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?

- 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?

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$/ha)
Equity	Production per unit of water (US$/m^3)

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.

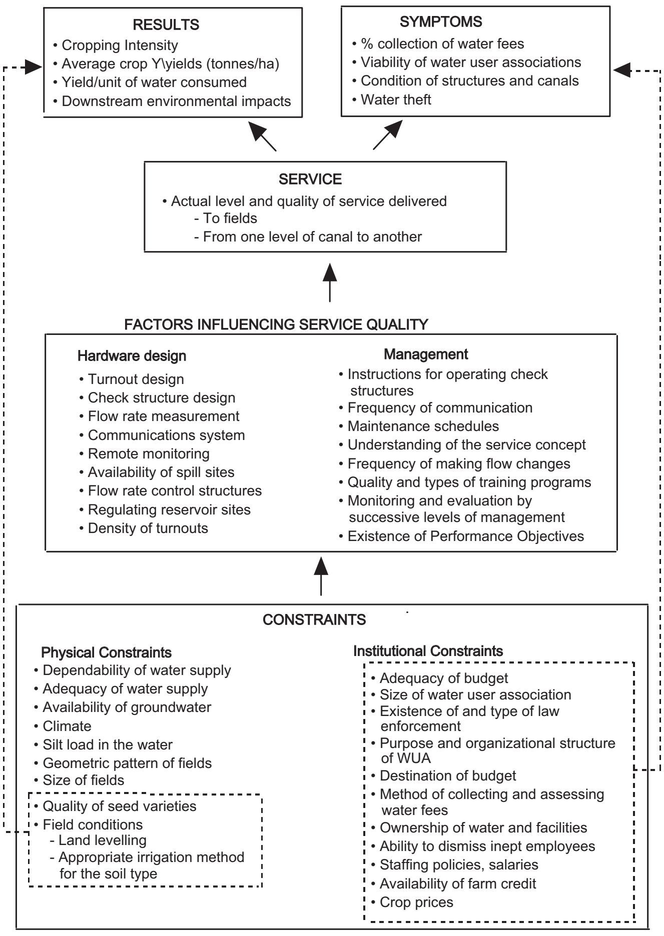
THE RAPID APPRAISAL PROCEDURE

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



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).

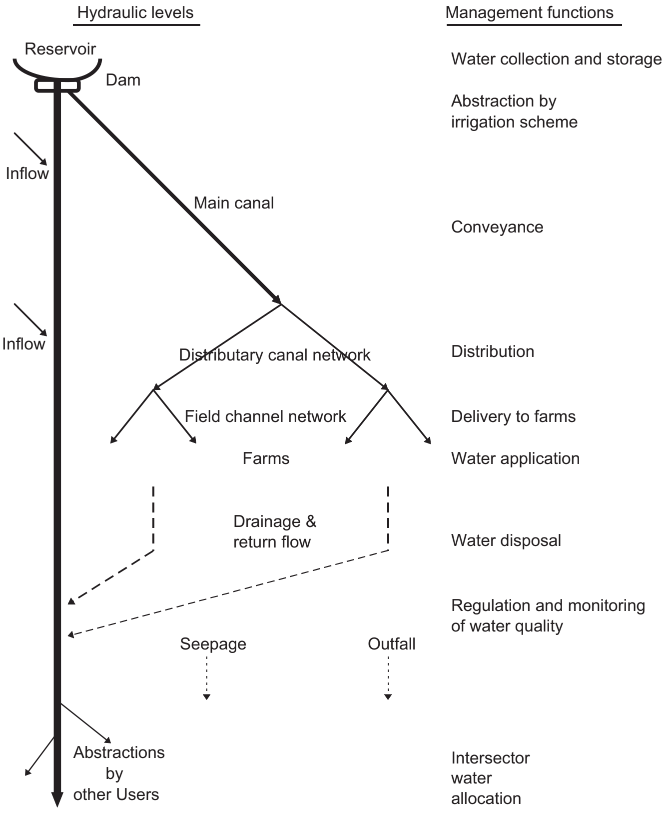
At each level in general and for water users in particular, it is very important to receive the required volume of water at the right time, thus adequacy, reliability and timeliness are crucial. However equity of water deliveries is also a critical target for managers. Therefore, adequacy. reliability 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



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 m^3/s (as low as 5 m^3/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

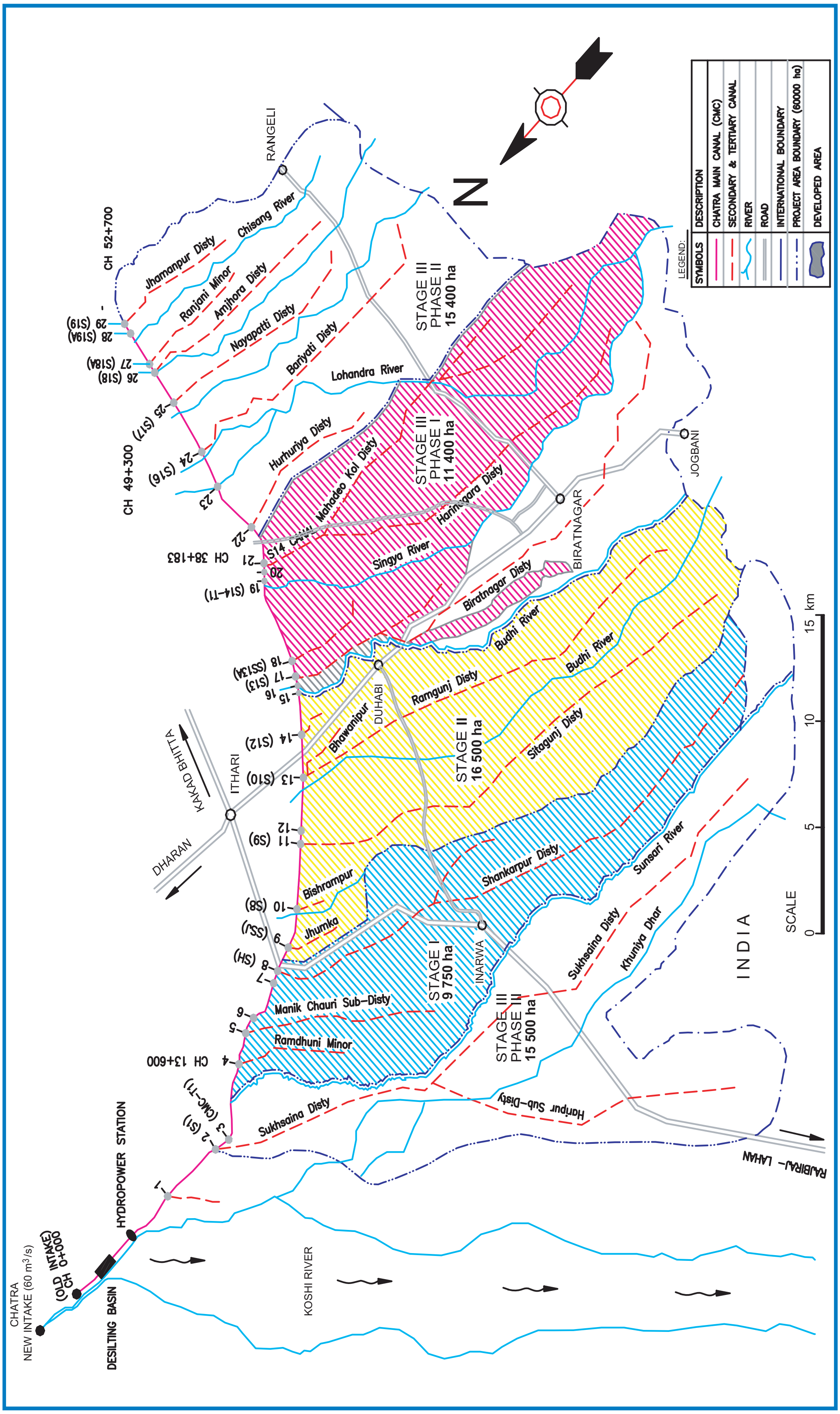
The primary objective of the initial rapid diagnosis was to obtain an initial sense of what and where the problems were, how to prioritize them, etc. The second objective was to start mobilizing the energy of the actors (managers and users) for modernization. The third was to generate a baseline assessment, 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 m^3/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 m^3/s to 60 m^3/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).

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

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 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

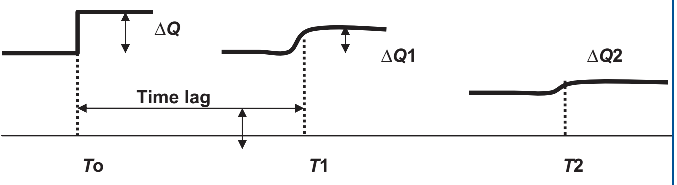
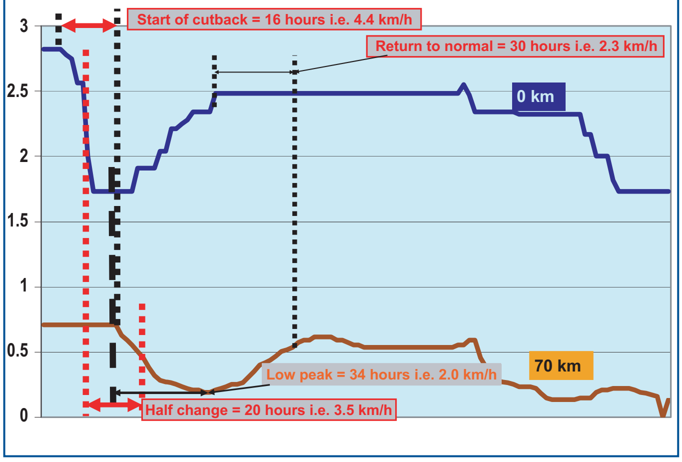


FIGURE 19
Estimations of time lag and celerity of change along the Ghataprabha Left Bank Canal for recorded discharge changes



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:

$$F = \frac{V}{\sqrt{g h_m}}$$

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

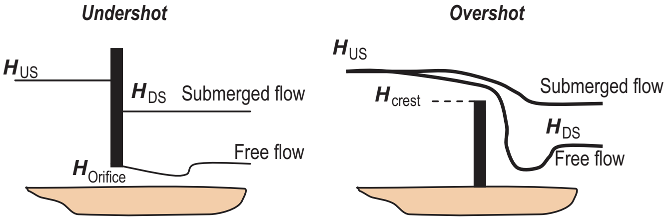
- ➢ Reduction in the flow capacity as a result of the reduced head at the structure.
- ➢ Modification of the behaviour of the structure. Flow becomes dependent on both upstream and downstream water level; discharge perturbations are propagated downward, water-level perturbations are propagated upward.
- ➢ 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

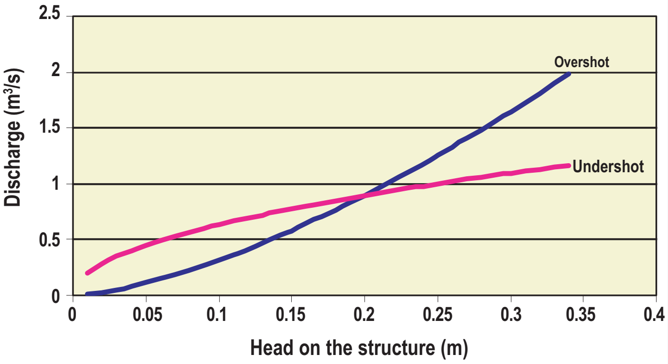


Plate 19

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:

TABLE 10
Seepage loss indications for different soil types

Soil type	Seepage loss (m^3/m^2/24 hours)
Clay loam	0.15–0.30
Sandy loam	0.30–0.45
Sandy/gravelly	0.45–0.70
Lined/clay	< 0.05

- 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.

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

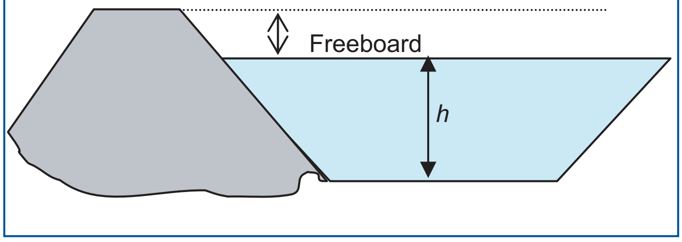


Plate 21
An operator using an old communications system in the Nara Canal, Sindh, Pakistan.

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.

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.

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.

SYSTEM BEHAVIOUR UNDER PERTURBATION

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

FIGURE 23
Input–output analysis

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:

$$\text{Sensitivity} = \frac{\text{Variation in output}}{\text{Variation in input}} \tag{1}$$

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.

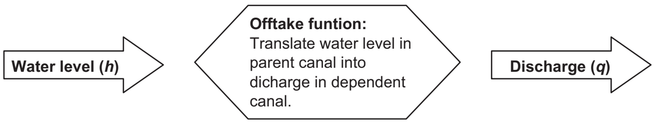
OFFTAKE SENSITIVITY

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).

FIGURE 24

Input and output for offtake structures



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):

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

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.

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.”

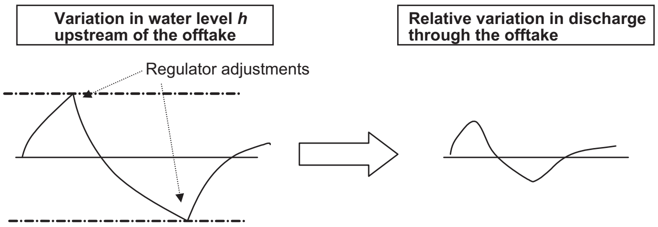
Use of the offtake sensitivity indicator

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).

FIGURE 25

Diversion behaviour of an offtake as a function of water depth variation



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).

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

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

TABLE 11

Relative variation in discharge for various values of sensitivity and perturbations

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:

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

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 $S_{\text{Offtake}} = 0.1/2 = 0.05$ 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 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:

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

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

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

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

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

Where S_{Offtake} is used to determine the impact of perturbations to the offtaking canal (high S_{Offtake} means high impact), the indicator for $S_{\text{Conveyance}}$ 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.

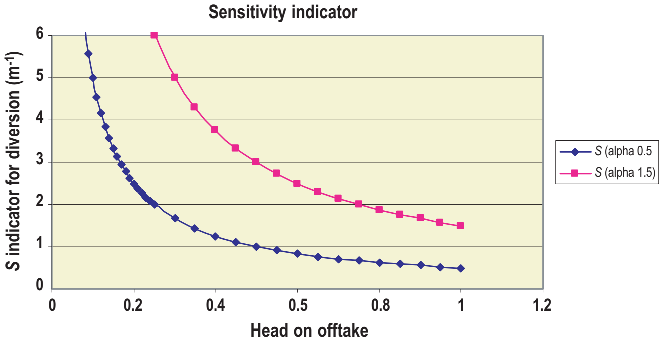
Taking the logarithm derivative of Equation 8 yields:

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

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)	$S = \frac{\Delta q / q}{\Delta h}$	$S = \frac{0.5}{h_E}$ h_E (head equivalent) includes effect of submergence	$S = \frac{0.5}{head}$ The "head" variable is the difference in head exerted on the structure (h_{US} - h_{DS})
Offtake (overshot)			$S = \frac{1.5}{head}$	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:

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

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 (α = 1.5) than undershot structures (α = 0.5) to changes in water level (Figure 26).

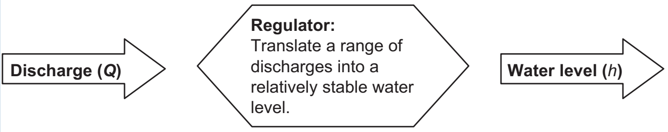
It should be remembered that sensitivity is not a static hydraulic characteristic of a specific structure. Operation at different heads gives different sensitivity indicators.

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



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):

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

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

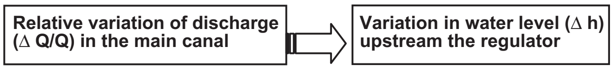


TABLE 14

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

	Sensitivity indicator ($S_{Regulator}$)		
Relative variation in canal discharge	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.

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

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

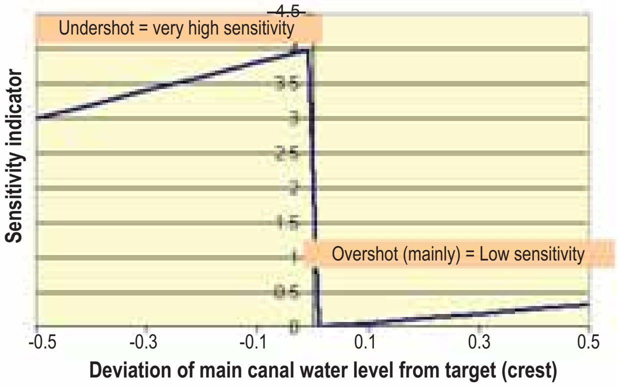
Structure	Variable studied	Definition	Geometric formulation	Approximate formula (ignoring submergence
Regulator (orifice)	Water level as a function of the relative variation in discharge *Q*	$S = \frac{\Delta h}{\Delta Q / Q}$	$S = 2h_E$	$S = 2 \cdot head$ The “head” variable is the difference in head exerted on the structure ($h_{US} - h_{DS}$)
Regulator (weir)			$S = \frac{head}{\left(3/2\right)}$	$S = 0.66 \bullet head$ 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*-).

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.

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.

FIGURE 29
Sensitivity of a mixed cross-regulator depending on the water level vis a vis 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

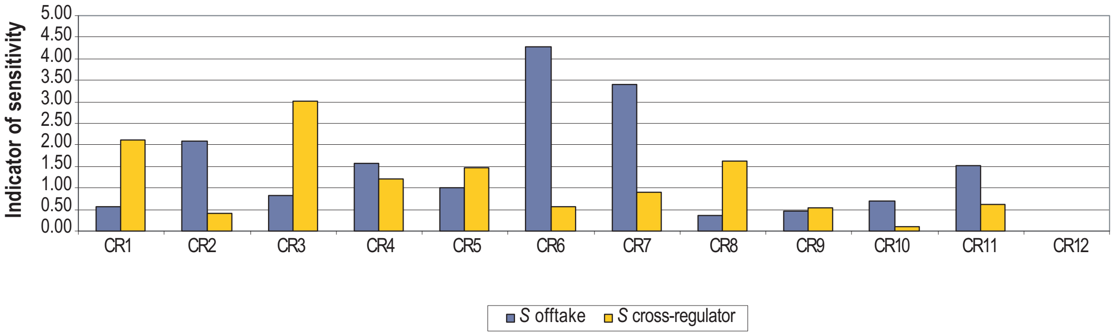


TABLE 16

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

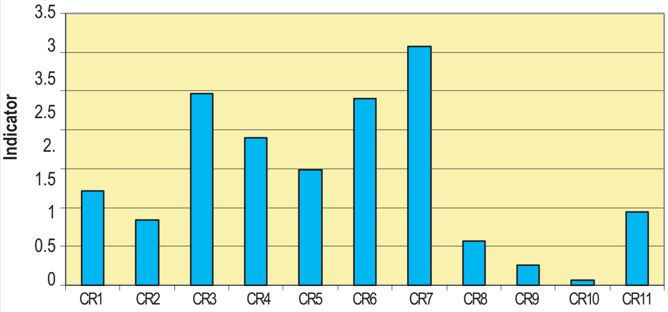
As a minimum, cross-regulators 6 and 7 should be operated with a tighter tolerance on water-level fluctuations than the others. A reduced target of ±5 cm would reduce the discharge variations at nearby offtakes to 21.5 and 17 percent, respectively.

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.

FIGURE 31
Hydraulic flexibility along the SMIS main canal, Nepal



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 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:

$$F = \frac{\Delta q / q}{\Delta Q / Q} \qquad (14)$$

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 ($S_{\text{Regulator}}$):

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

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

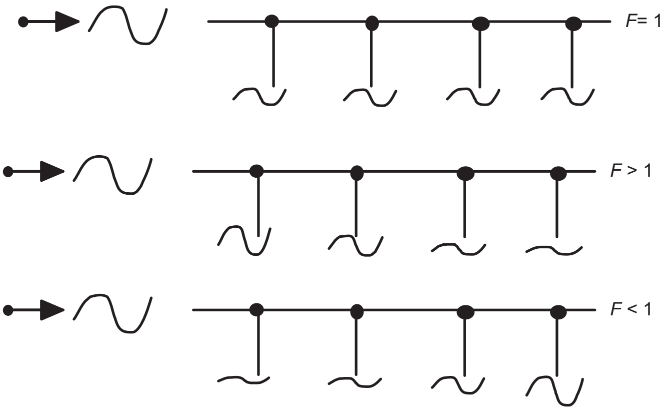
- $F < 1$ (underproportional): a relative change in discharge in the parent canal generates a smaller relative change in the offtaking canal. Fluctuations are diminished in the offtaking canal.
- $F = 1$ (proportional): a relative change in discharge in the parent canal generates an equal relative change 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.

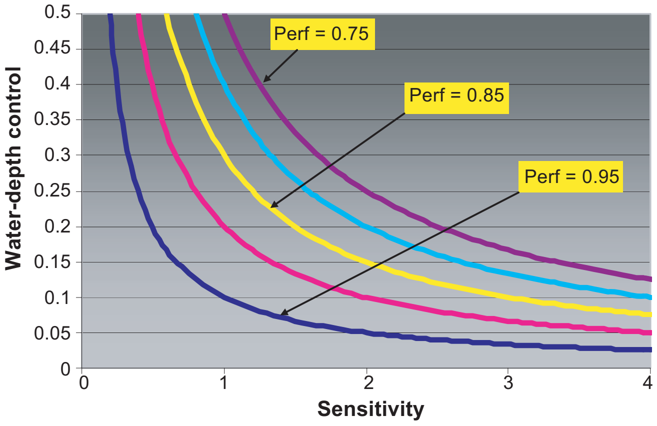
Use of sensitivity indicators for reaches

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.

FIGURE 33

Performance, control and sensitivity



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 (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:

$$P = 1 - \frac{1}{2} \Delta H_R S_S \qquad (16)$$

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:

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

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

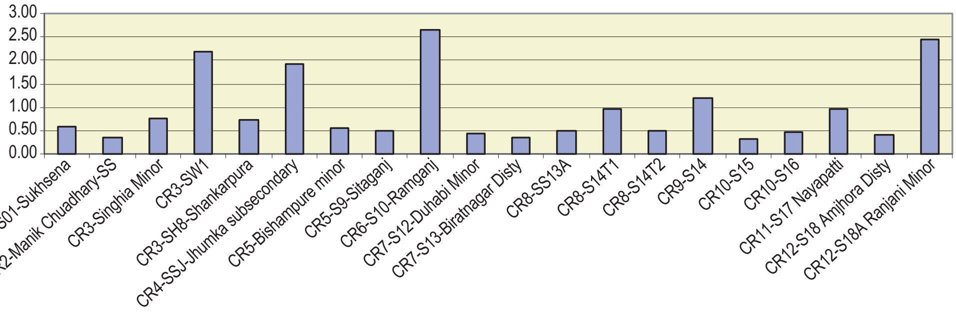


FIGURE 35

Simulation of perturbation along the SMIS main canal at main division points

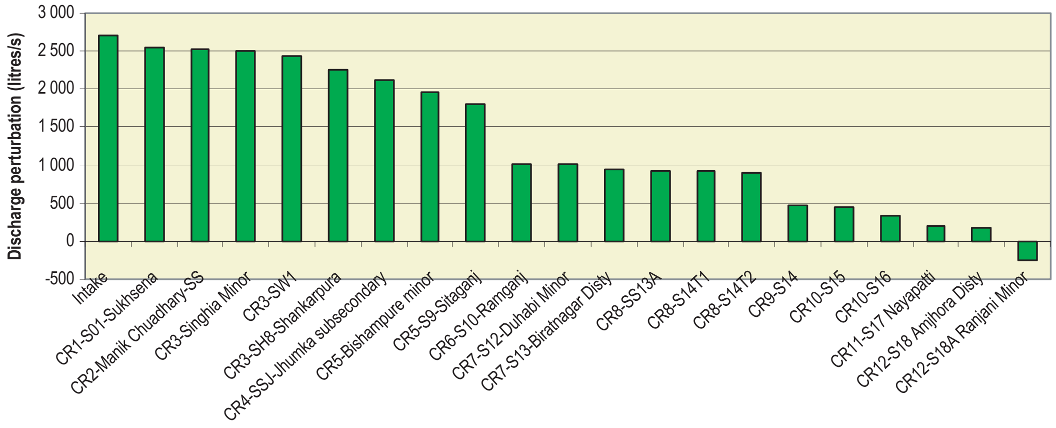
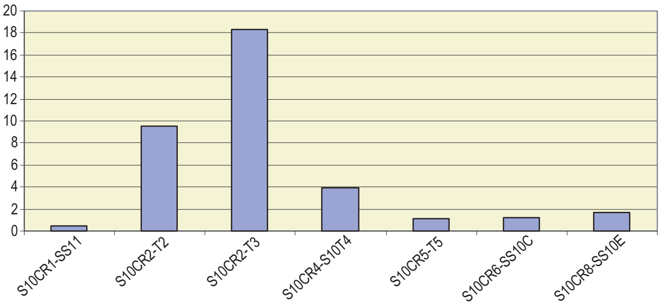


FIGURE 36

Proportionality along the Ramganj secondary canal, SMIS



- 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.

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.