility, and quality: Service agreement

The rationale for water management, services and operation, how main water management is performed, and whether it is consistent with the lower-level options, how perturbations or unscheduled changes will be accommodated along the main system, etc.

REACHING A COMPROMISE BETWEEN COSTS AND SERVICE

In order to agree upon an irrigation service, a compromise has to be reached jointly by the users and the management and operation agency. For a given system layout, it is a compromise between technical opportunities and constraints, farmers' desires influenced by the agricultural system, and the costs of operation incurred (Figure 75). Decision-making can be seen as comparing what is desirable with what is possible, which then leads to what is affordable.

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1. The agriculture and water management systems determine what particular water service is desirable by the users (farmers or others).
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When considering improvements in canal operation, it is necessary to distinguish between:

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The decisions taken as a result of all the above-mentioned negotiations and discussions are to be included in the service agreements between the service providers and the users. The service agreements describe:

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Chapter 15
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In a context characterized by rapid change in agriculture markets, water management, energy, labour costs, etc., modernization should be perceived as an ongoing activity that allows managers to adjust their performance at any moment of time to the conditions and opportunities.

The process of canal operation improvement is a long-term undertaking that needs to be phased into a proper time frame (which is also important for the financing of projects). The investment capacity of users and other stakeholders (state, local bodies, etc.) is usually limited. Therefore, establishing a realistic time frame is a key factor in the success of a project. Progress that is too slow may result in overly expensive improvements, while progress that is too fast may result in erroneous and expensive interventions.

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RAP | MASSCOTE | Modernization

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Monitoring refers to the systematic collection of information and its use to help managers make decisions regarding: (i) day-to-day operation and management; (ii) asset management; and (iii) medium-term to long-term planning for improvements.

It is a task of operation that, where done properly, can make a difference between good and poor performance, particularly in systems subject to variable inflows and perturbations. For example, without monitoring, it is almost impossible to detect any unscheduled perturbation and related action. A "smart" information system is a must for effective operation.

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Vulnerable or weak sections or reaches of the canal network need to be monitored frequently in order to ensure the safety of the infrastructure in the event of a sudden increase in discharge as a result of inflow or rainfall that may result in some damage, e.g. eroding the banks or causing a breach in the canal.

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There is no point in monitoring and collecting information if it is not analysed and used for making effective water management decisions. The information gathered through M&E is also used to determine the water balances (a must for good water management) and to assess achieved water delivery performance.

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Annex 1
Basic canal hydraulics

The aim of this annex is to refresh some basic knowledge on flow conditions and canal capacity. These are determined by hydraulic laws that are of use not only for design but also for diagnosis.

THE HYDRAULIC STEADY STATE

Steady-state open flow hydraulics is a branch of fluid mechanics. Steady-state hydraulics covers flows with a constant discharge in time. Specific laws have been established linking geometry, hydraulic properties and discharge for different types of structures and canals. These laws are translated into rules that are widely applied in irrigation design and operation (e.g. Chow, 1959).

Knowledge of steady-state hydraulics in open canals is fundamental in the design stage of a transport and delivery network. As far as the management and operation of irrigation systems are concerned, steady-state hydraulics is important for measuring, monitoring and managing discharges at various places along the system (measurement, control and operation infrastructure from headworks down to farm inlets). In open canals, discharges are rarely measured directly but are computed locally using a generic law such as Equation 1 and one or more measured proxy variables, e.g. water depth or gate opening:

$$Q = F(\text{geometry, hydraulic variables})\qquad(1)$$

Two types of flow (Box A1.1) should be distinguished while measuring or computing discharges:

➢ uniform (normal) flow;
➢ influenced flow.

Uniform flow occurs when all variables of flow are constant, i.e. discharge (Q), depth (h), width (w_o) and mean velocity (V). Non-uniform or influenced flow can also be in a steady state (Q = constant), but the other variables of flow (geometry of the canal, and velocity) may change gradually from section to section. Both types of flow can frequently be found in irrigation systems.

Geometrical characteristics of a canal section

Two main variables of open canal hydraulics are the wetted perimeter, p, and the hydraulic radius, R. These variables are necessary in the calculation of uniform canal flows. Figures A1.1 and A1.2 introduce the geometric characteristics of irregular (random) and trapezoidal canal sections.

Bed slope of the canal

In canal hydraulics, there are three determining variables: depth of flow,

FIGURE A1.1
Geometric variables of a canal section

A	Flow area	(m^3)
p	Wetted perimeter (m)	
$R = A/p$	Hydraulic radius	(m)
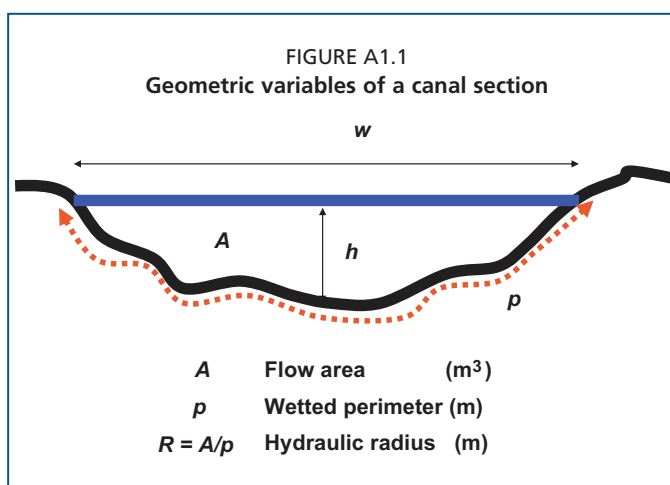
BOX A1.1
Definitions

Steady flow: A flow in which quantity of water passing a given point per unit of time remains constant.

Unsteady flow: As opposed to steady flow, it is a flow in which the elements of flow are subject to change in the course of time.

Uniform (or normal) flow: The flow in an open channel is said to be uniform when parameters, such as the cross-sectional area, the velocity and the hydraulic slope, remain constant from section to section. The water level in this case is parallel to the bottom line of the canal.

Influenced (or non-uniform) flow: The flow in an open channel is said to be influenced (non-uniform) whenever the depth and other features of flow, such as the cross-sectional area, the velocity and the hydraulic slope, vary from section to section. In an otherwise uniform canal, non-uniformity occurs under the influence of structures along the canal.

	Uniform cross-section of flow from point to point	Cross-section of flow varies from point to point
Flow is constant over time	Steady uniform flow	Steady influenced flow
Flow is variable over time	Unsteady uniform flow	Unsteady non-uniform flow

Wetted perimeter: The length of the wetted contact between a stream of flowing water and its containing conduit or channel, measured in a plane at right angles to the direction of flow.

Hydraulic radius: The cross-sectional area of the flowing water divided by the wetted perimeter.

Roughness coefficient: A factor that represents the effect of roughness of the pipe or the channel material upon the energy losses of water (K or n in hydraulic formulae).

Subcritical flow: A velocity of flow lower than critical; characterized by deep slow flows. Most open-canal flow is subcritical.

Critical flow: That velocity of flow at which the energy of flow is at a minimum; transition point.

Supercritical flow (shooting flow): A velocity of flow in excess of critical. Flows are superficial and very rapid. An important characteristic is that waves cannot travel upstream of flows that are above critical flow.

Open-channel flow: Flow in a channel with a free surface in contact with the atmosphere. This includes flow in pipes and closed conduits flowing partly full.

Free flow: A condition of flow through or over a structure where such flow is not affected by submergence or the existence of tail-water. The flow is governed only by upstream conditions.

Submerged flow (drowned flow): A condition of flow through or over a structure where such flow is affected by submergence or the existence of tail-water. The flow is governed by upstream and downstream conditions.

Overshot structure: A structure where the water passes from the parent channel to either the downstream canal or the offtaking channel by discharging over the crest of a wall, or over the top edge of a gate.

Undershot (orifice) structure: A structure where the water passes from the parent channel to the downstream canal or the offtaking channel below the gate opening formed between the sill of the gate opening and the lower edge of the gate or through an orifice formed by a pipe or a submerged hole in the structure.

Offtake (diversion) structure: A structure built at the head of an offtaking branch or distributary channel to control and admit regulated supplies into it from the parent canal.

Cross-regulator (check structure): A structure designed to control the water surface level and flow in a canal, maintaining a specified water depth or head on outlets or diversion structures, particularly when the flow is small.

width of flow, and the slope of the canal. Fixing two will give the third. The longitudinal bed slope is generally expressed as a fraction or a percentage (e.g. 0.001 or 0.1 percent for a slope of 1 m per 1 000 m). Under uniform flow conditions (Figure A1.3), the energy gradient of the water is parallel to the bed slope (and the mean water level). Stated differently, a constant velocity and water depth are obtained when the force moving water forward (weight as related to the bed slope) is in balance with friction forces.

The range of choice for longitudinal slopes of canals is limited. The slope should facilitate sufficient discharge and a minimum water level at control points, while not exceeding a maximum flow velocity. It should also allow a minimum velocity in order to avoid sediment deposit.

Flow velocity

Velocity in uniform flows (Figure A1.4) is generally calculated using the empirical Manning–Strickler equation:

$$V = KR^{2/3}S^{1/2} \qquad (2)$$

where:
- V = velocity (m/s);
- K = roughness coefficient ($m^{1/3}$/s);
- R = hydraulic radius (m);
- S = bottom bed slope (m/m).

Flow velocity in the canal has to be maintained within a small range. In order to prevent scouring in earth canals and maintain subcritical flow, maximum velocity values should not be exceeded. Flow in irrigation canals is nearly always subcritical (deep and slow flow). At diversion, division and especially measurement structures, supercritical flow may occur and even be necessary.

Minimum velocities should also be maintained in order to prevent sedimentation when the flow has a high sediment load and to limit the occurrence of water-borne diseases favoured by standing or slowly moving waterbodies. Recommended velocities are given in Table A1.1.

In Table A1.1, V refers to mean velocity, as the velocity is not spread uniformly over the whole cross-section of the canal owing to friction.

FIGURE A1.2
Geometric parameters of a trapezoidal canal

$A = h (w_o + m.h)$
$p = w_o + 2.h (1 + m2)^{0.5}$
$R = [h (w_o + m.h)]/[w_o + 2.h (1 + m2)^{0.5}$
If $m = 0$ and $h \ll w_o \rightarrow R = h$

FIGURE A1.3
Flow surface parallel to bed slope with uniform flow in an open channel

FIGURE A1.4
Velocity profile in a uniform flow section
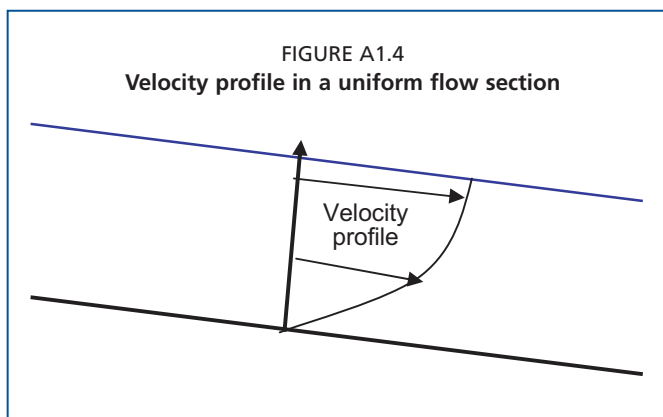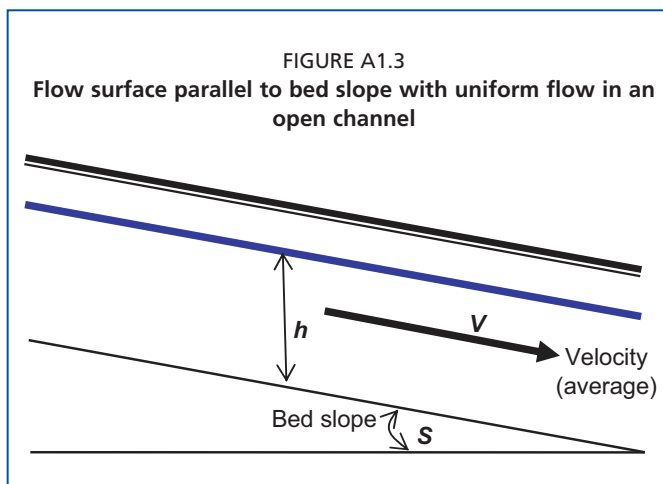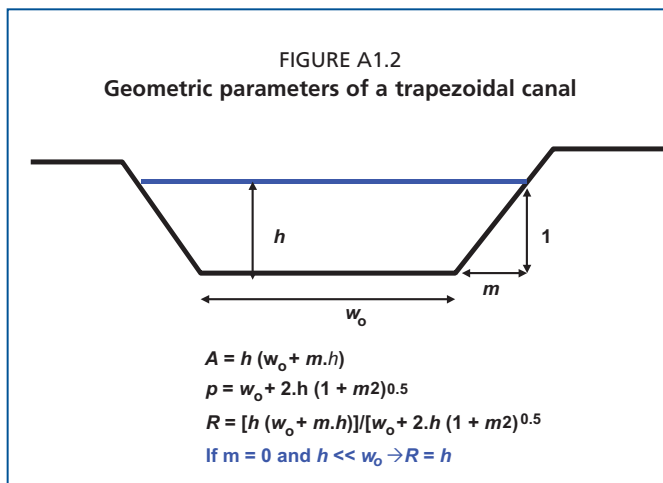
TABLE A1.1
Usual threshold velocity in irrigation canals

		Threshold velocity (m/s)
V_{maxi} (m/s)	Earth canals in sandy soils	0.3–0.8
	Earth canals in stable soils	1.0
	Concrete canals	2.0
V_{mini} (m/s)		0.5

TABLE A1.2
Values of discharge coefficient K (n) drawn from the literature

Canal alignment	State	
	Perfect	**Degraded**
Smooth cement walls	100 (0.010)	75 (0.013)
Concrete lined canals	83 (0.012)	55 (0.018)
Earth canals (regular) [1]	60 (0.017)	40 (0.025)
Canals with stony beds	40 (0.025)	25 (0.040)

[1] Earth canals show strong variation in roughness during the season owing to weed growth, etc.

Roughness

The Manning–Strickler equation shows that velocity depends not only on hydraulic radius and slope, but also on the surface roughness of the canal. As mentioned above, equilibrium is established between energy dissipated by friction along walls and bottom, and the potential head loss along a sloping canal.

Roughness can be expressed by the Manning coefficient (n) (n increases with roughness) or by the discharge coefficient of Manning–Strickler ($K = 1/n$). Roughness is not a long-term permanent property of a canal section. It generally tends to increase over time (Table A1.2). However, a decrease in roughness can be observed immediately after maintenance of the walls of an earth canal. Thus, the phenomenon is related to smoother walls and/or the deposition of fine alluviums on the bed bottom.

Steady flow regimes

The transport capacity ultimately and most importantly refers to the discharges of canal flows. The discharge is equal to the product of the flow cross-section (A) and velocity (V).

$$Q = V * A \tag{3}$$

For uniform flow, the standard Manning–Strickler equation applies:

$$Q = KAR^{2/3}S^{1/2} \tag{4}$$

where:
- Q = discharge (m³/s);
- K = roughness coefficient (m$^{1/3}$/s);
- A = canal cross-section (m²);
- R = hydraulic radius (m);
- S = bottom bed slope (m/m).

Where the canal is rectangular and large, the hydraulic radius R is equal to water height h and the equation can be simplified. Transport capacity can be calculated with:

$$Q = Kw\ h^{5/3}S^{1/2} \tag{5}$$

where:
- w = bed width (m);
- h = water depth (m).

Influenced flow

The flow is influenced where water depth is controlled by a singular point along the canal. The equations for uniform flow no longer apply as the water profile deviates from a normal flow profile to progressively reach the control point (Figure A1.5).

THE UNSTEADY-FLOW APPROACH

By nature, steady-state flow is rarely found in irrigation canals. Fluctuations occur continually as a result of management interventions or of unexpected fluctuations in inflows or outflows. Therefore, knowing the steady-flow properties of a canal system is not sufficient for efficient management.

Unsteady flow introduces the dynamics of flow variation with time. The discharge varies as a function of time. Therefore, the generic Equation 1 is rewritten as:

FIGURE A1.5
Flow regime under influenced flow

$$Q(x,t) = F(\text{geometry, hydraulic variables, time}) \tag{6}$$

The Saint Venant differential equations have been developed to describe these conditions. Several methods of integrating unsteady flow have been proposed and used in the past, with various levels of simplification depending on the prevailing computational capacity. In the field of flow regulation for example, simplified approaches have been developed using transfer functions (Laplace and Fourier functions) to simulate wave propagation. Fully hydrodynamic models, based on numerical resolution of the two Saint Venant equations, can be run on personal computers.

An unsteady flow approach is essential in order to describe fully the dynamics of the canal systems, for example to evaluate the time lag between issues and deliveries. For example, in order to anticipate operation of the headworks as a function of the expected demand, it is important to know the time taken for water to flow from the main reservoir to a user situated on the downstream network.

WAVE PROPAGATION

The characteristics of wave propagation along a canal are very important data for the management of a canal. In fact, the transit time of changes is relatively long on the canals. It is not rare that a change in supply to the canal takes more than 24 hours to become apparent downstream in the network. Thus, it is crucial for the manager to know how waves propagate in order to anticipate the changes in regulation to be implemented and so meet demand on time (Figure A1.6).

Knowing the transit time of the wave along a canal is also important for setting up a management strategy of the works and, in particular, for preventing that the type of rules established to operate the structures give rise to a large amplification of perturbations along the canal (oscillations).

HYDRAULICS OF IRRIGATION STRUCTURES

Singular structures of irrigation systems can be classified into two main hydraulic categories: the orifice type (also called undershot); and the overshot type (Table A1.3). For both categories, two types of flows can be distinguished with different hydraulic laws and consequent operational

FIGURE A1.6
Wave propagation along a canal
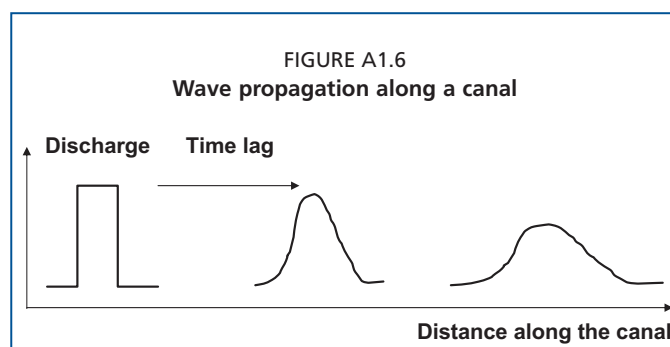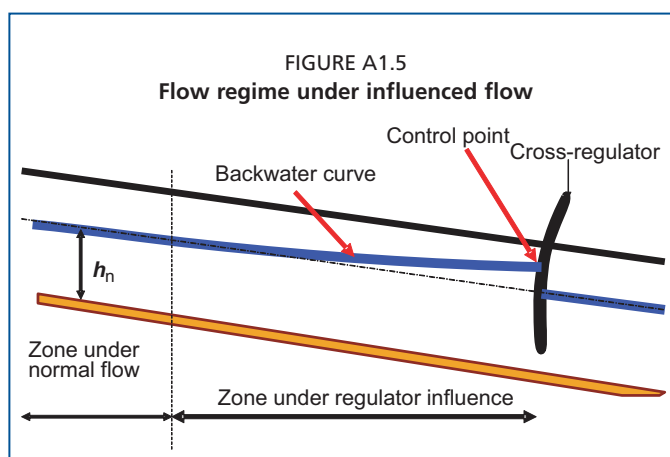
TABLE A1.3
Typology of irrigation structures

Hydraulic category	Examples	Type of flow	Modularity	Discharge determined by
Orifice type	Sluice gates, radial gates, baffle distributors	Free flow	Semi-modular	h_{US}
		Submerged	Non-modular	h_{US} & h_{DS}
Overshot type	Broad-crested weirs, duck-bill weirs, flumes	Free flow	Semi-modular	h_{US}
		Submerged	Non-modular	h_{US} & h_{DS}

FIGURE A1.7
Flow types at singular structures

FIGURE A1.8
Orifice-type offtake with downstream free-flow conditions
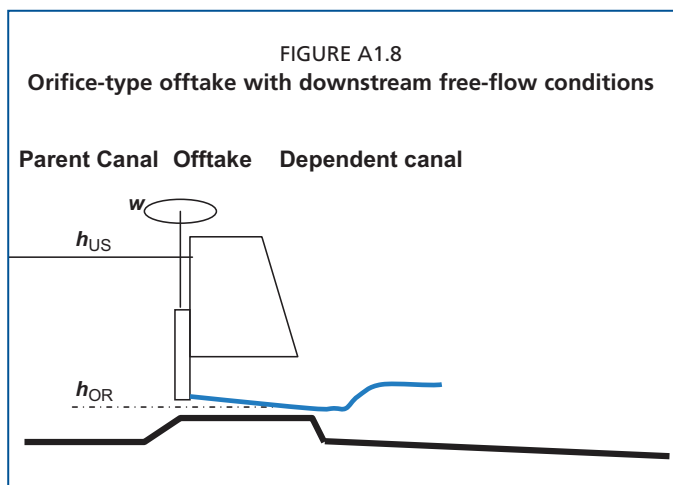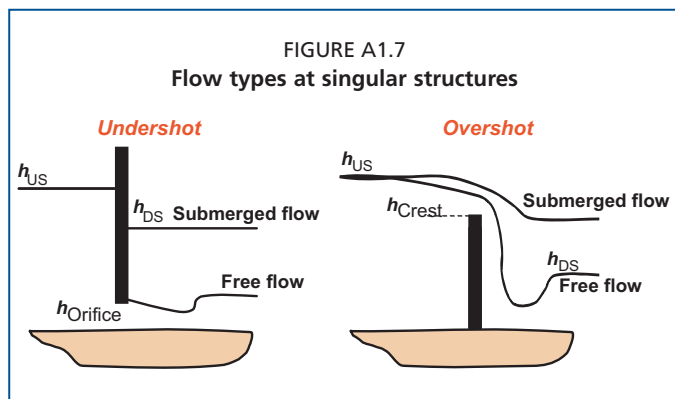
demands.

The flow is said to be free if it passes through a critical (or supercritical) flow stage that dissociates the downstream and the upstream of the structure (Figure A1.7). Only the water head exerted by the supply level on the axis of the gate controls the discharge in the structure. These structures are called semi-modular. The flow is said to be submerged when the downstream part is submerged by a water line controlled by a downstream point (sill or other). Under this condition, the head downstream of the intake equally affects the discharge passing through the structure. These structures are called non-modular.

Except for pumps and perhaps Neyrpic distributors, there are no practical examples of modular structures. This means that for non-proportional systems, water-level control is a very important subsidiary target of canal operation.

Hydraulics of an orifice (undershot) with free-flow characteristics

Orifice-type structures can be found in any part of irrigation systems. They are often used as offtakes. For an orifice-type offtake with downstream free-flow conditions (Figure A1.8), only one equation is required to describe the flow:

$$q = a A \left(h_{US} - h_{OR} \right)^{0.5} \tag{7}$$

where:
- q = discharge through offtake (m³/s);
- a = discharge coefficient equal to $c(2g)^{0.5}$;
- c = flow coefficient function of the shape of the orifice ($c \approx 0.5$);
- $A_{(w)}$ = flow cross-section of the structure, expressed as a function of the setting w (m²);
- h_{US} = water level upstream of the structure (m);

➤ h_{OR} = level of the orifice axis (m).

Examples of undershot structures are sluice gates, orifices (pipe outlets) and Venturi. One of the main hydraulic characteristics is that discharge (q) is related to the head (h) (= h_{US} - h_{OR}) with exponent 0.5.

Hydraulics of an orifice (submerged)

Structures are quite often submerged, i.e. the flow downstream of the structure is controlled by a control section or structure. The water level downstream of the gate is dependent on discharge and downstream setting and adjustment.

FIGURE A1.9
Undershot submerged by a measuring weir

Structures that fall under this category are:

➤ offtakes equipped with measuring devices (weir or flume) downstream of the structure at the entrance of the dependent canal;
➤ offtakes serving a submerged canal that is controlled by a downstream structure;
➤ offtakes or regulators for which the submergence is dictated locally by normal flow conditions;
➤ regulators under the influence of the next downstream regulator.

Under submerged conditions (Figure A1.9), discharge calculations are more complicated than under free-flow conditions. This is because downstream water levels vary according to conditions in this canal. A variation in water depth within the parent canal (Δh_{US}) generates a variation in the discharge (Δq), which in turn generates a variation in the downstream water level (Δh_{DS}) controlled by the weir. As a consequence, the variation in head on the offtake is no longer equal to (Δh_{US}) but to (Δh_{US} - Δh_{DS}). Solving the problem requires considering two stages and two equations.

The governing equations of flow are:

Stage 1:
$$q = a\, A \left(h_{US} - h_{DS} \right)^{0.5} \qquad (8)$$

Stage 2:
$$q = a'\, b \left(h_{DS} - h_{REF} \right)^{1.5} \qquad (9)$$

where:
➤ q = discharge through the offtake (m³/s);
➤ $A_{(w)}$ = flow section through the structure expressed as a function of the setting w (m²)
➤ a = discharge coefficient equal to $c(2g)^{0.5}$;
➤ c = flow coefficient function of the shape of the orifice ($c \approx 0.5$);
➤ a', b = hydraulic parameters of the second stage law;
➤ h_{US} = water level upstream of the structure (m);
➤ h_{DS} = water level downstream of the structure (m);
➤ h_{REF} = reference level downstream taken as the crest level of the weir (m).

Hydraulics of an overshot structure

Overshot structures are used mainly for water control, water measurement and as safety structures. They are less frequently used as discharge regulation structures (Figure A1.10) because of their hydraulic characteristics and often more complicated operation requirements related to adjustments. Examples of overshot structures are: broad-crested weirs, stop logs, Cipoletti weirs, and Parshall flumes. The main hydraulic

FIGURE A1.10
Overshot-type discharge regulator
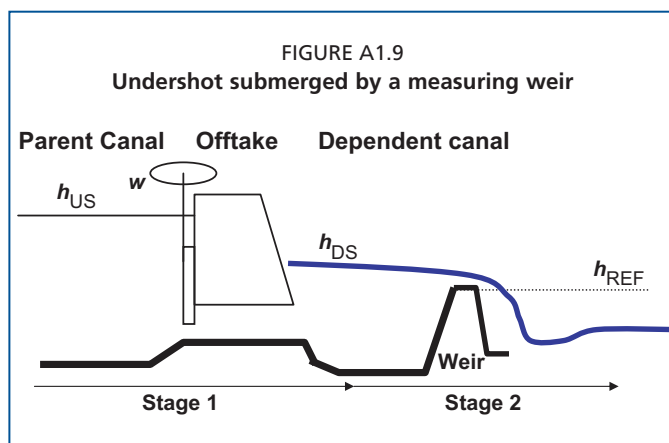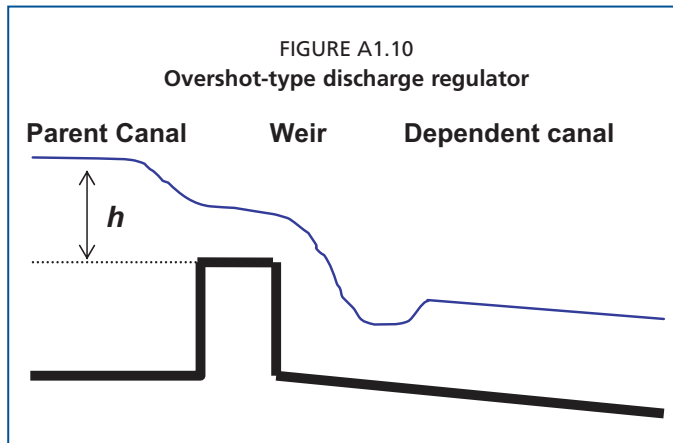
characteristic of all overshots is that discharge (q) is related to the head (h) (= h_{US} - h_{OR}) with exponent 1.5. The hydraulic equation is:

$$q = c \, b \, h^{1.5} \tag{10}$$

where:

➤ q = discharge through offtake (m³/s);
➤ c = weir coefficient for free flow (depending on size, shape and angle with cross-section; $c \approx$ 1.0–1.9);
➤ b = crest width (m);
➤ h = head above crest (m).

WATER-LEVEL CONTROL

Given that the demand for water is not constant in time, discharges are usually fluctuating along an irrigation network. The consequence is that, without specific control, water depths along canals vary considerably and so do water-level conditions at diversion points. As discharges through offtakes are related to the water level in the parent canal, water-level control is important to ensuring a good water service.

Where there is no cross-regulator in the parent canal, the water depth can be calculated from the standard Manning–Strickler formula, provided the flow is uniform. For a large, rectangular canal, the solution is explicit and given by:

$$h = \left[\frac{Q}{Kw \, S^{1/2}} \right]^{3/5} \tag{11}$$

where:

➤ Q = discharge;
➤ K = roughness coefficient;
➤ w = bed width;

FIGURE A1.11
Variation in water depth with discharge under normal flow conditions, with fixed overflow regulator and with gated regulator
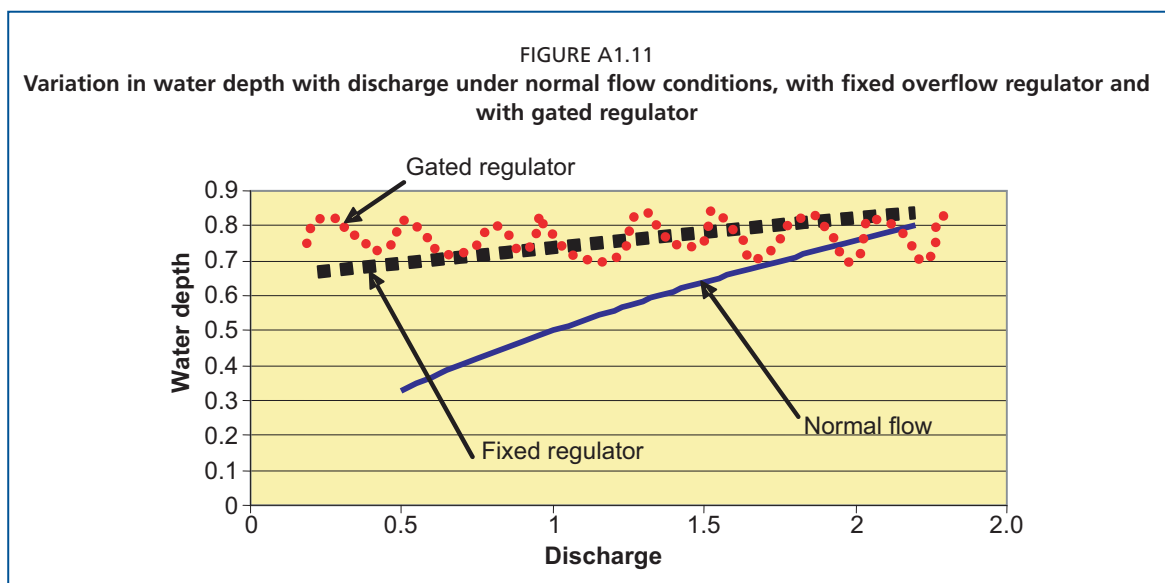
➢ S = bottom bed slope.

This implies that under normal-flow conditions, a variation in discharge of 50 percent will cause a variation in water depth of slightly more than 30 percent (Figure A1.11).

In order to ensure that offtakes (diversion structures) are properly supplied with enough and stabilized head, water heads must be regulated.

Discharge regulation structures can also serve as water-level control structures. These structures, also called check-structures or cross-regulators, are located just downstream of offtakes, their main function being to maintain a stable water level. The Q–h relations of water-level regulators are equal to those of discharge regulators. The same reason that makes overshots not suitable as discharge regulators – their insensitivity to variations in water heights – is a prime reason why they make excellent cross-regulators (Figure A1.12).

FIGURE A1.12
Q–h curves for hydraulic structures

A

B

Typical Q–h curves for undershots (A) and overshots (B)

NB: Specific curves should be developed for dimensions, characteristics, etc. At low heads, both formulae are inaccurate.

Weir crest

h (m)

Q (m³/S)
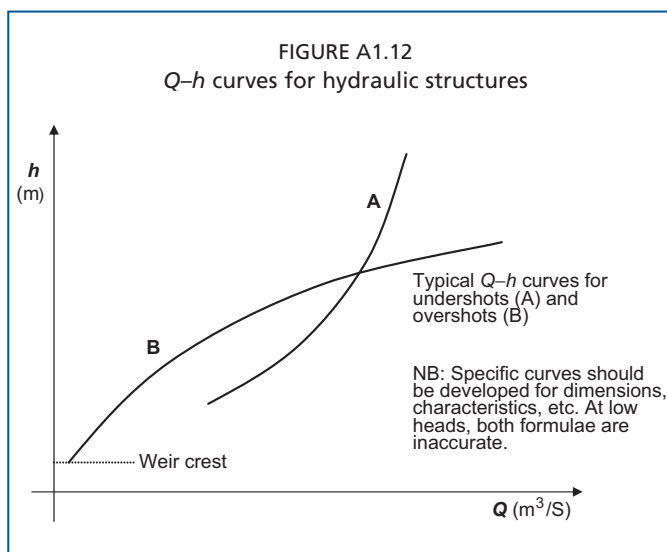
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Annex 2
Sensitivity of irrigation infrastructure and performance

ASSESSMENT OF SENSITIVITY INDICATORS OF OPEN-CHANNEL STRUCTURES
Definition
For water diversion (offtake), the sensitivity indicator is the ratio of relative variation in withdrawal (discharge q) to the variation in water level in the parent canal (H):

$$S = \frac{\Delta q / q}{\Delta H} \tag{1}$$

For water-level control (regulator), the sensitivity indicator is the ratio of the variation in (H) to the relative variation in discharge Q in the main canal:

$$S = \frac{\Delta H}{\Delta Q / Q} \tag{2}$$

Estimating structure sensitivity
There are three ways to estimate the value of the sensitivity indictor of a structure:
  ➢ hydraulic formulation;
  ➢ direct measurement;
  ➢ data processing of recorded heights.

Computing sensitivity indicators with hydraulic formulations
Flow conditions can be free flow or submerged. Free flow means that the downstream side of the structure does not bring any influence on the flow conditions through the structure, whereas submerged ones do. Figure A2.1 illustrates an example for an undershot structure with these two possible conditions.

Submergence can result from various features:
  ➢ the presence of a measuring weir;
  ➢ the presence of a weir further downstream;
  ➢ a normal flow condition downstream;
  ➢ an influenced flow from a further downstream cross-structure.

In the general case of submergence, the input–output sequence is twofold: a variation in input H_{US} produces a variation in discharge q, which in turn produces a change in the water depth H_{DS} downstream of the structure. As a result, the resulting variation in q is dependent on both H_{US} and H_{DS}.

With the same initial head, the submergence of structures tends to reduce the variation in discharge, therefore reducing the sensitivity compared with a structure with free flow.

FIGURE A2.1

Flow through an irrigation structure with different downstream conditions
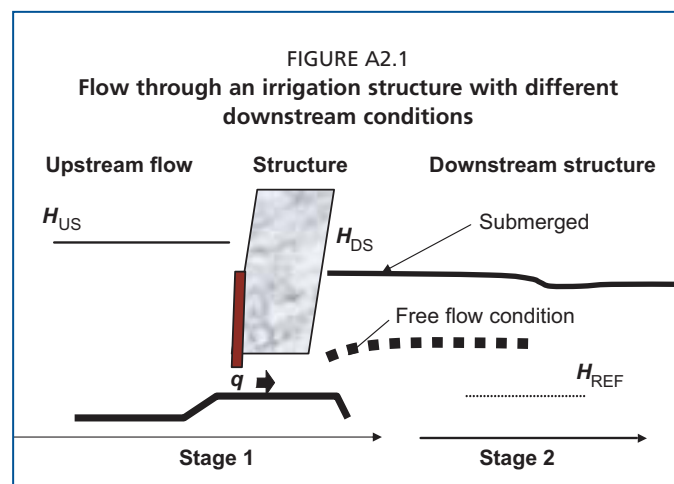
The exact computation requires two equations to be considered – one through the structure itself, and one for the flow regime immediately at the downstream side of the structure.

The general governing equations of flow through an open-channel structure are:

$$q = a A (H_{US} - H_{DS})^{\alpha} \qquad \text{Stage 1} \qquad (3)$$

$$q = a'b (H_{DS} - H_{REF})^{\beta} \qquad \text{Stage 2} \qquad (4)$$

where:

➢ A = flow section parameter through the structure (A = area through the orifice for an undershot flow, and A = the crest length for an overshot flow);
➢ a = discharge coefficient equal to $c(2g)^{0.5}$;
➢ c = flow coefficient function of the shape of the flow ($c \approx 0.5$ for an orifice);
➢ a' & b = hydraulic parameters of the second stage law;
➢ α, β = exponent equal to 1/2 for undershot flow, to 3/2 for overshot, and about to 1.6 for normal flow;
➢ H_{US} = water level upstream of the structure;
➢ H_{DS} = water level downstream of the structure;
➢ H_{REF} = a reference level depending on the downstream flow conditions;
➢ q = discharge through the structure.

H_{REF} is a constant reference level taken at: (i) the crest level of the weir where there is a measurement weir; or (ii) a reference level (bottom bed or a crest level) further down conditioning the flow at the structure (Table A2.1). It is assumed that $dH_{REF} = 0$.

Free-flow conditions

Under free-flow conditions at the offtake, Stage 2 (Equation 4) is irrelevant and the problem reduces to one equation, i.e. Equation 3. Then, H_{DS} is taken either as the crest level of the weir in the case of overshot, or as the orifice axis in the case of undershot.

Solution for the general case with submerged conditions

In a general case, rewriting Equations 3 and 4 produces:

$$\left(\frac{q}{aA}\right)^{1/\alpha} = H_{US} - H_{DS} \qquad (5)$$

and

$$\left(\frac{q}{a'b}\right)^{1/\beta} = H_{DS} - H_{REF} \qquad (6)$$

Adding Equations 5 and 6 yields:

$$\left(\frac{q}{aA}\right)^{1/\alpha} + \left(\frac{q}{a'b}\right)^{1/\beta} = H_{US} - H_{REF} \qquad (7)$$

TABLE A2.1
Conditions of flow and reference to be considered in calculations

Specific conditions	H_{REF}	2nd equation	α	β
Undershot free flow	Orifice axis	Not needed	0.5	no
Overshot free flow	Crest level of the weir	Not needed	1.5	no
Undershot submerged by a downstream measurement weir	H crest of the measurement weir	Needed	0.5	1.5
Undershot submerged normal uniform flow	H bed bottom of the downstream canal section	Needed	0.5	1.66

Then, taking the logarithm derivative with respect to the variable H_{US} gives:

$$\frac{1}{\alpha}\left(\frac{q}{aA}\right)^{\frac{1}{\alpha}-1}\left(\frac{\partial q}{\partial H_{US}}\right)+\frac{1}{\beta}\left(\frac{q}{a'b}\right)^{\frac{1}{\beta}-1}\left(\frac{\partial q}{\partial H_{US}}\right)=\frac{\partial(H_{US}-H_{REF})}{\partial H_{US}} \qquad (8)$$

From this can be derived, given that $dH_{REF} = 0$:

$$dH_{US} = \left|\frac{q^{\frac{1}{\alpha}-1}}{\alpha[aA]^{\frac{1}{\alpha}}}+\frac{1}{\beta}\frac{q^{\frac{1}{\beta}-1}}{[a'b]^{\frac{1}{\beta}}}\right|dq \qquad (9)$$

which can be rewritten as:

$$dH_{US} = \left[\frac{q^{\frac{1}{\alpha}}}{\alpha[aA]^{\frac{1}{\alpha}}}+\frac{1}{\beta}\frac{q^{\frac{1}{\beta}}}{[a'b]^{\frac{1}{\beta}}}\right]\frac{dq}{q} \qquad (10)$$

Replacing Equations 3 and 4 leads to:

$$dH_{US} = \left[\frac{1}{\alpha}(H_{US}-H_{DS})+\frac{1}{\beta}(H_{DS}-H_{REF})\right]\frac{dq}{q} \qquad (11)$$

which can be rewritten as:

$$dH_{US} = \frac{H_E}{\alpha}\frac{dq}{q} \qquad (12)$$

by introducing the term of head-loss equivalent (H_E):

$$H_E = (H_{US}-H_{DS})\left[1+\frac{\alpha}{\beta}\frac{(H_{DS}-H_{REF})}{(H_{US}-H_{DS})}\right] \qquad (13)$$

The head-loss equivalent, H_E, of a particular structure is equal to the head loss through the structure corrected by a factor expressing the influence of the submergence (Table A2.2).

A robust first approximation of sensitivity indicators, considering H_E = head, is:

$$\text{Approx.} \quad H_E = Head = (H_{US}-H_{DS}) \qquad (14)$$

$$S_{Offtake} = \frac{\alpha}{H_{US}-H_{DS}} \qquad (15)$$

$$S_{Regulator} = \frac{H_{US}-H_{DS}}{\alpha} \qquad (16)$$

Offtake sensitivity

Depending on the type of offtake and the head exercised on it, sensitivity varies between low and very high values. With low-sensitive offtakes, the distribution of water is not affected by perturbations that are passing downward.

In a system aiming at delivering specific service to users (discharge), it is generally desirable that the offtakes be low-sensitive. For a system that is based on proportional distribution, a low sensitivity is not desirable, and the sensitivity of the offtake should be adjusted with that of the cross-regulator in order to have a flexible indicator of 1 at partition points.

TABLE A2.2
Expression of sensitivity indicators

S diversion (offtake)	$S = \dfrac{dq}{q\,dH_{US}} = \dfrac{\alpha}{H_E}$
For S control level (regulator)	$S = \dfrac{dH_{US}}{(dq/q)} = \dfrac{H_E}{\alpha}$
H_E	$H_E = (H_{US}-H_{DS})\left[1+\dfrac{\alpha}{\beta}\dfrac{(H_{DS}-H_{REF})}{(H_{US}-H_{DS})}\right]$

TABLE A2.3
Ranking of sensitivity for an offtake

Offtake	Sensitivity indicator	Example
Highly sensitive	Greater than 2	Overshot type offtake
		Undershot type with very low head (0.25 m or less)
Medium-sensitive	Between 1 and 2	Undershot type with head between 0.25 and 0.5 m
Low-sensitive	Below 1	An undershot gated structure fed with head > 0.5 m
		Specific modulated structure (baffle see below)

In some case along a gated system, it might be useful to have some highly sensitive offtakes for the purpose of diverting the surplus or compensating the deficit.

Offtake sensitivity might vary, as summarized in Table A2.3.

An example of low-sensitive offtakes
Neyrpic distributors (baffles) are designed to control discharge when available head is low and variable. The control is obtained by changing flow regimes. At low head, the regime is overshot free flow on the sill. For greater head, baffles create undershot orifice-type flow regimes with contracted veins.

In the example of the baffle distributor shown in Figure A2.2, the discharge is controlled within 10 percent for water level fluctuating between 13.5 and 28 cm above the sill level. Thus, the sensitivity is equal to S_{Baffle} = 0.1/(0.28 - 0.1345) = 0.68, which is quite low.

A classic undershot offtake placed in the same situation would have experienced sensitivity as follows: S = 0.5/(average head) = 0.5/0.2 = 2.5.

Factors affecting offtake sensitivity: head/water level in the main canal
The sensitivity of a structures depends, as a first approximation, on the head exerted on it. This may vary as a function of the operation regime of the canal (average height in the parent canal) and of some interventions on the structures.

For example, in Sri Lanka, a canal that was originally of very low sensitivity has started to have chaotic operation as a result of the combined effects that have increased the sensitivity from 0.5 to 3. The first of these effects is related to the systematic construction of the gauging weir downstream the offtakes, and this has resulted in raising the water level by about 40 cm, and moved the average sensitivity to approximately 2.

FIGURE A2.2
Operation curve of a Neyrpic distributor and an estimate of its sensitivity

$$S = \frac{\Delta Q / Q}{H}$$

ΔH= (28 - 13.5) = 14.5

S = 0.05/0.145 = 0.34

Offtake orificie type with same elevation S = 0.5/0.2 = 2.5

Δq/q] = 0.05

FIGURE A2.3

Evolution of sensitivity vs the average level of the water observed in a canal (Sri Lanka), difference between the nominal value (FSD) and the observed median value

Sensitivity indicator (m^{-1}) vs Hus (m)

Median

FSD

The second effect is a subregime operation of the parent canal (median height of the water level in the main canal 10 cm lower with respect to the nominal value full supply depth [FSD]), and this further reduces the average head available at the offtakes. Thus, the average sensitivity has moved to 3.

The effect of the water line in the canal on the sensitivity indicator is illustrated in Figure A2.3.

A similar case of increased sensitivity caused by the construction of a measurement weir has been found in the Sunsari Morang Irrigation System.

Regulator sensitivity

Cross-regulators are irrigation structures controlling the water depth along a canal, by adjusting local head losses (Figure A2.4). The degree of control and the magnitude of variation in water depth between zero and full discharge vary with the type of structure. For example, a fixed weir has no control on water depth, but the magnitude of the resulting variation with respect to discharge change is very low. Inversely, gated regulators have a high control level, but where managed improperly the magnitude of variation in water depth can be high.

For cross-regulators, the distinction between delivery and conveyance makes no sense. However, both the upward effect as well as the downward effect have to be considered.

FIGURE A2.4

Orifice-type regulator

$S = 2 (H_{US} - H_{DS})$

H_{US}

H

Submerged

Free flow

H_{REF}

$$S = \frac{\Delta H}{\Delta Q / Q}$$

$S = 2 (H_{US} - H_{REF})$
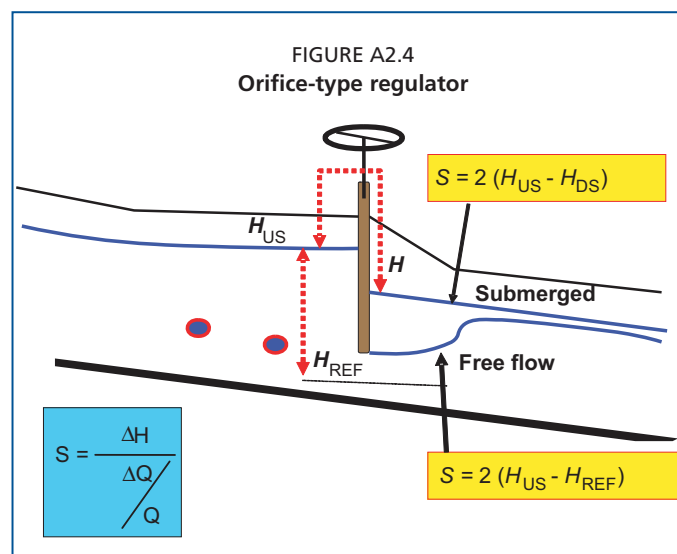
Downward cross-regulator sensitivity

The equations governing the flow of a regulator are those presented earlier (Table A2.1):

$$S = \frac{H_E}{\alpha} \tag{17}$$

In the case of a free orifice, H_E is equal to the difference between the upstream level H_{US} and the axis of the opening below the gate ($H_{REF} = H_{OR}$). In general, the regulators are submerged downstream, and the difference in head to be considered is the value of H_E in its complete formulation (Equation 13).

For an orifice-type structure, $\alpha = 0.5$ and thus:

$$S = 2.H_E \tag{18}$$

The orifice-type regulators are generally equipped with gated offtakes, and their control function is obtained by operating these gates.

For an overshot-type structure, $\alpha = 3/2$ and thus:

$$S = 2/3.h \tag{19}$$

with h the height of the flow on the crest.

The case of a weir-type level regulator (duck-bill)

A duckbill-weir-type regulator is a low-sensitive regulation structure. By design, its function is to transform an important variation in the flowing discharge into a close variation of the flow height, without any intervention on the work.

Assuming a free weir (with no influence downstream), the overshot-type flow equation is:

$$Q = c.\ L_c.\ [h]^{3/2} \tag{20}$$

where:

➢ c = flow coefficient on the weir depending on the shape of the crest ($c \approx 1.5$–1.7);
➢ L_c = length of the crest;
➢ h = water head on the weir (measured at a given distance upstream of the weir);
➢ Q = discharge flowing on the weir.

From the logarithm derivative expression of Equation 20, it is possible to determine the sensitivity indicator, which is equal to:

$$S = 0.66\ h \tag{21}$$

With h limited to 0.5 m, then $S < 1/3$.

Duck-bill weir sensitivity

$S = \dfrac{\Delta H}{\Delta Q / Q}$

$Q = c.\ L_c.\ [h]^{3/2}$

$S = 2/3\ h$

with h limited to 0.5 m the S < 1/3
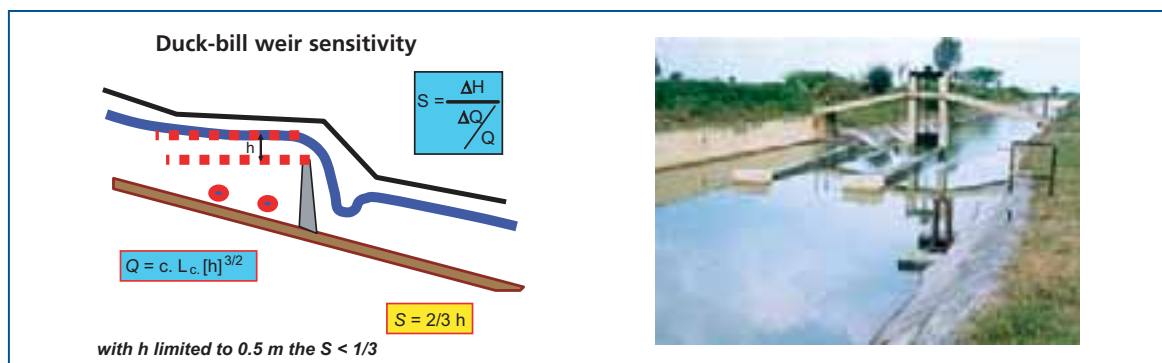
Cross-regulator interference

Regulators are often submerged downstream. A first approach that neglects submergence gives a preliminary indication on sensitivity based on the difference in head between upstream and downstream.

A difficulty in the vicinity of regulators can result from their mutual interference. The control point downstream of a regulator is sometimes the next regulator located downstream. Therefore, the flow condition downstream of a regulator may depend on the variations in regulations and the sensitivity of the next regulator.

Regulators that intrinsically are not sensitive may become so when influenced. This means that, taken independently, they react poorly in height upon a change in discharge. However, where situated in the backwater curve of a very sensitive downstream regulator, they might ultimately react by transforming the level variation downstream of them (ΔH_{DS}) into level variation upstream (ΔH_{US}).

FIGURE A2.5
Downstream influence of sensitive regulator on upstream regulators

In the example presented in Figure A2.5, the perturbation wave initially moves down the canal and crosses Regulators 1 and 2 (low-sensitive) without causing large variations in the height of the water level upstream. However, at Regulator 3 (very sensitive), a strong variation in the height of the water level upstream is generated, and this rises up along the canal so much as to provoke a similar variation in magnitude at Regulators 2 (first) and 1 (later).
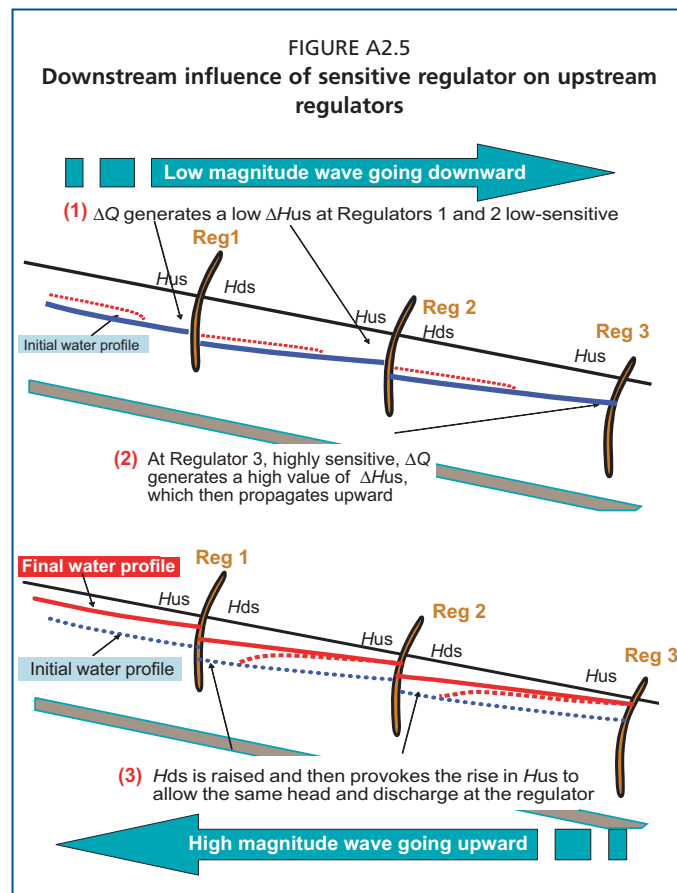
The direct measurement of sensitivity

For an offtake, the direct measurement consists in generating a variation in the water level in the parent canal, and measuring the resulting variation in discharge at the offtake. Thus, the indicator is given by the direct formula of Equation 1.

For a level regulator, the measurement is the opposite: generate a discharge variation in the main canal and measure the resulting one on the head upstream of the regulator; the indicator is thus equal to that given by Equation 2.

Influence of downstream submergence of the structure on sensitivity

The exact expression of the hydraulic formulations of indicators involves the back-effect of submergence on sensitivity through the expression H_E (Equation 13). With a similar head (upstream–downstream difference), submergence tends to reduce the sensitivity of the structure compared with a free-flow structure.

For offtake structures, this effect can initially be neglected by calculating the simple indicator (Table A2.2) with the difference in head ($H_{US} - H_{DS}$). Only the structures with a high sensitivity indicator (> 1.5) have to be calculated more exactly, taking into account the submergence effect.

Data processing of the recorded heights

Processing of frequently recorded data of the heights H_{US} and H_{DS} of the discharges, enables their evolutions to be estimated. Provided there is no change in the regulation of the opening of the gate, it is also possible to infer the operation law of the work. In particular, it is then possible to determine empirically the hydraulic laws of Stage 2 (inlet of the downstream canal), which are difficult to define, and identify the values for H_{REF} and for β. The calculation of the indicator is then made, starting from the hydraulic formulations.

Accuracy in assessing behaviour of canal structures

For capacity assessment of static characteristic such as transit capacity, a high degree of accuracy is required. However, for behaviour, a low degree of accuracy is sufficient.

It is necessary to know whether the sensitivity of the part of the system, subsystem reach or single structure under consideration is: very low, low, medium high, or very high. Therefore, knowing these parameters to within plus or minus 25 percent is acceptable.

AGGREGATED CHARACTERISTICS AT REACH AND SUBSYSTEM LEVEL

The sensitivity study of the offtakes and regulators is important as such for understanding the behaviour of the structures. However, it is even more important to examine the offtake–regulator combination. In fact, a sensitive offtake may cause no problems where a performing regulator controls it. However, an inefficient level regulator that generates important head variations in the canal can affect a low-sensitivity offtake.

The combined sensitivity of regulators and offtakes

Under the influence of an entering variation in discharge (ΔQin), a reach will react by absorbing a fraction of the flow change through its offtakes and by propagating the remaining part after the flow stabilizes. The balance between absorption and propagation is an indicator of the reach behaviour that managers are interested in.

A simple case of an offtake–regulator couple

Figure A2.6 shows an example that considers a reach as the pool between two regulators and a perturbation entering (ΔQin). After a period of transition caused by the variation in water level within the reach, the entering perturbation will be equal to the fraction absorbed by the reach itself and diverted at the offtake (ΔQdel), and that transmitted downwards at the downstream regulator(ΔQout). The share between the two parts depends on:

➢ the regulator sensitivity reflected through the variation in water depth (ΔH_US);
➢ the sensitivity of the offtakes within the reach;
➢ the ratio of discharge withdrawn within the reach compared with the main discharge.

The system can be analysed in a number of steps. First, a perturbation (ΔQin) entering the reach upstream results in a variation of water level within the reach (ΔH), which depends on both regulator and offtake sensitivities. For example, if (ΔQin) is

FIGURE A2.6
Sketch of a reach with downstream associated structures: regulator and offtake
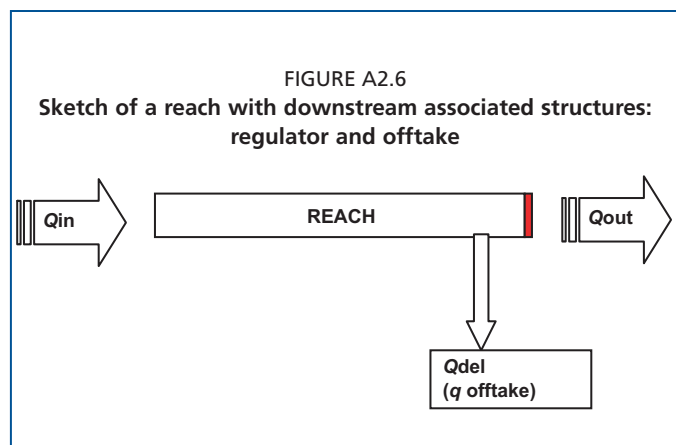
positive, then the water level will rise, causing an increase in the diverted flow at the offtake (ΔQdel) as well as at the regulator (ΔQout). The situation stabilizes when the perturbations compensate each other, i.e.:

$$\Delta Qin = \Delta Qdel + \Delta Qout \qquad (22)$$

At the regulator, the sensitivity equation is:

$$S_{reg} = \frac{\Delta H}{\Delta Q_{out} / Q_{out}} \qquad (23)$$

from which the value of ΔQout can be extracted.

$$\Delta Q_{out} = \frac{Q_{out}\,\Delta H}{S_{Reg}} \qquad (24)$$

Similarly, the offtake under the influence of the regulator will experience a variation in head corresponding to ΔH, which will then be converted into a variation in discharge (ΔQdel), which depends on the offtake sensitivity:

$$S_{Offtake} = \frac{\Delta Q_{del} / Q_{del}}{\Delta H} \qquad (25)$$

from which the value of ΔQdel can be extracted.

Replacing the calculated values of ΔQdel and ΔQout in the balance equation (Equation 22), allows the implicit value of *ΔH* to be resolved:

$$\Delta H = \left[\frac{\Delta Qin}{S_{Offtake}Q_{del} + \dfrac{Q_{out}}{S_{Regulator}}}\right] \qquad (26)$$

This value is then used in Equations 23 and 25 to compute the variation in discharge that is absorbed ΔQdel and that which is propagated ΔQout.

Defining the reach sensitivity for delivery, S_{RD}, as the ratio of perturbation absorbed, ΔQdel, vs that entering, ΔQin:

$$S_{RD} = \frac{\Delta Q_{del}}{\Delta Q_{in}} \qquad (27)$$

then replacing ΔQdel and ΔQin from their expression in Equations 25 and 26 leads to S_{RD} as:

$$S_{RD} = \frac{Q_{del}}{Q_{in}} S_{Offtake} S_{Regulator} \left[\frac{1}{1 + \left(S_{Offtake}S_{Regulator} - 1\right)\dfrac{Q_{del}}{Q_{in}}}\right] \qquad (28)$$

and for a diverted value *q* (or Qdel) that is small compared with Qin, an acceptable simplification of the above exact solution is:

$$S_{RD} = \frac{Q_{del}}{Q_{in}} S_{Offtake} S_{Regulator} \qquad (29)$$

The sensitivity for delivery in a reach depends on the product of the sensitivity indicators of the two structures and the weight of the withdrawal *q/Q* [Qdel/ Qin] within the reach.

This S_{RD} indicator can sometimes help in understanding the behaviour of canals under perturbation.

FIGURE A2.7
Aggregation of offtakes of the same reach
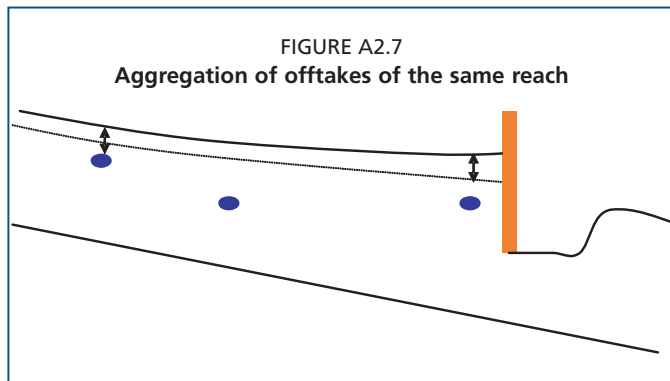
Aggregation for offtakes within a reach

The simple case described above is for an offtake controlled by a nearby regulator. In reality, it is often necessary to consider more than one offtake, and also the fact that some offtakes might not be close to the regulator (Figure A2.7) and, therefore, experience a reduced control and variation in water depth from the regulator.

In the general case, it thus assumed that the pool between two consecutive hydraulic control cross-structures serves "n" offtakes, which in the general case do not have the same values for sensitivity and discharge.

As with the case described above, ΔQin entering the reach will be partitioned into ΔQdel and ΔQout for which it is possible to use the same balance and flow-deviation equations (Equations 22 and 24).

It is then necessary to aggregate the diverted deviation at the offtakes. At each offtake of the reach, the diverted perturbation can be described as a function of the sensitivity and the deviation of water level, ΔH_i:

$$\Delta q_i = q_i \, S_{Offtake}(i) \Delta H_i \tag{30}$$

Then, the total deviation of discharge delivered ΔQ_{del} within the reach is computed by summing the offtake deviations:

$$\Delta Q_{del} = \sum_{i=1}^{n} q_i \, S_{Offtake}(i) \, \Delta H_i \tag{31}$$

If the offtakes are relatively close to the regulator, then the variation in water level experienced should be assumed constant and equal to the one at the regulator, ΔH. In this case, the equation simplifies to:

$$\Delta Q_{del} = \Delta H_{Reg} \sum_{i=1}^{n} q_i \, S_{Offtake}(i) \tag{32}$$

However, for more distant offtakes, the deviation in water depth will be only a fraction of that experienced at the regulator. In this case, it can be easily introduced a fixed parameter [0,1] for each offtake assuming that the change in water depth at the location of Offtake(i) [$\Delta H_{Offtake}(i)$] is linearly related to the change occurring at the downstream cross-regulator [ΔH_{Reg}, controlling the reach through a parameter m_i. This means:

$$\Delta H_{Offtake}(i) = m_i \Delta H_{Reg} \tag{33}$$

The coefficient m_i varies with ongoing discharge, but is relatively independent of usual water depth deviations. It can be considered as a site-specific parameter ($0 < m_i < 1$), and constant for each offtake within a limited range of discharge variation. Its value depends on the position of the point along the backwater curve and has to be determined by hydraulic computation or experimental measurements. Values of m_i range between 1 for offtakes close to a regulator and 0 for offtakes fed by a canal section under normal flow. For the latter, the offtake is still experiencing a water depth variation as a result of the change in the normal flow conditions.

The linear approximation, expressed in Equation 33, has been validated using computational outputs of hydraulic simulations in typical conditions of Sri Lanka. It

is also supported by the outputs of a study by Strelkoff *et al*. (1998) on the steadiness of the backwater curves once put into non-dimensional form.

Sensitivity and performance

Sensitivity is an indicator of how structures react when they are left unattended – the higher the sensitivity, the faster and higher the reaction. This has consequences on performance. Sensitive delivery structures tend to deviate from their initial setting. Assuming that this initial setting is the perfect target for the discharge, it is then possible to estimate the consequences of deviation in terms of performance.

In general, the overall objective in controlling a canal is to maintain a constant head on the upstream side of the delivery structures (offtakes – outlets) in order to maintain the required discharge within permissible limits. The control of the head in a canal is enabled by cross-structures, also called cross-regulators, at strategic points along the canal. The extent and the magnitude of control exercised by a particular cross-structure depends both on its property in controlling local water depth (precision) and on the extension (influence) of the backwater curve effect within the controlled reach (upstream in most cases). Therefore, the efficacy of any particular control structure and, by extension, of an entire system, can be expressed through two concepts: precision and influence.

Precision is a parameter under the control of the manager. The precision exerted by the operator can be assessed through the fluctuation in water depth (ΔH_R) experienced at the regulator. Influence is a more permanent property and depends on the density of control structures and the hydraulic characteristics of the canal.

Other structures, offtakes and outlets along a canal aim to deliver the targeted discharge. Their role is to convert an input, the water depth in the parent canal, into an output, a discharge series, feeding the dependent canal. For a delivery structure, the sensitivity of delivery expresses the link between a variation in water depth (ΔH_{Off}) in the parent canal and the resulting deviation in discharge (Δq) in the dependent canal. A highly sensitive structure generates high changes in discharge for slight deviations in water depth and vice versa.

By manipulating the control structures along the canal, managers attempt to reach and maintain a water profile close to the target, to achieve a given level of performance. Thus, assessing the performance of operation can be formalized in a conceptual relationship:

$$PERFORMANCE = Function \left[\begin{matrix} SENSITIVITY \\ of\ delivery\ structures \end{matrix} \quad and \quad \begin{matrix} CONTROL \\ on\ water\ depth \end{matrix} \right]$$

The objective here is to establish and validate analytical relationships between internal performance indicators related to the quality of the water service (performance), the physical properties of delivery structures (sensitivity), and the level of control (control) exercised on the water depth along the parent canal.

Adequacy and efficiency under uniform precision

For local relationships, given an offtake with an initial discharge corresponding to the target, the consequences of a perturbation in water depth ($\Delta H_{Off(i)}$) in the parent canal can be examined in terms of the discharge variation (dq_i) at the offtake. For the perturbed state, the performance indicator for adequacy is:

$$p_{A(i)} = \frac{q_i + dq_i}{q_i} = 1 + \frac{dq_i}{q_i} \qquad \text{(if } dq_i \text{ is negative, and 1.0 otherwise)} \qquad (34)$$

The performance indicator for efficiency is, in the same way, derived as:

$$p_{F(i)} = \frac{q_i}{q_i + dq_i} \qquad \text{(if } dq_i \text{ is positive and 1.0 otherwise)} \qquad (35)$$

which simplifies to:

$$p_{F(i)} = 1 - \frac{dq_i}{q_i} \tag{36}$$

The sensitivity for delivery for Offtake(i) is derived from Equation 1 as:

$$S_{(i)} = \frac{dq_i / q_i}{\Delta H} \tag{37}$$

which replaced in Equation 34 leads to the following local relationship:

$$P_{(i)} = 1 \pm \Delta H_{Off(i)} S_{(i)} \qquad \left(P_{(i)} \leq 1.0 \right) \tag{38}$$

In Equation 38, the minus sign applies for adequacy when ($\Delta H_{Off(i)}$) is positive and the plus sign applies for efficiency when ($\Delta H_{Off(i)}$) is negative. Equation 38 expresses explicitly the link between the adequacy or efficiency performance indicator, the sensitivity and the control exercised on the water depth at the local level.

For aggregated relationships, the objective is to derive a similar relationship to Equation 38 at an aggregated level to enable the performance of subsystems, or even whole systems to be compared considering a uniform precision (ΔH_R). A particular assumption has to be made regarding the way the deviations in water depth affect the system. It is proposed here to refer to a system where positive and negative deviations are fully balanced. Thus, this assumption is called the varied sign perturbation (+/- ΔH_R). Another possible option is to consider a constant sign perturbation (ΔH_R) at every regulator (either + or -).

The aggregation process, with varied sign perturbations, corresponds to the fully balanced system. Therefore, it is assumed that the number of offtakes (n) of the unit considered can be regrouped into two similar subsets of ($n/2$) offtakes. The similarity between the two subsets is based on the discharge delivery and the sensitivity of the offtakes. Reaches of one subset experience a positive perturbation ($+\Delta H_R$), while the others experience a negative one ($- \Delta H_R$), making a balance in the global discharge.

Performance indicators for adequacy and efficiency, as defined by Molden and Gates (1990), are aggregated here using a weighted process, the weight, k_i, being the relative offtake discharge

$$q_i \bigg/ \sum_{j=1}^{n} q_j$$

Only instantaneous values are considered in this estimation and the performance for the whole system is the sum of the two subset indicators derived from Equation 38, as follows:

$$P = \sum_{i=1}^{n/2} k_i \left(1 - \Delta H_R S_{(i)} \right) + \sum_{i=n/2+1}^{n} k_i \tag{39}$$

For adequacy, the first term in Equation 39 corresponds to the set of underfed offtakes, and the second term corresponds to the set of overfed offtakes. For efficiency, the first term corresponds to overfed offtakes, and the second term to underfed offtakes. Knowing that the sum of the weights k_i over the whole set is equal to 1, by definition, and including Equation 33 in Equation 39, leads to:

$$P = 1 - \Delta H_R \sum_{i=1}^{n/2} k_i m_i S_{(i)} \tag{40}$$

Assuming a similarity in discharge and sensitivity of the two subsets of offtakes enables the rewriting of Equation 40 as:

$$P = 1 - \frac{1}{2} \Delta H_R \sum_{i=1}^{n} k_i m_i \, S_{(i)} \tag{41}$$

Equation 41 has been established for a varied sign perturbation with a perfect initial state. It can also be shown, by a similar computation, that this relationship (Equation 41) holds true with any initial state $P_{(o)}$, under the restriction that no offtake switches from one condition to the other (overfed/underfed); in that case $P_{(o)}$ replaces 1 in Equation 41.

Equation 41 states the relationship between performance, the precision and influence of control, and the sensitivity of delivery structures along the canal. A system sensitivity indicator (S_s) can then be proposed for adequacy and efficiency as follows:

$$S_S = \sum_{i=1}^{n} k_i \, m_i S_{(i)} \tag{42}$$

and the performance indicator (Equation 41) is written:

$$P = 1 - \frac{1}{2} \Delta H_R \, S_S \tag{43}$$

For subnetworks, it is possible to define sensitivity indicators that enable better linking of the performance of the water service, the efficiency in the control of the water height and the sensitivity indicators, aggregated at the subnetwork level:

$$S_S = \sum_{i=1}^{n} k_i \, m_i S_{(i)} \tag{44}$$

where:

- k_i = contribution of the offtake to the whole set (weight), equal to $1/n$ if the weight is identical for each offtake, or to $q_i/\Sigma q_i$ for weighting by discharge;
- m_i = indicator of the regulator control on the offtake, $m_i = 1$ when the offtake is very close to the regulator, and becomes zero when the offtake is far from it.

The performance expected from an irrigation system is the product of two terms: the capacity of control on water depth (tolerance on water depth H), and the system sensitivity. This allows managers to estimate the control to exercise [tol.(H)] given the performance required for the service and the physical properties of the system. Different global sensitivity indicators at system level have been developed (Renault, 1999) for adequacy, efficiency and equity performance.

The performance for adequacy and efficiency is related to the precision and influence of control. A system sensitivity indicator along the canal can be proposed as follows:

$$P = 1 - \frac{1}{2} \Delta H_R \, S_s \tag{45}$$

in which S_s is a system sensitivity indicator, equal to:

$$S_S = \sum_{i=1}^{n} k_i \, m_i S_{(i)} \tag{46}$$

Using the coefficient of variation approach, a system sensitivity indicator for equity (S_{se1}) can be proposed as the square root of the arithmetic mean of the product of the square of local sensitivity and the influence factor:

$$S_{Se1} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} m_i S_{(i)}^2} \tag{47}$$

This global sensitivity indicator is related to the performance equity indicator by the following equation:

$$P_E = \Delta H \, S_{Se1} \tag{48}$$

For the analysis based on the Theil index, a system sensitivity indicator for equity (S_{se2}) can also be proposed as:

$$S_{Se2} = \sum_{i=1}^{n} \frac{q_i}{Q_D} m_I^2 S_{(i)}^2 \tag{49}$$

This system indicator is related to the system performance equity indicator by the following relationship:

$$Thi = \frac{1}{2} (\Delta H_R)^2 S_{Se2} \tag{50}$$

Table A2.4 summarizes the sensitivity indicators discussed in this annex.

TABLE A2.4
Summary of sensitivity indicators

Structure	Variable studied	Definition	Geometric formulation	Approximate formula by neglecting submergence
Offtake (orifice)	Offtake discharge q as a function of the variation in the supply water surface	$S = \dfrac{\Delta q / q}{\Delta H}$	$S = \dfrac{0.5}{H_E}$	$S = \dfrac{0.5}{\text{Head}}$ The "Head" variable is the difference in head exerted on the structure ($H_{US} - H_{DS}$)
Regulator (orifice)	Water level height as a function of the flowing discharge Q	$S = \dfrac{\Delta H}{\Delta Q / Q}$	$S = 2.H_E$	$S = 2\text{Head}$ The "Head" variable is the difference in head exerted on the structure ($H_{US} - H_{DS}$)
Sill regulator	Water surface height as a function of the flowing discharge Q	$S = \dfrac{\Delta H}{\Delta Q / Q}$	$S = 0.66\,h$ h = water head on the crest	
Canal section	Height of the water level as a function of the flowing discharge Q	$S = \dfrac{\Delta H}{\Delta Q / Q}$	S is variable between 0.5 and 0.8 D according to the geometry of the canal (D = flowing height)	$S = \frac{3}{5} D$ for a very large rectangular canal
Divider	Relative value of the discharge q of the branch with respect to the inflowing discharge Q	$P = \dfrac{\Delta q / q}{\Delta Q / Q}$	$P = S_{Offtake} \cdot S_{Regulator}$	

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Annex 3
The Rapid Appraisal Process

BACKGROUND

The Rapid Appraisal Process (RAP) enables qualified personnel to determine key indicators of irrigation projects both systematically and quickly. The RAP can generally be completed within two weeks of fieldwork and office work – assuming that some readily available data on the project have been organized by project authorities in advance of the RAP.

Key performance indicators from the RAP help to organize perceptions and facts, thereby facilitating informed decisions regarding:

- ➢ the potential for water conservation within a project;
- ➢ specific weaknesses in project operation, management, resources and hardware;
- ➢ specific modernization actions that can be taken to improve project performance.

A parallel activity to the RAP is called benchmarking. As defined in preliminary documents by the International Programme for Technology and Research in Irrigation and Drainage (IPTRID), benchmarking is a systematic process for securing continual improvement through comparison with relevant and achievable internal or external norms and standards. The overall aim of benchmarking is to improve the performance of an organization as measured against its mission and objectives. Benchmarking implies comparison – either internally with previous performance and desired future targets, or externally against similar organizations, or organizations performing similar functions. Benchmarking is in use in both the public sector and the private sector.

Benchmarking incorporates various indicators, many of which are developed from the RAP. Both the RAP and the IPTRID benchmarking activity are still evolving. Therefore, the indicators in this annex will not always be identical to those in IPTRID documents. This annex also reflects current efforts by the World Bank to combine the processes.

The RAP for irrigation projects was introduced in a joint FAO/IPTRID/World Bank publication titled *Modern water control and management practices in irrigation – impact on performance* (FAO, 1999). The report provides an explanation of the RAP and also gives RAP results from 16 international irrigation projects.

The RAP makes use of a computer spreadsheet (Excel) with 12 internal worksheets. The investigators input the data collected into these worksheets.

THE RAPID APPRAISAL PROCESS

The RAP for irrigation projects is a 1–2-week process of collection and analysis of data both in the office and in the field. The process examines external inputs such as water supplies, and outputs such as water destinations (evapotranspiration, surface runoff, etc.). It provides a systematic examination of the hardware and processes used to convey and distribute water internally to all levels within the project (from the source

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to the fields). External indicators and internal indicators are developed in order to provide: (i) a baseline of information for comparison against future performance after modernization; (ii) benchmarking for comparison against other irrigation projects; and (iii) a basis for making specific recommendations for modernization and improvement of water delivery service.

The RAP has only recently been used for diagnosis of international irrigation projects. However, variations of the RAP presented here have been used since 1989 by the Irrigation Training and Research Center (ITRC) at California Polytechnic State University on dozens of irrigation modernization projects throughout the west of the United States of America.

Traditional diagnostic procedures and research tend to examine portions of a project, whether they are the development of water user associations (WUAs) or the fluctuation of flow rates in a single canal lateral. Such research projects typically require the collection of substantial field data over extended periods.

The time and budgetary requirements of such standard research procedures are significant. Kloezen and Garcés-Restrepo (1998) state that: "three engineers worked full-time for more than a year to collect primary data and make measurements to apply process indicators at the level of selected canals and fields" for just one project. Furthermore, they state that: "In addition, the work in Salvatierra was supported by an M.Sc. student...In addition, much time was spent on visiting the selected field and taking several flow measurements per field, per irrigation... Five more months were spent on entering, cleaning, and processing data." Although time-consuming research can provide valuable information about irrigation, decisions for modernization improvements must be made more quickly and must be comprehensive.

An essential ingredient for successful application of the RAP is adequate training of the evaluators. Experience has shown that successful RAP programmes require: (i) evaluators with prior training in irrigation; (ii) specific training in the RAP techniques; and (iii) follow-up support and critique when the evaluators begin their fieldwork.

An RAP will be unsuccessful if its accompanying computer spreadsheet files are merely mailed to local irrigation projects to be filled out. Evaluators must understand the logic behind all the questions, and they must learn how to go beyond the obvious when obtaining data. Ideally, if two qualified persons complete a RAP on a single irrigation project, the indicators that are computed by both persons will be very similar.

Typical baseline data for external indicators (such as water balances and irrigation efficiency) are either readily available or they are not. Individual irrigation projects have differences in the ease of access to typical baseline data on the command area (CA), weather, water supply, etc. In some projects, the data can be gathered in a day; in others, it may take weeks. Usually, the delays in data organization are related to finding the time to pull the data out of files and organizing them. If the data do not already exist, spending an additional three months on the site will not create them.

A quick and focused examination of irrigation projects can give a reasonably accurate and pragmatic description of the status of the project and of the processes and hardware that influence that status. This allows for the identification of the major actions that can be taken quickly in order to improve water delivery service – especially if the RAP is conducted in cooperation with the local irrigation authorities.

The question of what is "reasonably accurate" in data collection and computations can always be debated. Confidence intervals should be assigned to most water balance data – reflecting the reality that there are always uncertainties in data and computation techniques. In irrigation matters, studies are typically concerned about 5–10-percent accuracy ranges, not 0.5–1-percent accuracy ranges (Clemmens and Burt, 1997). The problems encountered in irrigation projects are typically so gross and obvious to the properly trained eye that it is unnecessary to strive for extreme accuracy when

attempting to diagnose an irrigation project. Furthermore, projects typically have such unique sets of characteristics that the results from a very detailed study of just a few items on one project may have limited transferability to other projects. In addition, even with very sophisticated and detailed research, it is difficult to achieve better than about 5–10-percent accuracy on some key values, such as crop evapotranspiration of irrigation water.

For the RAP, it is necessary to begin with a prior request for information that can be assembled by the irrigation project authorities – information such as cropped areas, flow rates into the project, weather data, budgets, and staffing. Upon arriving at the project, the evaluators organize these data and interview project managers regarding missing information and their perceptions of how the project functions. The evaluators then travel down and through the canal network, talking to operators and farmers, and observing and recording the methods and hardware that are used for water control. Through this systematic diagnosis of the project, many aspects of engineering and operation become very apparent.

Experience has shown that an RAP is not suitable for the collection of some economic data. Data such as the overall cost of a project, per capita income, and the size of typical farm management units were not readily available in most of the projects described in FAO (1999).

In summary, where executed properly with qualified personnel, the RAP can provide swift and valuable insight into many aspects of irrigation project design and operations. Furthermore, its structure provides a systematic project review that enables an evaluator to provide pragmatic recommendations for improvement.

Some of the data collected during an RAP are also useful in quantifying various benchmark indicators established by the IPTRID. Most of the IPTRID benchmark indicators fall into the category of "external indicators", whereas RAP indicators include both "external" and "internal" indicators. As discussed below, internal indicators are necessary for understanding the processes used within an irrigation project and the level of water delivery service throughout a project. They also help an evaluator to formulate an action plan that will eventually result in an improvement in external indicators. External indicators and traditional benchmarking indicators provide little guidance as to what must be done in order to accomplish improvement. Rather, they only indicate that things should be improved.

EXTERNAL INDICATORS FOR WATER SOURCES AND WATER DESTINATIONS
External indicators
External indicators for irrigation projects are ratios or percentages that generally have forms such as:

$$\frac{\text{Water Required}}{\text{Total Water Available}}$$

or:

$$\frac{\text{Crop Yield}}{\text{Irrigation Water Delivered to the Fields}}$$

The IPTRID benchmarking indicators fall into the category of external indicators, and the RAP also generates a long list of external indicators.

The common attribute of external indicators is that they examine inputs and outputs for a project. External indicators are expressions of various forms of efficiency, whether the efficiency is related to budgets, water or crop yields. Moreover, they only require knowledge of inputs and outputs to the project. By themselves, external indicators do not provide any insight into what must be done in order to improve performance or efficiency. The identification of what actions must be taken to improve these external

indicators comes from an examination of internal indicators, which examine the processes and hardware used within the project.

However, external indicators do establish key values – such as whether or not it might be possible to conserve water (without defining how that might be accomplished). As such, low values of external indicators often provide the justification for modernization of projects – with the anticipation that modernization or intervention will improve the values of those external indicators.

The RAP external indicators focus on items of a typical water balance. As such, values such as crop evapotranspiration, effective precipitation, and water supplies must be obtained. The primary purpose of Worksheets 1–3 in the spreadsheet that accompanies the RAP package is to estimate water-related external indicators.

Confidence intervals

A certain amount of error or uncertainty is inherent in all measurement or estimation processes. Therefore, the true or correct values for the water volumes needed to calculate terms such as "irrigation efficiency" are unknown. Estimates must be made of the component volumes, based on measurements or calculations.

In reports that provide estimates of terms such as crop yield and water balance ratios, such as "irrigation efficiency" and "relative water supply", the uncertainties associated with these estimates should be acknowledged and quantified. Otherwise, planners may not know whether the true value of a stated 70-percent efficiency lies between 65 percent and 75 percent, or between 50 percent and 90 percent.

One method of expressing the uncertainty in a single-valued estimate is to specify the confidence interval (CI) for that estimate. Where it is believed that a reasonable evaluation of data indicates that the correct value lies within 5 units of 70, then it should be stated that the quantity equals 70±5. More specifically, the essence of a CI should be illustrated as follows when discussing an estimated quantity: "The investigators are 95-percent confident that their estimate of the irrigated area in the project is within ±7 percent of 500 000 ha (between 465 000 ha and 535 000 ha)."

Statistically, a CI is related to the coefficient of variation (CV), where: CV = (mean)/(standard deviation). The "CV" has no units. In addition, CI = ±2 × CV where the CI is expressed as a fraction (%/100) of the estimated value. Stated differently, if the CI is declared to be 0.10, this means that the ±2 standard deviations cover a range of ±10 percent of the stated value.

Assuming a normal distribution of data, then in about 68 percent of cases the true value is found within plus or minus one standard deviation of the estimated value. Similarly, in about 95 percent of cases (from which comes the "95-percent confident" statement), the true value is found within plus or minus two standard deviations of the estimated value.

A logical question could be: "How confident are you of the CI that has been selected?" The answer for an RAP is: "The CI is not precise, but it nevertheless gives a good idea of the evaluator's sense for the accuracy of various values." It is better to provide a relative indication of the uncertainty in a value than it is to ignore the uncertainty and have people treat estimates as if they are absolute values.

In the RAP, the evaluator is asked to provide CI estimates for various data quantities. These CI estimates are manually entered into blank cells of Worksheet 4 (External Indicators). The computer spreadsheet then calculates automatically CI estimates for indicators that use these data.

There are two common conventions for computing the CI of a computed value (result). If two independently estimated quantities are added, the CIs are related by:

$$CI_r = \frac{\sqrt{m_1^2 CI_1^2 + m_2^2 CI_2^2}}{m_1 + m_2}$$

where:

➢ CI_r = CI of the result;

➢ CI_1 = CI of the first quantity added to form the result;

➢ CI_2 = CI of the second quantity added to form the result;

➢ m_1 = estimated value of the first quantity;

➢ m_2 = estimated value of the second quantity.

If two independently estimated quantities are multiplied together, the CIs are related by:

$$CI_r = \sqrt{CI_1^2 + CI_2^2 + \frac{CI_1^2 CI_2^2}{4}}$$

A rigorous estimate of CIs would require assigning CI values to each of the original data in the first three "input" worksheets of the computer spreadsheet used for the RAP. However, for a typical RAP, it is not worth striving for more precision than can obtained by inserting CI estimates in the "Indicator Summary" worksheet. For the convenience of the evaluator, the "Indicator Summary" worksheet automatically computes the CI_r for some pertinent quantities, utilizing various CI values provided by the evaluator.

INTERNAL PROCESSES AND INTERNAL INDICATORS

The broad goals of modernization are to achieve:

➢ improved irrigation efficiency (an external indicator);

➢ better crop yields (another external indicator, which is not used here);

➢ less canal damage from uncontrolled water levels;

➢ more efficient labour;

➢ improved social harmony;

➢ an improved environment as accomplished by fewer diversions or better-quality return flows.

In general, these goals can only be achieved by paying attention to internal details. The specific details addressed by the RAP are: (i) improving water control throughout the project; and (ii) improving the water delivery service to the users.

Therefore, Worksheets 5–11 have the following purposes:

➢ identify the key factors related to water control throughout a project;

➢ define the level of water delivery service provided to the users;

➢ examine specific hardware and management techniques and processes used in the control and distribution of water.

Many of these items are described in the form of "internal indicators", with assigned values of 0–4 (0 indicating least desirable, and 4 denoting the most desirable).

A summary of the internal indicators is found in Worksheet 12. Most of the internal indicators have subcomponents, called "subindicators". At the end of the spreadsheet, each of the subindicators is assigned a "weighting factor".

As an example of the use of internal indicators, Primary Indicator I-1 is used to characterize the actual water delivery service to individual ownership units (Table A3.1). Primary Indicator I-1 has four subindicators:

➢ I-1A. Measurement of volumes to the field;

➢ I-1B. Flexibility to the field;

➢ I-1C. Reliability to the field;

➢ I-1D. Apparent equity.

Each of the subindicators (e.g. I-1A) has a maximum potential value of 4.0 (best), and a minimum possible value of 0.0 (worst).

The value for each Primary Indicator (e.g. I-1) is computed automatically in the "Internal Indicators" worksheet by:

TABLE A3.1
Primary Indicator I-1 information

No.	Primary Indicator	Subindicator	Ranking criteria	Wt.
I-1	Actual water delivery service to individual ownership units (e.g. field or farm)			
I-1A		Measurement of volumes to the individual units (0–4)	4 – Excellent measurement and control devices, properly operated and recorded.	1
			3 – Reasonable measurement and control devices, average operation.	
			2 – Useful but poor measurement of volumes and flow rates.	
			1 – Reasonable measurement of flow rates, but not of volumes.	
			0 – No measurement of volumes or flows.	
I-1B		Flexibility to the individual units (0–4)	4 – Unlimited frequency, rate and duration, but arranged by users within a few days.	2
			3 – Fixed frequency, rate or duration, but arranged.	
			2 – Dictated rotation, but it approximately matches the crop needs.	
			1 – Rotation deliveries, but on a somewhat uncertain schedule.	
			0 – No established rules.	
I-1C		Reliability to the individual units (0–4)	4 – Water always arrives with the frequency, rate and duration promised. Volume is known.	4
			3 – Very reliable in rate and duration, but occasionally there are a few days of delay. Volume is known.	
			2 – Water arrives about when it is needed and in the correct amounts. Volume is unknown.	
			1 – Volume is unknown, and deliveries are fairly unreliable, but less than 50% of the time.	
			0 – Unreliable frequency, rate, duration, more than 50% of the time, and volume delivered is unknown.	
I-1D		Apparent equity to individual units (0–4)	4 – All fields throughout the project and within tertiary units receive the same type of water delivery service.	4
			3 – Areas of the project receive the same amounts of water, but within an area the service is somewhat inequitable.	
			2 – Areas of the project receive somewhat different amounts (unintentionally), but within an area it is equitable.	
			1 – There are medium inequities both between areas and within areas.	
			0 – There are differences of more than 50% throughout the project on a fairly widespread basis.	

1. Applying a relative weighting factor to each subindicator value. The weighting factors are only relative to each other within the indicator group; one group may have a maximum value of 4, whereas another group may have a maximum value of 2. The only factor of importance is the relative weighting factors of the subindicators within a group.
2. Summing the weighted subindicator values.
3. Adjusting the final value based on a possible scale of 0–4 (4 indicating the most positive conditions).

THE SPREADSHEETS FOR THE RAP
Table A3.2 describes the worksheets for the RAP.

GENERAL GUIDELINES FOR WORKSHEET USAGE
Names and types
The worksheet names within any Excel file are identified at the bottom of the screen. These must not be changed.

The Excel file has two general types of worksheets:

➤ Input worksheets. These worksheets request data:

TABLES A3.2
Summary of the worksheets to be compiled as part of an RAP

Worksheets in spreadsheet	Worksheet description
1. Input – year 1	For an average water year, requires input (mostly monthly) of:
	- crop names
	- irrigation water salinity
	- crop threshold ECe values
	- field crop coefficients, by month
	- areas of crops
	- water supply
	- precipitation
	- recirculation and groundwater pumping
	- special agronomic requirements.
4. External indicators (ignore these, except to input needed "CI" values)	Automatic computations of monthly and annual values of various water supply indicators. These are temporary values- except the user must input "CI" values. The final, important values can be found in the Worksheet 14 "World Bank BMTI Indicators".
5. Project office questions	Most of the data for this sheet are obtained from the project office. They include:
	- general project conditions
	- water supply location
	- ownership of land and water
	- currency
	- budgets
	- project operation, as described by office staff
	- stated water delivery service at various levels in the system.
6. Project employees	Requests information on employee training, motivation, dismissal, & work descriptions.
7. WUA	Data for WUAs that were not obtained in the "Project Office Questions" are obtained here. This requires asking questions in the project office as well as having interviews with WUAs. Questions relate to:
	- size of WUAs
	- strength of organization
	- functions
	- budgets
	- water charges.
8. Main canal	Data for the main canal, including:
	- control of flows
	- general canal characteristics
	- cross-regulators
	- general conditions
	- operation rules
	- turnouts
	- communications
	- regulating reservoirs
	- the level of service provided to the next lower level.
9. Second-level canals	Same as main canal.
10. Third-level canals	Same as second-level canals.
11. Final deliveries	Information regarding the level of water delivery service to individual ownership units, and at the last point of operation by paid employees.
12. Internal Indicators	This worksheet summarizes the internal indicators that were calculated in the previous worksheets, plus asks for input regarding a few extra indicators. Weighted category indicators are computed for groups of subindicators.
13. Benchmark Indicators	This worksheet holds intermediate calculated values. Ignore this page.
14. World Bank BMIT Indicators	This, plus Worksheet 12, provides the final summary for the exercise.

- In the first worksheet, the data are manipulated and/or used in computations on the far right-hand side of the data sheets, out of view of the input pages. (Some computations can be seen by scrolling the pages to the right.)
- In the Worksheets 5–11, a few internal computations appear vertically in line with input data.

➢ Summary worksheets. These are Worksheets 4, 12, 13 and 14. The two important ones are 12 and 14. Worksheets 4 and 12 require a limited number of input values, but their primary function is to summarize various data, computed values, and indicators.

Cell colouring and input conventions

The colour convention for the first Input – Year "x" worksheet is:
➢ Blank cell – indicates a place for data input.
➢ Shaded cell – contains a default or calculated value or an explanation, or indicates that no data entry is required. In general, any values within the shaded cells should not be changed unless one understands all of the programming.
➢ Red letters – indicate computed values.
➢ Blue values – indicate values that were transferred from elsewhere in the file. They may be computed or input elsewhere.

The colour convention for Worksheet 4. – External Indicators is:
➢ Blank cell – in the "Est. CI" column only – requires the manual input of a value.
➢ Shaded cell – indicates values that are linked to previous worksheets or are calculated within this worksheet.
➢ Red letters – indicate values computed within this worksheet.
➢ Blue values – indicate values that were transferred from elsewhere in the file.

Conventions for Worksheets 5–13 are:
➢ Blank cells with a light-lined border require input.
➢ Blank cells with a dark-lined border indicate that the value is needed, but that it requires information that may only be available at a later time.
➢ Any cell that is filled with a pattern or which is shaded should not receive input.
➢ Shaded cells contain formulas and will show the results of automatic computations.
➢ Cells with patterns are merely dividers between sections, or indicate that no data are needed.

The first input worksheet requires data for a single year, but it is important to provide data for multiple years (i.e. run the program several times with new data), because an examination of only a single year can be misleading for many projects that have wide fluctuations in climate and water supply.

WORKSHEET DESCRIPTIONS
Worksheet 1. Input – Year 1

The worksheet contains ten tables that require data, as well as various individual cells for specific information. Information requests are described below.

Before Table 1

Total project area: This is the gross project area (hectares), including fields that are supported by a project water delivery infrastructure ("command") and fields that are not supported by the infrastructure.

Total field area in the CA: This is the number of hectares that are supported by a project water delivery infrastructure. There may be some zones of this CA that never receive water because of infrastructure damage, shortage of water, etc.

Estimated conveyance efficiency for external water:

$$\text{Conveyance Efficiency} = \frac{\text{Volume of external irrigation water delivered}}{\text{Volume of external irrigation water at the source(s)}} \times 100$$

where, in this case, the "point of delivery" is where farmers take control of the water – that is, where the WUA and project authorities hand the water over. Sometimes, a turnout (offtake) represents the final point of delivery by an irrigation authority, yet that turnout supplies 100 fields. Conveyance losses include seepage, spillage, water lost in filling and emptying canals, evaporation from canals, and evapotranspiration from weeds along the canals. The conveyance efficiency includes losses that occur between the point of original diversion and the entrance to the CA, which in some cases may be many kilometres apart.

Estimated conveyance efficiency for internal project recirculation: This is the conveyance efficiency for water that originates within the project, by project authorities. That is, it includes water that the agency pumps from wells or drain ditches or other internal sources. It does not include any water that is imported into the project boundaries.

Estimated seepage rate for paddy rice: There will only be an answer here if paddy rice is grown in a project. This is the percentage of water applied to fields that goes below the rootzone of the rice. Seepage rates are often expressed in millimetres per day, in which case they must be converted to a percentage of the field-applied irrigation water. Many studies combine "seepage" together with "evapotranspiration" for rice, to arrive at a combined "consumptive use". This convention is not used in the RAP because such a combination makes it very difficult to separate evapotranspiration (which cannot be recirculated or reduced) from seepage water (which can be recirculated via wells or drains). Furthermore, such a convention ignores the fact that deep percolation is unavoidable on all crops, not only on paddy rice. Therefore, the convention would apply to all crops, not just paddy rice.

Estimated surface losses from paddy rice to drains: There will only be an answer here if paddy rice is grown in a project. This is the percentage of irrigation water applied to fields, or groups of fields, that leaves the fields and enters surface drains. This does not include water that flows from one paddy into another paddy unless it ultimately flows into a surface drain.

Estimated field irrigation efficiency for other crops: This is an estimate for non-rice crops. The elements of inefficiency for paddy rice (deep percolation and surface runoff losses) have already been dealt with. The term "irrigation efficiency" has a rigorous definition (Burt *et al.*, 1997). However, the nature of an RAP is such that the values required for the rigorous application of the definition will not be available. Therefore, for the purposes of the RAP:

$$\text{Field Irrigation Efficiency} = \frac{\text{Irrigation Water Used for ET and Special Practices}}{\text{Irrigation Water Applied to the Field}} \times 100$$

where:

➢ The only water considered in the numerator and denominator is "irrigation" water. Water from precipitation is not included as this indicator is a measure of how efficiently irrigation water is used.

➢ "Special practices" include water for leaching of salts, land preparation, and climate control. However, for each of these categories, there is an upper limit on the amount that is accepted as beneficial use (and that can be included in the numerator). The RAP computations include an estimate of actual leaching requirement needs. The water assigned for land preparation for rice should not include excess deep percolation (caused by holding water too long on a field) or water that flows off the surface of a field.

➢ For crops such as rice, which are often farmed as a unit that includes several fields that pass water from one field to another, "field" efficiency can be based on the larger management unit of several smaller field parcels.

In general, this value is a rough estimate. The spreadsheet computes a correct value of "field irrigation efficiency" in Worksheet 4. External Indicators (Indicator No. 31), which should be compared against this assumed value. This value is only used for one purpose in the spreadsheet: to estimate the recharge to the groundwater from field deep percolation. If, upon completion of the RAP, this estimate is different from the computed estimate, the RAP user should adjust this assumed value (and/or the rice deep percolation and surface runoff values) until Indicator 2 approximately equals Indicator 31.

Flow rate capacity of the main canal (or canals) at diversion point (or points): This value should reflect the sum of the actual (as opposed to "design") maximum flow rate capacities from each diversion point. Sometimes, the actual capacities are higher than the original design capacities, and in other cases they have been reduced owing to siltation or other factors.

Actual peak flow rate into the main canal (or canals) at the diversion point (or points): The purpose of this question is to define the maximum flow rate of irrigation water that enters the project boundaries. It should not include any internal pumping or recirculation of water.

Average salinity (ECe) of the irrigation water: Where possible, this "average" should be the annual weighted average, based on the salt load (ppm × flow rate × time). It should be computed as a combination of the well water and surface water.

Table 1 – Field coefficients and crop threshold ECe
Water Year Month
The table provides 12 cells at the top of the Field Coefficient section into which the names of all 12 months are to be placed. Although the table could have had a default month of "January" in the first cell, many projects have "water years" that begin at other months, such as April in Southeast Asia, or October or November in Mexico. Place the appropriate month in the highlighted empty cell in order to begin the water year accounting.

Irrigated Crop Name
This column allows the user to input the names of the irrigated crops in the CA. A total of 17 crops are allowed, although the first three are already assigned to "Paddy Rice", leaving 14 other names blank for the user. A CA may have more than 17 crops. However, many of these crops have small areas of cultivation, and for practical purposes they can be lumped together as a single crop category. Where a crop is double-cropped, then that crop name should be entered twice. The table already has default names for three paddy rice crops, because so many projects have three or more rice crops per year. It is not possible to override the paddy rice crops; it is not possible to substitute other names for these 3 entries because certain computations assume rice in these cells. Crop names only need to be entered once – in Table 1. They are automatically carried into all other tables that require crop names. This ensures consistency between tables.

Salinity
There are two values for salinity:
➢ Average irrigation water salinity (ECw), dS/m. The average salinity of the irrigation water that comes into the project. The units of dS/m are equivalent to mmho/cm.
➢ Threshold ECe, dS/m. This is the salinity of a saturated soil-paste extract at which

TABLE A3.3
Salt tolerance of various crops to soil salinity, after germination

Crop	Threshold ECe (ECe at initial yield decline) dS/m	Crop	Threshold ECe (ECe at initial yield decline) dS/m
Alfalfa	2.0	Onion	1.2
Almond	1.5	Orange	1.7
Apricot	1.6	Orchard grass	1.5
Avocado	1.3	Peach	1.7
Barley (grain)	8.0	Peanut	3.2
Bean	1.0	Pepper	1.5
Beet, garden	4.0	Plum	1.5
Bermuda grass	6.9	Potato	1.7
Broad bean	1.6	Rice, paddy	3.0
Broccoli	2.8	Ryegrass, perennial	5.6
Cabbage	1.8	Sesbania	2.3
Carrot	1.0	Soybean	5.0
Clover	1.5	Spinach	2.0
Corn (forage and grain)	1.8	Strawberry	1.0
Corn, sweet	1.7	Sudan grass	2.8
Cowpea	1.3	Sugar beet	7.0
Cucumber	2.5	Sugar cane	1.7
Date	4.0	Sweet potato	1.5
Fescue, tall	3.9	Tomato	2.5
Flax	1.7	Wheat	6.0
Grape	1.5	Wheat grass, crested	3.5
Grapefruit	1.8	Wheat grass, tall	7.5
Lettuce	1.3		

Source: After Maas and Hoffman (1977).

a crop yield will begin to decline. Example values are found in Table A3.3.

The leaching requirement (LR) for each crop is computed within the spreadsheet as:

$$LR = \frac{ECiw}{(5 \times ECe) - ECiw}$$

where: $ECiw$ = EC of the irrigation water (dS/m); and ECe = threshold saturated paste extract of the crop (dS/m). For example, if $ECiw$ = 1.0 dS/m and the crop is grain corn (Table A3.3), then LR =

$$\frac{1}{(5 \times 1.8) - 1} = .125$$

The extra water required for each crop, to remove salinity that arrives with the irrigation water, is then computed as:

Extra water for salinity control = $(ET \text{ of irrigation water}) \times \dfrac{LR}{1 - LR}$

For example, if for a specific crop, ET of irrigation water = 100 000 MCM and LR = 0.125, then volume of water needed for salinity control = 14 286 MCM. However, deep percolation of rainwater will accomplish the same task (it washes accumulated salts out of the rootzone). Therefore, this RAP approximates the irrigation water requirement as: Volume of irrigation water needed for salinity control = Volume of water needed for salinity control - Rainfall deep percolation.

Field coefficients

Most irrigation specialists are familiar with the term "crop coefficient". Crop coefficients have been widely used in estimates of crop evapotranspiration (ET) since the mid-1970s. The general formula used is: ETcrop = $Kc \times$ ETo, where: Kc = the crop coefficient; and ETo = grass reference ET. Guidelines for estimating ET and ETo are given in FAO (1998).

"Reference" values other than ETo are sometimes used, but they are being replaced rapidly with weather stations that provide the hourly data needed to compute ETo. This spreadsheet uses ETo as defined in FAO (1998) because:

➢ ETo is the standard "reference".
➢ Most excellent ET research on a variety of crops uses ETo as the reference crop.
➢ ETo estimates tend to be more accurate than other reference methods, such as evaporation pans.

Where the only local data are from evaporation pans, it is advisable to consult with FAO (1998) in order to determine the proper conversion from monthly Epan to monthly ETo values. In Table A3.4, ETo = $Kp \times$ Epan.

This spreadsheet uses the term "field coefficient" because often a "crop coefficient" is only used during the crop-growing season, and often the common usage of "crop coefficients" ignores the impacts of soil moisture contents.

In reality, the "field coefficient, Kc" is the same as the "crop coefficient, Kc" if the crop coefficient is properly adjusted – using FAO (1998) guidelines – to include factors such as:

➢ stress (reduced transpiration) caused by a dry rootzone;
➢ soil surface evaporation due to rainfall or irrigation.

TABLE A3.4
Pan coefficients (*Kp*) for Class A pan for different pan siting and environment and different levels of mean relative humidity (RH) and wind speed

Class A pan description →	Case A: Pan placed in short green cropped area				Case B: Pan placed in dry fallow area			
RH mean		low	medium	high		low	medium	high
(%) →		(< 40)	(40–70)	(> 70)		(< 40)	(40–70)	(> 70)
Wind speed (m/s)	Windward side distance of green crop (m)				Windward side distance of dry fallow (m)			
Light (< 2)	1	.55	.65	.75	1	.7	.8	.85
	10	.65	.75	.85	10	.6	.7	.8
	100	.7	.8	.85	100	.55	.65	.75
	1 000	.75	.85	.85	1 000	.5	.6	.7
Moderate (2–5)	1	.5	.6	.65	1	.65	.75	.8
	10	.6	.7	.75	10	.55	.65	.7
	100	.65	.75	.8	100	.5	.6	.65
	1 000	.7	.8	.8	1 000	.45	.55	.6
Strong (5–8)	1	.45	.5	.6	1	.6	.65	.7
	10	.55	.6	.65	10	.5	.55	.65
	100	.6	.65	.7	100	.45	.5	.6
	1 000	.65	.7	.75	1 000	.4	.45	.55
Very strong (> 8)	1	.4	.45	.5	1	.5	.6	.65
	10	.45	.55	.6	10	.45	.5	.55
	100	.5	.6	.65	100	.4	.45	.5
	1 000	.55	.6	.65	1 000	.34	.4	.45

Source: FAO, 1998.

The proper selection of field coefficients depends on a good understanding of Table 8 in the input spreadsheets (Precipitation, effective precipitation, and deep percolation of precipitation). The computation procedure that the spreadsheet uses includes:

➢ effective precipitation and irrigation water are assumed to be the only external sources of water for field ET;
➢ the field ET is computed on a monthly basis as: ET = $Kc \times$ ETo.

Effective precipitation includes all precipitation that is lost through either evaporation (from the soil or plant) or transpiration, as computed by the formula above. Therefore, in order to account for soil evaporation for those months when the crop is not in the ground, it is necessary to do two things simultaneously:

➢ The effective precipitation must be computed to account for that evaporation.
➢ A field coefficient (*Kc*) of greater than 0.0 must be applied to those months.

The following procedure is recommended for the RAP:

➢ For crops with no irrigation water used for pre-plant irrigation. If for a month the crop has not yet been planted, or a crop is not in the field, assume that for that month:
  • crop coefficient = 0.0;
  • effective rainfall that is reported for that month will only include water that is stored in the rootzone for ET after the seeds are planted.
➢ For crops that use irrigation water for pre-plant irrigation (e.g. rice field preparation, cotton pre-irrigation). Follow the above procedure until the irrigation water is first applied. Then do the following for each month until the crop is planted or transplanted:
  • crop coefficient > 0 to account for soil evaporation of both irrigation water and effective rainfall;
  • effective rainfall that is reported for that month will include water that is stored for ET after planting, plus the rainfall contribution to the soil evaporation prior to planting.

For example, it is possible to consider a case in which:

➢ A pre-plant irrigation is applied to a field on the first day of the month.
➢ The crop will not be planted for another month.
➢ The soil remains bare and free from weeds for this month.
➢ The soil remains "dark" for three days after standing water disappears from the soil surface.

Table A3.5 indicates how to compute an average monthly *Kc* that takes the soil evaporation properly into account. Rules to follow include:

TABLE A3.5
Example computation of an average monthly *Kc* value for a month following a pre-plant irrigation, but prior to planting

Day	Kc	Explanation
1	1.05	Irrigation – wet soil surface.
2	1.05	2nd day of irrigation - wet soil surface.
3	1.05	1st day after irrigation. No standing water. Soil surface still dark.
4	1.05	2nd day after irrigation. Soil surface still dark.
5	1.05	3rd day after irrigation. Soil surface still dark.
6	0.70	4th day after irrigation.
7	0.50	5th day after irrigation.
8	0.30	6th day after irrigation.
9	0.15	7th day after irrigation.
10	0.15	8th day after irrigation.
11	1.05	Rain – wet soil surface.
12	1.05	2nd day of rain – wet soil surface.
13	1.05	1st day after rain. Soil surface still dark.
14	1.05	2nd day after rain. Soil surface still dark.
15	1.05	3rd day after rain. Soil surface still dark.
16	0.70	4th day after rain.
17	0.50	5th day after rain.
18	0.30	6th day after rain.
19	0.15	7th day after rain.
20	0.15	8th day after rain.
21	1.05	Rain – wet soil surface.
22	1.05	2nd day of rain – wet soil surface.
23	1.05	1st day after rain. Soil surface still dark.
24	1.05	2nd day after rain. Soil surface still dark.
25	1.05	3rd day after rain. Soil surface still dark.
26	0.70	4th day after rain.
27	0.50	5th day after rain.
28	0.30	6th day after rain.
29	0.15	7th day after rain.
30	0.15	8th day after rain.
Average *Kc* =	0.71	for this month of 30 days.

➢ The minimum value of *Kc* is typically 0.15.
➢ Where a soil surface is dark in appearance from moisture, even if there is no standing crop, a crop coefficient of 1.05 is appropriate.
➢ Most unstressed field crops (cotton, rice and corn) have a crop coefficient of about 1.1 once they have achieved 100-percent canopy cover.

Table 2 – Monthly ETo values
ETo values (in millimetres) by month should be entered. See the above discussion regarding crop coefficients. Ideally, ETo should be computed on an hourly basis using the Penman–Monteith method (FAO, 1998).

Table 3 – Surface water entering the command area boundaries (MCM)
All values for this table should be in units of million cubic metres (MCM), and should only include water that can be used for irrigation. In other words, flows from a river flowing through a CA that has no diversion structures or pumps would not be included. The table allows for three general categories of surface inflows:
➢ Irrigation water entering from outside the CA. The MCM should be the total MCM at the original diversion point (or points). Therefore, technically speaking it is not the MCM entering the CA. This category of "irrigation water" is the "officially diverted" irrigation water supply.
➢ Other inflows from External Source #2. This source can be defined by the RAP user, and can be a consolidation of several physical sources – but all placed in one category. However, these inflows must be accessed by users within the CA as an irrigation supply – either through diversion or through pumping from rivers.
➢ Other inflows from External Source #3. This has the same qualification as External Source #2.
The key concepts for Table 3 are:
➢ Table 3 only includes surface volumes that enter from outside the CA boundaries.
➢ The surface volumes are only included if they are volumes of water used for irrigation. For the purposes of the RAP, External Sources #2 and #3 are considered irrigation water if they consist of water that individual farmers or groups of farmers divert or pump. Many projects have such supplemental supplies that do not enter the CA through designed and maintained canals, yet these supplies are important parts of the overall irrigation supply in the CA.
The important value here is the volume of water that enters the CA, not the volume of water that is pumped from drains (as that may also include recirculation of spills and field runoff).

Table 4 – Internal surface water sources (MCM)
Table 4 values do not represent original supplies of water (as the surface sources were already accounted for in Table 3). Rather, this is the volume of water that is recirculated or pumped from surface sources within the project. This may be water that originated from the irrigation canal and was spilled, deep percolated, or ran off from fields. The origin of the water is not the important thing in Table 4. Rather, the important feature for Table 4 is which entity diverts or pumps this non-canal water.

Table 5 – Hectares of each crop in the command area, by month
Table 5 provides information on how much area is used for each crop during each month.
The *Kc* values for each crop are found in the row immediately above the row into which it is necessary to input the hectares of that crop. If a *Kc* value greater than

0.0 exists for a month for that crop, it is necessary to input the number of hectares associated with that crop, for that month.

Table 6 – Groundwater data

These questions only need to be answered where groundwater is used by farmers or by the project authorities.

Groundwater accounting in irrigation projects frequently ignores external sources of groundwater, and the fact that much of the groundwater may simply be recirculated surface water. The RAP eliminates the double-counting of recirculated water, which is what happens where groundwater is treated as an independent supply.

Table 6 recognizes that an aquifer may extend well beyond the confines of the CA.

The questions are divided into two categories: pumping from the aquifer within the CA; and pumping from the aquifer but outside the CA. Both areas must be considered if the aquifer is to be examined properly. The external indicators and benchmarking indicators do not utilize the external pumping information. However, the pumping from outside the CA is frequently completely dependent upon seepage and deep percolation from within the CA. In such a case, a "water conservation" programme within the CA to minimize seepage may actually eliminate the water source for groundwater pumpers outside the CA. There may also be considerations such as contamination of the groundwater as it passes through old marine sediments – increasing the salinity of groundwater as compared with surface water.

The "net" groundwater pumping within the CA can only be greater than or equal to zero (given the way the spreadsheet is designed). For the computations:

➤ estimates of deep percolation from fields are made;

➤ estimates of seepage from canals are made.

When combined, these two represent the recharge of the aquifer from external irrigation water.

Estimates are then made of the groundwater pumping that occurs within the CA – either by project authorities or by individual farmers. This groundwater pumping volume is then discounted for estimated losses. The result is an estimate of the groundwater that actually contributes to evapotranspiration.

The volume of groundwater that is used for ET is compared with the recharge from surface water supplies. If the recharge is greater than the ET of groundwater, then the "net" groundwater pumping = 0.0. If the ET of groundwater is greater than the recharge, the difference is the "net" groundwater pumping. In most projects, the "net" groundwater pumping will equal zero because typically the aquifer is recharged with the imported surface irrigation water.

Although groundwater pumping is an important aspect of recirculation of irrigation water, it is not a "new" supply of water any more than recirculation of surface water would be. Recirculation of any type will increase the irrigation efficiency of the project. However, it will not have any impact on the irrigation efficiency of the field units unless the recirculation occurs on the fields themselves.

Table 7 – Precipitation, effective precipitation, and deep percolation of precipitation

The monthly gross precipitation (in millimetres) is required at the top of the table. These values are generally easy to obtain.

The other values may be a bit of a mystery to most users although the concepts of effective precipitation and deep percolation are common concepts. The problem the users will have is in identifying proper values. Simple assumptions about deep percolation and the percentage of rainfall that is effective do not work for spreadsheets

such as these, which are designed to be applied over a wide range of geography, each having vast differences in climates and crops.

Effective precipitation is defined as precipitation that is destined for ET (evaporation or transpiration) either this month or in the future.

Effective precipitation and deep percolation can be input in this table for any or all months, regardless of whether a crop is in the field that month. The deep percolation of rainfall is used for only one computation purpose: as a computed reduction of the amount of irrigation leaching water that is necessary to wash salts from the rootzone.

In general, values for "effective precipitation" and "deep percolation" are not available as monthly values, and they are almost never available for individual crops. Nevertheless, it is important to make an estimate of these values.

As an aid to the spreadsheet user, the calculated ETfield values (in millimetres) are carried forward from previous tables (these tables are found on the far right-hand side of the pages of this worksheet, and include computations using ETo and *Kc* values). Once the spreadsheet user inputs an estimate of the percentage of effective precipitation, a corresponding depth of effective precipitation will appear in the next row.

In general, if there is a light rainfall during a month yet the ETfield is high, there will be very little deep percolation of rainfall. Conversely, if there is a large amount of rainfall and very little ETfield, then more deep percolation can be expected. Deep percolation also depends on the soil type (sandy soils have more deep percolation than do clay soils). The deep percolation cannot exceed the quantity: Precipitation - Effective precipitation.

Table 8 – Special agronomic requirements (mm)
Only a few crops will have values in this table. The most notable crop is paddy rice.

In the following example for a rice crop, the assumption is that the rice field needs to be flooded prior to planting:
➢ flooding – 1 March;
➢ planting – 15 March.
The field stays covered with a small depth of water the entire time, or at least the soil is very wet the entire time. Therefore, the "field coefficient, *Kc*" equals 1.05. It is further assumed that there is a monthly ETo of 120 mm during March.

Furthermore, it is assumed that the field coefficient, *Kc*, has been computed following the example at the beginning of this annex. The difference between this example and the earlier one is that this example is very simple – the soil is always wet, so the *Kc* is always equal to 1.05.

If the crop coefficient for March were entered as 1.05, then ET for the whole month of March would be computed separately. Therefore, Table 9 would not include any ET amount that occurred between 1 March and 15 March.

However, if the crop coefficient for March were entered as 1.05/2 = 0.53, this would indicate that the spreadsheet user only wanted to count the ET starting on 15 March as "crop ET", and the ET between 1 March and 15 March would be included in Table 8. It is recommended that the first approach be used (using a *Kc* of 1.05 for the month).

Assuming that the first approach is used (*Kc* = 1.05 for March), then the value in Table 8 must only include two things:
➢ the deep percolation amount of irrigation water;
➢ the amount of irrigation water that runs off the field, or group of fields, into surface drains.
If there had been rainfall during March, some of the runoff and deep percolation would have been rainwater. Table 8 only includes irrigation water amounts, so any rainfall amounts must be subtracted from total seepage and runoff.

Table 9 – Crop yields and values
Three types of input are needed:
- ➤ the local exchange rate (US$/local currency);
- ➤ typical average yields of each crop, in tonnes per hectare;
- ➤ the farmgate selling price of each crop, in local currency per tonne.

Worksheet 4. External indicators
This worksheet is a temporary holding place for some values and computations.

For the user, the primary usage of this worksheet is to enter confidence interval values.

INTERNAL INDICATOR SECTION
Worksheets 5–12 require a good field visit to the project by qualified evaluators. They focus on how the project actually works – what the instructions are, how water is physically moved throughout the canal/pipeline system, what perceptions and reality are, and other items such as staffing, budgets and communication. A quick look (rapid appraisal) of these items will immediately identify weaknesses and strengths in the project. Action items are virtually always readily apparent after the systematic RAP has been conducted.

Worksheets 5–12 contain a large number of pages. However, only about 25 percent of the lines require an answer (the other lines are explanations or blanks), and computations are only necessary for a few items such as budget questions. Furthermore, the questions for the main canal are identical to those for the second-level canals and the third-level canals. Once an evaluator understands the questions for the main canal, the remainder of the pages are easily answered after a field visit.

Worksheet 5. Project office questions
Most of the questions in this worksheet should be filled out by the irrigation project employees prior to the visit, as this includes many simple data values such as salaries, number of employees, and stated project policies.

However, the evaluator must answer some of the questions during the visit.

This worksheet includes questions that address the possibility of chaos existing in a project. "Chaos" exists when the reality in a project does not match what project authorities believe occurs. Therefore, the evaluator must ask the project authorities what levels of water delivery service the main canal delivers, what various operators do, and how water reaches individual farmers. These "stated" conditions are later compared against what the evaluator actually observes in the field.

In general, it is easiest to modernize irrigation projects that have a minimum of chaos. If the project authorities are either not aware of actual field conditions, or if they refuse to recognize certain problems, it is then very difficult to make changes.

This worksheet also introduces the concept of assigning a rating of 0–4 to project characteristics, with 0 being the worst rating and 4 being the best. In the majority of cases, the evaluator reads a series of descriptions, and assigns a rating to each of that "internal indicators" that are later summarized in Worksheet 12 (Internal indicators).

Some indicator values (such as "O&M adequacy") are calculated automatically based on previous answers. The rating scale for those values can be found by highlighting the calculated value and reading the formula in the cell.

This worksheet has some drainage and salinity information questions at the very end. These are used in various benchmarking indicators.

Where there is an "umbrella" WUA (elected by smaller WUAs) that manages the project, then that "umbrella" WUA is considered part of the "project office".

Worksheet 6. Project employees

Most of these questions require a qualitative assessment of conditions in the project, with the evaluator giving a rating of 0–4 for each question. Topics include:

➢ adequacy of employee training;
➢ availability of written performance rules;
➢ power of employees to make independent decisions;
➢ the ability of the project to dismiss employees with cause;
➢ rewards to employees for good work.

Worksheet 7. WUA

In the worksheets, the abbreviation WUA stands for water user association. Some irrigation projects have a large WUA that operates the whole project canal system, but the final water distribution is done by many smaller WUAs. In such a situation, the WUA questions pertain only to the smaller WUAs.

Many of the questions are identical to those in Worksheet 5 (Project office questions).

The answers must reflect average conditions throughout the whole irrigation project, rather than any single WUA. Therefore, several WUAs must be visited in order to answer the questions properly.

Worksheet 8. Main canal

This worksheet begins with six questions about general conditions throughout the project. The answers will have a large CI (defined earlier in the section covering external indicators). However, because there are large differences between various projects, the answers are meaningful.

The remainder of the questions are identical to those for the second-level and third-level canals. While most of the questions are self-explanatory, a few points warrant special explanation.

The wave travel time is the is the lag time between making a change in flow rate at one point in a canal and having the change stabilize at another point downstream.

Concerning the functionality of various structures and instructions, evaluators must always consider the operations from the point of view of the operator, and ask themselves: "If I were to walk up to this structure, how would I know what to do and would it be easy to do?" For example, where the objective is to maintain a constant water level with a structure:

➢ What does "constant" mean – within 1 cm or within 5 cm?
➢ How many times a day would the structure need to be moved, and even with that movement would it be possible to achieve the desired result?
➢ Is the structure dangerous or difficult to operate?

If an operator is told to deliver a flow rate into a canal, yet there is no flow rate measurement device (or the device is inaccurate, improperly maintained, improperly located, or requires significant time to stabilize), then it will be almost impossible to accurately achieve the desired result.

Therefore, the evaluator should not simply listen to explanations. The evaluators must put themselves into the operator's shoes. It is not sufficient to know that the operator moves something and then looks at something; the evaluators must understand whether those "somethings" do indeed give the proper answer.

The format of Worksheet 8 is:

➢ General observations are recorded.
➢ Ratings are given to various aspects of operation, maintenance and process. Some of these ratings depend on the general observations that are recorded in the same worksheet. Other ratings stand on their own.

It may appear that some of the general observations are not necessary because they are addressed later in the form of ratings. However, they have been included in order to force the evaluators to make a more systematic examination of various features – which are summarized in later ratings.

The questions about actual service are key. RAP evaluators must recognize that the RAP has been designed under the assumption that all employees of an irrigation project have their jobs for one reason only – to provide service to customers.

By analysing a project by "levels" (office, main canal, second-level canal, third-level canal, distributaries, and field), a huge project can be understood in simple terms. The operators of the main canal have one objective only – everything they do should be done to provide good water delivery service to their customers, the second level canals (and perhaps a few direct turnouts from the main canal). This "service concept" must be understood and accepted by everyone, from the chief engineer to the lowest operator. Once it is accepted, then system management becomes very simple. Personnel on each level are only responsible for the performance of that level.

Main-canal operators do not need to understand the details of that day's flow-rate requirements on all the individual fields. In order to subscribe to the service concept, operators generally need to know that their ultimate customer is the farmer. However, the details of day-to-day flow rates do not need to be known at all levels. Rather, the main-canal operators have one task to accomplish – to deliver flow rates at specific turnouts (offtakes) with a high degree of service. Service is described in the RAP with three indices:

- ➢ flexibility, composed of:
  - frequency,
  - flow rate,
  - duration;
- ➢ reliability;
- ➢ equity.

For very simple field irrigation techniques, reliability and equity are crucial. Without good reliability and equity, there are generally social problems, such as vandalism and non-payment of water fees. Thus, reliability and equity are cornerstones of projects that have good social order.

In order to have efficient field irrigation practices, some minimum level of flexibility is required. Even with the most basic irrigation methods, such as paddy rice, the flow rates are completely different at the beginning of the season (for land preparation) compared with when the rice crop is established. Moreover, not everyone plants at the same time, meaning that the irrigation project must have some flexibility built into it.

In order to obtain a high project efficiency, the canal system must have sufficient flexibility built into it to be able to change flows frequently in response to continually changing demands and weather. However, most irrigation projects are not very flexible. Furthermore, most irrigation projects have low project efficiencies.

Finally, evaluators need to consider that a major purpose of the RAP is to identify what can be done in order to improve project performance. Modern field irrigation methods, e.g. sprinkler and drip, require a much higher degree of flexibility and reliability than do traditional surface irrigation methods. The evaluators must always be asking themselves during the RAP: "I do not only want to recommend how to rehabilitate the project – I want to recommend steps that will move the project closer to a higher efficiency and better water management as the future will certainly demand. Will these structures and operating instructions and personnel be capable of meeting the new requirements, and if not, what adjustments must be made?"

Therefore, the examination of the main canal must be thorough. The evaluators need to start at the source, and work their way to the downstream end of the canal. This

is not to say that every single structure must be analysed. However, evaluators must examine the key structures along the complete length of the canal.

Common challenges that evaluators have to overcome are:

➢ The project authorities want to spend a disproportionate amount of time at the dam, discussing dam maintenance, the watershed, and politics. Actually, the only items of interest at the dam are: (i) the storage; and (ii) how discharges are computed and actually made and measured.

➢ Evaluators will be told: "the canal is all the same". The explicit or implied conclusion is that the evaluators only need to examine portions of the canals near the headworks. It may be true that the canal is indeed identical along its complete length. However, in general, there are significant differences in maintenance, slope, structures, etc. along its length. Only by physically travelling along the canal will the evaluators learn about those differences.

➢ The operation will be explained by project authorities that are accompanying the evaluators. This is a difficult challenge. The office visit (Worksheet 5) is designed to obtain the perspective of the office staff and bosses. A purpose of the field visit is to talk to the actual structure operators and review their notes – without having their bosses interrupt and give the "official" answer. In many cases, it is necessary to separate the bosses from the operators, so that the operators are not cautious with the answers they give. Therefore, the "rules of the game" must be understood before the field visit is made.

BOX A3.1
Advice for evaluators

Understand everything. Understand how the operators think things should work. Question everything. If you do not understand explanations, continue to question the explanations until you understand the perspective of the operators. But go beyond that. Every structure has a function. Do not be satisfied with attempting to visualize how that function can be accomplished more easily or better; question the very reason why the structure has been assigned that function. Perhaps in a modernization plan, a structure that is currently operated under flow-rate control should instead be operated under upstream water-level control. In other words, question the very nature of the strategies of operation – not just individual structures. The RAP is not an examination of individual structures – it is a comprehensive examination of a whole process…in which structures have functions. One must understand the pieces (operators, rules and structures) in order to understand the process, but the RAP also questions the assumptions behind the specific processes themselves. The RAP requires evaluators who can look beyond the individual pieces; it requires evaluators who can visualize how the pieces can be manipulated and re-arranged as parts of a complete process that provides good service and high efficiency.

Another challenge arises in the selection of which canals to visit. Sometimes, a project will have two or more main canals, and dozens of "second-level" canals. However, in general, operator instructions, hardware, and maintenance levels will be similar on all of the canals at a specific level. Visiting more canals is helpful, but it is not necessary to visit all of the canals in a project.

Different main canals each have a few specific engineering/hydraulic challenges. One canal may have a bottleneck (restriction) at a river crossing, and another canal may have a peculiar control problem – even though everything else seems the same. If the RAP evaluators can provide good recommendations for such specific hydraulic problems (that are not covered specifically in the RAP forms), the credibility of the evaluators will be enhanced, and RAP recommendations will have a better chance of being accepted. Therefore, the evaluators should take ample pictures and notes during the visit.

Basic advice for evaluators as they tour the canals (main, second, third, etc.) is summarized in Box A3.1.

Worksheet 9. Second-level canals

See the discussion for Worksheet 8. Second-level canals are those that receive water from the main canals. In general, the second-level canals are operated differently from the main canals.

Worksheet 10. Third-level canals

See the discussion for Worksheet 8. In many medium-sized projects, the "third level" does not exist; therefore, this worksheet would not be filled out in such cases.

Worksheet 11. Final deliveries

There are two possible points that are considered in this worksheet. One is the Individual Ownership Units – the smallest unit that is owned by a single individual (where private ownership is allowed) or that is managed by a farmer. The Individual Ownership Unit may be larger than a single field where one farmer receives water and then distributes the water over several fields from a single turnout (very common in the United States of America). The key feature of the Individual Ownership Unit is that, at this point, there is no cooperation needed between individual farmers.

The second point is the Point of Management Change. In projects with a high density of turnouts, the Point of Management Change may be the same as the point of Individual Ownership Units. In other words, the irrigation project authority (or the WUA) employee delivers water all the way to the field level. The Point of Management Change is the "hand-off" point between paid employees and volunteers or farmers.

In some projects, the irrigation authorities place great emphasis on the number of farmers within a project. It is necessary to go beyond this statistic when examining the present operation, because the project authorities may relinquish control of the water to groups of 200 farmers – who are expected to somehow provide equitable and reliable water distribution among themselves. Therefore, there are two important indicators for this discussion:

➢ The number of fields (Individual Ownership Units) downstream of the Point of Management Change. The greater is the number, the poorer is the reliability, equity and flexibility of water delivery service. Furthermore, any number greater than 1 or 2 indicates that drip and sprinkler irrigation are almost impossible to support.

➢ The number of turnouts that are operated per employee. This is much more meaningful than the "number of farmers per employee", because employees may never provide water directly to individual farmers.

Worksheet 12. Internal indicators

This worksheet contains three types of values:

➢ Summaries of the various internal subindicators that were rated in the previous worksheets, and then computed weighted values for each primary indicator. The shaded columns on the right-hand side provide information about the values, the weighting factors, and the worksheet location for detailed rating criteria of the subindicators. All of these values are given a rating of 0–4, with 4 being highest and most desirable.

➢ Subindicators and primary indicators, the values of which are input directly into this worksheet (as opposed to being transferred from previous worksheets). These are indicators I-32, I-33 and I-34. These values all have a rating of 0–4.

➢ A few indicators (I-35+) that do not conform to the rating scale of 0–4. Rather, these are direct ratios of values or individual values that have special significance.

Worksheet 13. IPTRID indicators

This worksheet is an intermediate worksheet that should not be used. Instead, refer to Worksheet 14, as described below.

Worksheet 14. World Bank BMTI indicators

This worksheet contains the "Benchmarking Technical Indicators", or BMTI values, as of October 2002 for the water year described. The definitions of the various BMTI values are given in Tables A3.6–A3.9.

HOW TO INTERPRET RAP RESULTS

The RAP, by itself, is only a diagnostic tool. It allows a qualified evaluator to examine an irrigation project systematically in order to determine the external indicators and the internal indicators.

The external indicators give an indication of whether it is possible to conserve water and enhance the environment through improved water management. The internal indicators give a detailed perspective of how the system is actually operated, and of the water delivery service that is provided at all levels.

The interpretation of the results requires one or more irrigation specialists who have a clear understanding of the options for modernization. Without a thorough knowledge of these options, the recommendations can be ineffective and even counterproductive.

The basic rules are:

➢ In almost all projects, modernization requires both hardware and management changes.

➢ In general, it is quite possible to provide high levels of water delivery service to turnouts without good water control if the system is very inefficient and there is a very abundant supply of water. However, if the system must also be efficient, the only way to provide good water delivery service is to have excellent control of the water.

➢ In almost all projects, water delivery service needs to be improved in order to meet the basic objectives of lower labour costs, reduced spill, improved crop yields, and less environmental damage. The RAP process allows the evaluator to target the appropriate level (or levels) on which to begin modernization.

➢ In general, there are many very simple changes that can be made in operational procedures, and numerous others that require only a moderate investment in capital for hardware changes.

➢ All changes must be accompanied by quality control and excellent training.

➢ There must be a clear understanding the difference between CA irrigation efficiency and field irrigation efficiency. In projects without internal recirculation, the CA irrigation efficiency is generally lower than the field irrigation efficiency. However, in projects with internal recirculation of water, the CA irrigation efficiency may be greater than the field irrigation efficiency.

The CA irrigation efficiency benchmarking indicator combines many of the previous indicators into a single indicator value:

$$\frac{\text{Crop ET - Effective precipitation + Leaching irrig. water needed}}{\text{Surface irrigation water into the project } + \text{ Net groundwater pumping}} \times 100$$

This expression of irrigation efficiency does not conform to the precise requirements defined by Burt *et al.* (1997), but it is close enough to give a reasonable estimate of the CA irrigation efficiency.

A CA irrigation efficiency of 100 percent is impossible. In general, efficiencies greater than 60 percent require internal recirculation of losses – either as surface water recirculation or from groundwater pumping, or both.

In short, improvement in command area irrigation efficiency can be achieved in two ways: (i) reduce first-time losses; and (ii) recirculate first-time losses.

First-time losses occur in two areas:

➢ Conveyance losses. These include:

TABLE A3.6
Definitions of Benchmarking Technical Indicators: water balance indicators

Indicator	Definition	Data specifications
Total annual volume of irrigation water available at the user level (MCM) (also called "irrigation water delivered").	Total volume of irrigation water (surface water plus groundwater) directly available to users, MCM – using stated conveyance efficiencies for surface and groundwater supplies. It includes water delivered by project authorities as well as water pumped by the users themselves. Water users in this context describe the recipients of irrigation service; these may include single irrigators or groups or irrigators organized into water user groups. This value is used to estimate field irrigation efficiency; it is not used to estimate project irrigation efficiency.	Calculated from the stated value of system water delivery efficiency (from the dam or diversion point to the final project employee delivery point). Includes farmer pumping, because this is a "delivery" in the sense that it is irrigation water that is available to the farm/field.
Total annual volume of irrigation supply into the three-dimensional boundaries of the command area (MCM).	This is the irrigation water that is imported into the project boundaries, to include river diversions, reservoir discharges, and net groundwater extraction from the aquifer. This value is used to estimate project irrigation efficiency; it is not used in the computation of field irrigation efficiency.	Determination of this value requires a detailed water balance where there is groundwater pumping, because the net extraction must be estimated.
Total annual volume of irrigation water managed by authorities (MCM).	This is the irrigation water that is imported into the project boundaries by the authorities, plus any internal groundwater pumped by the authorities. The value is not used to compute any efficiencies, as some of the internal pumping may be recirculation of original source water. However, this is the volume of water that the project authorities administer, so it is used for the computations related to costs.	
Total annual volume of water supply (MCM).	Total annual volume of surface water diverted and net groundwater abstraction, plus total rainfall, excluding any recirculating internal drainage within the scheme.	This is the irrigation water that is imported into the project boundaries, to include river diversions, reservoir discharges, and net groundwater extraction from the aquifer. Plus, this includes total rainfall.
Total annual volume of irrigation water delivered to users by project authorities.	Total volume of water delivered to water users by the authorities over the year that was directly supplied by project authorities (including WUA) diversions or pumps. Water users in this context describe the recipients of irrigation service, these may include single irrigators or groups or irrigators organized into water user groups. This does not include farmer pumps or farmer drainage diversions.	This can be measured directly, or is more commonly estimated based on an assumed conveyance efficiency.
Total annual volume of groundwater pumped within/to the command area (MCM).	Total annual volume of groundwater that is pumped by authorities or farmers that is dedicated to irrigated fields within the command area. This groundwater can originate outside of the command area.	An answer must be provided even if the user does not precisely know the volume of groundwater pumped. The uncertainty can be handled by assigning a large confidence interval, if necessary.
Total annual volume of field ET in irrigated fields (MCM).	Total annual volume of crop ET. This includes evaporation from the soil as well as transpiration from the crop. Depending on how the user entered the data, this may include off-season soil evaporation.	This is computed based on crop coefficients and ETo values.
Total annual volume of ET – effective precipitation (MCM).	The volume of evapotranspiration that must be supplied by irrigation water. Regardless of how one enters data for ET (above), if one follows the guidelines in this manual, one obtains the same final answer of (ET – effective ppt.) – which is the net irrigation requirement.	The user gives an estimate of the effective rainfall, by month, and by crop. Effective rain contributes to the ET.
Peak net irrigation water ET requirement (CMS).	The net peak daily irrigation requirement (ET – effective rainfall) for the command area, based on actual cropping patterns for this year (CMS).	Calculated as the peak monthly (ET – effective rainfall) value, divided by the number of days in that month.
Total command area of the system (ha).	The physical hectares of fields in the project that that are provided with irrigation infrastructure and/or wells.	

TABLE A3.6
Definitions of Benchmarking Technical Indicators: water balance indicators (Continued)

Indicator	Definition	Data specifications
Irrigated area, including multiple cropping (ha).	The hectares of cropped land that received irrigation. If a 1-ha field has two irrigated crops per year, the reported irrigated area would be 2.0 ha.	
Annual irrigation supply per unit command area (m³/ha)	(Total annual volume of irrigation supply into the command area) / (Total command area of the system)	Total annual volume of irrigation supply into the command area: see earlier definition.
		Total command area of the system: see earlier definition.
Annual irrigation supply per unit irrigated area (m³/ha)	(Total annual volume of irrigation supply) / (Total annual irrigated crop area)	Total annual volume of irrigation supply: see earlier definition.
		Total annual irrigated crop area: see earlier definition. Includes multiple cropping.
Conveyance efficiency of project-delivered water (%). (Weighted value using stated values)	(Volume of irrigation water delivered by authorities) / (Total annual volume of project authority irrigation supply)	Volume of external irrigation water delivered by authorities: total volume of irrigation water supply that is delivered to water users by the project authorities over the year. Water users in this context describe the recipients of irrigation service; these may include single irrigators or groups or irrigators organized into water user groups.
		Total annual volume of project authority irrigation supply: see earlier definition.
Estimated conveyance efficiency for project groundwater (%).	(Annual volume of project groundwater delivered to users × 100) / (Annual volume of groundwater pumped by authorities)	Annual volume of project groundwater delivered to users: This refers to a weighted value of conveyance efficiency for groundwater that is pumped by authorities from wells both inside and outside of the command area, but which is delivered within the command area.
		Annual volume of groundwater pumped by authorities: self-explanatory.
Annual relative water supply (RWS).	(Total annual volume of water supply) / (Total annual volume of field ET in irrigated fields)	Total annual volume of water supply: see earlier definition.
		Total annual volume of field ET: see earlier definition.
Annual relative irrigation supply (RIS).	(Total annual volume of irrigation supply into the 3-D boundaries) / (Total annual volume of ET – effective precipitation)	Total annual volume of irrigation supply into the 3-D boundaries: see earlier definition.
		Total annual volume of ET – effective precipitation: see earlier definition.
Water delivery capacity.	(Canal capacity to deliver water at system head) / (Peak irrigation water ET requirement)	Canal capacity to deliver water at system head: actual gross discharge capacity of main canal (canals) at all diversion points (CMS).
		Peak irrigation water ET requirement: : see earlier definition (CMS).
Security of entitlement supply (%).	The frequency with which the irrigation organization is capable of supplying the established system water entitlements.	System water entitlement: the bulk volume (MCM) or bulk discharge of water (CMS) to which the scheme is entitled per year.
Average field irrigation efficiency (%).	((ET - Effective precipitation + LR water) × 100) / (Total public and private water delivered to fields)	All values are expressed in 12-month volumes.
Command area irrigation efficiency (%).	((ET + Leaching needs - Effective ppt.) × 100) / (Surface irrigation imports + Net groundwater)	All values are expressed in 12- month volumes.

TABLE A3.7
Definitions of Benchmarking Technical Indicators: financial indicators

Indicator	Definition	Data specifications
Cost recovery ratio.	(Gross revenue collected) / (Total MOM cost)	Gross revenue collected: total revenues collected from payment of services by water users.
		Total MOM cost: total management, operation and maintenance cost of providing the irrigation and drainage service excluding capital expenditure and depreciation/renewals.
Maintenance cost to revenue ratio.	(Maintenance cost) / (Gross revenue collected)	Maintenance cost: total expenditure on system maintenance.
		Gross revenue collected: total revenues collected from payment of services by water users.
Total MOM cost per unit area (US$/ha).	(Total MOM cost) / (Total command area serviced by the system)	Total MOM cost: see earlier definition.
		Total command area serviced by the system: see earlier definition.
Total cost per staff person employed (US$/person).	(Total cost of personnel) / (Total number of personnel)	Total cost of personal: total cost of personnel employed in the provision of the irrigation and drainage service, either in the field or office (including secretarial and administrative staff). Includes WUA employees and project employees.
		Total number of personnel engaged in irrigation and drainage service: total number of personnel employed in the provision of the irrigation and drainage service, either in the field or office (includes secretaries, administrators). This includes WUA employees and project employees.
Revenue collection performance.	(Gross revenue collected) / (Gross revenue invoiced)	Gross revenue collected: total revenues collected from payment of services by water users.
		Gross revenue invoiced: total revenue due for collection from water users for provision of irrigation and drainage services.
Staff persons per unit irrigated area (Persons/ha).	(Total number of personnel engaged in irrigation and drainage service) / (Total irrigated area serviced by the system)	Total number of personnel engaged in irrigation and drainage service: total number of personnel employed in the in provision of the irrigation and drainage service, including secretarial and administrative staff – in WUAs plus project employment.
		Total irrigated area (ha): see earlier definition.
Number of turnouts per field operator.	(Total number of turnouts [offtakes]) / (Total number of personnel engaged in field irrigation and drainage service)	Total number of personnel engaged in irrigation and drainage service: total number of field personnel employed in the provision of the irrigation and drainage service, including supervisors.
		Total number of turnouts: the number of turnouts (offtakes) to fields, farms, or groups of farmers, plus offtakes to laterals and sublaterals, that are physically operated by the field personnel.
Average revenue per cubic metre of irrigation water delivered to water users by authorities (US$/m³).	(Gross revenue collected) / (Total annual volume of project irrigation water delivered)	Gross revenue collected: total revenues collected from payment of services by water users.
		Total annual volume of irrigation water delivered: see earlier definition.
Total MOM cost per cubic metre of irrigation water delivered to water users by the project authorities (US$/m³).	(Total MOM cost) / (Total annual volume of irrigation delivered by project authorities)	Total MOM cost: total management, operation and maintenance cost of providing the irrigation and drainage service excluding capital expenditure and depreciation/renewals.
		Total annual volume of irrigation water delivered by project authorities: see earlier definition.

TABLE A3.8
Definitions of Benchmarking Technical Indicators: agricultural productivity and economic indicators

Indicator	Definition	Data specifications
Total annual value of agricultural production (US$).	Total annual value of agricultural production received by producers.	
Output per unit command area (US$/ha).	(Total annual value of agricultural production) / (Total command area of the system)	Total annual value of agricultural production: total annual value of agricultural production received by producers.
		Total command area of the system: the command area is the nominal or design area provided with irrigation infrastructure that can be irrigated.
Output per unit irrigated area, including multiple cropping (US$/ha).	(Total annual value of agricultural production) / (Total annual irrigated crop area)	Total annual value of agricultural production: see earlier definition.
		Total command area of the system: see earlier definition.
Output per unit irrigation supply (US$/m³).	(Total annual value of agricultural production) / (Total annual volume of irrigation supply into the 3-D boundaries of the command area)	Total annual value of agricultural production: see earlier definition.
		Total annual irrigated crop area: see earlier definition.
Output per unit water supply (US$/m³).	(Total annual value of agricultural production) / (Total annual volume of water supply)	Total annual value of agricultural production: see earlier definition.
		Total annual volume of water supply: see earlier definition.
Output per unit of field ET (US$/m³).	(Total annual value of agricultural production) / (Total annual volume of field ET)	Total annual value of agricultural production: see earlier definition.
		Total annual volume of field ET: see earlier definition.

TABLE A3.9
Definitions of Benchmarking Technical Indicators: environmental performance indicators

Indicator	Definition	Data specifications
Water quality: average salinity of the irrigation supply (dS/m).	Salinity (electrical conductivity) of the irrigation supply.	Weighted (by volume) value, using monthly data. Should include both surface water and groundwater supplies.
Water quality: average salinity of the drainage water (dS/m).	Salinity (electrical conductivity) of the drainage water that leaves the command area.	Weighted (by volume) value, using monthly data.
Water quality: average biochemical oxygen demand (BOD) of the irrigation supply (mg/litre).	Biological load of the irrigation supply expressed as BOD.	Weighted (by volume) value, using monthly data. Should include both surface water and groundwater supplies.
Water quality: average BOD of the drainage water (mg/litre).	Biological load of the drainage water expressed as BOD.	Weighted (by volume) value, using monthly data.
Water quality: average chemical oxygen demand (COD) of the irrigation water (mg/litre).	Chemical load of the irrigation supply expressed as COD.	Weighted (by volume) value, using monthly data. Should include both surface water and groundwater supplies.
Water quality: average COD of the drainage water (mg/litre).	Chemical load of the drainage water expressed as COD.	Weighted (by volume) value, using monthly data.
Average depth to shallow water table (m).	Average annual depth of the shallow water table calculated from water table observations over the irrigation area.	This is an average value for the area of high water table.
Change in shallow water table depth over time (m) (+ indicates up).	Change in shallow water table depth over the last five years.	This is an average value for the area of high water table.

- spillage from canals and pipelines;
- seepage from canals;
- phreatophtye water consumption.

➢ Field losses. These include:
- conveyance losses in field channels;
- surface runoff from fields;

- deep percolation in fields, caused by: standing water in rice fields, non-uniformity of irrigation water application, and excess duration of irrigation water application.

There is considerable merit in reducing first-time losses because these can have a direct effect on required canal capacity, fertilizer loss, pesticide losses, local waterlogging, etc. In most projects, seepage from canals is targeted, although often other components of first-time losses are more important and cause greater damage to the environment.

Options for the recirculation of first-time losses:
➢ Surface recirculation. Surface drains, creeks, and rivers pick up first-time losses that originated as:
  - seepage or deep percolation that returns to creeks from a high water table;
  - surface runoff from fields;
  - spillage from canals.
➢ Pumping from the groundwater. This recirculates first-time losses that originated as:
  - seepage;
  - field deep percolation.

In some cases, recirculation is the least expensive and quickest option for improving project irrigation efficiencies.

A common mistake in modernization is the elimination of first-time losses with the belief that this will improve project irrigation efficiencies. However, where such first-time losses are already recirculated within the project, there may not be any true water conservation.

However, other benefits can be obtained from the elimination of first-time losses:
➢ easier operation of the distribution system from lining;
➢ better crop yields through better first-time water management;
➢ less contamination of water by fertilizers and pesticides.

At the beginning of the RAP input sheets, the RAP user is asked to provide estimates of field irrigation efficiency for rice and other crops. These estimates should account for all conveyance losses, field deep percolation, and surface runoff downstream of the delivery point from the project authorities. However, Worksheet 14 (World Bank BMTI indicators) gives a better estimate of field irrigation efficiency – based on a water balance of the project. This value should be compared with the stated value in Worksheet 1 in order to see whether the stated value corresponds to the water balance values. In general, the water balance values are much closer to the truth.

How to use field irrigation efficiency values

Where the field irrigation efficiency is low, it should not necessarily be concluded that the farmers need better education on how to irrigate properly. In many projects, such training is worthless because project authorities dictate the schedule and amounts of water delivery, and the farmers have almost no choice in the matter.

Low field irrigation efficiencies are typically an indication of a water delivery system that is unreliable, inequitable and/or inflexible. Generally, the water delivery system must be improved before significant field efficiency improvements can take place.

However, there is one practice that can be implemented immediately without changing the water delivery system. This is land grading. Most of the world's irrigation projects use surface irrigation, and good land grading is important for good in-field distribution uniformity of water.

Where the project irrigation efficiency is greater than the field irrigation efficiency, then there is considerable recirculation within the project.

Project irrigation efficiency is the key indicator as to whether there is an opportunity to conserve water. Field irrigation efficiency gives no indication of this by itself, because a large share of the field losses is often re-circulated.

"Water conservation" in a hydrological basin (as opposed to a specific irrigation project) can only be achieved where one of the following occurs:

➢ Water flows to salt sinks (ocean, localized salty groundwater) are eliminated.

➢ Excess evapotranspiration (ET) is reduced (weed and phreatophtye and drain ET is reduced).

Even where good water management does not conserve water in the basin, it does has appreciable benefits, including:

➢ improving downstream water quality;

➢ improving the timing of water usage;

➢ reducing the flow-rate requirements into a project;

➢ reduction in pumping (sometimes);

➢ improving crop yields through better timing of applications and reduced fertilizer leaching.

➢ improving the quality and quantity of flows in rivers and streams immediately downstream of irrigation diversion points.

Summary of the interpretation process

In general, the process of interpretation is as follows:

➢ Field irrigation efficiencies are examined. Good field efficiencies depend on receiving good water delivery service at the field.

➢ Project irrigation efficiencies are examined. It is very common for irrigation project personnel to want higher flow rates into the project, although the inefficiencies may be quite high. An important alternative to increasing the water supply is to improve efficiencies.

➢ Conveyance efficiencies are noted, and compared against field irrigation efficiencies. Both of these are considered in light of any recirculation (groundwater or surface water) that may occur. The comparison helps to determine where efforts might be made.

➢ The attributes of water delivery service are examined for each level.

➢ The appropriateness of hardware and operator instruction is reviewed.

➢ The existence of recirculation systems is noted. In many projects, installing surface water recirculation systems in strategic areas is a simple way to improve performance and water delivery service.

➢ Where employees spend their time is an important indication of where changes can be made. For example, many projects have a large staff of hydrographers who continually take current meter readings at many locations in the main canals. In general, this inaccurate (owing to the inherent nature of unsteady flows and point-in-time measurements) work can be eliminated completely if a new strategy for water delivery is adopted.

With modernization, some actions can be taken in parallel with others, but some actions require a foundation. For example, automation with electronic programmable logic controllers (PLCs) first requires excellent access to sites, excellent communications, and a strong infrastructure for electronic troubleshooting and repairs. They also require a project that has an excellent maintenance record. In other words, PLC automation requires a substantial foundation that is often lacking in irrigation projects. PLC implementation without that foundation is almost guaranteed to fail.

Typically, the key steps for modernization are:

1. Eliminate the discrepancy between "actual" and "stated" service. Where project managers refuse to accept reality, it is best to spend time and money on other projects.

2. All levels of staff must understand and adopt the "service mentality". While this is not achieved overnight, modernization concepts are rooted in this mentality. Without it, attempts to modernize a project will typically have minimal benefit.

3. Examine instructions that are given to operators, and modify them as needed. A classic example in many Asian projects is where the objective of cross-regulators is to maintain an upstream water level, but the gate operators must move the cross-regulators in strict accordance with instructions (of specific gate movements) from the office – based on computer programs or spreadsheets. A simple check in the field will show that water levels are not maintained properly. The instructions for the operators must be changed, and they are very simple: "Maintain the upstream water level within a specified tolerance of a defined target".

4. The first three items are the easiest, but they may also be the most difficult with some senior staff. If the first three items cannot be achieved, it is best to either walk away from a project, or else dismiss the senior staff. Changes in the first three items may take some training, study tours, etc.

5. The next steps, more or less in order of sequence, are to improve the following areas:

   ➢ Understanding of what actually happens in the system. Experts can evaluate a project quickly and because of their background, understand almost immediately the cause/effect relationships and the probable level of service. The operators and supervisors often do not see things the same way. It is very helpful to install simple dataloggers and water-level sensors at key locations in order to record spills, flow-rate fluctuations, and water-level fluctuations. This is almost always revealing for operators who can only visit a location once per day.

   ➢ Communications at all levels. This starts with person-to-person communications (often by radio).

   ➢ Mobility of staff. In general, a small yet mobile staff is much more efficient than a large, immobile staff. This is because a small mobile staff is not responsible for just one or two structures, but must understand how various structures and actions affect other areas. Mobility may be improved by better roads, motorcycles, trucks, etc.

   ➢ Flow-rate control and measurement at key bifurcation points. "Measurement" and "control" are not the same. Both are needed. There are many combinations of structures and techniques that provide rapid and accurate control and measurement of flow rates. This is typically a weak area for many irrigation projects.

   ➢ Existence of recirculation points or buffer reservoirs in the main canal system. "Loose" water control may be very adequate in the main system – provided there exists a place to re-regulate about 70 percent of the way down a canal.

   – Improved water-level control throughout the project. The flow-rate control and measurement (above) pertain only to the heads of canals and pipelines. Downstream of the head, it is important to easily maintain fairly constant water levels so that turnout flow rates do not change with time, and so that the canal banks are not damaged. With the proper types of structures, this is easy to do without much human effort.

   ➢ Re-organization of procedures for ordering and dispersing water. In most modern projects, one group is responsible for operating the main canal; another is responsible for the second level, and so on. Each group then has a very specific service objective. If a main canal is broken into "zones" with different offices controlling different "zones", there is almost always conflict between the zones. Re-organization of the operators is typically necessary. In addition, the whole

➢Remote monitoring of strategic locations. Such locations are typically buffer reservoirs, drains, and tail-ends of canals.

➢Remote manual control of flow rates at strategic locations. These are the heads of the main canal, and heads of major offtakes (turnouts) from the main canal.

➢Provision for spill, and the recapture of that spill, from the ends of all small canals.

The above points do not mention canal lining and maintenance equipment. Maintenance equipment must be adequate, and canal lining can reduce maintenance and seepage. However, these topics have been discussed for many decades, and the large sums of money spent on canal lining have generally not brought about modernization. This is because modernization is not just a single action. The items under point 5 represent a departure from traditional thinking of "concrete civil engineers" and a focus on operations.

Another "missing" item is a discussion about downstream control and sophisticated canal control algorithms. This is because an irrigation project must walk very well before it runs, and these technologies might be considered as "high risk". Sophisticated controls should be selected only after other options have been ruled out, and never before an adequate support infrastructure exists. There is no "magic pill" for modernization and improved irrigation performance, and simple options often provide excellent results.

It is good to listen to the operators and try to detect a few things that give them a lot of problems. It is sometimes possible to solve some of these problems quickly. By solving these problems for the operators, they will become advocates of further modernization efforts.

CONCLUSIONS

When conducted and analysed by a qualified irrigation engineer, the RAP provides indicators that explain the results and processes of an irrigation project. Many of these indicators can be used for benchmarking purposes, allowing for a comparison between projects and pre-/post-modernization performance. In a short period of only a few weeks, the RAP provides sufficient information to target key action items for modernization. Therefore, it serves as a valuable tool for countries to prioritize investments in different projects, and to prioritize specific actions within individual irrigation projects.

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Note

This version of the Rapid Appraisal Process (Annex 3) was modified in October 2002 by Charles Burt from his original manual and spreadsheets which he developed for Thierry G. Facon – FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. It had the financial support of the "Irrigation Institutions Window" of the World Bank.

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