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:

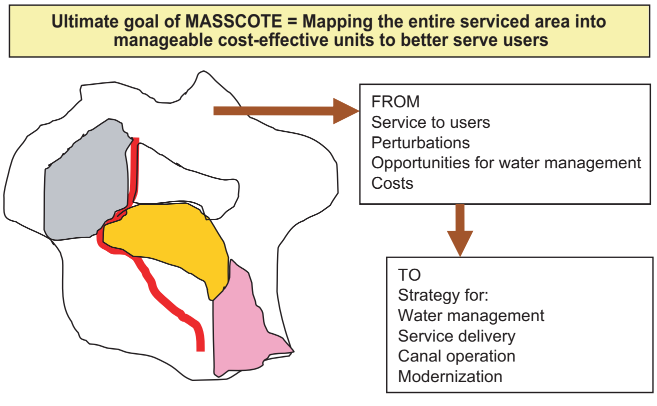
- water resources management;
- the service to irrigated agriculture;
- the cost-effectiveness of infrastructure management.

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



- 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.

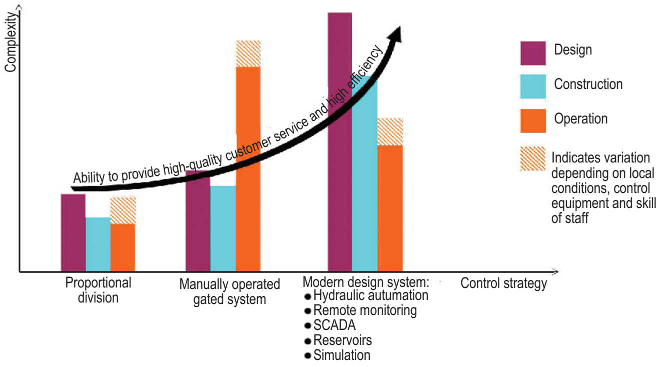
MASTERING THE INCREASED COMPLEXITY OF CANAL MANAGEMENT

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.

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.

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.

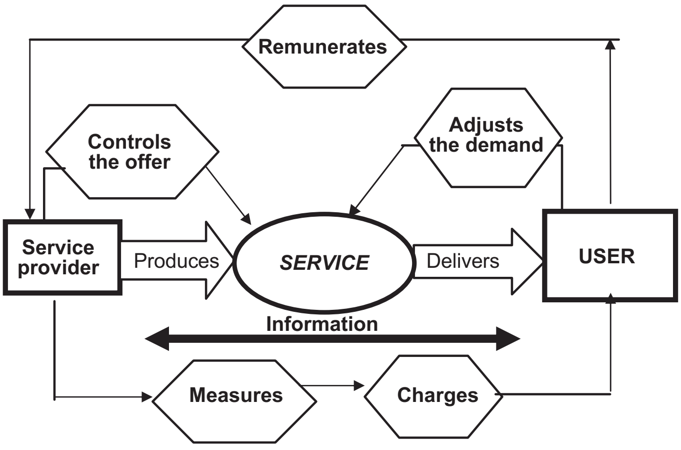
Service-oriented management can be modelled at the interface of agency–user (or supplier–receiver), as shown in Figure 3. In simple terms, the agency and the user first agree upon the specific details of the service of water (where, when, how, how much, etc.). The agency provides the service to the user, 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 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.

FIGURE 3

The service-oriented management approach



Source: Renault and Montginoul, 2003.

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

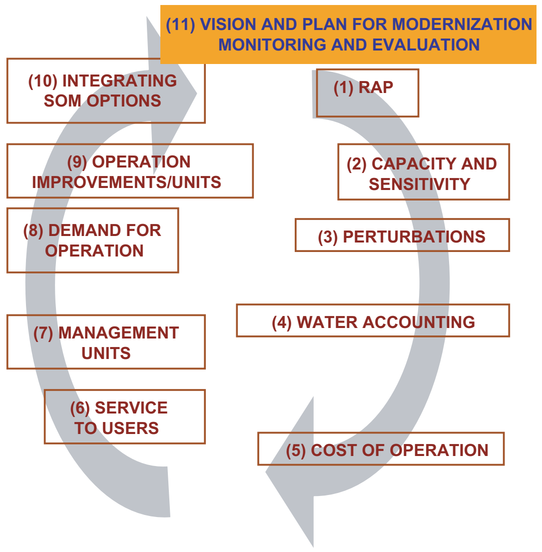
The MASSCOTE framework

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.

canal operation can be designed and implemented.

FIGURE 4

The steps in the MASSCOTE approach



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.

FIGURE 5
Embedded nature of the RAP and MASSCOTE

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.

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.

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

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:

- 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.

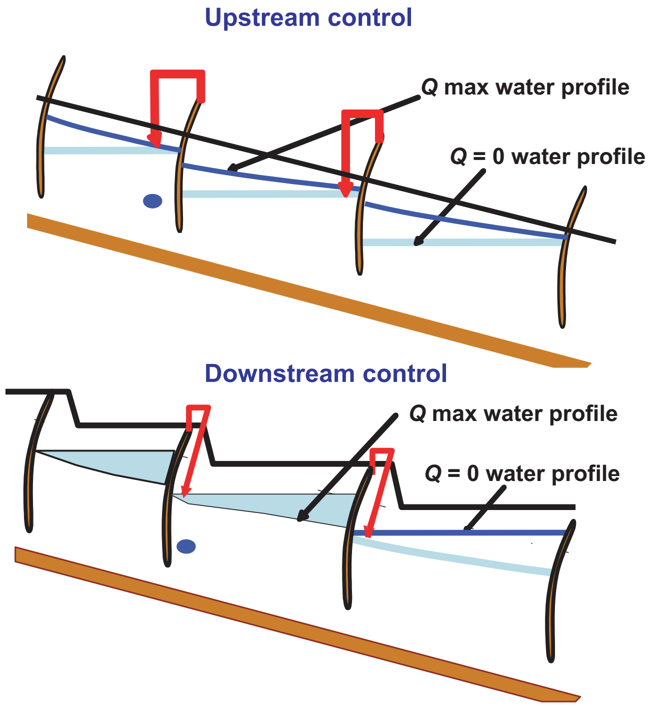
DEFINING THE CONTROLLED WATER VARIABLE

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

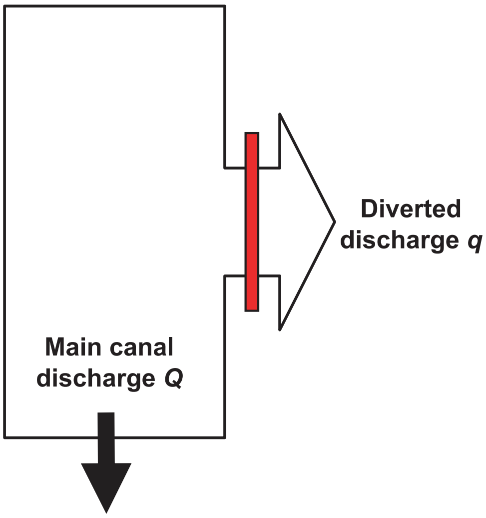
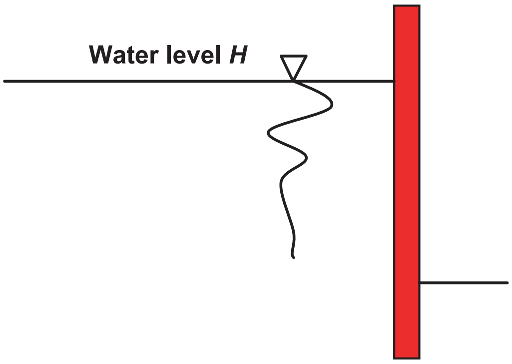


Figure 8
A regulator gate controls the water level upstream



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.

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

ORGANIZING THE OPERATION OF IRRIGATION STRUCTURES

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

- 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).

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

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

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 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.

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

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

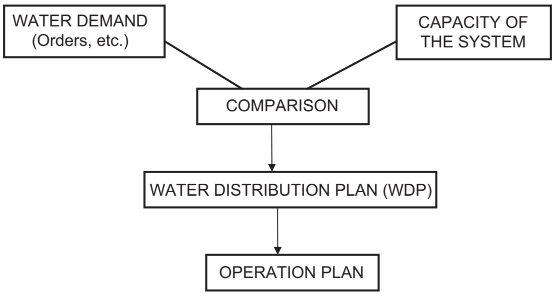
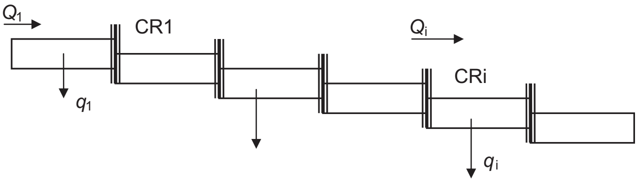


FIGURE 10
Sketch of a canal as a set of pools



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:

- 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.

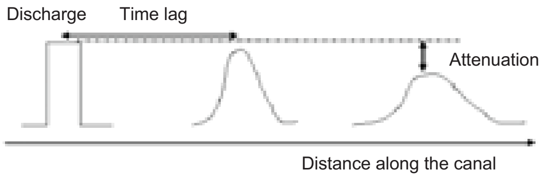
OPTIONS FOR SCHEDULED/PREDICTIVE OPERATIONS

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).

FIGURE 11

Downward wave propagation along a canal



Sequential downward TLO

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.

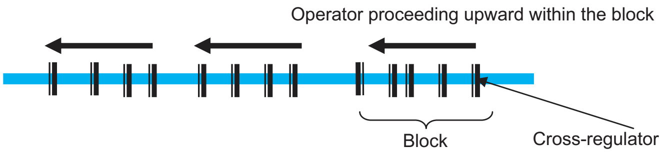
When the time lag to reach the tail-end exceeds one day, then this method creates large delays in enabling delivery changes, which may or may not be compatible with the water schedule. Where these delays are not acceptable, the managers should proceed with anticipation of the deliveries by issuing in 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



the wave is maximum in bottom-up operation.

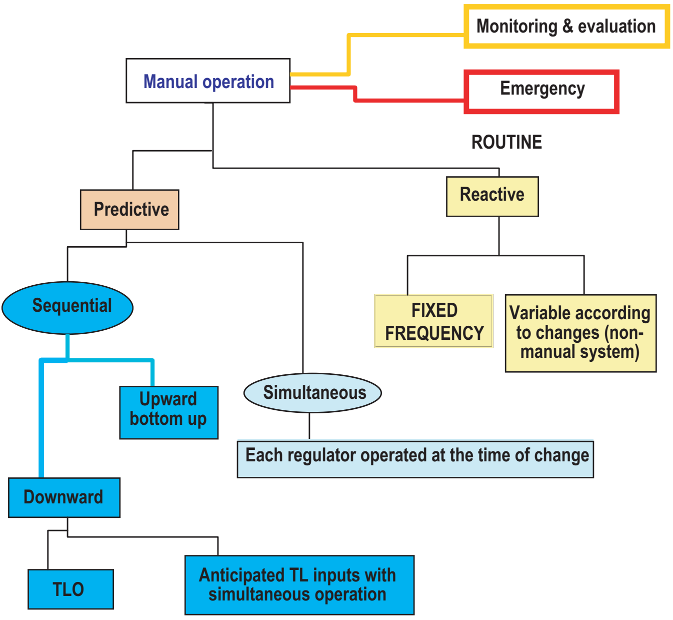


FIGURE 13
Operating options

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