RESEARCH PROJECT R6259

IRRIGATION CANAL CONTROL

FINAL REPORT OF STUDIES

VOLUME 1 THE MANUAL

CONTENTS

SUMMARY

The mounting pressure on available water supplies is resulting in a need to increase the productivity of water for irrigation. With increasing demands for water for domestic use, industry and the environment supplies of water for irrigation can be expected to fall, hence the need for "more from less" in irrigated agriculture.

These guidelines address the issue of water conservation and increased water use efficiency through measures of canal control. They act on the premise that better control and distribution of irrigation water within a canal network results in increased agricultural performance by providing water in a more adequate, timely and reliable manner to suit the needs and expectations of the farming community.

In the design of new irrigation schemes the selection of the appropriate method of canal control for a given operating environment is a fundamental decision to be taken at the planning stage. In the case of performance assessment of an existing scheme it will be necessary to consider if the existing method of canal control is the most appropriate for the current and possible future situation(s). The characteristics of the various canal control methods that are currently in use worldwide and the consequences and impacts of their use are described. A method is presented for selecting the most appropriate method of canal control according to the characteristics of the operating environment using the "Compatibility Matrix" developed in this study.

Although equally applicable to new projects, the Guidelines are expected to be applied principally in improving the water use efficiency in existing irrigation schemes. Guidelines relating to the performance evaluation of existing schemes and to the formulation of alternative improvement measures/strategies are presented. Measures used to assess the performance of irrigation schemes, and in particular water control and distribution are introduced and discussed.

Areas where problems are often encountered in relation to canal control are identified and possible solutions identified, analysed, and discussed. A hydraulic simulation model (ISIS) has been used to model, analyse, and quantify flow behaviour in relation to canal control structures and different operational procedures, enabling a deeper and quantified understanding of the constraints and potential improvements possible. The hydraulic model proved very successful in assessing the performance of some of the current operating procedures and in quantifying the improvements in performance due to enhanced control and operation.

Where possible quantified examples have been provided using case studies from selected irrigation schemes and a virtual system especially designed for this study.

The problem of water loss and inefficient water use in irrigation schemes cannot be attributed to canal control and operation only. Institutional and socio-economic factors also contribute to the problem. An integrated approach should be adopted if water use efficiency is to be improved.

It is hoped that the Guidelines will prove useful for designers of new or rehabilitated schemes, and for scheme managers. For designers the Guidelines provide a comprehensive guide to the canal control methods currently in use together with guidance on measures to ensure, as far as canal control is concerned, optimum operability of the irrigation network.

For scheme managers the Guidelines provide a ready reference, with worked examples, of typical operation scenarios where performance can be enhanced through more efficient use of the existing control structures and/or improved operational procedures.

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GLOSSARY OF TERMS

Command/Design water level (Full supply level

The water level in parent canal which will allow the intake of a branching canal to pass the full design flow.

Command area

Area served by irrigation canal.

Controls

Structures used on irrigation canals for controlling water level (cross-regulators), discharge (head regulators), or both.

Distributary

Canal taking off from a secondary/branch canal (and sometimes from main/primary canal directly), usually supplying water to tertiary/minor canals or directly to field offtakes.

Field channel

Channel carrying water from a watercourse to individual fields.

Field level

The area below the outlet from a canal irrigation system.

Hydraulic modelling/simulation

Making a representation of an irrigation system in a computer program to study the hydraulics of the system under different scenarios.

Irrigation project

Time bounded development of a new irrigation scheme or rehabilitation of an existing scheme.

Irrigation scheme

Refers to all aspects of irrigation; including the physical irrigation facilities, the people involved in irrigation (operation staff, farmers, labourers), the crops, and socio-economic factors.

Irrigation system

The physical part of irrigation schemes, i.e. the irrigation canals, drainage network and control structures.

Leakage

Passage of more flow than required flow through gates and other control structures due to poor maintenance or imperfect construction (usually refers to the situation when the gates still allow some water to pass when they are fully closed).

Main/Primary

Canal conveying water from the main intake of an irrigation system to secondary/branch canals.

Main system

The canal irrigation system above the outlets, including diversion works, reservoirs, control structures, main, secondary, and distributary canals.

Offtake/Outlet

The structure on a distributary or tertiary canal through which water is delivered to field channels. It is usually the point at which water control is taken over directly by farmers, separating the main system from the field level.

Performance

The measurement of how an irrigation system or scheme compares with targets in terms of water use efficiency and other parameters (indicators).

Performance indicators

Parameters used for assessment of actual achievement compared with targets (expressed as ratios).

Rejected flow

Flow wasted through canal tail-escapes or other rejection structures due to imperfect management and/or operation or sudden reduction in demand.

Response time

The time period between a change in the flow at the upstream end of a canal reach and the arrival of the full modified flow at the downstream end of the reach, Figure I.

Rotational flow

In its simplest for this involves dividing the command area into two or more sections and diverting all available water to each section in turns. The duration of a turn above the tertiary level can be fixed or variable depending on the rotation schedule though more complex rotational arrangements are also practised in some countries. Usually practised above the tertiary level only when the supply is short.

Scheduling

Planning the distribution of water including specifying water allocations and making necessary adjustments to control structures.

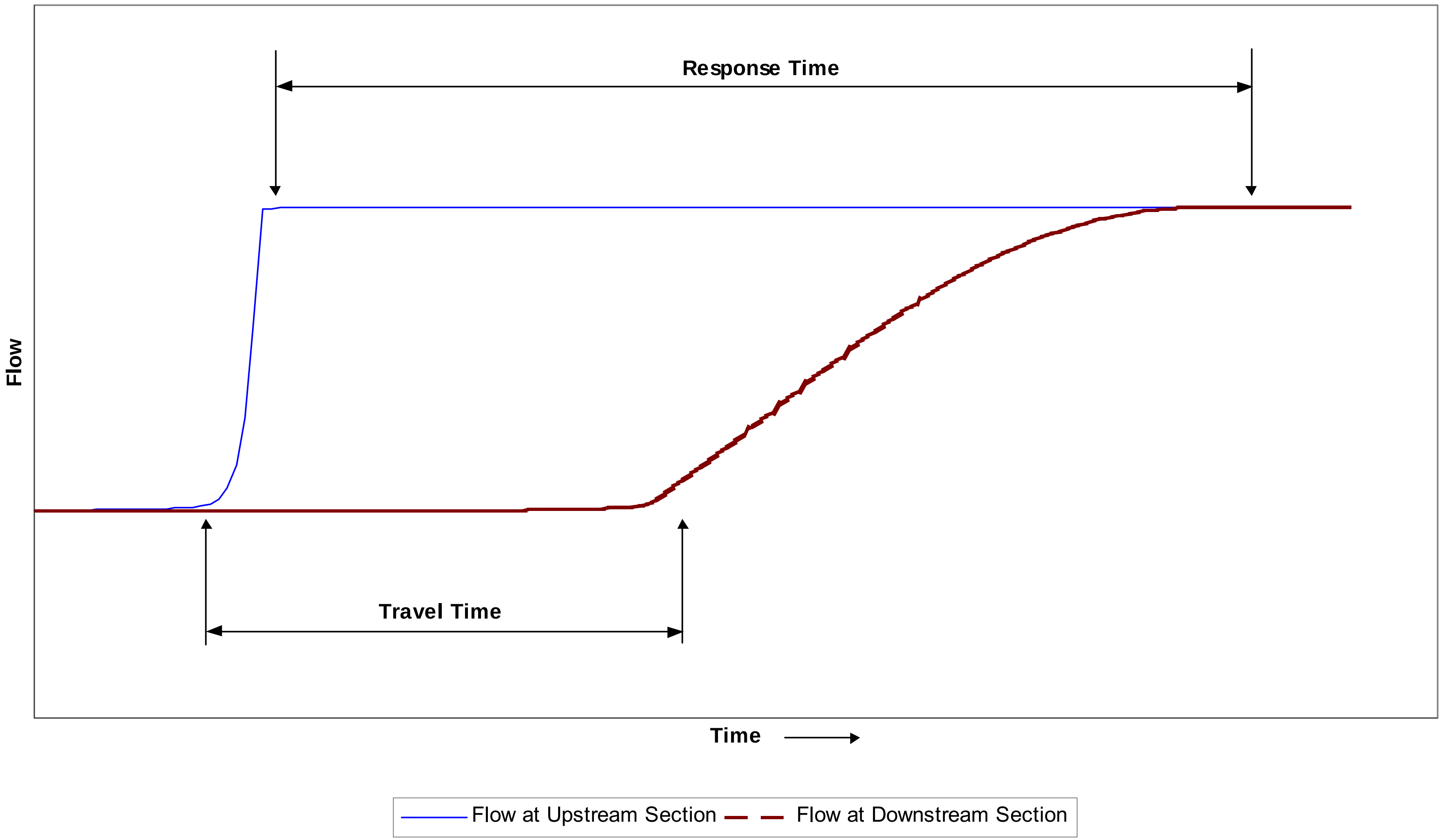
Secondary/Branch

Canal taking off from a main/primary canal and supplying distributary canals plus some minors.

Seepage

The loss of water through infiltration into the soil from a water source such as a reservoir or an irrigation canal delivering water supplies.

Figure 1   Definition of Flow Travel and Response Times



Surface reservoirs

Enlargements to some canal cross-sections (in-line reservoirs) or separate water storage areas (off-line reservoirs) used to store excess water and supply water to the command area when the supply is short.

Tertiary/Minor

The lowest level of canal on an irrigation system supplying water to field offtakes/outlets.

Travel time

The time period between a change in the flow at the upstream end of a canal reach and the arrival of the first wave (flow disturbance) at the downstream end of the reach, Figure I. The travel time depends on many factors such as the hydraulics of the canal under consideration and the flow rates before and after the change.

Warabandi

A system of water distribution, mainly practised in northwest India and Pakistan, where canal design and regulation permit fairly constant flow of water through fixed outlets. The flow is allocated to farmers at fixed times with duration of turn proportional to landholding area.

Wastage

Loss of water through failure to control it (e.g. not stopping water diversion to the fields when it is not needed at night).

Water delivery

Distribution of water through controlling its movement from a point of origin to a point of handover.

Watercourse

Channel supplying water from an outlet to field channels or fields directly.

1 OBJECTIVES OF THE RESEARCH PROJECT

1.1 Objective

The overall goal of the project is to support sustainable food production and rural development.

The objective of the project is, under conditions of competing demands for water, to improve the efficiency of use and thus enhance the amount of water available for irrigated agricultural production.

1.2 Purpose

To achieve the overall objective, the purpose of the project is to prepare a set of Guidelines which will facilitate increased water use efficiency and reduced water losses. To achieve this purpose the Guidelines focus on improvement of the operational control of irrigation systems either existing or new at the distribution level.

2 INTRODUCTION

During the distribution of irrigation supplies in open channels, a large proportion of the water diverted is lost and is not available at field level. The losses in distribution have been estimated in various studies at between 20 and 55% of the water originally diverted at the head of the distribution system. **(insert recent source for this information and include in references)**These losses are dependant on a variety of factors including the efficiency of distribution, the size of the irrigated area, the level of technology employed in distribution and other institutional and sound factors. Principally variation in the magnitude of losses varies widely according to the appropriateness of the operating environment.

Whilst part of the distribution losses within the scheme may be recovered downstream in the drainage basin and thus contribute to river or groundwater flow the losses result in reduced agricultural production, lower returns to the investments made in construction and operation of the irrigation infrastructure and an inefficient use of land and water resources.

The present Research Project identifies possible strategies by which these losses may be reduced.

2.1 Organisation of the Report

The report is divided into two volumes:

Vol 1 - Irrigation Canal Control: The Manual

Vol 2 - Irrigation Canal Control and The Guidelines

The Guidelines (Vol 2) are designed from the detailed discussion and assessment of schemes presented in The Manual (Vol 1). As such both volumes deal with both qualitative and quantitative performance assessment.

The information presented in The Manual has been compiled from three principal sources:

- a literature search;
- project records and questionnaires;
- the experience of Irrigation Practitioners

In Part 1 of the Manual, Section 3 deals with the causes of water losses and principally physical measures to overcome them whilst Section 4 presents background information concerning different methods of canal control

These are followed by Section 5 which gives details about the approach to assessing performance of irrigation schemes whilst Section 6 presents a method for evaluating the performance of irrigation schemes under different methods of canal control presented using the “Compatibility Matrix” approach. This enables the influence of a range of parameters affecting performance to be evaluated and has been used in the Study to identify those features where intervention or improvements may be required to improve.

Part II of the Manual deals with results from the simulation of canal control scenarios applied to real irrigation schemes using hydraulic modelling techniques.

The application of the research schemes, would enable quantitative evaluation of the performance of those schemes and provide information on investment decisions to implement of water saving strategies.

2.2 Potential Uses of the Guidelines

The Guidelines have been prepared either:

- As Guidelines for good practice when planning or designing new or extended schemes, or when considering the rehabilitation or modification of existing schemes; or

- As Guidelines about important factors to be borne in mind when evaluating the performance of existing schemes, or when considering the possibility of changing the type of operational control of a scheme in order to improve operational performance.

They will be provide a useful aid to both designers and operators, at the planning stage for new schemes when the design concept are being formulated, and for evaluating potential reasons for problematic operation for existing schemes. At this stage the need for in-scheme storage and rotational supply would be evaluated together with the appropriate method of canal control.

Using the Guidelines scheme designers would be able to consult with farmer groups and organisations and to take account of the social and institutional constraints which may apply in the development area. Typical major constraints are presented in the "Compatibility Matrix", (Table 6.1), which illustrates the relative importance of various factors on the operating environment for different canal control methods. Appendix A gives a proforma checklist/questionnaire.

Where varied flow regimes are expected in distribution system, appropriate methods of analysis should be adopted to analyse for these conditions. Hydrodynamic models of the distribution system have proved very useful in this process and the Guidelines provide information about their use process. The mathematical models could be used.

- To enable alternative design concepts or operational routines to be evaluated for new schemes.

- To develop operational procedures for existing schemes where performance can be enhanced through more efficient use of existing control structures.

- To evaluate the effect of modification or rehabilitation during the life of a project for example the construction of major extensions.

2.3 Proposals for the Dissemination of the Results of the Research

The Consultant's Principal Researcher, Khaled El-Askari, presented a paper on the interim results of the Study to a joint technical meeting of ICID on "Regulating Water" which was held on 11 February 1998 at the Institution of Civil Engineers.

It is expected that the present research will provide the opportunity to present technical papers to International Bodies such as ICID and IIMI and the

Consultants will monitor calls for Papers in the relevant publications for such an opportunity.

The Consultants recommend that abstracts of the research could be published in "GRID" the journal of "IPTRID" and/or "DfID Water", and that the relevant Working Group of ICID Forum should be notified.

The Consultants recommend that an effective means of dissemination of the results of the research would be by holding seminars at overseas centres where the application of the research to local conditions could be discussed and appropriate water saving strategies developed.

2.4 Implementation of the Guidelines

Halcrow will apply the research where opportunities arise in future assignments overseas which involve the design of new irrigation infrastructure or rehabilitation of existing systems.

IIDS are currently using the methodology employed in the research in ongoing studies related to asset management and system improvement.

Dissemination of the results of the research as described above and the wider availability of the relevant software will generate opportunities for application of the guidelines in those countries where water shortages exist for agriculture and other purposes.

3 CAUSES OF WATER LOSSES AND MEASURES TO OVERCOME THEM

In irrigation as with other industries, some loss and wastage of the resources used in the production will be experienced.

As water availability at the field is a major factor determining agricultural production, the reduction of water losses is key to maximising production from a limited resource.

In the distribution of water for irrigation, water is lost through seepage and evaporation from canals, by spillage direct to drains because of inefficient utilisation and management and occasionally by abstraction for other, unauthorised uses. Such losses are possible to quantify, although only rough estimation may be possible some times, either in the field or by using hydraulic modelling as illustrated in Sections 8 to 10 later in this report.

Although the present study focuses principally on irrigation conveyance and distribution systems, it is widely acknowledged that effective reduction of water losses in irrigation schemes will encompass a wider range of consideration including social and institutional aspects. These factors are qualitative in nature and therefore their impacts are more difficult to assess. However, they should not be neglected if effective water saving strategies should be formulated.

Section 4.1 describes the major causes of water loss and inefficient water use in irrigation schemes. They are classified in five categories according to the nature of the cause (problems related to the physical system, the management and operation, system maintenance, the field-level, and socio-economic factors). Some of the measures which may be implemented to overcome them are outlined in Section 4.2.

3.1 Causes of Water Losses and Low Performance

3.1.1 Irrigation System

Project Development

After the construction of the major works in a new irrigation project, it often takes many years before all parts of the system are completed. During the long development process the parts of the project which have been constructed are usually operated.

If the full water supply is allowed in the system, water will be abundant and in the relatively small area that is equipped farmers become used to oversupply. It is often difficult to redress the situation after the completion of the whole project when oversupply to some areas has become established practice (Jurriëns and Jong, 1989). From the beginning of the operation of a staged development, the supply which enters the system should always match the design flow of the area in operation. This may however cause other problems if the control structures are fixed-crest weirs for example because the flow released in the canals will be less than the full design discharge and the water levels will be lower than the full supply levels causing difficulty in commanding and diverting the required flow to the offtakes.

Improper and Erroneous Layouts and Designs

The review of the literature covering irrigation scheme evaluation and the study of representative schemes in this project reveal that some problems in scheme layout and design are common worldwide. Examples of problems which are commonly encountered are:

- Improper choice of control structures and/or the use of incompatible components such as manually operated undershot gates in cross-regulators for water level control and weir-type structures in offtakes for flow rate control (refer to Section 8.1 for more details).

- Location of offtakes of tertiary and minor canals at too great a distance from the commanding cross-regulators. If the offtakes designed to operate successfully at or near full supply discharge, under low flows, many of those offtakes may not be effectively commanded and hence fail to divert the required flow (refer to Sections 9.4 & 9.5 for more details).

- Standard designs focus mainly on the *critical* operating conditions e.g. the maximum head on the structures and the maximum flows in the canals. In addition, designs are often based on steady state flow. Other operating conditions may not be considered and the system may fail to function effectively under these conditions.

Slow Response to Changes

The upper limit of the flow velocity in open channels is set to safeguard the physical components of the system against excessive erosion and other damage. This limitation adversely affects the speed of making changes in the flow.

The time lag between a change in the flow in an upper part of the system and the arrival of the change in a lower part is known as the flow travel time. The longer the travel time, the slower the response of the system will be. Long travel and response times may cause potential water wastage. The travel time is typically longer in long and oversized canals.

Canal automation can reduce lag times by a factor of almost two (Ahmed & Jeppson, 1993). The type of control structures can also influence the flow travel time. Weirs have faster response to changes in the flow and hence do not cause further delays, while undershot gates cause some delay to the flow and hence add to the time delay of the system (refer to Section 8.1 for more details). Irrigation systems which have weir-type cross-regulators are therefore expected to have a much faster response to changes than those with undershot gated cross-regulators.

Flow Measurement

Flow measurement is a key issue and requirement in the efficient operation and management of most irrigation systems. Without flow data managers and operators are unlikely to be able effectively and efficiently match supply with demand.

In spite of this, there is usually an insufficient number of flow measurement facilities installed in irrigation systems. In these cases, minimising the number of flow measurement structures has always been justified on technical and economic grounds. From the hydraulic point of view, installing more flow measurement structures increases head losses in the system. In many irrigation systems, the terrain is relatively flat and the head loss in the system is always kept to the minimum possible in order to avoid water lifting and to allow farmers to irrigate by gravity. The installation of more structures in a system means higher design, construction, operation, and maintenance costs.

Passive Control

Passive control refers to control structures which cannot be controlled by operation staff such as weirs with fixed crests and fully automated gates. Although the main advantage of using these structures is to minimise operator input, a manual override mode must still be provided for abnormal situations such as the emergency closure of a canal.

For an upstream control to respond to reductions in the demands it must be able to not only reduce the flow at the head of the system but also control the water stored in canal reaches by operating the cross-regulators. Fixed-crest cross-regulators which are not provided with additional on/off undershot gates to stop the flow will not be able to function as required in such a case and will cause unnecessary water wastage.

Despite the fact that the provision of manual override modes in automated structures provides the opportunity for mismanagement of the system, the provision of those further facilities adds to the flexibility and efficiency of the system.

Insufficient Controls

The ability of canals to allow water which is not required to flow to waste without damaging either the canal system or the surrounding land requires strategically placed escape structures to be provided. On most of the large irrigation systems in the Indian sub-continent constructed during the colonial period, escapes were not provided. Water flows down canals into watercourses through fixed division and ungated offtake structures. Thus when irrigation is not required, say when heavy rainfall provides the crop water requirements without irrigation, farmers still receive water into their watercourses. This contributes to flooding, waterlogging and salinity problems. Where farmers block their watercourse inlets, canal flow continues down the main canal until the flow exceeds the diminishing capacity of the canal and the canal breaches causing even greater damage. Adequate escapes, flowing to drains, are therefore critical to the safety of the canal system and to the irrigated land. Diverting excess water to the drains when it is not possible to store it can be useful in some cases when other downstream irrigation schemes make use of the water in the drains.

3.1.2 Management and Operation

Incompatible Operational Plans

Another type of error made by designers is to prepare operational plans which are not compatible with the physical system and the environment. A good operation plan should be based on a clear and comprehensive understanding of the project and its requirements. Factors such as how the scheme will be operated, by whom, with what level of salary and incentives, in what social and institutional environment are as important in design as factors such as climate, soil types, crops to be grown, and water availability and quality. The "software" is as important as the "hardware".

Lack of Communication

All irrigation systems, except for the fixed proportional distribution systems, require communication networks. For manually operated systems the communication is human, for automated control systems the communication is either hydraulic or electrical. In either case information needs to be collected, processed, analysed and acted upon in order that water is delivered to the farm unit.

Chambers (1988) identifies lack of communication as one of the causes of poor water scheduling and delivery in manually operated irrigation systems. Communication is required both upwards to managers and downwards to farmers. Managers need to have continuously updated information about the status of their systems in order to be able to take proper decisions. Improving the response of a source-oriented system (manual upstream water level control for example) requires that those controlling the upper parts of the system are swiftly notified of any changes in the demands in the lower parts. Efficient communication should therefore be considered as an integral component of such systems not as an option.

Communication between the scheme manager and the farmers and between the scheme manager and operation staff are equally important. Greater efficiency will be attained in general if irrigation systems are managed to satisfy the requirements of the farmers.

Inadequate/Improper Training

Adequate training of operation and maintenance staff is a key component of a well managed irrigation system. In some cases, training of field staff may emphasise the design assumptions and the operational rules that have been drawn up during project development. Such training does not take into consideration the reality of system operation in the field and the situations actually faced by operation staff, and is therefore unrealistic since it does not reflect the fundamental problems of design assumptions and operational reality.

Training of design and operation engineers is also important to introduce them to the new technologies and techniques which come out continuously and to make them aware of the national and scheme-wise problems which arise with time.

Pressure on Management

The daily schedules of irrigation managers include issues such as politics, finance, personnel, and others. Although these issues are within the managerial activities, they quite often dominate their daily schedules leaving very little, if any, time for the technical aspects. The external pressure on managers from politicians, strong farmers, and lack of operation and maintenance funds not only consumes most of their time to deal with these problems but also may sometimes influence their decisions concerning technical issues as well.

3.1.3 System Maintenance

The need for irrigation system rehabilitation demonstrates that the system has previously not been properly maintained. Under these circumstances, the system performance and water use efficiency may be very low in the period before the rehabilitation.

In many irrigation systems prior to rehabilitation control structures are frequently reported as being either in a very poor condition or totally inoperable. Leakage from canal tail-escape structures, for example, can cause large quantities of water to be wasted. Seepage through damaged canal linings can be as much as that from unlined canals. It is also more difficult for farmers to stop diverting irrigation water to their fields when it is not needed if offtake structures are broken or have been removed.

A further example where performance is affected by poor maintenance is when canal capacity is reduced by sedimentation and weed growth. Such a condition leads not only to inadequacy, but also to inequity, in water supply.

3.1.4 Field Level

The magnitude of water losses, and the opportunities for water saving, at the field-level are often greater than at other levels. With a worldwide average field application efficiency of about 50% or less, a large percentage of the water lost in irrigation schemes can be saved by implementing water saving measures at the field level. Such measures might include training/awareness creation amongst farmers of irrigation scheduling for their crops, changing of irrigation method (surface to sprinkler/drip), improvement in adequacy and reliability of irrigation water supply to the farm unit, etc (refer to Section 4.2.4 for more details). The full list of the possible causes of water losses at the field-level is extensive. However, water loss must be treated if an effective solution to the problem of irrigation water wastage in irrigation schemes is to be found.

3.1.5 Socio-economic

Cropping Patterns and Unauthorised Abstractions

Some irrigation schemes are designed for the cultivation of subsistence crops that do not require the application of large quantities of water. In some cases allowance for a limited area of high-value crops, which usually have higher water requirements, may be made. It is very common, however, that farmers at the top-end of the system who have better access to water exceed the permitted allowance and plant larger areas to crops with a high-water requirement. Since the offtakes to the fields of these farmers will not be designed to deliver the large quantities of water required, the farmers resort to increasing the capacity of their offtakes by damaging the original structures, installing additional water abstraction devices, or even breaching the embankments of the canals delivering water to the offtakes. This increases the conveyance losses and creates water scarcity to tail-end farmers. In addition to the adverse impact of low water distribution equity, inefficient water use, and damage to the environment, farmers who grow high-value crops and make higher profits may prejudice those at the tail-end to be able to subsist. The socio-economic impacts of these practices can be highly undesirable.

Irrigation at Night

Most irrigation systems are designed to deliver water to the fields continuously throughout 24 hours of each day and assume that farmers will practice irrigation at night. This assumption is usually made because simply there is nowhere else to store the water at night or because the other alternatives are much more expensive. If farmers do not practice irrigation at night, however, substantial quantities of water will be lost.

Whether irrigation at night is to be practised in a scheme or not should not be entirely an engineering decision; farmers' opinion is important. Irrigation at night may or may not be accepted by farmers because of many factors (Chambers, 1988). Among the factors that make irrigation at night appealing to farmers are:

- In hot climates where working during the daytime is very hard. In general, the hotter the climate, the more acceptable it is to be active at night;

- Where farmers are part-time and have work during the day. Although it cannot be argued that this category of farmers represents a majority, it is, interestingly, on the increase;

- Other, often upstream farmers, are not irrigating and there is therefore improved access to water.

It is, however, much more common for farmers to dislike irrigating at night for the following reasons:

- It is inconvenient and anti-social;

- It usually costs more to irrigate at night. Not all the labour available for day work will accept to work at night, and the charges are higher at night. More labour is required for irrigation at night because of the poor visibility. Family members who may be able to take part in irrigation during the day like women and children are less likely to be used at night. Lights will be required to irrigate in dark nights;

- The danger of attacks by wild animals and robbers during the hours of darkness.

3.2 Irrigation Water Saving Measures

3.2.1 Irrigation System

Regulating and Storing Water

Although dams and reservoirs are widely criticised for their adverse impacts on the environment, they are effective water saving tools, especially in run-of-river irrigation schemes. Water can be efficiently regulated by storing excess water in reservoirs during low-demand periods and releasing the deficit from the reservoirs during periods of high-demand. Groundwater reservoirs may be developed by pumping from boreholes and the water abstracted during the dry season replenished by natural rainfall at other times of the year.

Smaller water storage reservoirs can be used in different locations of the irrigation system to increase its operational flexibility. The primary use for those reservoirs will be to balance the daily or weekly operation of supply-oriented systems where water is to be available to the users nominally on-demand.

When quantities of water in excess of demand enter the system while the demand is low this excess can be stored in regulation reservoirs for later use. Locating the reservoirs as close to the water users as possible helps to reduce the long travel times in large and complicated irrigation networks. When users within the system request or use more water, the increase in the demand is met from the nearest storage reservoir(s) until it is balanced by flow arriving following changes made at the intake to the system.

If off-line reservoirs are not to be used, allowance for some in-line storage can be made by over-sizing the cross-sections of the canals at the lower end of the system.

Flow Measurement

More emphasis must be given to flow measurement at flow division locations and at the lower levels of irrigation systems, especially at the offtakes close to the fields. This is to enable the implementation of water distribution plans with a reasonable degree of accuracy. Also, measuring the actual flows delivered to farmers or groups of farmers makes it possible to apply water charges based on actual volumes of water used.

Flow measurement structures should be regularly calibrated to ensure the accuracy of measurements made. The accuracy of most flow measurement structures is relatively low (between 5 and 15%).

3.2.2 Management and Operation

Matching Supply with Demand

Matching water supply with demand is a two-phase process. The first phase is a planning activity which should be carried out on a scheme-wide scale before the beginning of every growing season. In this phase a trial of *matching demand with supply* is made. A forecast of the water resources that are expected to be available should be made and then a suitable cropping pattern planned whose water demand will closely match the expected supply. Farmers or water user associations must be consulted and involved in the planning of the cropping pattern.

In the second phase of this activity the average flow to be diverted is forecast for, say the nearest 10 day period, based on the water requirements of the crops under cultivation at that time (*matching supply with demand*). This activity will require a major effort in data collection and processing. Office automation might be necessary for the proper implementation of this task.

Conjunctive Use of Multiple Water Resources

The conjunctive use of surface water and groundwater may offer the possibility of increasing agricultural production when water availability from surface sources alone would otherwise be limited. Groundwater abstracted from shallow aquifers may enable some of the water lost in conveyance to be recovered and thereby increase the schemes water use efficiency. The use of water from deep aquifers would incur higher pumping costs and in addition, unacceptable negative benefits in other areas.

Reduction of the Amount of Water Applied to Crops

In order to ensure that water is not wasted at the field level and the correct amount of water applied to crops, agricultural extension and training programmes will be necessary. As over-irrigation represents wastage of resources, the application of the correct amount of water to crops would be an essential complementary measure to be applied with other water saving strategies.

3.2.3 System Maintenance

Regular System Maintenance

Regular maintenance of the physical components of irrigation systems is essential to keep them in a serviceable condition. Seepage losses as a result of damaged canal linings and other sources of water losses e.g. canal breaches and broken structures should be minimised by regular inspection and maintenance.

The condition of all the different components of the system should be maintained within close tolerances by regular monitoring and maintenance. It is obviously not sensible to focus on maintenance of selected components (such as lining) when other components (such as damaged gates) are ignored.

Prioritisation of Maintenance Work

In those irrigation schemes where water charges are not levied operation and maintenance budgets are usually provided from central government. In many cases the maintenance budget does not cover the cost of all the maintenance work required and in such cases the prioritisation of maintenance activities is necessary. The experience from some irrigation schemes in China indicates that seepage losses from 1 kilometre of a distributary canal can be almost half the total quantity of the water lost from the whole farm distribution system.

Although exact figures will vary from one scheme to another, the losses from distributary canals will usually be much higher (total in quantity) than those from farm distributary canals. The maintenance works of the distributary system should therefore take higher priority over those for the farm system.

The same principle applies to main and distributary canals. Although main canals carry larger flows and thus have larger cross-sections than distributary canals, the total length of the main canal(s) in a scheme is always much shorter than the total length of all distributary canals. Consequently, the total wetted area of distributary canals, and thus the total quantity of seepage water lost, will be much greater than that of main canal(s). The maintenance of distributary canals should therefore be given a higher priority than main canals.

3.2.4 Field Level

Improvement of Surface Irrigation Methods

Surface irrigation is the oldest and most commonly used method for applying irrigation water to the field. Numerous surface irrigation methods exist. Each method has its own characteristics which justify its use in certain environments. These characteristics are extensively covered in the literature.

An experiment carried out on four surface irrigation methods in China yielded the following results (Pei Liu-yun and Shi Jiong-lin, 1988):

- when all other conditions are the same, the greater the area of a "bay" in basin and flood irrigation, the higher the losses;
- for the same yield, border irrigation can save 48%, 23%, and 14% compared with basin, flood, and wild-border irrigation respectively;
- small check border irrigation can lead to 29%, 12%, and 11% more yield than that from basin, flood, and wild-border respectively;
- the uniformity coefficient of long border irrigation (longer than 100 m) is as high as 80-85%, the water saving accounts for 40-60% compared with common border irrigation. In addition the irrigation efficiency can be as much as two times greater.

Where potential benefits from the use of alternative methods exist there could be advantage in demonstrating these methods to farmers in pilot trial plots.

Introduction of Pressurised Irrigation

Changing traditional surface irrigation methods to the more water efficient methods such as sprinkler and drip irrigation methods should be encouraged provided that the suitable conditions for the application of such methods exist, i.e.

power supply, spare parts, large land holdings, etc. Pressurised irrigation offers the following benefits:

- lower water usage and hence reduced problems of drainage and waterlogging. The advantage will be immediately apparent where farmers are charged at real costs for volume of water delivered;

- more efficient application of chemicals. This offers additional benefits as regulations concerning the use of chemicals become more stringent worldwide.

Again, pilot areas can be set up to promote and demonstrate the benefits of these methods to the farmers.

Land Levelling

Land levelling using modern laser techniques enables the final field grading to be very precise. Land levelling not only minimises water losses but also increases the uniformity of water application.

On completion of land levelling the land will be ready for irrigation. Land smoothing operations, which can be undertaken by the farmer, will then be required after each cropping season to maintain a uniform profile within the field.

Adoption of Plastic Membrane Cultivation Technique

Based on practical experiments in China (Pei Liu-yun and Shi Jiong-lin, 1988) it was found that plastic membrane cultivation in early spring can keep the soil temperature 2-3 degrees Centigrade higher than bare soil and the soil moisture 1-3% higher. When practised over a whole growing season, plastic membrane cultivation can increase the available soil moisture through conservation by about 19% and thus saving considerable quantities of water.

Using Pipelines for Farm Distribution Systems

Traditional open channel distribution systems below tertiary canals can be converted to low pressure or gravity pipeline systems. Closed and semi-closed pipelines will minimise or eliminate seepage and operational losses from that part of the system, supply water to farmers on demand (provided that storage is available), and increase the are of land in production.

Farmers may however not accept to replace open channels with pipelines because they prefer to "see" the water in the open channels. Farmer awareness and education programmes will be required to demonstrate the advantages offered by technologies which may be new to them.

3.2.5 Socio-economic

Irrigation at Night

When irrigation is practised at night, the efficiency of water use is generally lower than in irrigation in daylight hours.

If irrigation is not practised over the full 24 hour cycles because farmers prefer to operate only during daylight hours, the water which would have been used albeit inefficiently will be wasted if storage facilities are not provided.

(a) Improving Irrigation at Night

Several different strategies are available for improving the efficiencies of irrigation at night. These strategies may need to be applied in combination to maximise improvement.

Making working at night easier: The working hours of irrigation operation staff usually last during daytime hours only. In some cases a small number of operation staff will be responsible for monitoring the system at night (mainly for safety purposes). It is often the case that the responsibility for operating the distribution system is temporarily handed over to farmers at night. In order that night irrigation is carried out with the maximum efficiency possible, it is essential that operating staff should carry out their duties during the hours of darkness and that night irrigation is seen to be a "formal" activity.

System designers must appreciate the need for working at night by giving more attention to safety. Canal banks may need to be a bit wider and obstacle free, more canal crossings will be required, emergency facilities must exist and should always be maintained in good condition, electricity should be available at night if possible, etc.

Making flows predictable: One of the performance measures of the efficiency of irrigation systems is the predictability of flow deliveries. While the advantages of a predictable flow during daytime are well known, this requirement is of great relevance for night deliveries. By nature, handling stream flows at night is more difficult and thus more labour-demanding. Variable flows add to these difficulties and reduce the efficiency of water usage. High flows which are manageable during the day can be unmanageable at night. Consequently, farmers may need to subdivide and share stream flows at night. The design and management of a system where night irrigation is anticipated should be based on farmers' needs and capabilities at the field level and give more attention to the system of water allocation between farmers.

Prioritising farm outlets: The efficiency of night irrigation can be improved by choosing the farms, crops, and soils to be irrigated at night. Small farmers should be given the priority to irrigate during the day because of the difficulty of uniform irrigation on small fields during the night. Paddy rice, trees, and young sugarcane are easy to irrigate, and can tolerate flooding (relatively) well and thus may be irrigated at night, while upland crops are more difficult and sensitive and thus it is preferable that they are irrigated during the day. Similarly, it is easier to irrigate heavy soils at night and to irrigate light ones during the day. It is feared, however, that giving higher priorities to some farms over others may face strong resistance from farmers and may also cause conflicts over water rights which may exist.

Adjusting rotation schedules: If a rotation schedule is worked out such that irrigation is to continue at night, the schedule can be improved by designing it such that no farmer will have to irrigate by night or on the same day and time of the week on every rotation. To do so, the rotation period could include a fraction of a day so that a farmer's successive turns will occur at different times each rotation.

(b) Reducing Irrigation at Night

Whether irrigation at night is planned or not it will remain entirely a farmer's decision. If farmers are not willing to irrigate at night or if the prevailing conditions do not permit efficient night irrigation, the only remaining alternative will be to reduce the water supply to the fields at night if water is to be saved. Two options are obvious: to store the water during the night for later use during the day and/or to divert it to other locations at night.

Diverting the water to other locations at night so that it is not wasted is only feasible if the diverted water can be efficiently used in those locations. In a small irrigation system (200 hectares or smaller) the water released at the head of the system can be reduced or totally shut down at night. Since the system is not large, starting up the system again early in the day would not take too long. The consideration of long travel and filling times, however, makes this solution inefficient in large systems. Instead, the flow released at the head of a large system is maintained for 24 hours of each day and the excess water during the night is allowed to flow to the drains through the tail escapes of the canals. Water in the drains can then be used in other downstream schemes. The disadvantage of this solution is the deterioration of the quality of the fresh water when it mixes with drainage water, and the potential health hazard associated with low flows in large drains.

If the water allowed to drains will not be beneficially used by other schemes or if the supply available to the system during the day is not enough to cover its full requirements, night water must be stored within the scheme.

Storage can be achieved in three main ways: in surface reservoirs, on fields, or in underground aquifers. The most efficient method of storage might be a combination of several of these measures.

Storing water in surface reservoirs is investigated in detail in a later section of this report (see Section 10, **WATER STORAGE IN SURFACE RESERVOIRS**). On-field storage is only possible where physical conditions and crops permit. Holding the water as far as possible in the upper paddy fields and then releasing it to the lower ones on the following day(s) can be practised provided that the soils are heavy enough to hold the water. This arrangement is attractive because it does not involve loss of land or additional physical control structures but may not be so efficient in storing the large quantities of water that need to be stored during the night.

Another solution is to allow the water to percolate through the soil to recharge the groundwater. The main drawback of this arrangement is the extra cost associated with lifting the water from the ground by pumping.

Water User Associations

It is generally assumed that the irrigation agency will deliver water from the headworks down the system to a point after which control is taken over by farmers. The point of handing control over is generally at the tertiary unit intake after which the farmers arrange the distribution of water. In order to organise the procedure to secure fair water distribution and efficient water use, water user associations (WUA) can be formulated. The functions of the water user associations, amongst others, include managing the water in the command area, fee collection, organising and carrying out maintenance work, communicating between the irrigation agency and the individual farmers, and resolving conflicts. Consequently, the presence of water user associations has been recently considered as an important aspect for achieving efficient water use in the lower parts of the system where large quantities of water are lost and for the long-term sustainability of irrigation schemes (Plusquellec et al., 1994).

Revising Water Charges

Although water charges are effective when levied to cover some or all the operation and maintenance costs of irrigation schemes, some also regard them as a means of enforcing farmers to be more efficient in the use of water. The argument is that if farmers have to pay for the water they use, they will limit their water application and economise on water use. However, for water economy to be obtained through water charges:

- the charge rate for water must reflect the value of the crop or the production cost. If not, farmers will not change their current practice of over irrigating because the cost of under irrigation and the subsequent yield loss will be more expensive than spending more money on applying more water;

- the water charges must be based on the actual volumes of water used by a farmer or a group of farmers (water user group). Charges which are based on land holdings or the types of crops grown do not increase water use efficiency because the sums paid will not be related to the water used. Flow measurement is required in order to allow *realistic* water charges;

- the charge rate for water could be made variable such that higher rates are applied to volumes of water which are in excess of optimum targets or water rights. On the other hand, an arrangement should exist for rewarding farmers who achieve higher water use efficiencies such as reducing their subsequent charge rates.

Because of their complexity in application the alternative charging schemes outlined above may be difficult to apply in practice.

3.3 Summary and Conclusions

The causes of low water use efficiency and loss and/or wastage of water diverted for irrigation were outlined above. The major strategies and methods which might be adopted to reduce water losses due to various mechanisms were presented.

The effectiveness of each of the measures when used in isolation is not in general quantified and it is emphasised that an effective overall strategy for improved water use efficiency will probably be a combination of several of the strategies/approaches outlined.

A summary of the causes of water losses and the potential water saving measures is presented in Table 3.1 below.

As has been shown in this section, the low performance of an irrigation scheme may be due to physical, institutional, and/or socio-economic constraints. An evaluation framework is required to help identify the constraints which cause the problem. Due to the difference in the nature of the constraints, the physical and some institutional constraints being quantitative and the rest being qualitative, it is difficult to formulate one framework for assessing the performance of all the elements. Instead, two frameworks are used, one for the quantitative evaluation and another for the qualitative evaluation. Such frameworks are presented in the following two sections of the report.

Table 3.1 Summary of Causes of Water Losses and Water Saving Measures

Cause of Water Loss		Outcome	Remedial Action or Potential Water Saving Measure
1.0 Environmental			
1.1	Evaporation from free water surfaces, especially reservoirs and aquatic weeds	Loss of water diverted for irrigation.	In new schemes, adopt cross-section design having minimum top width, if possible (see also Item 3.2 below).
1.2	Seepage from canals	Loss of water diverted for irrigation	Provide suitable impermeable lining system to reduce seepage losses from canals. Consider practising rotational flow if possible.
2.0 Operation			
2.1	System designed to deliver irrigation water for 24 hours while farmers irrigate during daytime hours only (no night irrigation)	Water diverted for irrigation discharged during non-irrigation periods (at night) to drains. Ditto, to fields (in the absence of adequate escape structures).	Operation of in-scheme storage (Section 10). Construction of escape structures and adequate drainage system.
2.2	Inappropriate design of rotations	Inequitable supply to tertiary offtakes.	Review design of rotations to improve equitable supply between offtakes. Adopt shorter canal reaches if necessary to reduce travel time or canal filling time (Section 9).
2.3	Inadequate communication between gate operators and scheme managers	Errors in gate operation leading to inequitable supply and wastage of water.	Improve methods/means of communication such as radio or permanent telephone links.
2.4	Inaccurate calculation/updating of crop water requirement calculations	Errors in calculation of canal discharge and inability to supply correct discharge to tertiary offtakes.	Review basic crop data and calculation of crop and scheme water requirements. Improve data collection quantity and quality

Cause of Water Loss		Outcome	Remedial Action or Potential Water Saving Measure
			and consider office automation.
2.5	Insufficient numbers and/or training of gate operators	Errors in gate operation leading to inequitable supply and wastage of water.	Review operator requirements and alternative canal control options, recruit and train operators. Introduce incentives which are based on performance.
2.6	Unacceptable variation in upstream water levels and discharge to tertiary offtakes	Failure to satisfy criteria of equity, adequacy, timeliness and efficiency of supply.	Review gate operation procedures and operator training. (Also see Item 4.2 below).
2.7	Incorrect use or calibration of flow measurement facilities	Inability of field staff to obtain data to adequately manage the distribution of water supplies, errors in gate operation and water application to cultivated areas.	Review calibration of flow measuring structures. Train operators in the use of flow measurement installations.
2.8	Failure to operate water control gates correctly	Errors in flow regulation on main and secondary canals, in application of water to fields and in farmers' ability to adjust discharge of tertiary offtakes during irrigation periods according to crop requirements.	Review gate operating procedures and gate operator training (see also Item 2.3 above).
2.9	Inadequate supervision of night irrigation	Inaccuracy in quantity of water applied to fields. Loss of water from canals via tail escapes and from fields (overflow/runoff into drains)	Review night security arrangements and communications. Irrigate large fields. Store water at night (Section 10).
3.0 Maintenance			
3.1	Inadequate maintenance of	Overtopping of canal bunds and wastage to drains	Review inspection and maintenance

Cause of Water Loss		Outcome	Remedial Action or Potential Water Saving Measure
	canal embankments and design freeboard	or fields when high water levels occur in canals.	schedules and availability of mechanical equipment. Secure sufficient funds to cover all maintenance activities required.
3.2	Inadequate silt clearance and/or weed control	Reduction in canal capacity. Occurrence of high water levels in canal reaches affected.	Review inspection and maintenance schedules and availability of mechanical equipment.
3.3	Failure of tertiary offtake gates to seal correctly	Reduced supply to downstream offtakes. Wastage of water during off phase where rotations are practiced.	Inspect and maintain gate seals.
4.0 Infrastructure Design			
4.1	Excessive distance between offtakes and commanding cross-regulators	Variation in water level upstream from distant offtakes, particularly at times of reduced canal flow.	Review performance under reduced flow in supply canal and either install additional cross-regulator(s) or modify design of offtakes affected (Section 9.5).
4.2	Wrong choice of control structures and/or use of incompatible components for main canal control and control of main canal offtakes	Unacceptable variation in flow diverted to secondary canals and offtakes. Unacceptable flexibility values (F >> 1 or F << 1)	Review design of main canal structures and compatibility of regulators and offtakes (Section 8.1).
4.3	Inadequate provision of flow measurement facilities	Inability of gate operators to correctly monitor flows and operate gates on main and secondary canals, and for farmers to apply the correct quantity of water to fields.	Review minimum flow measurement facilities required and install measurement facilities to maximise distribution efficiency.
5.0 Socio-economic			

Cause of Water Loss		Outcome	Remedial Action or Potential Water Saving Measure
5.1	Existence of unauthorised offtakes/illegal abstractions or tampering with control structures	Disturbance to canal operation and interference with supply to downstream users. Increased costs of canal maintenance.	Monitor system for unauthorised activities and regularise water use as soon as possible. Formation and training of water user groups.
5.2	Existence of poor water management practices at farm level	Inability of farmers to apply correct quantities of water to crops according to local rainfall and stage of crop development. Over-irrigation and reduced yields. Possibility of environmental damage and inequitable supply to other users.	Extension advice and training of farmers. Promotion of water saving measures on radio and television. Formation and training of water user groups.
5.3	Mismatch of current irrigation practices and original design assumptions	If farmers do not practice irrigation at night and design assumes 24 hour operation, waste of water, if storage facilities are not provided and operated. If unused water is discharged to fields, possibility of environmental damage and waterlogging. Reduction of area irrigated.	Consultation with farmers in the area at all stages of design and adopt practical, farmer-friendly operation procedures throughout.

4 CANAL CONTROL METHODS

4.1 Classification of Control Methods

Different classifications of canal control methods can be found in the literature. No standard methodology is used in those classifications and therefore it is quite possible to encounter a situation where the same control method is given different names in different references which can be misleading.

The review of canal control methods presented below follows a slightly different methodology to describe the different control methods. Instead of giving a distinctive name to each control method, they are identified in terms of the following control characteristics: *control response*, *control type*, *control location*, and *control mechanism* (Figure 4.1).

4.2 Characteristics of Control Methods

Control Response

Irrigation systems make a connection between the source(s) and the users. Canal control methods can respond to the changes at either end of the irrigation system or at both. When a control method responds to the changes at the source location(s) only, it is called **upstream/supply/source**-oriented, while a control method which responds to changes made or required by users is called **downstream/demand**-oriented. When responding to both types of changes a control method is called **combined upstream and downstream control.**

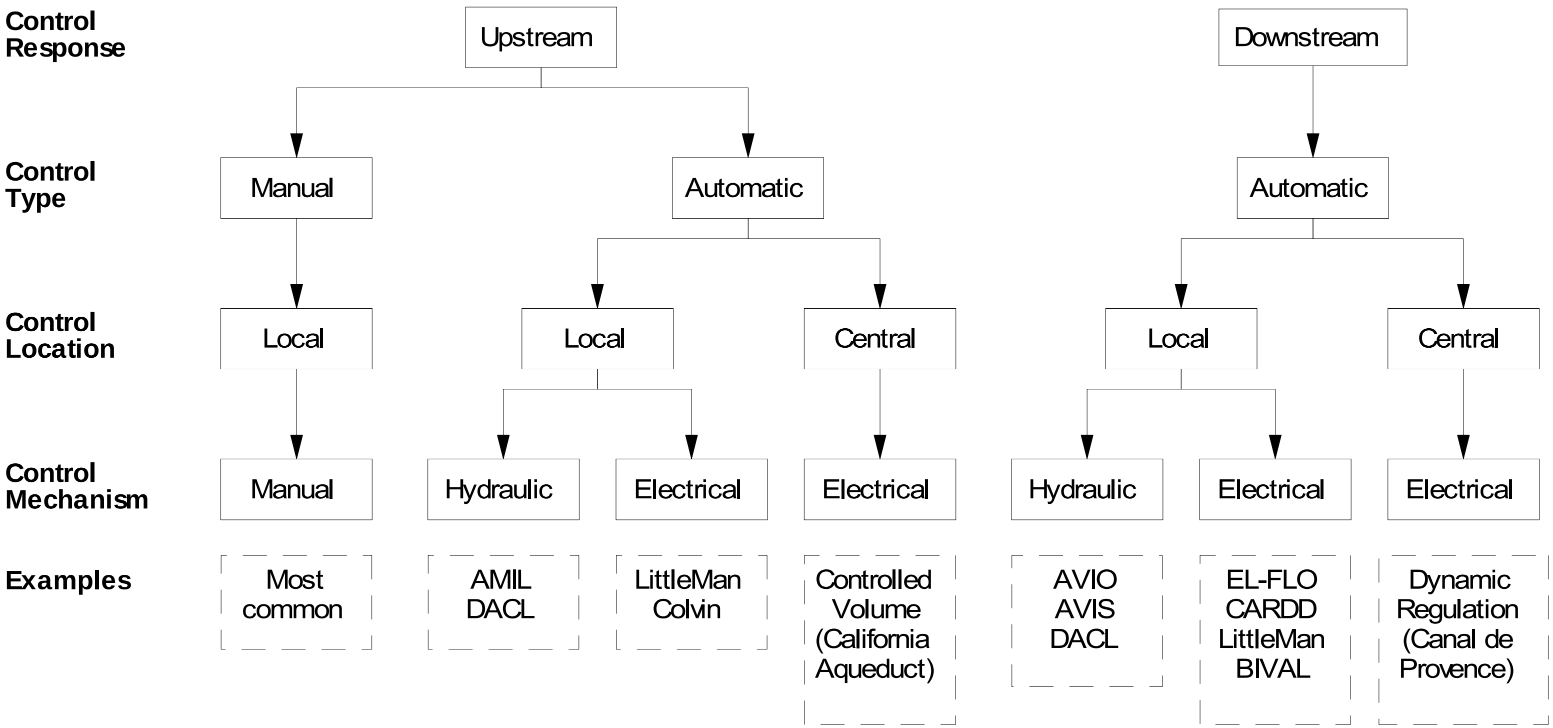
Control Type

This characteristic indicates the type of input to the controls, i.e. the method employed in making decisions and giving commands to the control structures in the system. Three different alternatives are possible: (i) No commands need to be given to the control structures because they are **fixed** (e.g. weirs); (ii) the decisions and commands are made by operation staff and/or farmers which is referred to as **manual** control to be compatible with the terminology used in the literature, and (iii) control in which decisions and commands are made by hydraulic equipment, electronic circuits, or computer software. This latter type of control is commonly referred to as **automatic** in the literature.

Control Location

The process of operating control systems begins with collecting data about the current situation of the system, evaluating the condition and performance, and then taking decisions and giving commands to the control structures for corrective action if required. This process can take place **locally** at every individual control structure or **centrally** in one or two locations in the whole scheme.

Figure 4.1 Characteristics of Canal Control Methods



Control Mechanism

This characteristic indicates the mechanism used to set control structures (**manual**, **hydraulic**, **electrical**, etc.). It is often confused with the *control type* characteristic discussed above. For example, a control system where gate operators set the gates of the structures through electric motors may be mistakenly classified as automatic control. According to the classification methodology described here, however, the *control type* is *manual* and the *control mechanism* is *electrical*. A comparison between the characteristics of the different control mechanisms used for structure automation is outlined in Table 4.1.

The *control type* and *control mechanism* are here defined as two separate characteristics since they have different impacts on system performance and the environment where a control method can be used. For example, the *control type* can influence the hydraulic performance of the system while the *control mechanism* will influence the maintenance and power requirements which should be available in the scheme for a control method to be adopted.

Figure 4.1 illustrates the characteristics of the commonly used types of canal control systems. Although theoretically all the different combinations of the control characteristics described above should be possible, only some are viable in practice (for example, manual downstream control is hardly utilised).

4.3 Control Methods

4.3.1 Upstream Control

Upstream water level control is the most commonly used control method in irrigation systems (Clemmens, 1998). The method is supply-oriented which makes it easy to operate by project staff but also means that it does not respond to the changes in the demand. The flow released in the system must therefore be regularly adjusted to meet the demand if high water use efficiency is to be maintained (no water shortage or wastage). This can prove to be a difficult task in many cases.

Fixed Upstream Control

Control response: Upstream/Supply

Control type: Fixed

Control location: Local

Control mechanism: None

Water distribution is controlled by dividing incoming flow into predetermined and generally fixed proportions (usually based on the area served) by means of proportional dividers at each bifurcation point. Control structures are designed to divide flow proportionally whatever the flow rate arriving at the structure. Variations include the Warabandi system of Northwest India and Pakistan where flow is proportional down to tertiary level (proportionally fixed by size of outlet, based on command area) and is then rotated between farmers within a block (proportionally fixed by time share based on landholding size).

Table 4.1 Characteristics of Automatic Canal Control Mechanisms

Criterion	Hydraulic Automation	Electrical Automation
Durability	• Not easily affected by severe weather conditions • Difficult to vandalise • Longer life	• Heavy rain, storms, or lightning can seriously damage equipment • Electronic equipment must be upgraded from time to time in order that spare parts will be available for the equipment when replacements are needed • Vulnerable to vandalism
Robustness	• Structures can be easily tampered with if not properly guarded/locked • Not dependant on external power supply	• Structures are not so difficult to tamper with • Require reliable power supply otherwise system may fail • Vulnerable to programming errors in control algorithms • Can cause highly unsteady flow due to frequent oscillation of structures (hunting) if controllers are not fine tuned
Flexibility	• Control set point can be changed in very limited range • Not easy (or even impossible) to change control to manual mode • Cannot be centrally controlled	• Easier to change control set point • Easy to change control to manual mode • If locally controlled, can easily be upgraded to centralized control
Operation	• Almost no operation input or cost	• Power will be consumed in operation
Maintenance	• Does not require frequent maintenance • Maintenance is relatively simple (mainly painting and lubricating parts)	• Must be frequently maintained (preventive maintenance) • Qualified technicians are required for maintenance

All structures throughout the system (or part of system with fixed upstream control) are non-adjustable and therefore operational requirements are minimal. The irrigation agency needs only to control the flow into the system and to fulfil the maintenance requirements of the system. Operational costs are therefore relatively low.

Although the system is entirely equitable, in practice equity is difficult to achieve because structures rarely divide flow in the correct proportions for all incoming flows. The range of flow conditions may also result in damage to canal lining. Siltation will cause variations in the behaviour of control structures.

Because there is no control in the canal system it is difficult to respond to unexpected events in the distribution system, e.g. canal breaches. Water cannot be used efficiently in terms of crop production per unit of water, and fixed control is unable to respond to the varying demands of farmers with differing water needs.

Manual Upstream Control

Control response:	Upstream/Supply
Control type:	Manual
Control location:	Local
Control mechanism:	Manual or electrical

The gates of the inlet structure of each canal are adjusted to allow the required flow into the canal. The cross-regulators downstream from the inlet structure are adjusted to maintain a specified water level immediately upstream. The controlled water levels in the canals determine the flow through the offtakes commanded by the cross-regulators.

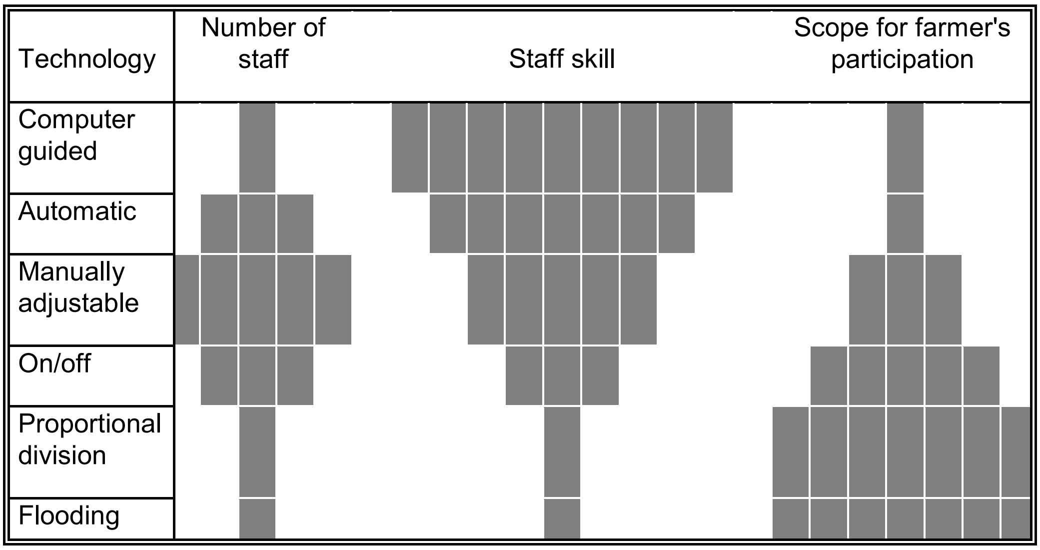
The objective of upstream control is to deliver a known flow rate to specific offtakes. However, when extra flow is added to the system it may take hours or days to arrive at the desired location. The supply and demand cannot be easily matched. Any errors in control structure settings will be magnified at the tail-end of the system leaving either a deficiency or wastage of water. Corrections are difficult to make accurately.

A range of different structures (sluice gates, radial gates, underflow, overflow, etc.) can be used which are either manual or motorised. These are adjusted according to schedules determined either by the irrigation agency alone or by the agency in conjunction with the farmers. An investigation into the characteristics of some types of structures is given in Section 8.

This method may be used for a range of delivery schedules except demand schedules. It is best suited to arranged delivery as adjustments can be made according to farmer's predetermined requirements and gate settings coordinated throughout the system. However, this requires good communication between the farmers and the irrigation agency. If there is good communication between the control centre and the structure operators this method of control will be able to respond quickly to sudden changes in circumstances. As the gates are operated independently, one part of the irrigation system may be shut down without affecting other parts of the system.

If manually operated, gated control also requires a large number of dedicated and trained staff to operate gates throughout the system. Although this type of control is relatively cheap to install, the high staffing levels required make it expensive to operate (Figure 4.2). As labour costs increase, this level of staffing could become economically unsustainable.

Figure 4.2 Staff and Farmer Participation for Canal Control (Horst, 1990).



Automated Upstream Control

Control response: Upstream/Supply

Control type: Automatic

Control location: Local or central

Control mechanism: Hydraulic or electrical

Because of the operational procedure followed with upstream control the flow delivery is highly dependent on the water levels in the canals. High variability in the flow diverted to the offtakes is very common when the supply is not reasonably steady. Continuous adjustments to the gates of control structures will be required if the flow variability is to be minimized. Gate automation is one alternative to overcome the problem. Adjustments to gates can be more precise using automatic control rather than manual control.

Automated control is more expensive to install but the staffing costs are lower than for manual control. Automation requires a higher degree of maintenance than manual control. Staff should be well trained in the operation of automatic systems and in preventive maintenance of control structures. An unreliable power supply (if power is required) or a poor control programme will also lead to poor operation of the system. The control system must have a manual override mode which enables operation staff to take over control in emergency situations.

Examples of the different techniques used for automating upstream control systems are shown in Figure 4.1 and listed in Plusquellec et al. (1994).

Consequences and Impacts of Upstream Control

- For upstream control to be effective and efficient the supply should be regularly matched with the demands. A mismatch between the supply and the demand will result in either water wastage or shortage (poor performance). Control structure automation alone cannot solve this problem; input from operation staff will be required in order to collect data about expected or required demands such that the supply can be adjusted accordingly. The process is not easy to undertake and will require a large number of operation staff which increases the cost of the operation of the system.

- The performance of upstream control in large irrigation systems can be improved by providing for water storage. Storage reservoirs located in different places in the system can regulate the mismatch between supply and demand, reduce system response time, and improve the safety of the system. The operation of the system with surface storage, however, is not as easy as operating the system without storage as unsteady flow occurs more frequently in the canals. Some automation will be required to safeguard the system against mistakes in the operation of the reservoirs (Section 10 contains a detailed discussion about surface storage in irrigation systems).

- Although the low flexibility of upstream control is regarded as a major disadvantage in the system, this feature can be useful to enforce water delivery schedules. An example of this is the situation where the supply is less than the demand. Upstream control can be used efficiently in such a situation to ensure equitable water distribution, and hence efficient water use, provided that sufficient inputs are available (such as dedicated operation staff, proper control structure, well maintained facilities, etc.).

4.3.2 Downstream Control

Because of certain disadvantages of upstream control, such as the difficulty of matching supply with demand and the long response time of the system, downstream control is more desirable from the farmers standpoint. Systems under downstream control are demand-oriented and respond to changes in demand by adjusting the supply accordingly. It is therefore a much more flexible system than upstream control. Theoretically, the system should respond from the downstream and proceed upstream, i.e. it should satisfy the needs of downstream farmers first.

As demand can vary at any time, even with an arranged schedule system automation is essential. Control structures must have some way of sensing the change in the downstream conditions (demand) either hydraulically or electronically. Usually, the water levels downstream from control structures are used to indicate the need for either more or less flow to be supplied from the upstream canal reaches.

Downstream Control with Level-top Canals

Control response: Downstream/Demand

Control type: Automatic

Control location: Local

Control mechanism: Hydraulic or electrical

The most commonly used technique to achieve downstream control is to monitor the water level immediately downstream from control structures. As more flow is abstracted from the downstream reaches of the system the local storage in the canals is depleted and hence the water levels drop, triggering the control logic to increase the opening of the upstream structures to compensate for the depleted water. When the demands decrease, the water levels increase until the water surface becomes almost horizontal at zero abstraction. The canals must therefore have level banks to prevent canal overtopping and breaching under such conditions. For the system to be economic, the average land slope should not exceed about 0.25 m/km. On steeper gradients the additional earthworks necessary to maintain a level top become prohibitively expensive (Burt, 1987).

Downstream Control with Sloping Canals

Control response: Downstream/Demand

Control type: Automatic

Control location: Local

Control mechanism: Electrical

Many techniques have been developed to achieve downstream control on sloping canals. With these techniques the water level at the lower-end of the canal reach is controlled by the structure at the top end of the reach. When the control location is far from the structure which is effecting the control, it becomes more difficult due to the lag time between the adjustment of the structure and the arrival of the change at the controlled location. This also requires data to be transmitted between the control structure and the controlled location. Control is therefore more complicated and expensive than that used with level-top canals.

Examples of automatic canal control mechanisms are shown in Figure 4.1 and listed in Plusquellec et al. (1994).

Centralized Dynamic Regulation

Control response: Downstream/Demand

Control type: Automatic

Control location: Central

Control mechanism: Electrical

This variant of downstream control is the most advanced and sophisticated canal control method. Almost all of the system is electrically controlled by central computer(s). Sensors transmit data defining the condition of the system (water levels, gate settings, etc.) at frequent intervals to central computer(s) which analyse the situation. The computer(s) then issue commands to the electrical controllers of the water control structures, either via laid lines or radio signals. The only example of this type of control system is the Canal de Provence in France.

There is minimal human intervention in the operation of the canal system which can operate fast and effectively in response to user's needs. It combines the advantages of downstream control with a coordinated centralised system. Canals do not have to be as large or as level as for level-top canals and therefore this control system may be used on steeper topography.

The equipment necessary is complex, sophisticated and expensive although some savings are made in canal sections and the elimination of regulating reservoirs.

Consequences and Impacts of Downstream Control

- Although control is by demand this does not necessarily mean that demand schedules are being used. Canal capacities may permit only limited-rate demand schedules, however, water supplies may be turned off by the farmers at will, without risking damage to the canal system.

- Because of the responsive nature of downstream control, the need for data collection and processing, and communication systems is much reduced which in turn lowers staffing costs. Neither does level-top control require electronic communications to coordinate gate opening and closing because all structures are connected hydraulically through the canal system. However, this requirement may reduce the maximum spacing between control structures which will be expensive on steep terrain.

- There is a common misunderstanding that downstream control eliminates the need for flow measurement. Flow measurements at key locations in most irrigation systems with downstream control are required in order to determine the quantities of water used and charge for it. Without charging for water farmers could take excessive quantities of water, thus draining down the reservoirs which are often required at the head of such systems. Even if water is not charged for the use of water can be limited by allowing each farmer a water right. The farmer can then take water as and when required up to that limit.

- Because control is virtually taken over by farmers, farmer awareness and extension services are paramount if the system is to achieve high performance. Farmers should be advised on how to use water more efficiently. The impact of wrong habits and practices, such as over-irrigating and leaving the water flowing to the fields or the drains after finishing irrigation, must be made clear to farmers. When the supply is short no measures can be taken to ensure equitable water distribution.

- Unlike upstream control, downstream control requires automation of the structures. As a consequence the construction and operation costs of the system are usually higher than those for upstream control, for which structures do not have to be automated. Automation can be a constraint to the adoption of downstream control in those environments where the introduction of higher technology would not be appropriate (refer to Section 5 for more details about the compatibility between canal control methods and given environments).

4.3.3 Combined Upstream and Downstream Control

Control response:	Combined upstream and downstream
Control type:	Automatic
Control location:	Local
Control mechanism:	Hydraulic (usually) or electrical

In large irrigation projects where downstream control is to be used, the cost of automation if downstream control is used throughout the system can be reduced by using combined upstream and downstream control. Upstream control can be used at the upper parts of the system (conveyance system) and downstream control in the lower parts.

The part of the system under upstream control may or may not be automated. To cater for flow transients between the upstream and downstream systems regulation reservoirs are used in the locations where the control type changes. The water levels in the reservoirs should be regularly monitored such that the supply can be adjusted to prevent water shortage or wastage.

Although there is an additional cost for building storage reservoirs, overall construction costs are lower than that for downstream control throughout the system. The reservoirs should be designed to cater for 1-2 day surplus or deficit flow to allow for the lag time of the adjustments made to the supply at the head of the system. If the topography is flat, it may not be possible to avoid pumping the water in or out of the reservoirs and thus adding to the running costs of the system.

4.3.4 Pressurised Systems

A pressurised system uses closed pipes and operates in much the same way as a municipal water supply. It is a fully demand-oriented system limited only by the capacity of the pipes at the given pressure. If well designed and installed then closed pipe systems require minimal maintenance. They are very efficient conveyors of water with minimal losses. It is normally simple to operate unless pumping is required within the system. The initial cost is usually higher than open channel systems but they have the advantage of taking minimum land out of production. Depending on the terrain, pumping can be expensive. High silt loads in the water can be detrimental to the pumps and hence water must be screened before entering the system. Flows and water volumes are much easier to measure and hence such systems may be preferred if water charges are to be levied.

4.4 Summary

The major categories of canal control methods are upstream and downstream control. Downstream control tends to be flexible and demand-oriented while upstream control is usually associated with rigid top-down water delivery.

The *level of technology* required for each control method varies. Fixed upstream control (proportional distribution) is technologically very simple in terms of construction, operation and maintenance. Responsive centralised control, however, requires sophisticated computer equipment, regular complex maintenance, skilled operators, and is likely to pose significant levels of risk on the system due to equipment failure, even in the most sophisticated environments.

A summary of the various canal control methods and their characteristics is given in Table 4.2.

Table 4.2 **Summary of the Characteristics of Various Canal Control Methods**

Canal Control Method	Water Control	Water Delivery[1]	Automation	Control Location	Hardware
1. Fixed upstream control	Upstream water level	Continuous	--	--	Proportional dividers (weirs)
2. Manual upstream control	Upstream water level	C, R, A	Manual	Local	Manual or motorized sluice and/or radial gates or weirs
3. Auto-electrical upstream control	Upstream water level	C, R, A	Auto-electrical	Local	Undershot or overshot gates with electrical controllers such as Littleman (upstream) and Colvin
4. Auto-hydraulic upstream control	Upstream water level	C, R, A	Auto-hydraulic	Local	AMIL gates and DACL controllers
5. Centralized arranged upstream control	Upstream water level or flow	Arranged	Auto-electrical	Central	Electrically controlled gates operated by central computer program
6. Downstream control with level-top canals	Downstream water level	Demand	Auto-hydraulic	Local	Level-top canals with AVIO & AVIS gates and DACL controllers
7. Downstream control with sloping canals	Water level, flow or volume in downstream pool	Demand	Auto-electrical	Local	Sloping canals with electrical controllers such as Littleman (downstream), BIVAL, ELFLO, and CARDD
8. Combined upstream & downstream control	Upstream & downstream water levels	Arranged	Automatic	Local	Any combination of the above arrangements for automatic control (usually hydraulic)
9. Centralized dynamic regulation	Flow and water volume	Demand	Auto-electrical	Central	Almost all system is electrically controlled by central computer(s)
10. Pressurised systems	Flow	A, D	Automatic	Central	Pipelines and pumps. Gravity pressure possible in some circumstances.

[1] C = Continuous, R = Rotation, A = Arranged, D = Demand

5 PERFORMANCE ASSESSMENT

Performance assessment is inherent to any management activity, including the management of irrigation systems. The utilization of water and other resources for irrigation require that the efficiency of their use is evaluated periodically.

Since this research project deals with improving the performance of irrigation systems through improving canal control methods, performance assessment is a fundamental tool in the research. The use of the performance assessment techniques described in this section with the relevant performance measures and indicators will enable:

- The efficiency of alternative systems and operating procedures to be compared and
- The effect of improvement measures or water saving strategies to be evaluated.

This section is divided into two main sub-sections: in Section 6.1, a general framework for assessing the performance of irrigation projects is outlined and then the performance measures which are considered to be those most appropriate to the current research and the relevant performance indicators to quantify them are discussed in Section 6.2.

5.1 Framework for Performance Assessment

In the context of irrigation scheme performance assessment it is necessary to define such matters as the purpose and objectives, the boundaries of the analysis, the measures and the indicators. The proposed framework is presented in Figure 5.1 and is discussed in the following sections. The main components are presented in Table 5.1.

5.1.1 Purpose

Before an assessment of the performance of an irrigation scheme can be carried out, the purpose of the performance assessment must be established. This purpose can be broadly categorised as being of the following nature:

- Operational
- Accountability
- Intervention
- Sustainability

Operational assessment provides scheme managers with information to enable them to manage the scheme and operate the system.

Accountability assessment provides information to assess the performance of those responsible for the scheme's performance.

Intervention assessment is undertaken to determine how to improve some aspects of the scheme's performance.

Sustainability assessment enables planners to assess the long term viability of a scheme.

5.1.2 Objectives

There are two forms of objectives that are important in performance assessment for irrigation schemes:

- The Project's Objectives
- Performance Assessment Objectives

The Project's Objectives

Objectives should exist for a project before a performance assessment is carried out. The project will include not only the irrigation system but also the agricultural system and any socio-economic influences. Performance cannot be assessed unless there are objectives for that performance against which assessment may be made. The relevant objectives must be defined either using existing objectives or by defining new ones.

The objectives can be at different levels and with different emphases. There can be many different objectives and these may be complementary or conflicting. Jurriëns (1991) provides some useful examples of objectives at different levels:

- National
- Regional
- Scheme
- Water User Association / Village Water Management
- Farmer

The emphases of objectives include:

- Technical
- Political
- Economic
- Social
- Environmental

Performance Assessment Objectives

The purpose for which a performance assessment might be carried out has been outlined earlier. Within this purpose it is necessary to define specific objectives for the performance assessment. These objectives will enable the parameters of the assessment to be established and the direction of the assessment to be controlled.

Table 5.1 Performance Assessment for Irrigation Schemes Main Components

Framework Category	Components		
Purpose	* Operational * Accountability * Intervention * Sustainability		
Objectives	Performance Assessment Objectives	Overall Objectives * Levels * Emphases	Setting Targets * Internal * External * Relative
Boundaries	System * Inputs * Outputs * Processes	Space * Geographical * Social	Time
Performance Measures	Measures * Adequacy * Reliability * Variability * Equity * Efficiency * Accuracy * Command * Productivity		
Performance Indicators	Attributes * Scientific * Quantifiable * Without bias * Ease of use * Targets	Domains * Land * Crop * Water * Financial * Social * Infrastructure	Nature * Ratio * Quantitative * Qualitative

Setting Targets

In order for most objectives to be assessed it will be necessary to set specific targets against which performance can be measured. These targets must be set according to certain standards which can be classified as:

- Internal

- External
- Relative

Internal standards are set within a scheme. The targets will be set within the organisation and will reflect the management's ideal operation of the system.

External standards are derived from various sources including technical, political, economic and ethical sources. They are based on an irrigation agency's accountability to outside organisations.

Relative standards are derived from the performance of other similar schemes or systems. A normal standard can be set using data from all comparable schemes or systems against which performance is measured.

5.1.3 Boundaries

The boundaries of a performance assessment exercise can be defined in terms of the following dimensions:

- the system
- space
- time
- domain

The system The system under consideration and its relation to other systems need to be identified and defined. Small and Svendsen (1992) define irrigation within the context of nested systems (Figure 5.2) with the outputs from one system forming the inputs to the next.

Once the system under consideration has been defined the spatial and dynamic boundaries can be defined in relation to the inputs and outputs of that system. Consideration should also be taken of the *processes* within a system that convert *inputs* to *outputs*.

Space The spatial boundaries include geographical and social boundaries which are partly defined by the system under consideration. A well defined performance assessment exercise will only be concerned with outputs at the defined boundaries though it may be interested in the impacts elsewhere. An example would be the performance assessment of the main canal system where water delivery would be assessed at tertiary offtakes, though the impact on production at field level is of interest.

Time Dynamic boundaries can be short term, within the cropping cycle, or longer term, relating to the lifetime of the project.

Domain Social boundaries are not so clearly defined as performance assessment may address a farmer's contentment with the water supply provided without taking into consideration his other concerns.

5.1.4 Performance Measures

Once all the limits of the assessment have been established the appropriate performance measures must be chosen. Commonly used measures of performance are:

- Adequacy
- Equity
- Reliability
- Variability
- Efficiency
- Accuracy
- Command
- Productivity

These "measures" are quantified by the use of indicators, many of which are ratios (e.g. the relative water supply is the ratio of supply to demand). The spatial distribution of the performance indicators provides the information necessary to assess system performance. Different indicators may be required to quantify in detail one performance measure. Conversely, one indicator may be useful for two or more measures. The commonly used measures are defined below.

Adequacy provides a measure of the ability of the system to meet the demand either for water or for other resources. The assessment of performance will come from measurements of how well demand is satisfied at different locations in the system.

Equity compares performance (mainly water distribution equity) at different points in the system. Some indicators that are not directly measuring equity can be used to assess equity by comparing data collected from different points in the system.

Reliability is a measure of how closely actual performance matches expected performance. This expectation can be real or perceived. Real (technical) reliability measures focus on the frequency which target levels are achieved, perceived reliability measures focus on people perceptions, and are thus difficult to quantify.

Variability can be used as a measure of reliability although it measures deviations from a mean rather than from a target value.

Efficiency measures are used to compare the actual performance of a system to its potential performance and as a measure of the efficiency of resource use. Measures can be taken of the whole system or of parts of the system.

Accuracy measures help assess the extent to which supply is able to respond to demand.

Command measures can be used for comparison of design with actual command levels within a system.

Productivity measures are used to assess the absolute performance of a project. Some productivity measures can be compared to resources used to give efficiencies.

Figure 5.1 Performance Assessment Framework

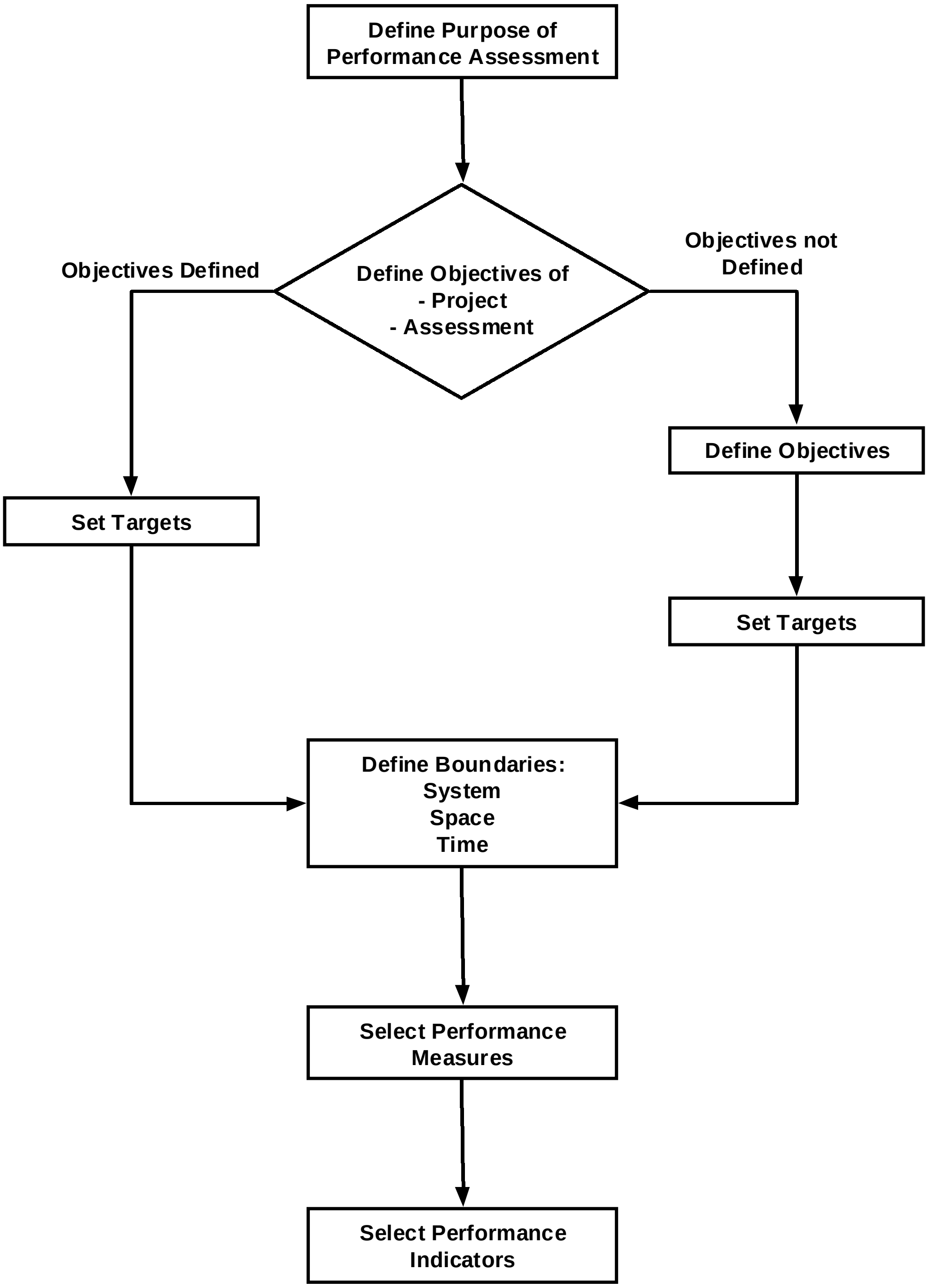
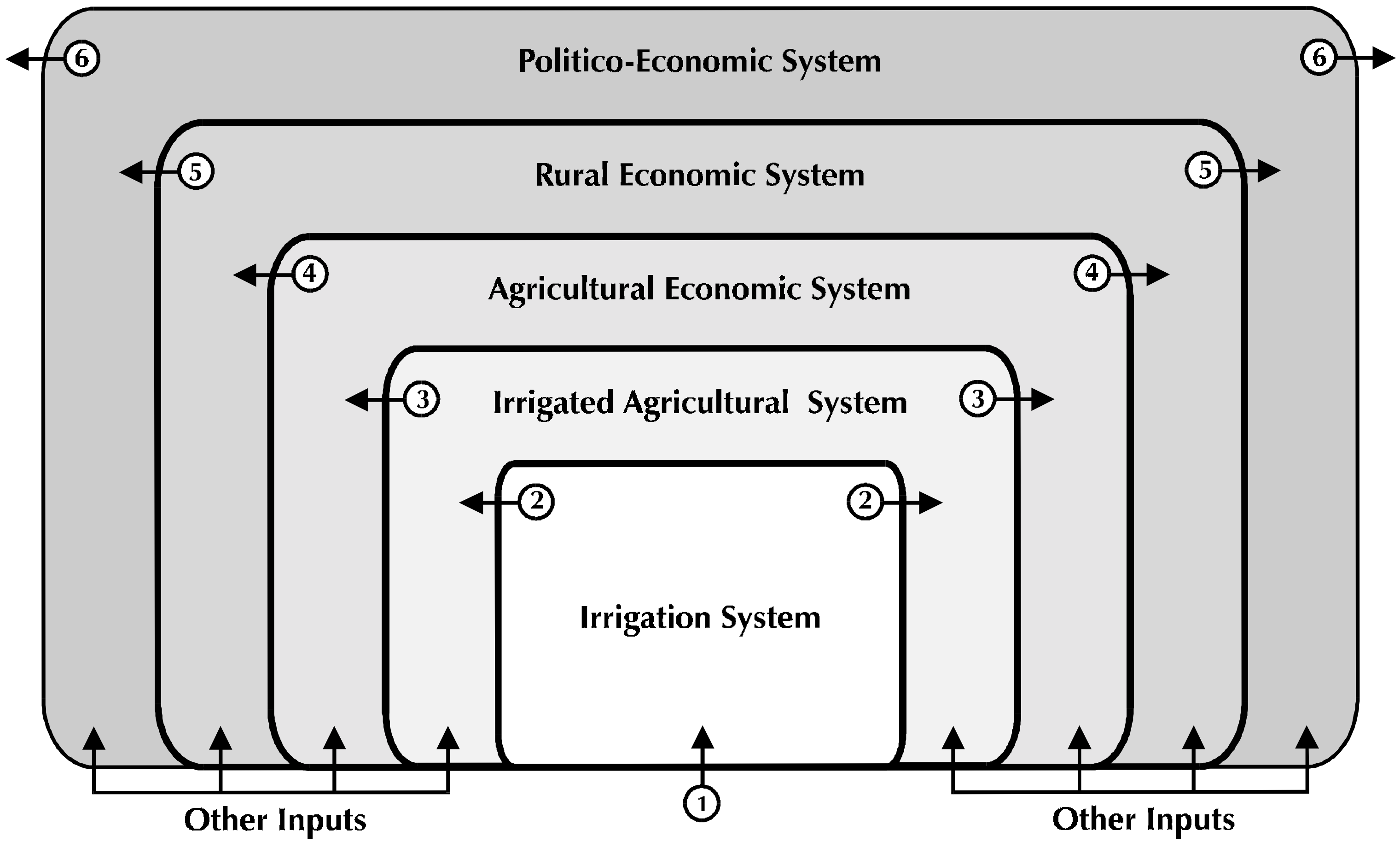


Figure 5.2 SYSTEM BOUNDARIES SHOWING INPUTS AND OUTPUTS (after Small and Svendsen, 1992)



Key to Inputs/Outputs

1. Operation of irrigation facilities
2. Supply of water to tertiary units
3. Agricultural Production
4. Incomes in rural sector
5. Rural economic development
6. National development

5.1.5 Performance Indicators

Performance indicators are variables for which data can be collected to enable quantification of performance. They are often quoted as ratios.

Performance indicators themselves can be grouped according to a number of different criteria:

- Measures
- Attributes
- Domain
- Nature

Measures

Every performance indicator is used to quantify one or more performance measure (adequacy, equity, etc.).

Attributes

A performance indicator should have certain attributes that make it practical and reliable for measuring performance (adapted from Bos 1997):

Scientific basis. An indicator should be based on an empirically quantified, statistically tested model of that part of the irrigation process it describes.

Quantifiable. The data needed to quantify the indicator must be available or obtainable (measurable) with available technology. The measurement must be reproducible.

Without bias. Ideally, performance indicators should not be formulated for a narrow ethical perspective. This, in reality, is difficult to achieve so it is necessary to be aware of what bias may be inherent in an indicator.

Easy to use. Particularly for routine management, performance indicators should be technically feasible and easily used by agency staff given their level of skill and motivation. Further, the cost of collecting, processing and analysing data for indicators in terms of finances, equipment, and commitment of human resources, should be well within the agency's resources.

Reference to a target value. Although most performance indicators will by their nature refer to a target value this is not a necessity. Those that do refer to a target imply a relevance and appropriateness of that target and that tolerances can be established for the indicator.

Domain

Indicators may be categorised according to the domains in which they operate:

- Land

- Crop
- Water
- Financial
- Institutional

The domain of an indicator may be compared to the domains used to define performance assessment exercise boundaries outlined earlier.

Nature

The nature of indicators can also be classified as follows:

Ratio indicators usually relate an actual measurement to a target value. They are particularly useful as they relate achievement to targets set, and are readily understood.

Quantitative indicators are absolute measures of performance which can be used when comparing the performance of a project with external standards.

Qualitative indicators are usually subjective indicators related to perceptions rather than to numerical values for performance.

5.2 Application to this Research Project

The framework for assessing the performance of irrigation schemes presented in the previous section is general and applies to all the boundaries of irrigation schemes. In the context of this research project, however, performance assessment of irrigation systems is only applicable. The focus in the following sections will therefore be on the performance assessment of irrigation systems and in particular irrigation delivery and distribution systems.

5.2.1 Performance Measures

The exercise of assessing the performance of irrigation delivery and distribution systems has been often carried out and reported in the literature. Murray-Rust and Snellen (1993) used the *adequacy*, *equity*, and *reliability* as the main performance measures in the evaluation of the performance of 15 irrigation systems. Velde (1990) reported on the performance of the distributary level of large irrigation systems in Pakistan. The main performance measures he used in the evaluation were the *equity* and *variability*. Clemmens and Dedrick (1984) studied the performance of irrigation water delivery by assessing the *variability* in the flow rate.

The performance measures which have been adopted to ascertain the impact of changes in canal control methods in the distribution system within the context of this study are:

- Equity
- Variability
- Command
- Efficiency

- Management Input

These measures will be applied to the irrigation canal networks of the case studies in this research and particularly to the tertiary offtakes (delivery points) of the networks.

5.2.2 Performance Indicators

Numerous indicators for quantifying the performance measures of irrigation delivery and distribution systems are available in the literature. It is not of value to give a long list of all those indicators here. Instead the commonly used, and probably the most important performance indicators are given below. In addition to the most commonly used indicators, an indicator has been devised to enable the operational inputs of different operating scenarios to be evaluated, this is the *Management Input Index* and is also described below.

$$\text{Delivery Performance Ratio (DPR)} = \frac{\text{Actual Discharge}}{\text{Target Discharge}}$$

Measures: Equity and variability

Range:

0.0 .... 1.0 ....>

Poor Ideal Oversupply (waste)

$$\text{Water Delivery Performance (WDP)} = \frac{\text{Actual Volume of Water Delivered}}{\text{Target Volume of Water to be Delivered}}$$

Measures: Equity, adequacy, and water use efficiency

Range:

0.0 .... 1.0 ....>

Poor Ideal Oversupply (waste)

$$\text{Relative Water Supply (RWS)} = \frac{\text{Irrigation} + \text{Rainfall}}{\text{Seepage} + \text{Percolation} + \text{Evapotranspiration}}$$

Measures: Equity, adequacy, and water use efficiency

Range:

0.0 .... 1.0 ....>

Poor Ideal Oversupply (waste)

$$\text{Interquartile Ratio (IQR)} = \frac{\text{Water Received by Best Supplied Quartile}}{\text{Water Received by Worst Supplied Quartile}}$$

Measures: Equity

Range:

1.0 ....>

Equitable Inequitable

$$\text{Spatial Interquartile Ratio (SIQR)} = \frac{\text{Water Received by Top – end Quartile}}{\text{Water Received by Tail – end Quartile}}$$

Measures: Equity related to the location of the site within the system

Range:

1.0 ....>

Equitable Inequitable

$$\text{Coefficient of Variation } (C_V) = \frac{\text{Standard Deviation}}{\text{Average}} = \frac{s}{\bar{x}}$$

Measures: Variability in flow or command

Range:

0.0 ....>

Ideal Variability increases

$$\text{Delivery Duration Ratio (DDR)} = \frac{\text{Actual Duration of Supply}}{\text{Target Duration of Supply}}$$

Measures: Accuracy of operation and scheduling

Range:

0.0 .... 1.0 ....>

Poor Ideal Oversupply (waste)

Management Input Index (MII) = Number of structure settings to be made in a certain operation scenario

Measures: Management input

Range: N/A

Note: This indicator can be used in two different ways: it can be used as an absolute index to quantify the work load to be input by operation staff in order to successfully carry out a certain operation procedure, or the indicator can be modified to measure the number of structure settings per unit of time (say per day) or by each operator. In this way, the indicator is used to decide on the feasibility of operation scenarios in terms of the required input relative to the number of available operation staff. The other use of this indicator is as a ratio of the number of actual to required structure settings to measure the relative performance of operation staff.

The ranges given next to the indicators define their possible values and also indicate the interpretation of the possible values in terms of performance levels. It must be noted that the values corresponding to "Ideal" performance are those that purely satisfy the mathematical formulae of the indicators. In practice, some tolerance around those values will be allowed. For example, the Water Delivery Performance (WDP) can be considered highly adequate if its value lies in the range between 0.9 and 1.1. The 10% allowance covers the difficulties in operating the system in the field and the errors in field measurements (most flow measurement methods have an inherent error of between 5% to 15%). The tolerance level to be allowed in the assessment is scheme specific. It depends on the "agreed level of service" accepted by the farmers as should be stated in the objectives of the scheme.

Similarly, the interpretation of the performance levels corresponding to the values of the indicators may vary from a scheme to another. As an example, in a scheme whose water resources are abundant, the performance of the scheme in terms of adequacy of supply to the offtakes will be considered ideal or satisfactory when the Water Delivery Performance (WDP) is equal to or greater than 1.0. However, in situations where water scarcity exists, a Water Delivery Performance that is much greater than 1.0 will be considered as an unsatisfactory performance leading to water wastage.

Some of the indicators listed above need field data to be evaluated while others can be evaluated by using either field observations or data from the output of hydraulic modelling simulation. The following section gives the indicators that can be evaluated from the output of hydraulic modelling and describes how they were calculated in this study.

5.2.3 Evaluating Performance Indicators from the Output of Hydraulic Modelling

A hydraulic model of irrigation system is defined by a group of "nodes". A node in a hydraulic model is a location in the modelled system where the hydraulic parameters such as the flow and water level are of interest (e.g. at control structures, changes in open channel dimensions, etc.). Every node in a hydraulic model is given a unique ID. When a hydraulic simulation is run, a simulation start time (T_o), end time (T_e), and time step (ΔT) have to be entered into the software. The output from the hydraulic simulation model includes the following hydraulic parameters for all the nodes at the different simulation time steps:

$Q_{i,t}$, $Stage_{i,t}$, $v_{i,t}$, etc.

where $Q_{i,t}$ = flow at node *i* at simulation time *t*

$Stage_{i,t}$ = stage (water level) at node *i* at simulation time *t*

$v_{i,t}$ = average velocity at node *i* at simulation time *t*

Thus:

- The Delivery Performance Ratio (DPR) at any node *i* and simulation time *t* can be evaluated as:

$$DPR_{i,t} = \frac{Q_{i,t}}{Q_{T_{i,t}}}$$

where $Q_{Ti,t}$ is the target flow at node *i* at time *t*

- The actual volume of water (V_a) delivered to node *i* during the time period T_o to T_e is:

$$V_{a_i} = \sum_{t=T_o}^{T_e-\Delta T} \frac{Q_{i,t} + Q_{i,t+\Delta T}}{2}$$

And the target volume (V_T) to be delivered to the node is:

$$V_{T_i} = Q_{T_i}(T_e - T_o)$$

The Water Delivery Performance (WDP) at node *i* can then be calculated as:

$$WDP_i = \frac{V_{a_i}}{V_{T_i}}$$

- The coefficient of variation (C_v) in the flow delivered to node *i* during the time period T_o to T_e is:

$$C_{V_i} = \frac{\sqrt{\dfrac{\sum_{t=T_o}^{T_e}(Q_{i,t} - \overline{Q}_i)^2}{n_T}}}{\overline{Q}_i}$$

where

$$\overline{Q}_i = \frac{\sum_{t=T_o}^{T_e} Q_{i,t}}{n_T}$$

$$n_T = \left(\frac{T_e - T_o}{\Delta T}\right) + 1$$

Similarly, the coefficient of variation in command can be calculated by using the water levels instead of the flows in the previous equations.

When evaluating the variability in the flow diverted to an offtake (coefficient of variation in the flow, C_v) in a simulation model where the flow diverted to the offtakes drops to zero (such as when simulating rotational flow), the evaluation time period covers only the time steps when the flow diverted to the offtake is equal to or more than 5% of its target flow. Smaller flows are ignored because they will not in practice be used and would result in relatively high variability if included in the evaluation. An example of such a case can be found in Section 9.3.

- The interquartile ratio (IQR) and the spatial interquartile ratio (SIQR) are special indicators. The input to these indicators should be the values of other indicators like the Water Delivery Performance (WDP) or the coefficient of variation (C_v) in order to assess the equity of the performance measures represented by these indicators. For instance, in order to assess the *equity* of the variability in the flow delivered to different locations, the coefficient of variation (C_v) of the flow should be worked out first and then the interquartile ratio of the coefficients of variation is evaluated. Similarly, to assess the equity of water distribution one may work out the interquartile ratio of the Water Delivery Performance (WDP) as follows:

$$IQR = \frac{Average\ of\ Highest\ WDP\ Quartile}{Average\ of\ Lowest\ WDP\ Quartile}$$

$$SIQR = \frac{Average\ WDP\ of\ Top-end\ Quartile}{Average\ WDP\ of\ Tail-end\ Quartile}$$

5.2.4 Application to other Irrigation Schemes

As will be shown in later sections of this report, the performance indicators listed above are used to assess the performance of the various scenarios and interventions tested using hydraulic modelling. It should be noticed that the values of the performance indicators and the associated levels of performance in any of those scenarios are not absolute, i.e. testing those scenarios in different schemes might produce different performance levels according to the features of individual schemes. Performance assessment is used primarily in this study to make comparisons between the different scenarios tested and to clarify the merits and drawbacks of some over others.

6 THE COMPATIBILITY MATRIX APPROACH

In this section an approach which uses the "Compatibility Matrix for Canal Control" is presented. The primary objective of this approach is to identify the potential problems in the different features of the operating environment of irrigation schemes which can cause water loss and inefficient water use. The approach is more orientated towards assessing the performance of the qualitative aspects of irrigation which are difficult to assess using quantitative performance indicators.

6.1 Changing Canal Control Methods

6.1.1 Justification for Change

A change of canal control method is only necessary if the current method is not achieving satisfactory performance. There are a number of reasons why control methods become unsatisfactory. These may be *passive* - the irrigation system does not change while the environment in which it operates is rapidly changing or *active* - there is a desire to improve the irrigation system.

Passive circumstances include increases in the cost of labour which make manually operated gates too expensive. As schemes age the physical components will deteriorate causing a reduction in performance. When all or part of the scheme is rehabilitated either all or in part there is an opportunity to change the canal control system to make it more appropriate to its changed environment. A scheme may demand changed canal control methods if it becomes unsustainable under current canal control methods, for example waterlogging due to large rejection overflows.

Active circumstances requiring a possible change in canal control methods include:

- Scheme enlargement
- Improved efficiency
- Increased flexibility thereby increased agricultural production potential

Enlarging a scheme may require larger flows through higher level canals and more efficient distribution within tertiary units in order to service the increased demand for irrigation supplies. Different canal control systems may be able to facilitate this without the need to reconstruct the main canal system.

Improving the efficiency of irrigation supplies reduces water wastage which may be causing environmental problems such as rising water tables. Improved efficiency will also allow more valuable crops with higher crop water requirements to be grown or the extra water to be used for non-irrigation purposes such as domestic water supply.

There is a growing trend in irrigation to supply water according to the demands of the water user. Consequently canal control systems also need to operate on a demand basis. Systems originally designed for rigid supply may be converted to demand systems using certain types of control. Flexibility can also be increased in supply-oriented systems by speeding up communications between the users and the irrigation agency without the need to changing the control to become demand-oriented.

A change in canal control method does not necessarily mean abandoning the existing control system. There are ways of improving control without altering the control system entirely (e.g. automating manual gates using controllers). This can be much cheaper than introducing a completely new control method as fewer structures will need to be altered.

6.1.2 Appropriateness of Change

Irrigation system control regulates the supply of water to the fields by controlling the movement and storage of water throughout the system above field level, including reservoirs and the catchment supplying the irrigation system. Control must be accurate in order to achieve a good supply at the field level. Control includes the *procedures* used to *operate structures* and therefore the *people* and *processes* involved in irrigation. When assessing canal control, account must be taken of not only *technical* and *economic* issues, but also what *operational methods* are in use and where and how the *water users* are considered in planning.

In assessing the need to change canal control methods, consideration needs to be taken of the potential effect not only on the infrastructure, but also on the people who will be running the system (irrigation agency, water user associations, etc.) and their ability to adapt to new and potentially more complicated operating systems, and the social environment in which irrigation takes place.

If an improvement or change is to be made to a canal control method then the method used must be appropriate for the environment, technical and non-technical, into which it will fit. The *compatibility matrix* approach has been developed in order to assist in judging whether a canal control method will fit into a certain environment or not.

6.2 The Compatibility Matrix Approach

The compatibility matrix can be applied to the problem of defining the requirements of the operating environment under various methods of canal control. The matrix developed would enable the identification of the new environment required if an alternative control method were to be adopted. The improvement which would be necessary in various aspects of the operating environment could then be assessed.

The compatibility matrix produced is shown in Tables 6.1a & 6.1b. A qualitative assessment of the requirements of the operating environment with each canal control method is denoted by a code number between 5 and 0, 5 indicating that the particular aspect is of major importance and 0 that the particular method of control does not depend on it (Table 6.1a). An additional colour coding is used in Table 6.1b. While the numeric coding includes six different possibilities (from 0 to 5), the colour coding reduces them to four possibilities only by assigning white to code 0, yellow to codes 1 & 2, cyan to code 3, and purple to codes 4 & 5. The colour coding can therefore be used as a simple alternative to the numeric coding by reducing the degrees of importance of the aspects of the operating environment to four: purple = high importance, cyan = medium importance, yellow = low importance, and white = no concern. A brief description of each of the factors of the operating environment which are listed in the compatibility matrix is given below.

Table 6.1a **Compatibility Matrix for Canal Control Methods**

Features of the Operating Environment			Canal Control Method: (1) Fixed upstream control	(2) Manual upstream control	(3) Auto-electrical upstream control	(4) Auto-hydraulic upstream control	(5) Auto-hydraulic downstream control with level-top	(6) Auto-electrical downstream control with level-top	(7) Downstream control with sloping canals	(8) Combined upstream and downstream control	(9) Centralized arranged upstream control	(10) Centralized dynamic regulation	(11) Pressurized systems	(S) Studied scheme (……………………)
Physical/Technical	1	Water supply reliability	0	2	2	2	3	3	4	3	4	5	3	
	2	Permissible silt load (water quality)	4	5	4	4	2	2	2	2	2	2	1	
	3	Climate (humid region)	1	1	1	1	5	5	5	3	4	5	5	
	4	Topography	0	0	0	0	s	s	0	s	0	0	L	
	5	Scheme size	0	0	0	0	0	0	0	4	5	5	0	
	6	Possible scheme extension	5	5	3	3	2	2	2	2	4	4	1	
	7	Access roads condition	1	5	3	3	2	2	2	2	1	1	2	
	8	Power availability (Electrification)	0	0	4	0	0	4	4	0	5	5	2	
	9	Spare parts	0	0	4	3	3	4	5	3	5	5	3	
	10	Durability	5	5	3	4	4	3	2	4	2	2	3	
Irrigation Agency	11	Organizational structure	0	5	4	4	2	2	2	2	3	3	2	
	12	Strength & influence within society	0	5	5	5	3	3	3	3	3	0	0	
	13	Scheduling preparation	0	5	5	5	0	0	0	2	2	0	0	
	14	Data collection (quantity & quality)	0	3	3	3	1	1	1	2	4	5	1	
	15	Office automation & technology	0	2	2	2	0	0	1	1	4	5	0	
	16	Operational plan & manual	0	4	3	3	1	1	1	3	5	5	2	
	17	Monitoring & evaluation	1	4	3	2	1	2	2	2	1	1	2	
	18	Communication	0	4	3	3	1	1	1	1	5	5	1	
	19	Staff numbers	1	5	3	3	2	2	2	2	1	1	2	
	20	Staff skill (in operation)	1	3	2	2	1	1	5	1	5	5	3	
	21	Staff motivation	0	5	3	3	0	0	0	0	0	0	0	
	22	Maintenance level	1	2	4	3	3	4	5	3	5	5	3	
	23	Training facilities	0	4	3	3	2	2	2	3	5	5	3	
Organizational	24	WUA & farmer participation	0	3	3	4	5	5	5	5	3	0	5	
	25	Legislation	1	2	4	5	5	4	3	5	3	3	3	
Social/Community	26	Water rights	5	5	2	2	0	0	0	0	5	0	0	
	27	Labour availability & cost	0	5	5	5	2	2	2	2	3	2	2	
	28	Farmer experience & traditions	3	5	5	5	2	2	2	2	4	2	3	
	29	Education & technology	0	0	2	1	1	2	3	1	3	4	3	
Environmental	30	Water logging and salinity problems	5	4	3	3	1	1	1	1	1	1	1	
	31	Spills from canals	5	4	4	4	1	1	1	2	2	1	1	
Economic & Financial	32	Water charges and water accounting	0	1	1	1	5	5	5	3	1	4	5	
Operational Objectives														
Performance Criteria	33	Equity	5	4	3	3	1	1	1	2	4	2	2	
	34	Adequacy	0	2	3	3	5	5	5	4	4	5	5	
	35	Reliability	3	2	3	3	5	5	5	4	5	5	5	
	36	Accuracy	4	2	3	3	4	4	4	4	5	5	5	
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(S)

Table 6.1b **Compatibility Matrix for Canal Control Methods**

Features of the Operating Environment		(1) Fixed upstream control	(2) Manual upstream control	(3) Auto-electrical upstream control	(4) Auto-hydraulic upstream control	(5) Auto-hydraulic downstream control with level-top	(6) Auto-electrical downstream control with level-top	(7) Downstream control with sloping canals	(8) Combined upstream and downstream control	(9) Centralized arranged upstream control	(10) Centralized dynamic regulation	(11) Pressurized systems	(S) Studied scheme (..............................)
		Canal Control Method											
Physical/Technical	1 Water supply reliability	0	2	2	2	3	3	4	3	4	5	3	
	2 Permissible silt load (water quality)	4	5	4	4	2	2	2	2	2	2	1	
	3 Climate (humid region)	1	1	1	1	5	5	5	3	4	5	5	
	4 Topography	0	0	0	0	s	s	0	s	0	0	L	
	5 Scheme size	0	0	0	0	0	0	0	4	5	5	0	
	6 Possible scheme extension	5	5	3	3	2	2	2	2	4	4	1	
	7 Access roads condition	1	5	3	3	2	2	2	2	1	1	2	
	8 Power availability (Electrification)	0	0	4	0	0	4	4	0	5	5	2	
	9 Spare parts	0	0	4	3	3	4	5	3	5	5	3	
	10 Durability	5	5	3	4	4	3	2	4	2	2	3	
Irrigation Agency	11 Organizational structure	0	5	4	4	2	2	2	2	3	3	2	
	12 Strength & influence within society	0	5	5	5	3	3	3	3	3	0	0	
	13 Scheduling preparation	0	5	5	5	0	0	0	2	2	0	0	
	14 Data collection (quantity & quality)	0	3	3	3	1	1	1	2	4	5	1	
	15 Office automation & technology	0	2	2	2	0	0	1	1	4	5	0	
	16 Operational plan & manual	0	4	3	3	1	1	1	3	5	5	2	
	17 Monitoring & evaluation	1	4	3	2	1	2	2	2	1	1	2	
	18 Communication	0	4	3	3	1	1	1	1	5	5	1	
	19 Staff numbers	1	5	3	3	2	2	2	2	1	1	2	
	20 Staff skill (in operation)	1	3	2	2	1	1	5	1	5	5	3	
	21 Staff motivation	0	5	3	3	0	0	0	0	0	0	0	
	22 Maintenance level	1	2	4	3	3	4	5	3	5	5	3	
	23 Training facilities	0	4	3	3	2	2	2	3	5	5	3	
Organizational	24 WUA & farmer participation	0	3	3	4	5	5	5	5	3	0	5	
	25 Legislation	1	2	4	5	5	4	3	5	3	3	3	
Social/Community	26 Water rights	5	5	2	2	0	0	0	0	5	0	0	
	27 Labour availability & cost	0	5	5	5	2	2	2	2	3	2	2	
	28 Farmer experience & traditions	3	5	5	5	2	2	2	2	4	2	3	
	29 Education & technology	0	0	2	1	1	2	3	1	3	4	3	
Environmental	30 Water logging and salinity problems	5	4	3	3	1	1	1	1	1	1	1	
	31 Spills from canals	5	4	4	4	1	1	1	2	2	1	1	
Economic & Financial	32 Water charges and water accounting	0	1	1	1	5	5	5	3	1	4	5	
Operational Objectives													
Performance Criteria	33 Equity	5	4	3	3	1	1	1	2	4	2	2	
	34 Adequacy	0	2	3	3	5	5	5	4	4	5	5	
	35 Reliability	3	2	3	3	5	5	5	4	5	5	5	
	36 Accuracy	4	2	3	3	4	4	4	4	5	5	5	
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(S)

6.2.1 Features of the Operating Environment

Physical/Technical

Water Supply Reliability

(Code 5 = water supply should be highly reliable)

Downstream control is a demand-oriented system which is designed to supply water to the farmers as they require, provided that there is sufficient water available to the system. A highly variable water supply with downstream control will increase the frequency of system failure in satisfying farmers' requirements. Consequently, farmers will tend to use too much water when it is available for the fear that it may not be available in the future, resulting in inequitable water distribution and inefficient water use. Upstream control on the other hand can force delivery schedules which ensure equitable distribution when the supply is short, thus they can better tolerate a relatively variable water supply.

Permissible Silt Load (Water Quality)

(Code 5 = heavy silt loads may be allowed in the system)

The hardware and the operational procedures commonly used with some control methods can influence the quantity of silt that may be allowed in the system. Pipeline systems for example are sensitive to silt loads because cleaning the silt which deposits in the pipes is not an easy maintenance activity. Downstream control is prone to the same problem because with this control method water can be stand still in canal reaches when the demand diminishes giving a good opportunity for any silt in the water to deposit in the canal network.

Climate (Humid Region)

(Code 5 = system is very efficient in humid climates)

Responsive systems such as downstream control and centralized automated upstream control can respond swiftly and efficiently to changes in the demands which can occur when heavy rainfalls occur causing farmers to stop taking water from the irrigation system. The quick response of such systems saves irrigation water by reducing the supply. Manually controlled upstream systems may not be able to respond quickly enough, and hence will result in large quantities of water being wasted. Responsive systems are therefore more efficient in more humid climates.

Topography

(Code s = average land slope should not exceed 0.25 m/km)

(Code L = land levelling is not required)

Topography is an important factor to consider in two types of irrigation control methods: downstream control with level-top canals and pressurised systems.

Downstream control with level-top canals requires relatively flat terrain for the system to be economical. Pipelines, on the other hand, have the advantage that they can cope well with undulating terrain and do not require extensive earth works to adjust the land to the canal slope.

Scheme Size

(Code 5 = system is more suited for large schemes)

One of the important factors that favour the use of centralized control is when the scheme is large. Centralized control is more efficient in such cases because it saves the cost of the large number of staff that would be required if the system were manually operated. It also speeds up the communication and data collection processes, thus enabling faster and more efficient control.

Possible Scheme Extension

(Code 5 = system can easily accommodate scheme extension)

When a scheme is to be enlarged after some time of operation, it will be required in most cases to modify the physical system to give it larger capacity. Some control systems will be able to accommodate the required modifications better than others. For example, enlarging a canal with manual upstream control can be done by enlarging its cross-sections and adding extra bays to existing control structures if required. This modification will be much more expensive if the canal is under downstream control with level banks because more earth work will be required and the fixed-target control structures (such as AVIO and AVIS gates) will have to be totally re-positioned/removed if new target levels are required.

Access Roads Condition

(Code 5 = it is essential that road conditions are good all year round)

In manually operated systems operation staff must be able to travel to and between their service areas in order to monitor the system and make any required adjustments to control structures. The condition of the roads in schemes with manual control should therefore be good all year round to enable staff to move. Automated systems do not access in this way.

Power Availability (Electrification)

(Code 5 = a highly reliable power supply is essential)

Automated systems with electrical controllers must have a good and reliable power supply to minimise system failure.

Spare Parts

(Code 5 = high-technology spare parts should be available in local market)

Some control methods depend on highly sophisticated electronic equipment. The spare parts of such equipment should be available in the local market. Securing foreign currency and the procedure of importing spare parts if they are not locally available can cause significant delay to the maintenance of the system which can lead to low performance of the system and potentially damage the canals.

Durability

(Code 5 = system is highly durable)

The hardware used in the different control systems affects their durability (refer to Table 4.1 for more details).

Irrigation Agency

Organizational Structure

(Code 5 = the irrigation agency should have a well defined organizational structure)

The agency or other institution that runs the irrigation scheme has organizational structures for the operation of the system. These structures may be complex or simple, well established or new, rapid or slow. Different control methods require different degrees of operation through these organizational structures and usually rely on them for the effective operation of the system. Manually operated systems require well defined, efficient, and well managed organisations.

Strength and Influence within Society

(Code 5 = the irrigation agency must be strong and have significant influence on the farmers)

Whether the irrigation agency is private or public and if it is a strong or weak institution is important in the degree of commitment the staff and management have to the scheme and the farmers on the scheme. A weak publicly run agency will not be able to have effective control over a system that requires frequent close control. An irrigation agency will usually benefit if it is already established and has found its place within the wider society. Other people and institutions who have to work with the irrigation agency will know better what to expect from it and the agency will know how it can and cannot rely on people and institutions outside the irrigation scheme.

Scheduling Preparation

(Code 5 = efficient system operation depends heavily on scheduling calculation)

To achieve high water use efficiency and prevent water shortage and wastage, matching the supply with the demands in supply-oriented systems is a must. Matching supply with demand requires precise estimation of the demands (irrigation scheduling) or collecting requests for water from the farmers in systems with arranged-delivery schedules. This task is not required for demand-oriented systems to operate efficiently.

Data Collection (Quantity & Quality)

(Code 5 = large quantity and high-quality data must be collected)

Data is essential for the management to be able to take optimum decisions. The quantity and quality of the data which should be collected is dependent on the canal control method employed. As discussed in the previous section more data needs to be collected in supply-oriented systems. Centrally automated systems which use mathematical algorithms to achieve control require reliable and accurate data from sensors positioned at control structures.

Office Automation and Technology

(Code 5 = use of computers and other office automation equipment is essential)

Centrally automated control methods usually use computer software to control the irrigation system. Manually operated systems can also benefit from some office automation (computers) to help organize and process the large quantities of data that need to be collected in such cases.

Operational Plan and Manual

(Code 5 = an operation plan and manual must be available and should be followed)

One of the direct causes of poor performance of manually operated systems is the lack of clear and workable operational plans and manuals that clearly state the responsibilities of every staff member. Automation relatively reduces the need for detailed manuals since operation is carried out by the equipment.

Monitoring and Evaluation

(Code 5 = more monitoring and evaluation is required)

The final activity in the operation process is to monitor the system being managed and evaluate its performance. This activity is more important in manually operated systems to ensure that planned allocations/control settings are implemented in practice.

Communication

(Code 5 = efficient means of communication are essential)

Responsive systems have their own means of communication (usually hydraulic) to transmit changes from downstream to upstream. Supply-oriented systems, however, lack such built-in communication and should therefore have other means of communication between operation staff. Communication does not have to be between operation staff only, automated systems with centralized control require very efficient communication systems to link the central control location with control equipment and sensors in the field.

Staff Numbers

(Code 5 = large number of operation staff is required)

By nature, manually operated systems require a larger number of operation staff than automated ones.

Staff Skill (in operation)

(Code 5 = operation staff must have high skills)

The effect of control methods on the required skill of operation staff is opposite to that on the number of staff; highly skilled operation staff are required for automated systems, especially those with electrical automation.

Staff Motivation

(Code 5 = staff must be highly motivated)

The large effort that is required from operation staff to efficiently operate manual systems can only be realised if staff are highly motivated and willing to improve the performance of the system they run.

Maintenance Level

(Code 5 = high levels of maintenance are essential)

The operation and maintenance requirements for a system become more critical as the level of technology and computerisation increases. As a general rule, simple systems such as fixed proportional distribution structures can operate with lower levels of maintenance than automatic systems. For automatic systems, the staff maintaining the system must be skilled and familiar with the way the irrigation system works in order to identify and correct system malfunctions. There needs to be an appropriate level of support so that, once identified, problems can be quickly resolved. This is particularly important for computer controlled systems where minor operational problems can have a major impact on the whole system.

Training Facilities

(Code 5 = operation staff must take advanced training)

Generally, training of all operation and maintenance staff is important to keep their knowledge up to date. Training of operation staff is more important when the irrigation system is highly automated. The technology used in electronic equipment changes rapidly and it is most likely that such equipment will be updated from time to time. Staff must receive proper training about how to use new equipment efficiently as soon as they are installed. Staff running manually operated systems require training in order to know how to do their jobs.

Organizational

WUA and Farmer Participation

(Code 5 = the formulation of WUA and farmer participation is highly recommended)

Where landholding is small and there are many farmers within an irrigation system there is a need for Water User Associations (WUA) to facilitate communication between the agency and the farmers. For manually operated smallholder systems these Water User Associations and farmer participation in management, operation, and maintenance can improve system performance.

Demand-oriented systems give the farmers much more flexibility to use water whenever they want. This high flexibility can be misused leading to inefficient water use and poor performance if farmers are not well organized, not individually responsible for the water (and payment for it), and do not understand the basics of such control methods. To improve the water use efficiency it is essential that farmers are organized in water user associations to take the responsibility of controlling the system properly.

Legislation

(Code 5 = effective legislation must exist)

This factor is closely related with the previous feature. Local downstream control (especially with hydraulic equipment) can be easily tampered with by farmers. Effective and implementable legislation must exist to prevent such behaviour. Manually controlled structures are generally more difficult to tamper with.

Social/Community

Water Rights

(Code 5 = possible to respect water rights when distributing water)

Some old irrigation schemes have well established water rights which must be respected when distributing water. Although this point particularly affects distribution at the very low levels of the systems, it can still be affected by the control system at the higher levels. Downstream control methods do not make allowance for water rights whereas upstream control methods can be adjusted to accommodate them.

Labour Availability and Cost

(Code 5 = labour must be available most of the time at reasonable cost)

Availability of labour is one of the factors which play an important role in the economics of system operation and agricultural production. Manually operated systems may be more appropriate and economically feasible to adopt in countries with large populations where labour is available and relatively cheap. As cost of labour gets higher moving to automated systems could be more viable.

Farmers need to hire labour form time to time to help them in the labour-intensive farming activities. When water is available on demand farmers can schedule the farming activities which need additional labour to best match with labour availability. Rigid water delivery schedules on the other hand do not give much freedom to the farmers to decide upon the optimum timing for farming activities and can cause labour shortage when all the farmers on the same canal need to do the same farming activity at the same time because of the limited time during which water is available.

Farmer Experience and Traditions

(Code 5 = farmers must be very experienced with irrigated agriculture)

This factor is again affected by the flexibility of water delivery schedules (rigid/flexible). Supply-oriented systems are more rigid than on-demand ones thus require more experienced farmers to adapt to them. Arranged-delivery schedules also require that farmers know when and how much water is needed to order it. On-demand systems adapt to farmers needs instead, but can be wasteful if farmers misjudge crop water requirements.

Education and Technology

(Code 5 = it is advantageous if community is reasonably educated)

The level of education and technology awareness of the community are important factors to consider when deciding upon the proper control method to implement. Although the community may have nothing to do with the control system, their awareness and respect of the technology used may affect whether the technology is accepted or not. When the community is not aware of the importance of electronic control equipment for example they may tamper with them or even try to steal them. Hydraulic gates do not function properly if farmers tamper with them or debris or other waste is disposed of in the immediate vicinity of the control structures. Children playing on automatic upstream or downstream level control gates can have serious consequences on canal operation and the safety of the system.

Environmental

Water Logging and Salinity Problems

(Code 5 = increased risk of water logging and salinity problems)

Supply-oriented systems deliver water to the farmers according to schedules prepared by the irrigation agency. Consequently, it is not always guaranteed that delivered water will be required or optimally used. Excess water will be allowed to flow to the drains or left in the fields and water table levels may be raised causing water logging and salinity problems.

Spills from Canals

(Code 5 = more spills from irrigation network)

This problem is very similar to the water logging and salinity problems discussed above. A failure to correctly match supply with demand, or to adjust control structures correctly at diversion points may lead to water shortage or spillage at different locations in the canal system.

Economic and Financial

Water Charges and Water Accounting

(Code 5 = very important to charge for water)

To guard against over use of water in demand-oriented systems some form of self-control needs to be imposed on farmers. This can either be in the form of charges per unit of water used, or in the allocation of a limited volumetric water right for each season. If the value of the crop relative to the price of water is high charging for water will not be as effective as limiting the water right.

Performance Criteria

Equity, Adequacy, Reliability, and Accuracy

(Code 5 = possible to achieve high performance)

The operational objectives of irrigation schemes vary from one to another. Similarly, canal control methods vary in their adaptability to easily achieve the different operational objectives. Fixed proportional distribution mainly aims at achieving equitable distribution without giving much attention to adequacy, while downstream control targets the adequacy, reliability, and accuracy but not equity.

6.2.2 Correlation between Canal Control Methods and Aspects of the Operating Environment

As described earlier, the importance of a given feature in the operating environment is denoted by the code number inserted in each cell of the compatibility matrix, Table 6.1a. These numbers indicate the requirements of an ideal environment for operation under a given method of canal control. It must be emphasised that the numbers or rankings assigned to the cells are relative and do not represent actual values.

The matrix can be used in two different ways: it can be used to assess the potential shortfalls in an existing system which lead to poor performance, or it can be used to check whether a control method is compatible with a particular environment or not. In both cases the environment under consideration must be evaluated such that codes can be given to the nodes of the compatibility matrix. For example, if the power supply in the scheme under consideration is not very reliable then code 3 should be given to the that aspect in the matrix, while code 0 would be used if no power supply is available at all. Comparing between the codes given to the environment and those already in the matrix, which describe the ideal environments for each control method, can then show the points of strength and weakness.

When a canal control method is not fully compatible with the environment within which it should work two options are available. One is to try to close the gap between the actual capabilities and features of the environment and the ideal situation. The second is to select another control method which more closely matches the already existing features in the environment. The decision of which option to choose is dependent on how wide the gap is between the actual environment and the ideal situation. Wide gaps indicate that the control method investigated will not easily fit in the environment unless radical changes are made. A more feasible option in this case will be to choose another control method which is more compatible with the existing environment without the need for major changes.

6.3 Data Collection Using Questionnaires

6.3.1 General

Questionnaires may be used to collect qualitative and quantitative data on irrigation schemes for routine monitoring purposes or, as in the present study, to collect specific data for special studies or investigations.

When information is required from a number of schemes and is not available in existing records it may be necessary to design special questionnaires for the purpose. The availability of information will depend on how active the agency responsible for operating the scheme has been, bearing in mind that the data required for special studies may not have been collected in the past.

6.3.2 Use of Questionnaires in the Present Study

The questionnaire presented in Appendix A.1 has been developed and used in this study to gather information relating to selected schemes. The data collected by the questionnaire was required to enable completion of the compatibility matrix such that an analysis of the situation in those representative schemes could be made. As will be apparent from Table 6.1a, the aspects of the operating environment which were to be covered and the information required for their investigation is diverse. In the development of a questionnaire to collect such information there is of necessity a trade-off between the simplicity of the questionnaire and the quantity and usefulness of the data to be collected. The process may be iterative, the questionnaire being modified as responses are analysed from field trials. In this way the form of questionnaire that best achieves the objectives of the study could be developed.

A revised shorter questionnaire was also produced in this study, Appendix A.2. It is aimed mainly at collecting specific information concerning the configuration and performance of irrigation distribution systems. The revised questionnaire does not cover the wide spectrum of the aspects of irrigation schemes, thus cannot be used to collect the data required for completing the compatibility matrix. For this purpose the questionnaire presented in Appendix A.1 would be required.

6.3.3 Linking the Questionnaire to the Compatibility Matrix

Table 6.2 outlines the linkages between the different questions in the questionnaire in Appendix A.1 and the different features of the operating environment in the compatibility matrix (Table 6.1). It should be noted that some of the features in the compatibility matrix should be evaluated based on information from different parts of the questionnaire not from one or two directly related questions only. On the other hand, some questions in the questionnaire do not have *direct linkage* with the features in the compatibility matrix but are required to complete our picture of the scheme under investigation and to provide better understanding of the operating environment.

6.3.4 Coding the Compatibility Matrix

The last column in the compatibility matrix, Table 6.1a, is left blank for the user to fill it in with the codes of the scheme under investigation. Using the questionnaire presented in Appendix A.1 for data collection and Table 6.2 for linking the questions to the matrix, the condition of the features of the operating environment can be assessed and hence a code given to each feature. It must be stated however that the coding still remains a highly subjective process and hence it may be necessary that this process is carried out by experienced irrigation practitioners.

6.4 Summary and Conclusions

Each canal control method will operate most efficiently given a certain "ideal" environment (technical and non-technical). Where one or more features of the operating environment fall short of the optimum this is likely to result in a lower efficiency of operation and/or water shortage or wastage.

When considering a change of canal control method, the environment within which the new control method will be operated must be examined to determine whether the necessary conditions for effective operation exist or have the potential to exist. The *compatibility matrix* approach can be used as a checklist to assess the suitability of the different canal control methods in certain environments, thus enabling the choice of that which is most appropriate.

Two questionnaires have been developed in this study for the purpose of collecting the information required to define the physical and operational constraints which influence the performance of irrigation systems, Appendices A.1 and A.2. The following points are important to take into consideration when questionnaires are to be used in any study for data collection:

- the response to questionnaires is often poorer than hoped for, especially when the questionnaires are to be completed by personnel not directly concerned with the studies concerned;
- the longer the questionnaire and the more the data required to complete it, the less likely is the return of a useable response;
- for the reasons listed above, it is recommended that data should be collected personally by those carrying out the study as far as possible.

Table 6.2 Compatibility Matrix for Canal Control Methods
Links between the Questionnaire and the Matrix

Features of the Operating Environment		**Questions in Questionnaire**
Physical/Technical	1 Water supply reliability	Q 22
	2 Permissible silt load (water quality)	Q 24
	3 Climate (humid region)	Q 4, 25, 26
	4 Topography	Q 14
	5 Scheme size	Q 8
	6 Possible scheme extension	Q 8
	7 Access roads condition	Q 17
	8 Power availability (Electrification)	Q 18
	9 Spare parts	Q 19, 65
	10 Durability	Q 35, others
Irrigation Agency	11 Organizational structure	Q 40-41
	12 Strength & influence within society	Q 60-62, 80, 85
	13 Scheduling preparation	Q 50
	14 Data collection (quantity & quality)	Q 44-46, 96
	15 Office automation & technology	Q 46, 50
	16 Operational plan & manual	Q 48, 49
	17 Monitoring & evaluation	Various
	18 Communication	Q 53
	19 Staff numbers	Q 35, 42, 44, 55
	20 Staff skill (in operation)	Q 42, 51, 55
	21 Staff motivation	Q 42, 43, 54
	22 Maintenance level	Q 68, 69
	23 Training facilities	Q 42, 51, 55
Organizational	24 WUA & farmer participation	Q 79
	25 Legislation	Q 85
Social/Community	26 Water rights	Q 13
	27 Labour availability & cost	Q 82-84
	28 Farmer experience & traditions	Q 77
	29 Education & technology	Q 75, 76
Environmental	30 Water logging and salinity problems	Q 15, 16, 23, 29, 31
	31 Spills from canals	Q 48, 56, 57
Economic & Financial	32 Water charges and water accounting	Q 91
Operational Objectives		
Performance Criteria	33 Equity	Various
	34 Adequacy	Various
	35 Reliability	Various
	36 Accuracy	Various

7 USING HYDRAULIC SIMULATION OF IRRIGATION NETWORKS

7.1 Introduction

Rapid developments have been made in the application of computers in recent years. These techniques are in widespread use in many fields of engineering.

In the fields of irrigation and drainage, commercial software is now available for a number of different aspects including planning, design, management and operation of projects.

Modelling and simulation play an increasing role and the present research project is an example of how these techniques might be used more widely in the future in irrigation studies.

7.2 Flow in Canal Networks

Most irrigation schemes have distribution networks consisting of open channels. Different types of open channel flow can be distinguished: Uniform/non-uniform flow, and steady/unsteady flow.

The simplest flow type is steady uniform flow where flow rate does not change with time and location (distance along a channel). Friction formulae like Manning's and Chezy's are used for the calculation of this flow type.

Steady non-uniform flow takes place at the entrances and exits of canals and at obstructions like weirs, cross-regulators, bridges, etc. The flow is non-uniform because the rate of flow changes with location, and steady because the rate does not change with time. Non-uniform flow may extend over long reaches of canals to form what is known as ‘backwater curves’. Backwater curves usually occur in canal reaches upstream from control structures. The solution of non-uniform flow is based on different formulae for the different types of obstructions that cause this type of flow.

Unsteady flow in open channels may be characterised by the change of flow rate with time and location as in the case of wave propagation. The phenomenon is complicated and analytical solutions are limited. The solution may be found by combining the continuity and the momentum equations (together called Saint Venant equations). For computerised calculations, various techniques for the solution of the set of equations have been developed such as the finite difference scheme, the Preissmann scheme, etc. Although unsteady flow calculations are important for flood routing and urban drainage computations, the increased computing power now available has extended the application of unsteady flow calculations to the simulation of irrigation canal flow.

7.3 Applications of Hydraulic Modelling in Irrigation

7.3.1 Potential Uses of Hydraulic Modelling in Irrigation

Hydraulic simulation models are applied in the field of irrigation engineering, mainly at the conveyance and distribution levels of irrigation networks. Some of the potential uses of hydraulic modelling in irrigation are:

- To test the effectiveness and efficiency of different operational procedures and to correct those procedures if the resulting performance is not satisfactory or needs improvement. Sections 9 & 10 show some examples of this type of application.

- To evaluate the characteristics of existing or planned irrigation systems such as the lag times, in-storage capacity, physical constraints, incompatible and interfering structures, storage reservoirs, and others. Knowing these characteristics and thus taking them into consideration can greatly improve the operation and performance of the project. The examples given in Section 8 are typical of this type of application.

- To analyze the impact of floods which may enter irrigation systems and test the effectiveness of the available alternatives to route the flood waves through the system in order to prevent or minimise the damage.

- To develop and test canal control algorithms (examples of which are CARDD, BIVAL, and EL-FLO). This application for hydraulic modelling is indispensable since testing canal control algorithms on real systems is in practice not possible. Testing the algorithms using hydraulic modelling is essential before implementing them on real systems.

- To assess the effect of improper or lack of maintenance such as weed growth, sedimentation, malfunctioning or damaged structures on system operation and performance.

- To assist in system rehabilitation and modernisation studies by assessing the improvement in system performance due to modified canal sections and control structures.

- To train design engineers and system operators on the basic principles of unsteady flow in open channels and the consequences of changes made in system design and operation on the flow and water levels in the system. The better understanding of such issues by design and operation engineers should help them make better designs and plan more effective and achievable operational procedures.

The user of simulation models must however be aware of the differences between the real system and the model being simulated. An important example to give here is the difference between the availability and accuracy of flow measurements in the field and flow data from hydraulic models. While most flow measurements in the field have an accuracy of about ±10%, flow data from hydraulic models will usually appear to have much higher accuracy. Assuming that this high accuracy in flow measurement will be reached in the field can be over-optimistic. Hydraulic models also give information about the flow and the water levels at many different locations in the system being modelled. Such information will be available in the filed only if measuring structures/devices are available at the same locations.

7.3.2 Limitations of Hydraulic Modelling Application

Regardless to the wide range of applications of hydraulic simulation models in the operation and management of irrigation systems, the current status and capabilities of available software impose difficulties on their use for:

Real-time Management

There is an argument in the literature about whether hydraulic modelling can be used for real-time management of irrigation systems or not. The experience from this study supports the opinion that it is still very difficult to use hydraulic modelling for real-time management. Simulating unsteady flow in complicated and large irrigation networks is not easy and cannot be done very accurately. Almost all simulation models have built-in assumptions to simplify some modelling problems. Investigating the possible causes of model failure which frequently occurs, requires inputs by experienced modellers with knowledge of the software employed and can be time consuming. Such cases can therefore be hazardous in systems which rely on hydraulic modelling for real-time management.

Studying the Physical Losses from Irrigation Canals

The review of hydraulic modelling software in Appendix B.1 shows that only one model of these reviewed can account for seepage losses and none takes evaporation losses into consideration. In most of the others, seepage losses cannot be directly accounted for and should be approximated by other arrangements. Those approximations may be sufficient to generally account for the losses but will not be satisfactory if seepage losses are of major concern or the central issue of a study.

Simulating Manual Operation

Although all hydraulic simulation models allow the user to control the settings of adjustable structures in ‘manual’ mode, i.e. the adjustments made to the settings of the structures are not based on computer algorithms, this *virtual* manual mode does not allow exact simulation of the *real* manual operation in the field. For the manual mode in simulation models is usually achieved by means of user-defined set of simulation run times and corresponding structure settings (time-setting relationship). The actual manual operation, however, rarely relates structure operation to time but to changes in the hydraulic conditions (water levels or flows) in the irrigation system. Consequently, simulating what exactly happens in the manual operation of irrigation systems may not be a straight forward task with the hydraulic modelling software used.

7.3.3 Data Requirements

The data required for building hydraulic models of irrigation systems can generally be grouped as data regarding the irrigation canals and data of control and other structures in the network.

Design canal cross-sections can be used for modelling lined canals and newly constructed or rehabilitated earth canals. Surveyed cross-sections will be required for modelling earth canals which have been operating for some time in order to consider the deformation in actual cross-sections. Essentially, canal cross-sections will be required at the locations where changes exist such as changes in cross-section dimensions and drops in bed level. However, other cross-sections will be required at more or less regular spacing in order to improve the accuracy of the simulation results and to prevent model failure. The spacing between the cross-sections in a model depends on many factors such as the steepness of the canals and more importantly on the requirements of the specific hydraulic model used.

The piece of information that is usually not available, mainly because it is more difficult to measure in the field, is the actual roughness of the canals. The common practice in this case is to assume the values of the roughness of the canals based on experience or as recommended in standard texts and then refine the assumptions by model calibration. In this way, hydraulic modelling can be used in reverse to estimate the roughness of irrigation canals.

Information about every structure in the modelled canal network must be available to enter into the model. Required information varies from one model to another but generally structure type (weir, vertical gates, radial gates, etc.), location (chainage), dimensions, design flow, discharge/friction coefficients, design head loss, and their operational schedule will be required. This information will most probably not be readily available, especially the discharge/friction coefficients. Also, available data will usually be the design data not as actually constructed. Missing data may be estimated and the results from hydraulic modelling calibrated using field observations.

Not only design and hydraulic data of the physical system are required for modelling irrigation systems. Information concerning the operational procedure of the system and structure operation schedules will also be required in order to simulate those procedures in the simulation model to test their efficiency. This latter information is quite often forgotten when modelling irrigation systems, thus modelled scenarios can be different from those actually practised in the field. The consequences are clear: while a system may prove efficient when simulated in hydraulic models, the real performance of the system as actually operated may be much poorer.

The output from hydraulic modelling software can be reasonably accurate only if the input data is accurate. Since this is not usually the case, model calibration should be carried out by comparing the results from some runs which simulate already known situations with data from the real system. Input data can then be refined such that the output from hydraulic modelling closely matches the real data.

7.4 Using Hydraulic Modelling in this Research Project

Sections 8 to 10 of this report demonstrate some of the techniques used in this study to investigate potential measures for improving canal control and irrigation system performance using hydraulic modelling.

7.4.1 Modelled Systems

Three irrigation systems have been modelled in the present work: systems *A* and *B*, which are real case studies, and the *virtual* system which was designed specifically for this study. The layouts and brief descriptions of these systems are available in Appendices C.1 to C.3. Table 7.1 highlights the main differences between these systems.

Table 7.1 The Main Differences between the Characteristics of the Modelled Systems

Characteristic	System *A*	System *B*	The *Virtual* System
Control method	Manual upstream control		
Total length of modelled network	65 km	40 km	16 km
Canal material	Earth	Lined	Earth
Canal cross-sections	Irregular	Trapezoidal	Trapezoidal
Average canal slope	Gentle	Steep	Gentle
Control structures	Undershot gates	Undershot gates/weirs	Undershot gates

7.4.2 Hydraulic Modelling Software

The hydraulic model ISIS Flow has been used to run the simulations reported in the following sections of the report. The program has a large library of control structures which proved to be helpful in modelling various irrigation structures. It is also capable on modelling automated structures by using the Control Module with ISIS Flow. The capability on modelling both open channels and pipelines together is particularly useful in modelling irrigation networks which consist of open-channels but also have culverts and other piped parts. A more detailed description of ISIS Flow and its features is available in Appendix B.2.

8 CONTROL STRUCTURES

An irrigation system is principally defined by the canal control method employed and the types of control structures. The main objective of this section is to investigate the hydraulic characterictics of canal control structures and how they influence the performance of the irrigation system. The selection of the proper type of structure to perform a certain function along with their operational implications are also investigated.

8.1 Weirs Versus Orifices

The basic principle of water level and flow control in open channels is to use structures that function as either weirs or orifices and sometimes as a combination of both. An example of irrigation structures that function as weirs are broad, sharp, and long crested weirs (and essentially any structure where water passes over its top). While irrigation structures that function as orifices are undershot sluice gates whose gates are immersed in the water (drowned flow).

The decision of which type of structure to use in the different locations of an irrigation network is not sometimes clear to many designers, and the impact of the type of a structure on the performance of the canal network it controls may not be comprehended by operation staff. Horst (1996) compiled a list of the different types of check and offtake structures proposed by various consultants for different irrigation projects in Indonesia. The list shows a wide diversification of structure combination. The reasons for choosing particular structures were not clear in many cases which led Horst to come to the conclusion that the wide diversification in the types of structures proposed was mainly influenced by the technical backgrounds and the design traditions of the various consultants from different parts of the world.

The hydraulic behaviour of a structure is characterised by the formula relating the flow through the structure to the head difference across it. The basic formula for the free flow over weirs and through orifices can be written in the form:

Weir	Orifice
$Q = C_d\, b \sqrt{}\ (2/3\ h)^{3/2}$	$Q = C_d\, A \sqrt{2g}\, h^{1/2}$

where Q = flow through structure

C_d = coefficient of discharge

b = weir breadth

A = cross-sectional area of the orifice

h = head difference across the structure

8.1.1 Free Flow and Drowned Flow

The equations given above are valid for **free** flow over weirs and through orifices. Generally, a structure is said to be flowing freely when the water level downstream from it is lower than the upstream water level by a certain ratio, called the *modular* or the *submergence ratio*. For broad crested weirs, the modular ratio is around two-thirds. When the downstream water level is higher than the modular ratio, the structure is said to be **drowned**. The important hydraulic difference between free and drowned structures is that the flow and the water level upstream from free structures are not affected by the changes in the conditions downstream from those structures, while with drowned structures they are affected. In other words, drowned structures *transmit* the signals from the disturbances in the hydraulic conditions at their downstream sides to the upstream sides while free structures *isolate* their upstream sides from the downstream ones.

8.1.2 Operational Implications of the Different Structure Types

The operational implications associated with the choice of a certain type of structure can be assessed in terms of two hydraulic concepts. These concepts are the *sensitivity* of a structure and the *flexibility* of offtakes at canal bifurcation points (Bos, 1989 and Horst, 1996). In this study it is also useful to further subclassify the sensitivity of a structure into *flow sensitivity* and *head sensitivity*. The flow sensitivity in this study is synonymous with the sensitivity criteria as generally used in the literature.

Flow Sensitivity

The flow sensitivity (Sf) of a structure is defined as the proportional change in the flow through the structure caused by a unit change of the upstream water level (head on structure):

$$\text{Sf} = \frac{\Delta Q}{Q}$$

$$\Delta Q = \frac{\text{dQ}}{\text{dh}}\,\Delta\text{h}$$

$$Q = \text{Const. h}^{\text{u}}$$

$$\frac{dQ}{dh} = Const.\,uh^{u-1}$$

$$\Delta Q = \text{Const. uh}^{u-1}\,\Delta\text{h}$$

$$Sf = \frac{Const.\,uh^{u-1}\Delta h}{Const.\,h^{u}}$$

$$Sf = u\,\frac{\Delta h}{h}$$

where u = power of head in flow equation

= 1.5 for weirs and 0.5 for orifices

It is obvious that this criteria is very important to evaluate when selecting offtake (outlet) structures.

Head Sensitivity

The head sensitivity (Sh) of a structure can be defined as the proportional change in the head (water level) on the structure caused by a unit change of the flow through the structure:

$$Sh = \frac{\Delta h}{h}$$

$$\Delta h = \frac{\mathrm{dh}}{\mathrm{dQ}}\,\Delta Q$$

$$h = \mathrm{Const.}\;\mathrm{Q}^{\frac{1}{u}}$$

$$\frac{dh}{dQ} = Const.\,\frac{1}{u}Q^{\frac{1}{u}-1}$$

$$\Delta h = \mathrm{Const.}\;\frac{1}{u}\mathrm{Q}^{\frac{1}{u}-1}\;\Delta Q$$

$$Sh = \frac{Const.\,\frac{1}{u}Q^{\frac{1}{u}-1}\Delta Q}{Const.\,Q^{\frac{1}{u}}}$$

$$Sh = \frac{1}{u}\frac{\Delta Q}{Q}$$

To test the head sensitivity of each type of structure to the variation in the flow, we assume that the same flow change will occur through both structures and then make a comparison between the changes in the other variables. For instance if a 20% change in the flow rate is to occur (Q →1.2 Q), then:

Weir	Orifice
$Q = C_d\, b\, \sqrt{g}\, (2/3\, h)^{3/2}$	$Q = C_d\, A\, \sqrt{2g}\, h^{1/2}$
$1.2 = \mathrm{Const}\; h^{3/2}$	$1.2 = \mathrm{Const}\; h^{1/2}$
h = 1.13	h = 1.44
i.e. 13% change in head	i.e. 44% change in head

Two assumptions were made in the above analysis: 1) The opening of the orifice (openings of structure gates) was not altered to cater for the change in the flow rate, and 2) The coefficient of discharge remained constant or had the same rate of change in both types of structures as the flow changed.

It can be seen from this analysis that the change in the head on the structure, and therefore the change in the water level upstream from the structure, due to a change in the flow rate will be much smaller in the case of weir structures than in the case of orifice structures. This characteristic highlights the advantage of using **weirs as upstream water level control structures** when a large variation in the canal flow is expected (cross-regulators in systems which have manual upstream water level control). In addition to the benefits of their hydraulic performance, weirs are much easier to operate and maintain.

Reversing the above exercise to test the flow sensitivity of the structures is also of interest. In the same procedure explained above, if we assume this time that a 20% change in the head on the structure is to occur we can see that the change in the flow through an orifice will be almost one third of the change in the flow over a weir. The conclusion that can be reached from this analysis is that orifice (sluice) structures are advantageous to use where the flow through a structure is to be kept as steady as possible when the water levels at the structure fluctuate. Such a feature is highly desirable in offtake structures.

Flexibility

The flexibility (F) can be defined as the ratio between the rate of change of the discharge through an offtake to the rate of change of the discharge in the supply canal:

$$F = \frac{\frac{\Delta q}{q}}{\frac{\Delta Q}{Q}} = \frac{Sf_0}{Sf_c}$$

where q = flow through offtake

Q = flow in supply canal

Sf_o = flow sensitivity of offtake structure

Sf_c = flow sensitivity of canal check structure

The impact of the different combinations of check and offtake structures according to the type of structure used for each can be analysed in terms of the sensitivity and flexibility of each structure. The flexibility (F) can be used to assess the impact of flow fluctuations at the head of a system on its different parts as follows:

- F = 1 flow fluctuations will be spread evenly over the whole system
- F > 1 flow fluctuations will be more pronounced at the upper parts of the system and will damp as we move further down
- F < 1 flow fluctuations will be weak at the upper parts of the system and will build up to be more pronounced at the lower parts.

8.1.3 Long Crested Weirs[1]

As the name implies, a long crested weir has the length of its crest perpendicular to the flow direction elongated to minimize the effect of the flow change on the variation of the head on the weir and hence the variation in its upstream water level.

To study the effect of increasing the length of the weir crest we follow the same procedure utilised above in making the comparison between weirs and orifices. Here we assume that the flow is constant while the length of the weir crest (b) varies. If we consider a case of making the weir crest ten times longer then:

$Q = C_d\ b \sqrt{g}\ (2/3\ h)^{3/2}$

$Const_1 = Const_2 * 10 * h^{3/2}$

so, h = 0.215

i.e. when the flow over the weir is constant the head on the weir of length 10*x* will be 22% of the head on the weir of length *x*.

This further enhancement in the weir design promotes the idea of **using long crested weirs instead of undershot gates as upstream water level control structures**.

8.1.4 Hydraulic Modelling Tests

A study of the comparison between using long crested weirs and undershot gates as upstream water level control structures (cross-regulators) was carried out using hydraulic modelling of system *B*, Figure 8.1 (see Appendix C.2 for a brief description of the system). Two models were set up for canal *B1*; one which simulates the original design of the system with undershot gated cross-regulators, and another with the gated cross-regulators replaced with long crested weirs. The weirs were designed to maintain the same upstream design water levels (DWL) achieved by the gated cross-regulators in the original design of the system such that a comparison between the results of the two models could be made.

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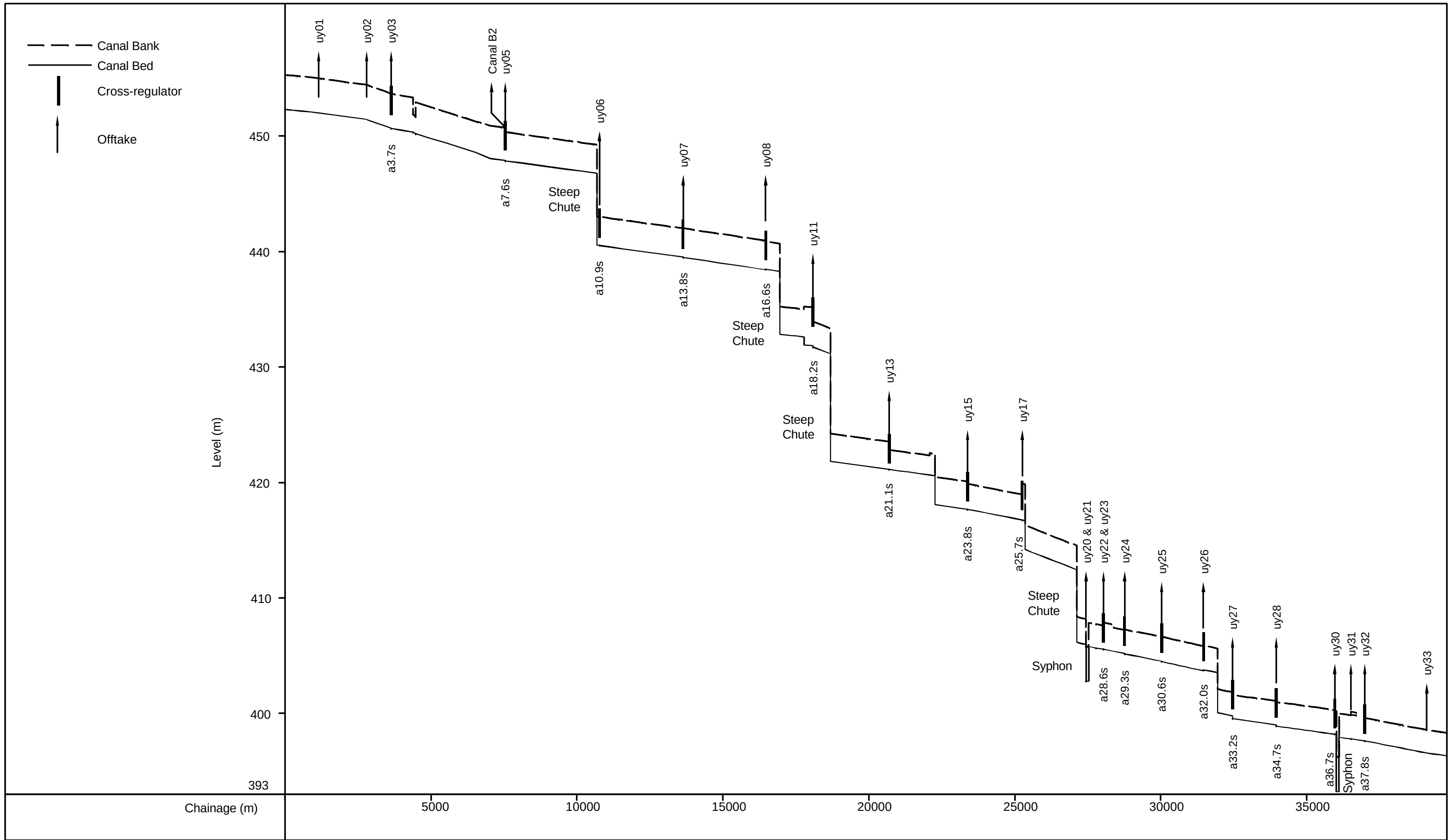
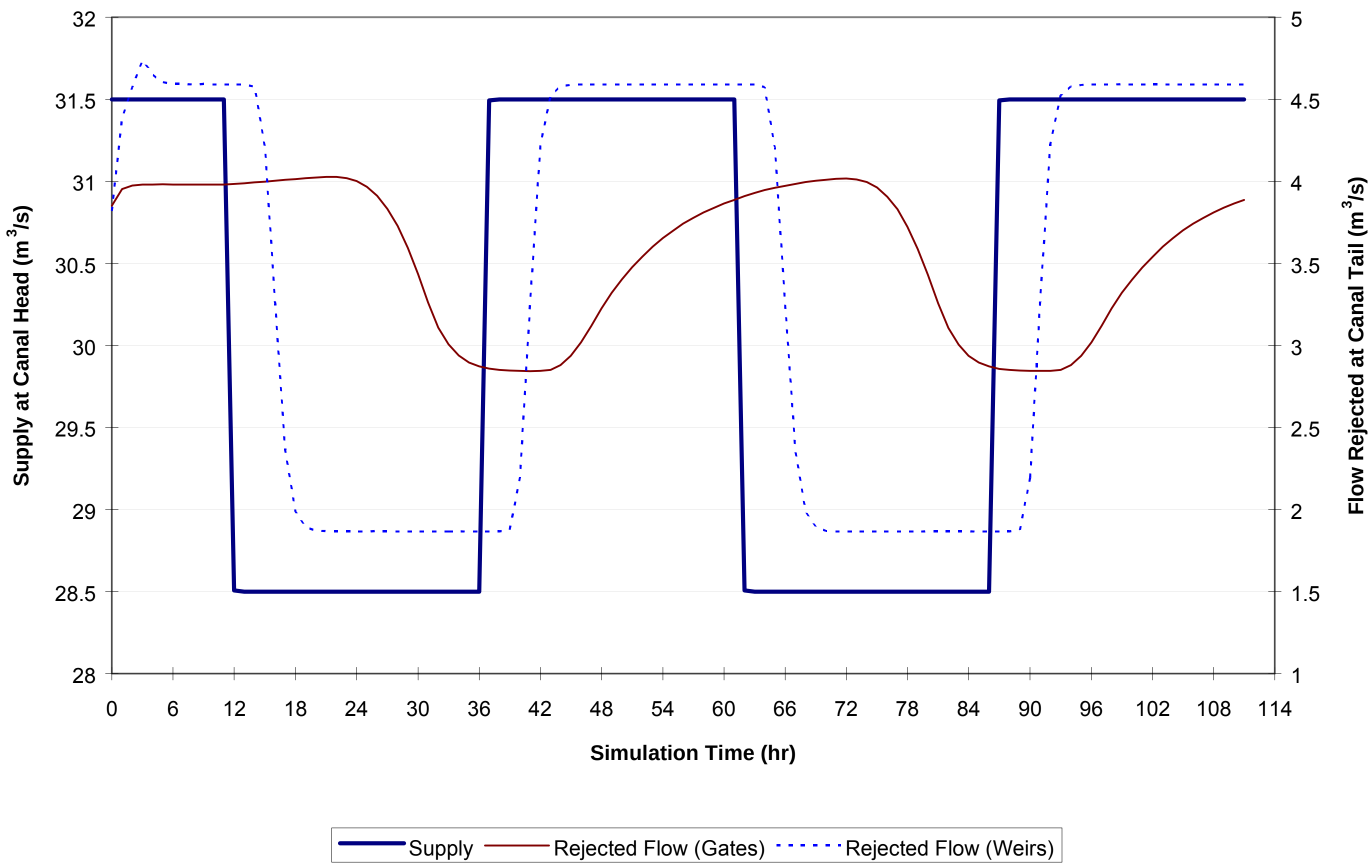
1 Long crested weirs – duckbill weirs are those with long crests in the direction perpendicular to the flow, while broad and short crested weirs refer to the length of their crests in the flow direction.

Figure 8.1 Longitudinal Section of Canal B1 - Irrigation System B



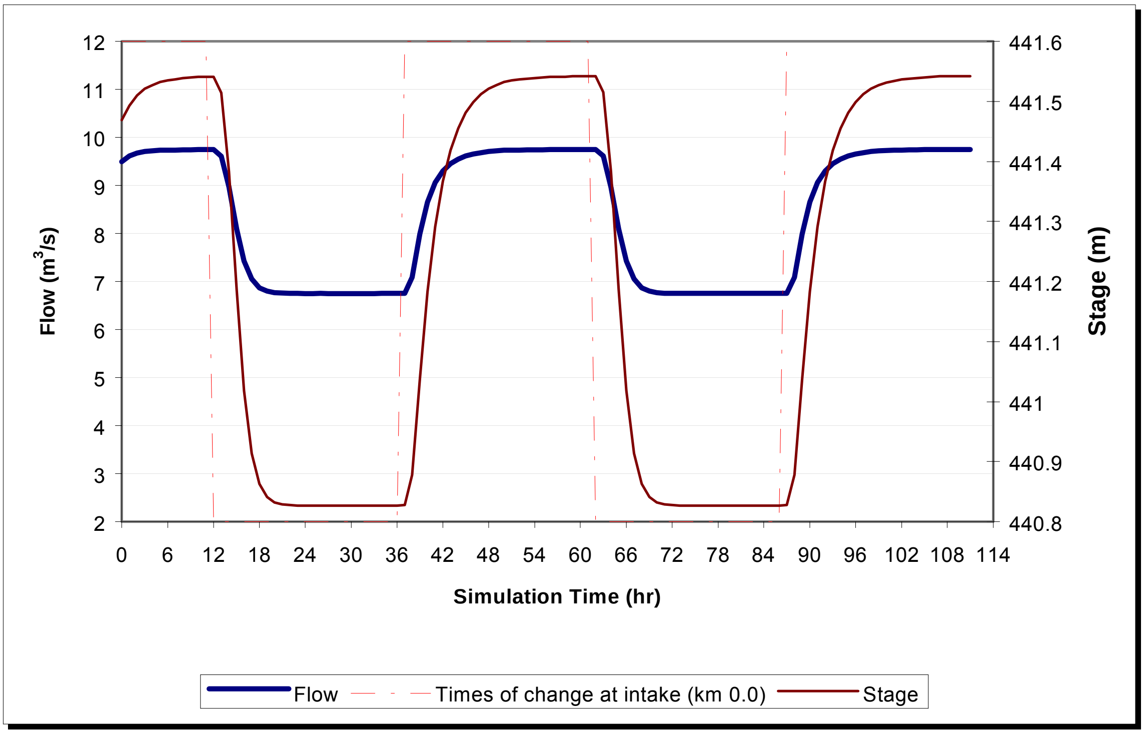
Chainage (m)	Bank Level (m)	Bed Level (m)
0	455.30	452.30
576	455.16	452.16
1152	455.02	452.02
1702	454.82	451.82
2252	454.63	451.63
2802	454.43	451.43
3362	453.92	450.92
4015	453.49	450.49
4998	452.50	449.80
5508	452.09	449.39
6018	451.69	448.99
6528	451.28	448.58
7038	450.90	448.05
7548	450.72	447.87
8072	450.17	447.68
8596	449.98	447.49
9120	449.80	447.31
9644	449.62	447.13
10168	449.43	446.95
10692	449.25	446.76
11592	442.72	440.23
12412	442.44	439.95
13232	442.15	439.66
14046	441.86	439.34
14854	441.55	439.03
15662	441.25	438.73
16470	440.95	438.43
17296	435.15	432.75
18084	435.18	431.84
18690	433.33	431.13
19492	423.95	421.55
20294	423.67	421.27
21042	422.71	421.01
21736	422.47	420.77
22263	422.51	420.59
23009	420.22	417.82
23695	419.73	417.53
24321	419.42	417.22
24947	419.11	416.91
25612	416.05	413.95
26116	415.54	413.44
26620	415.04	412.94
27124	414.54	412.44
27787	407.73	405.67
28387	407.73	405.38
29018	407.15	405.03
29524	406.90	404.78
30030	406.65	404.53
30645	406.30	404.15
31260	405.95	403.80
31950	405.64	403.55
32460	401.85	399.80
32960	401.43	399.38
33460	401.25	399.20
33960	401.07	399.02
34560	400.79	398.69
35160	400.58	398.48
35760	400.37	398.27
36312	399.93	397.87
36989	399.73	397.64
37627	399.31	397.31
38264	398.99	396.99
38902	398.68	396.68
39578	398.41	396.41

Figure 8.2 Supply vs Rejected Flows When Using Different Types of Cross-regulators on Canal *B1*



In both models, the flow supply at the head of canal *B1* (inflow at 0.0 km) was decreased by 11% below the design discharge and then restored to design discharge again in repetitive cycles to study the impact on the hydraulics of the canal (Figure 8.2). It should be noted that the gate settings of the gated cross-regulators in the first model were not changed as the flow into the canal varied to simulate the lack of operation input and study the characteristics of the control structures.

Figure 8.3 Flow and Stage Variation When Using Gated Cross-regulators on Canal B1 – Cross-section at Chainage 13.8 km



The results of the hydraulic modelling runs are presented in Figures 8.3 to 8.6 which depict the flow and water level upstream from the two cross-regulators at chainage 13.8 km and 36.7 km on canal *B1* respectively. The figures support the previous discussion about the differences in the characteristics of weir and orifice structures. The difference is more vivid in Figures 8.5 & 8.6 which represent the cross-regulator relatively near the tail-end of the system (chainage 36.7 km). The following observations can be made from the results shown in Figures 8.3 & 8.4:

- the constant flow and stage at the first 12 hours of the simulation time are the design flow and full supply level at the cross-regulator at chainage 13.8 km. Notice that the values are very similar in Figures 8.3 and 8.4 which ensure that the two systems are almost identical when operated at steady design flow

Figure 8.4 **Flow and Stage Variation When Using Long-weir Cross-regulators on Canal B1 – Cross-section at Chainage 13.8 km**

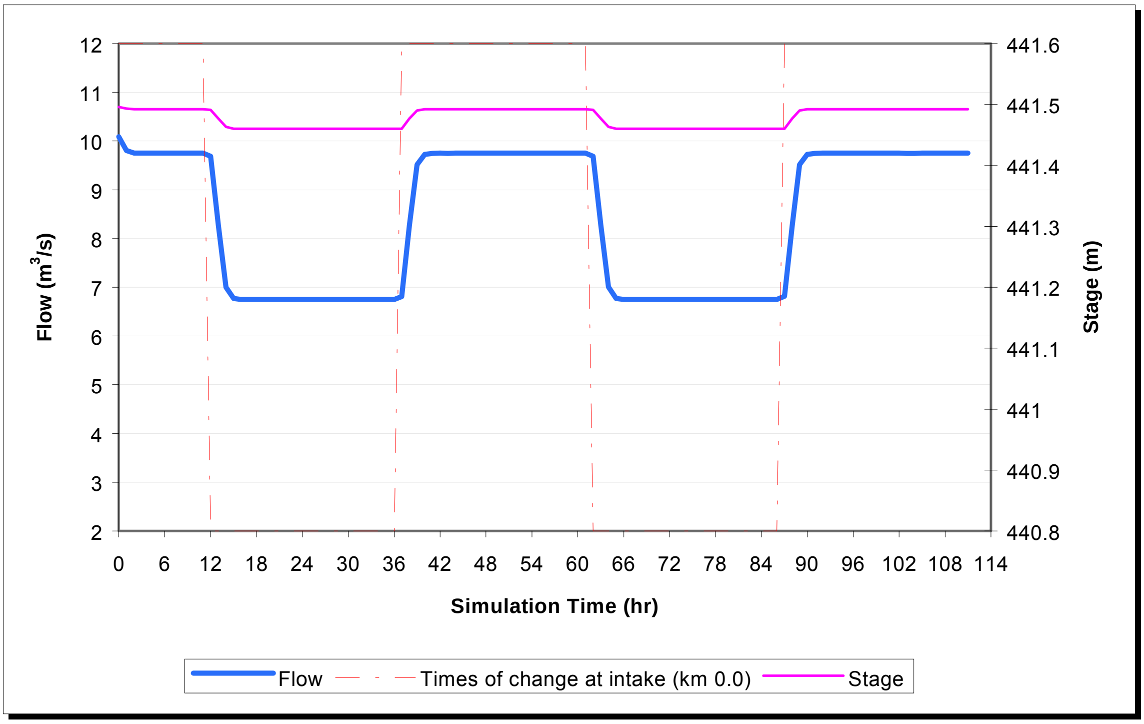


Figure 8.5 **Flow and Stage Variation When Using Gated Cross-regulators on Canal B1 – Cross-section at Chainage 36.7 km**

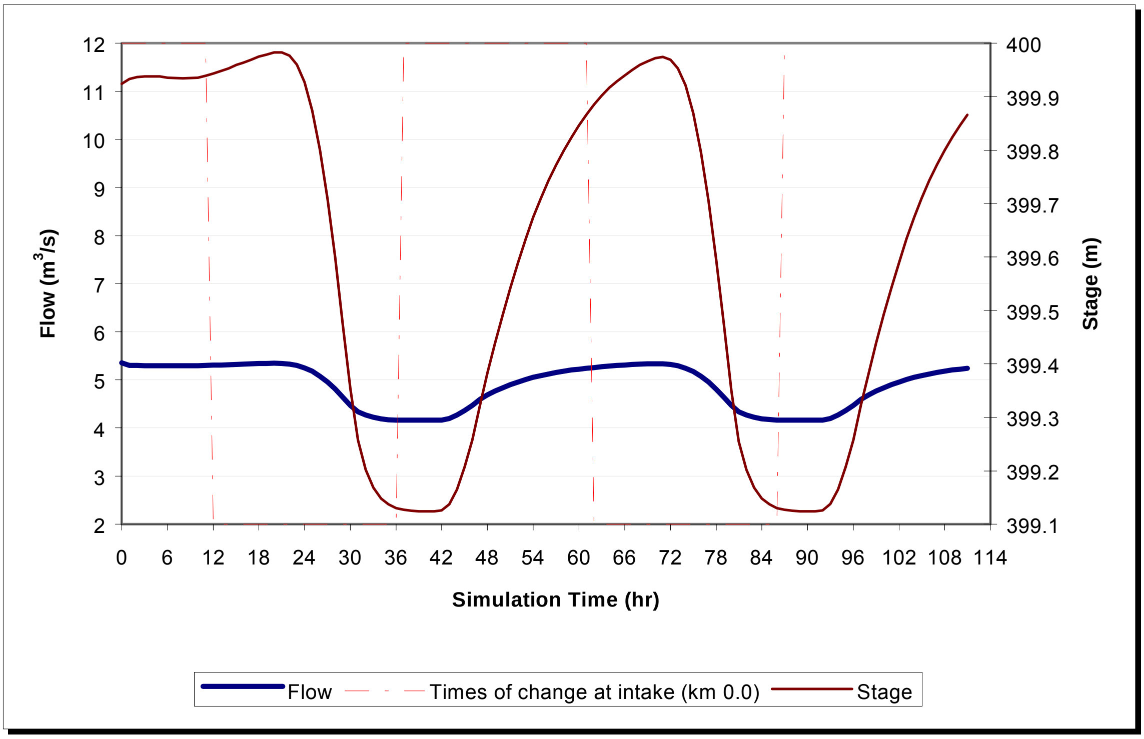
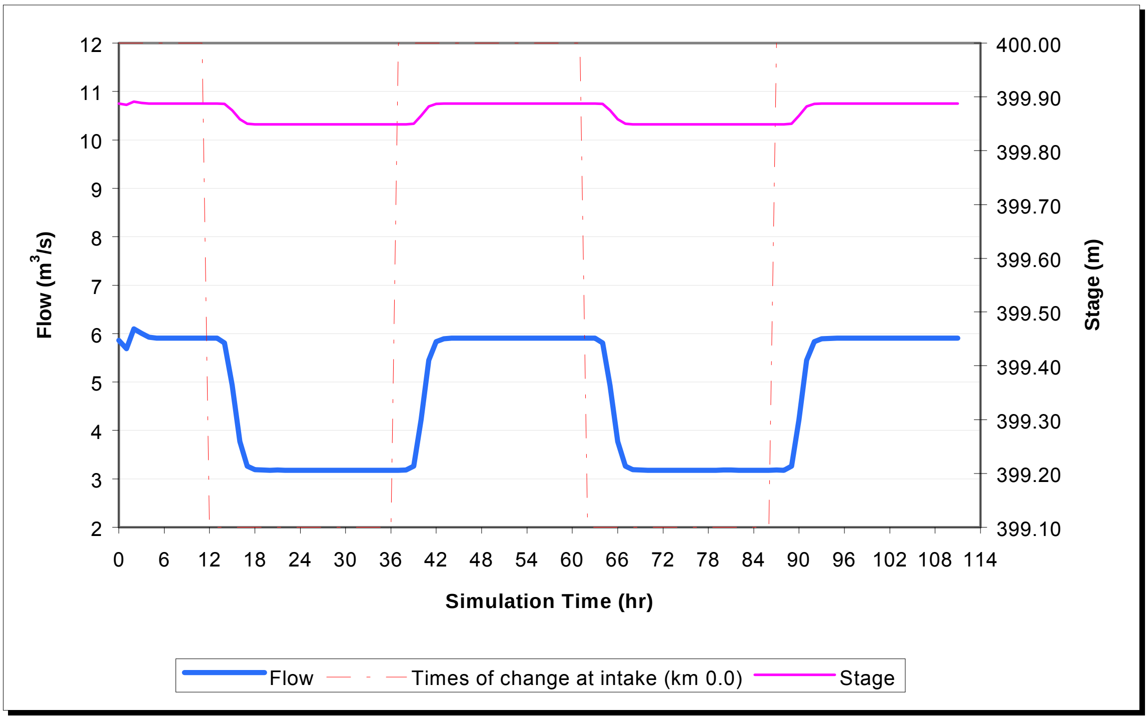


Figure 8.6 Flow and Stage Variation When Using Long-weir Cross-regulators on Canal B1 – Cross-section at Chainage 36.7 km



- the variation in the stage (water level) is much higher in the case of the gated cross-regulator (Figure 8.3). The long-weir cross-regulator almost maintained the design full supply level when the flow was reduced without the need for any adjustment to the structure (no input from operation staff). The same characteristic also applies when the flow increases above design value. Long crested weirs are therefore much safer as water level control structures on conveyance and distribution canals because they ensure reasonable freeboard for a wide range of flows

- the variation in the flow at the designated cross-regulator due to varying the supply at the canal head is similar in both models

- the variation in the flow and water level occurs much faster (in a shorter time period) in the case of the weir cross-regulator (the first reductions in the water level and flow reach their peak within four hours in the case of the weir cross-regulators and within 10 hours in the case of the gated cross-regulators)

- all the previous points highlight the fact that the travel and response times are much shorter in the case of weir cross-regulators than in the case of gated ones.

The above observations are not attributed only to the characteristics of the long weirs and the gated cross-regulators but also to the changes in the behaviour of the system as a whole. Figures 8.2, 8.5 & 8.6 depict the results at the tail-end of the canal (chainage 39.6 km) and the cross-regulator at chainage 36.7 km respectively. It can be seen from the figures that in the case of gated cross-regulators the relationship of rejected discharge (at canal tail) against time shows wide variation from the relationship of supply against time at the head of the canal (chainage 0.0 km).

On the other hand, in the case of weir cross-regulators, the relationship between rejected flow and time matched that at the head of the canal.

- the timely change in the flow in the case of weir cross-regulators reflects the rapid response of the whole system due to the short travel time. In the case of the weir cross-regulators the change in flow at chainage 36.7 km starts 2 hours after the change at the canal head (chainage 0.0 km). In the case of the gated cross-regulators the change in flow at chainage 36.7 km starts 12 hours after the change at the canal head. The travel time of the canal with gated cross-regulators is therefore 6 times longer than that of the canal with weir cross-regulators in this particular case study.

- the mismatch between the magnitudes of the decrease in the supply and the rejected flow in the case of the gated cross-regulators is an indication of the high in-canal storage capacity in such systems. The rejected flow did not decrease by the same magnitude of the decrease in the supply because part of the volume of the water stored in the different reaches of the canal was depleted during the recession of the supply causing attenuation of the rejected flow.

Table 8.1 summarises the differences between the characteristics of the two models in the case of variable discharge.

Table 8.1 Comparison between the Characteristics of Systems with Gated Cross-regulators and Weir Cross-regulators

Characteristic	Gated Cross-regulators	Weir Cross-regulators
Water level sensitivity to discharge variation	Very high especially at the tail end of the system	Very low especially with long crested weirs
Flow sensitivity due to water level variation	Relatively low	Very similar to the change in the supply at the head of the system if the excess flow is not used
Travel time	Longer	Shorter
In-system storage capacity	Higher	Much Lower
Flow control	Possible	Very difficult

8.1.5 Conclusions and Guidelines

- Control structures have great impact on the performance of the irrigation system where they are installed. The selection of the proper type of structures is important for the proper and efficient operation of the system.

- It is preferable to use weirs as upstream water level control structures (cross-regulators) since they are less sensitive to discharge variation, require less operation effort and are much easier to maintain.

- When canal dimensions allow and when the range of discharge variation is wide, long crested weirs are advantageous over short ones for upstream water level control (cross-regulators) because of their lower sensitivity to the variation in the flow.

- Undershot gates are preferable for discharge regulation (canal head-regulators, offtake structures, etc.) since they are less sensitive to water level changes.

- A canal with weir cross-regulators has shorter travel and response times than a similar canal with gated cross-regulators. This feature supports the use of weirs for regulating the water levels on long canals in order to improve the response of the system.

- A canal with weir cross-regulators has a much lower in-line storage capacity than a similar canal with gated cross-regulators. For example, any increase in the supply at the head of a canal with weir cross-regulators will quickly travel down the canal and will be lost through the tail escape if it is not used by the users on the canal. This feature indicates that the operational losses from a canal with weir-type cross-regulators will be higher than those that may occur if the canal has gated cross-regulators.

- Weir structures could be provided with emergency gates to enable canal closure for rotation and maintenance purposes.

8.2 Studying the Mismatch between Actual Flows and Gate Settings

8.2.1 Introduction

One of the reasons for the poor performance of manually operated irrigation systems in terms of low equity of water distribution among the users is the mismatch between the settings of the gates of control structures and the actual flows in the different parts of the system. An example is where the gates of control structures will be set for full design flow while the actual flows in the canal network are much less. Adjusting water control structures on main and distributary canals may not be in accordance with the operation plan due to lack of operation input from the operation staff and/or lack of flow measurement facilities in the different parts of the system. The gates of the offtakes diverting water to tertiary canals and farm ditches are often set by the farmers who tend to keep them fully open to divert the maximum possible flow to their fields.

8.2.2 Impact of the Variation in Water Supply

A question that arises in the operation of irrigation schemes is how often adjustments need to be made to the settings of control structures when the water supply at the intake increases or decreases. Is it necessary for example, to adjust the gates of control structures if the flow at the head of a canal network decreases by 15%?. Will the reduced flow be distributed evenly if we maintain the gate settings as for the original flow?

The direct answer to such questions is generally **yes, we do need to adjust the gated control structures when the water supply changes** unless the system is designed for this situation. However, the design of such a system is not easy. This conclusion is supported by the results of a run of the hydraulic model of system *A*, Figure 8.7 (see Appendix C.1 for a brief description of the system). The model tested is described in the following paragraph.

The model run started with 100% of the design flow at the head of the canals with an equitable distribution of water between the offtakes of both distributary canals. After six hours of the model run time, the supply at the canal head was reduced to 85% of the full design value. No other adjustments were made so the gates of the cross-regulators and offtakes were set for full supply flow during the whole run time.

Figures 8.8 and 8.9 show the changes in the water levels and the flow at the different cross-regulators on canal *A1*. The reduction in the flow with time at the cross-regulators shown in Figures 8.8 and 8.9 is expressed as the ratio of the actual flow at any time to the full design flow at that regulator. The changes in the upstream water levels in Figure 8.9 are calculated with reference to the full supply water levels (a positive change would indicate that the water level is higher than the full supply level and a negative change, that the water level is lower). The observations that can be made from the figure are:

- as the flow into the system started to decrease, the flow passing through the cross-regulators also began to decrease. The reductions started at the top-end cross-regulators first and then moved downstream with a time difference equal to the wave travel time (Figure 8.8)

- the magnitudes of the flow reductions relative to the full supply consistently increase as we move from the upstream to the downstream ends of the canal, i.e. the first cross-regulator on the canal had the smallest reduction in the flow passing through (flow was reduced to 85% of the full supply flow) while the regulator further downstream had the biggest reduction (40% of the full supply flow)

- the changes in the water levels upstream from the cross-regulators did not exactly follow the same pattern as the reductions in flow (Figure 8.9). The water levels started to drop at the upstream cross-regulators first and then proceeded downstream as with the flow reductions, but the magnitude of the drop in water level did not increase from upstream to downstream. It will be observed that cross-regulators 1 and 7 experienced the greatest drop in upstream water levels.

Figure 8.7 Schematic Diagram of
Distributary Canals A1 and A2

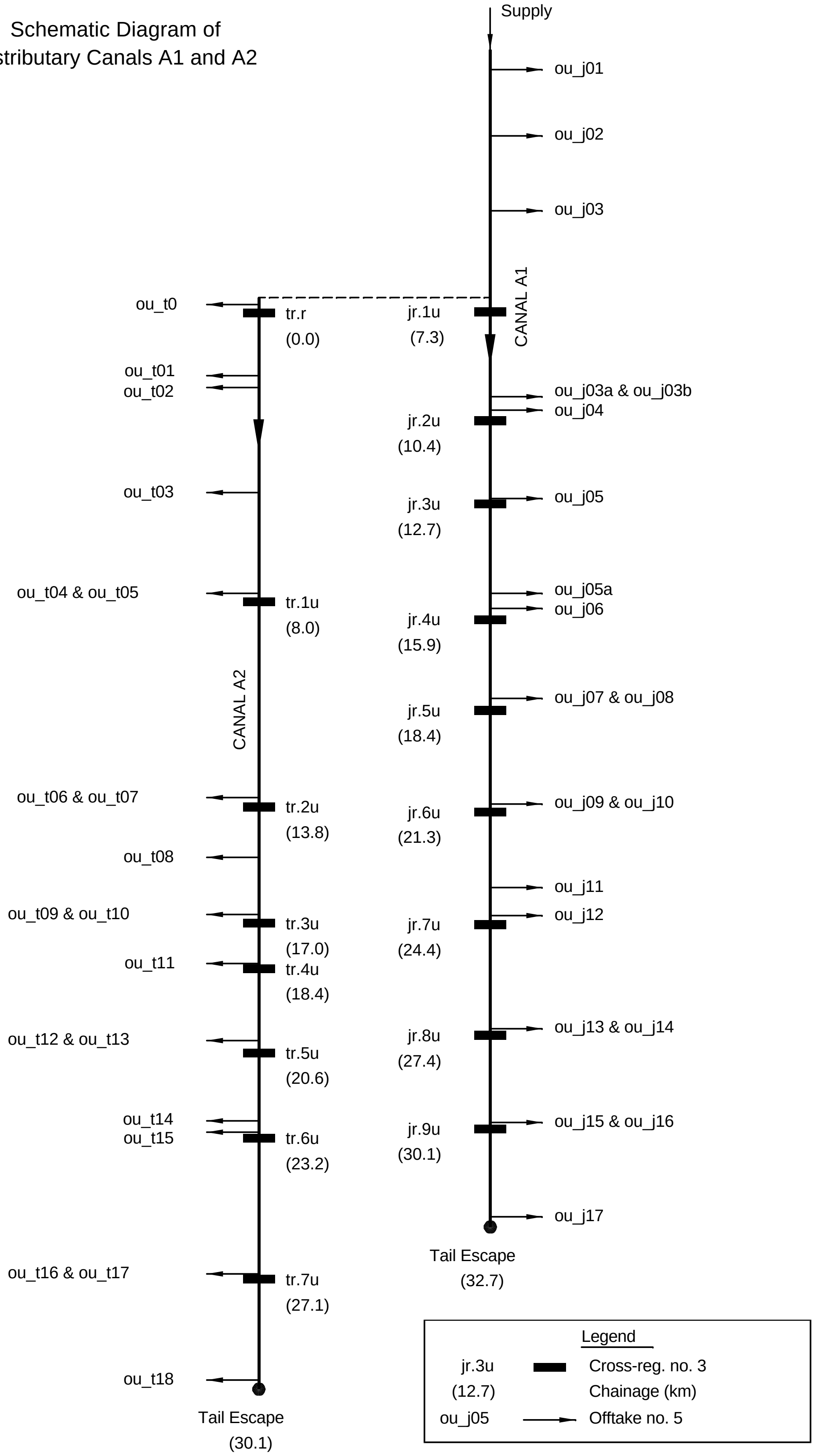


Figure 8.8 Change in the Flow Passing the Cross-regulators on Canal *A1* as Supply Changes

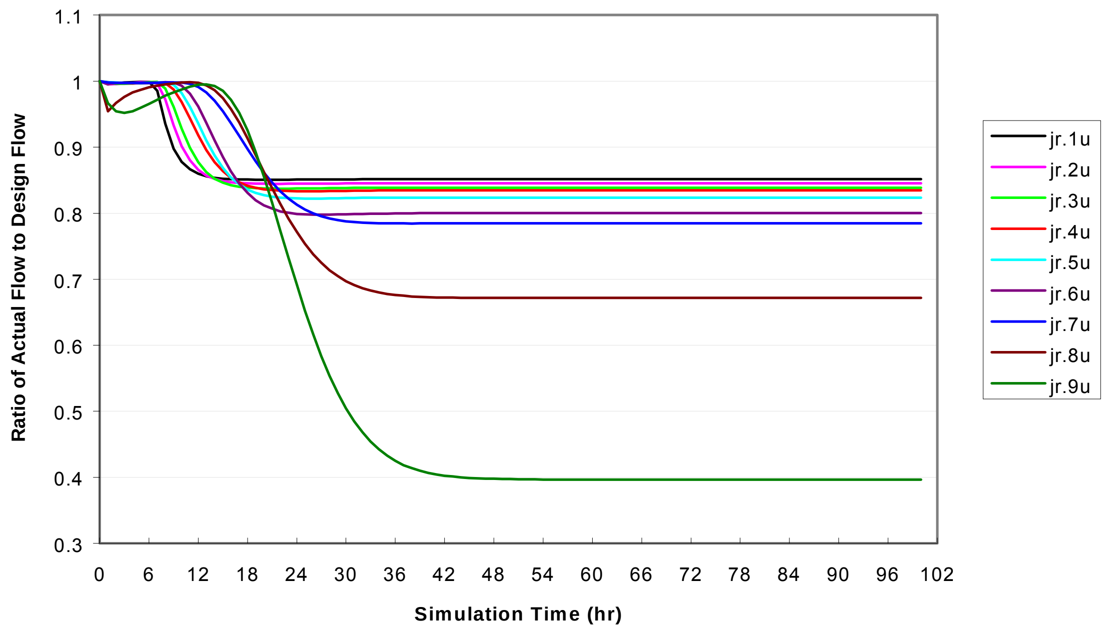


Figure 8.9 Change in the Water Levels Upstream from the Cross-regulators on Canal *A1* as Supply Changes

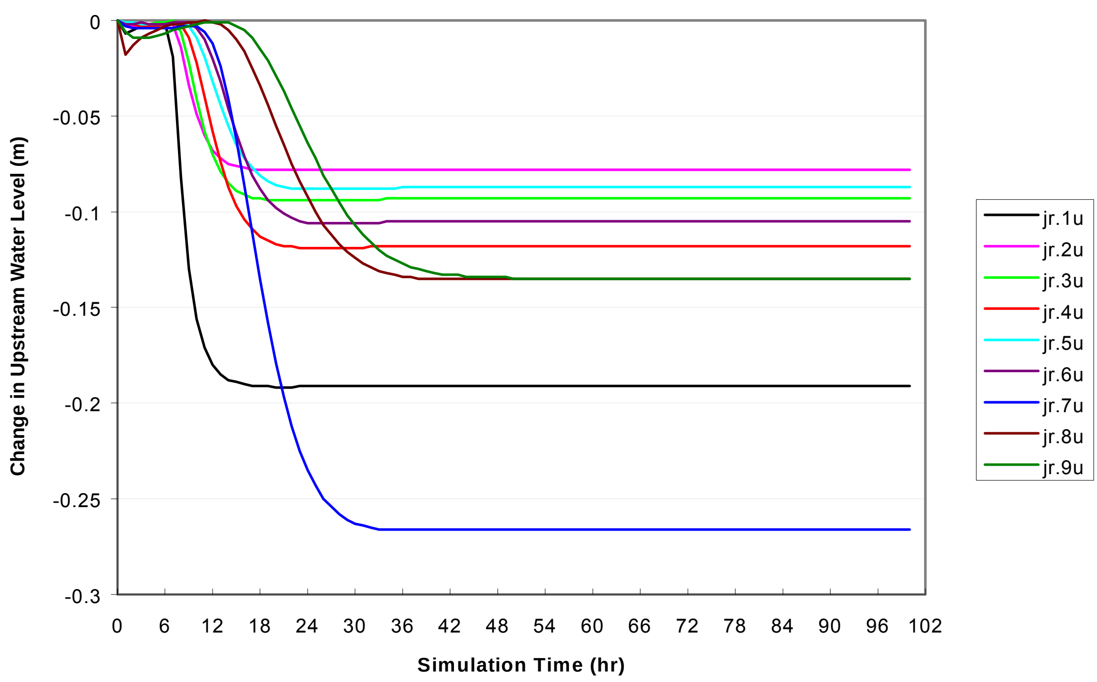


Figure 8.10 Water Delivery Performance and Equity of Flow Abstracted by the Offtakes on Canal *A1* Under Variable Water Supply

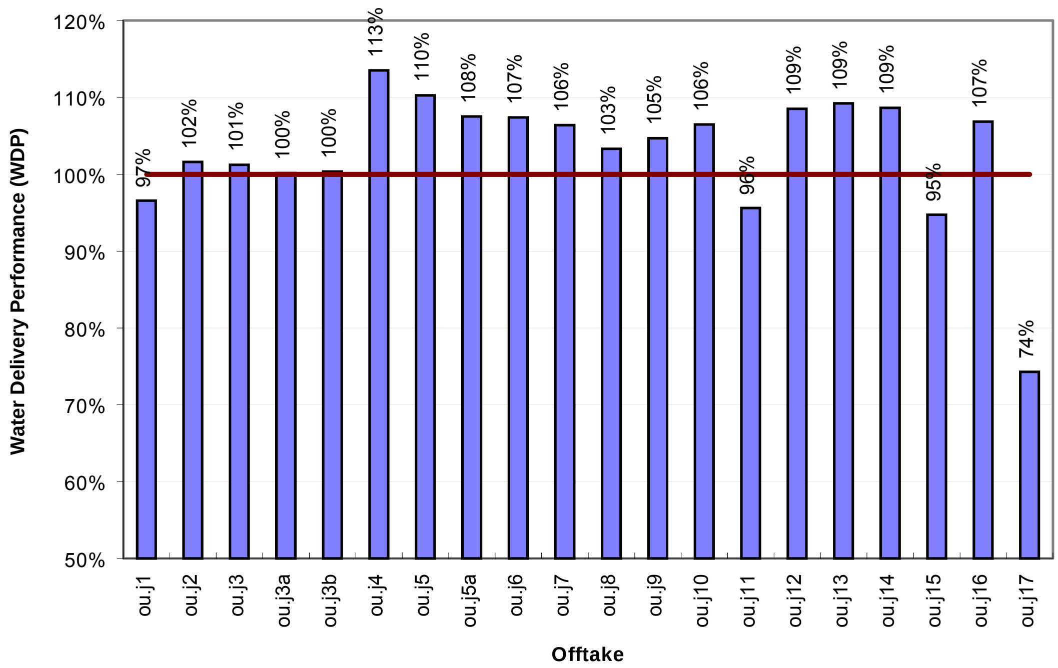
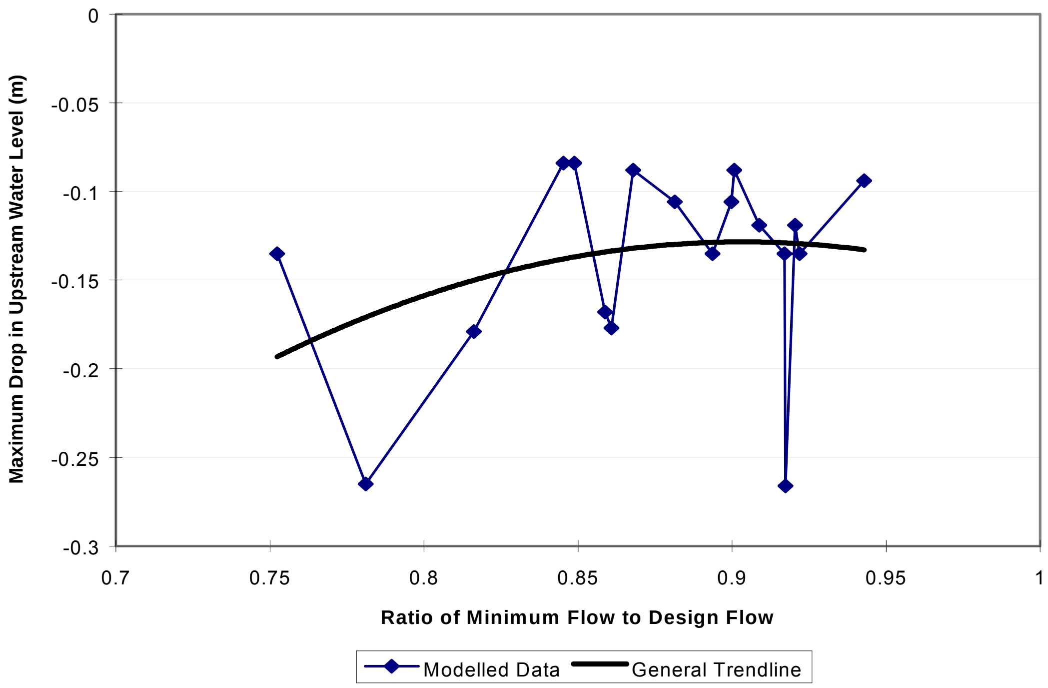


Figure 8.11 Relation between the Drop in the Water Levels Upstream from the Offtakes on Canal A1 to the Reductions in their Flow



The impacts of the variations in water levels and flows in canal *A1* on the actual volumes of water abstracted by the offtakes on the canal (Water Delivery Performance) and hence the water distribution equity are shown in Figures 8.10 and 8.11. It is clear from Figure 8.10 that the distribution of the Water Delivery Performance of the offtakes is not related to their spatial distribution. The variation in the Water Delivery Performance of the offtakes is linked to the changes in the water levels upstream from the offtakes. Figure 8.11 shows that there is a correlation, though relatively weak, between the actual flow abstracted by the offtakes and the change in the upstream water levels.

The mismatch between the changes in the flows and the water levels at the cross-regulators is attributed to the hydraulic characteristics of the canal reaches. As the flow supply at the head of canal *A1* decreased to 85% of the full design flow (at 6.0 hours) a recession wave travelled downstream - lowering the water level in each reach. Because of the irregularity of the cross sections of the canals and due to the fact that the cross-sections are generally oversized, each canal reach has a different storage capacity. When the flow at the head decreased, some of the volume stored in every reach started to deplete with a rate dependent on the hydraulic characteristics of the reach. Some reaches depleted some of their storage quicker than others. The depletion was faster in the upstream reaches because the downstream reaches received all the flow rejected from upstream. When the condition finally stabilised and a steady state was reached (after about 50 hours), the new water levels in the different reaches had dropped by different amounts causing a corresponding flow abstraction pattern by the offtakes. Because many offtakes abstracted more than 100% of their target, a deficiency in the flow occurred in the downstream reaches of the canal as can be seen from Figure 8.8 (the flow at cross-regulator 9 decreased to 40% instead of 85% when the steady state condition was reached).

8.2.3 Impact of Erroneous Gate Settings

A similar situation to that investigated above is when the gates of a control structure are not properly set to match the actual flow. A run of the hydraulic model of system *A* was carried out to investigate such a problem. In this run, the flow at the head of canal *A1* was kept constant at the design full supply value. All the gates of the cross-regulators and offtakes were adjusted to equitably deliver full supply flow to the different parts of the system. After six hours of the model run time, the openings of the gates of the first cross-regulator on canal *A1* (jr.1u) were increased by 0.1 m to simulate a situation of an erroneous gate setting. The results of this model run are shown in Figures 8.12 to 8.15.

As one would expect, all the offtakes on canal *A1* downstream from the first cross-regulator (offtake ou.j3a and down) benefitted from the increase in its gate openings and abstracted more than 100% of their targets (Figure 8.12). It must be noticed that the first three offtakes on the canal (labelled ou.j1, ou.j2, and ou.j3) are located upstream from the first cross-regulator and therefore they abstracted less flow than their targets.

Figure 8.12 Water Delivery Performance of the Offtakes on Canal *A1* after Adjusting the First Cross-regulator on the Canal

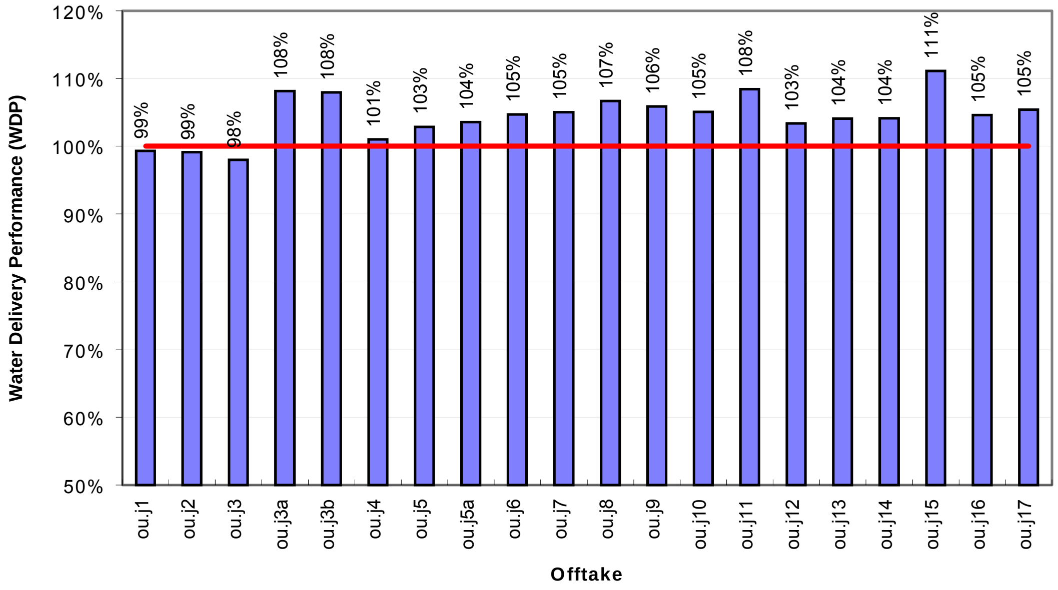


Figure 8.13 Impact of Adjusting the First Cross-regulator on Canal *A1* on the Water Levels Upstream from Selected Offtakes on the Canal

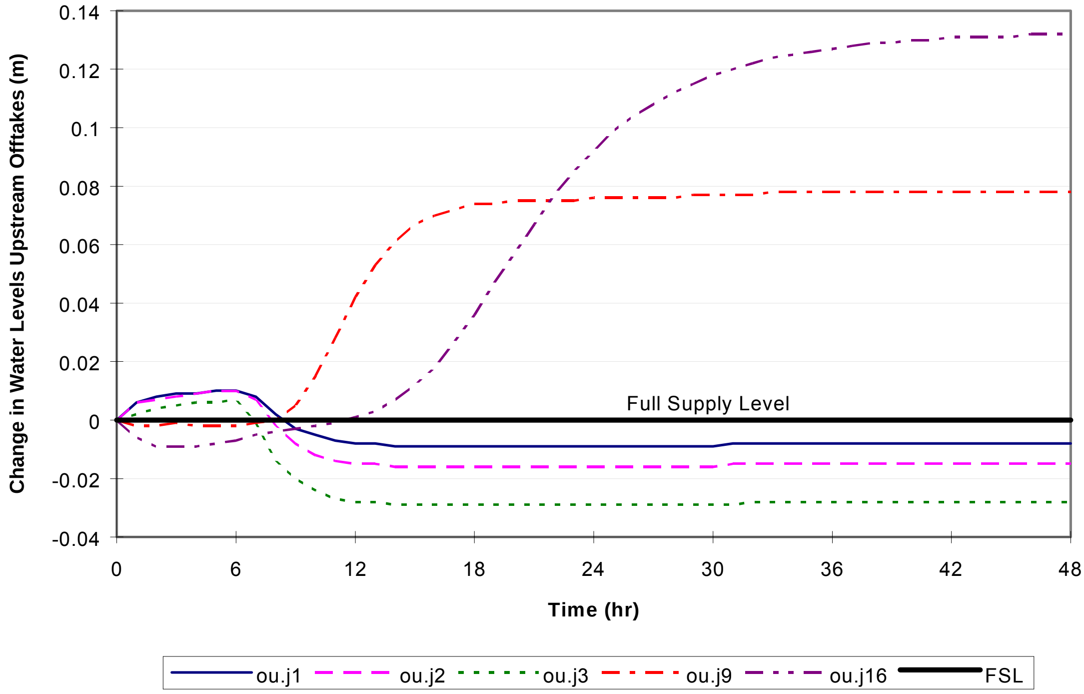


Figure 8.14 **Water Delivery Performance of the Offtakes on Canal *A2* after Adjusting the First Cross-regulator on Canal *A1***

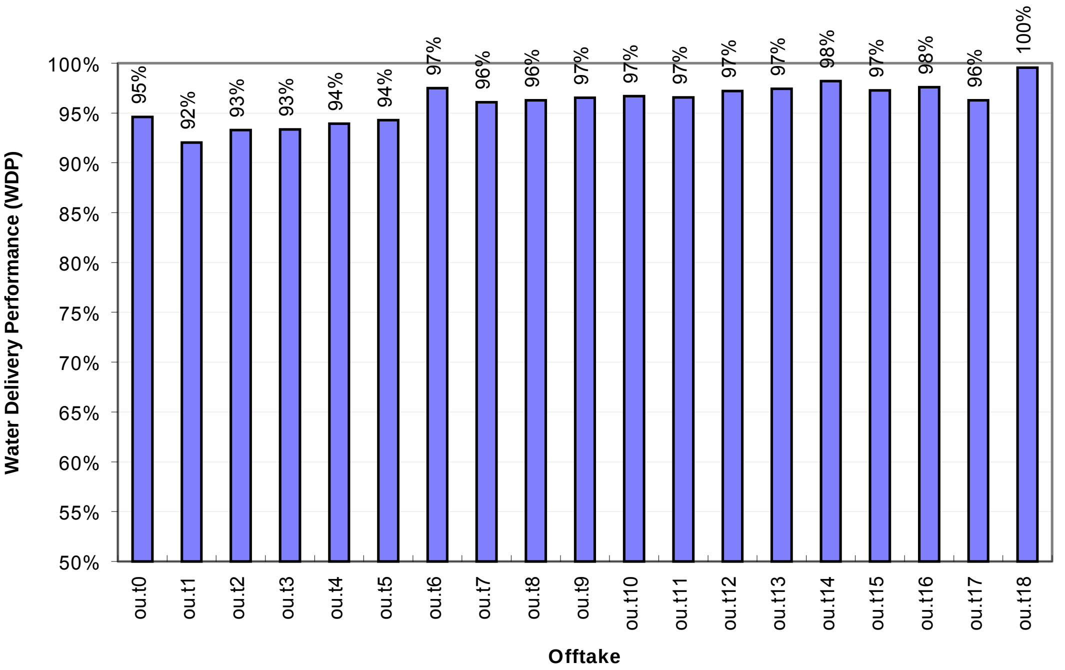
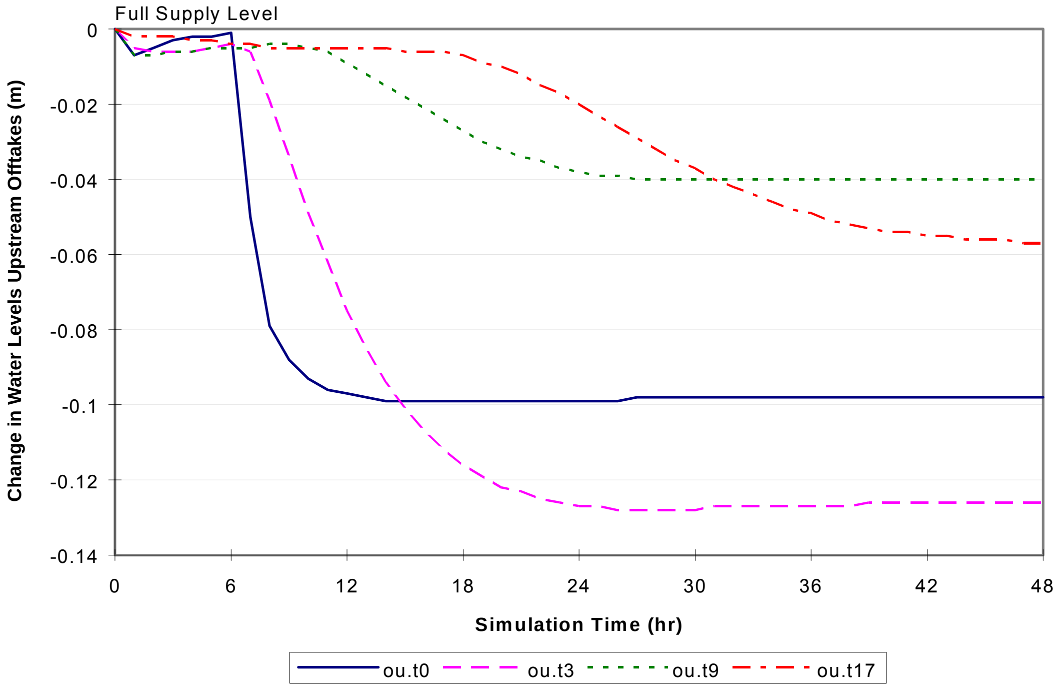


Figure 8.15 **Impact of Adjusting the First Cross-regulator on Canal *A1* on the Water Levels Upstream from Selected Offtakes on Canal *A2***



upstream from the offtakes. The changes are calculated with reference to the full supply water levels, so a positive change indicates that the water level is higher than the full supply level and a negative change that the water level is lower than full supply level. The first three offtakes suffered from drops in the upstream water levels (the water levels in that reach of canal *A1* dropped), while the rest of the offtakes had an increase in the upstream water levels and thus abstracted more flow than they should have had.

The effects on canal *A2* are shown in Figures 8.14 and 8.15. The results indicate that, as expected, the flow abstracted by the offtakes on that canal decreases due to the changes made in the cross-regulator on canal *A1*. However, the greatest reductions in the abstractions occurred at the offtakes at the top-end of the canal; not at the tail-end as one might expect.

The explanation can be found in Figure 8.15 which shows the change in the water levels upstream from some selected offtakes with reference to the full supply levels. It is clear that larger drops occurred in the water levels upstream from the offtakes at the top-end of the canal. Also the drops in the water levels occurred much faster (at an earlier time) at the top-end offtakes. This behaviour is attributed to the unsteady hydraulics of canal *A2*. As the flow into the canal decreases, a recession wave travels downstream reducing the water levels in the different reaches. The drop in the water levels occurs therefore earlier at the upstream reaches with a time difference equal to the wave travel time. The magnitude of the drop in water level in each reach is dependent on factors such as its in-line storage capacity and the difference in the head on the cross-regulator at the downstream end of the reach.

Consequently, the drop in the water level in different reaches of a 'typical'[2] canal like *A2* are not related to the position of the reach alone (Figure 8.15).

8.2.4 Conclusions and Guidelines

Systems with manual upstream water level control are source-oriented, i.e. they do not respond to changes in the demand unless the supply at the head of the system is manually adjusted. A deficit/excess in the flow in any part of the irrigation network will be offset by an excess/deficit in the flow in other part(s). Regular checking and adjustments of control structures are therefore essential for maintaining equitable and efficient water distribution.

The results of the hydraulic modelling runs reported above clearly show that the water distribution between tertiary canals and the offtakes to the fields cannot be equitable in manually operated control systems without the input of operation staff. A mismatch between the flow available in the canal network and the settings of the gated control structures will inevitably lead to uneven flow distribution and hence inefficient water use and poor performance. Flow measurement structures are key facilities for the successful management of manually operated systems. Unless reasonably accurate flow measurements can be made in the different parts of a system, setting control structures will have to be based on experience and speculation rather than facts.

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[2] The term 'typical' here refers to an old earth canal whose cross-sections take irregular shapes after some time of its operation and thus the hydraulic characteristics of the different reaches of the canal become non-homogeneous.

Given that the gates of the offtakes to the fields are often kept fully open regardless of the actual water supply, it is essential that this fact is acknowledged in the design of systems with such control. They should be designed and operated such that when the water supply is less than the full design supply, only the settings of the cross-regulators need to be adjusted. The new settings should not restore the full supply water levels upstream from the cross-regulators, but should achieve the water levels that force the offtakes to abstract their target water shares when they are still fully open. This will be more difficult to achieve when offtakes are located in the middle of canal reaches rather than in the vicinity of control structures. The design of the offtakes must also consider this feature. The use of hydraulic modelling in formulating such designs is essential to find the optimum settings for the cross-regulator gates and the water levels that should be maintained at different flow values to maintain the target share of offtakes.

8.3 Control Structure Interference

8.3.1 Introduction

The process of designing irrigation networks generally comprises two main stages: (1) Planning the layout of the irrigation network in terms of proposed field sizes and shapes and the consequent alignment of the canals and drains, and (2) Designing the different components of the network according to the required capacities. One of the tasks of the first stage is to determine the number and location of flow control and division structures. These decisions are closely related to the layout of the network.

It might not be possible therefore to change the locations of control structures because of the possible interference between them if, for example, they are located too close to each other. However such constraints must be appreciated when formulating design and system operation plans. Control structure interference can influence the performance of a system as demonstrated by the following hydraulic modelling simulations.

8.3.2 Hydraulic Modelling Tests

In this exercise the hydraulic model of the virtual system (Appendix C.3) was run for 24 hours with constant full supply flow of 10 m^3/s entering the system. All the gates of the head and cross-regulators had the correct settings for the full supply flow for the first four hours of the run time after which the opening of the gate of the first cross-regulator on canal 'Da' (Da-X.Reg 1 = 1st cross-regulator on distributary canal 'Da') was reduced by 0.15 m.

The actual impact of this changed gate setting on the flow distribution and the water levels in the canal network is depicted in Figure 8.16. The figure shows the distribution of the Water Delivery Performance (WDP) of the offtakes and the change in the water levels due to closing the cross-regulator. It is clear from the figure that the change in the setting of the cross-regulator on canal 'Da' has an impact on canal 'Da' and also 'Db'.

Figure 8.16 Impact of Partly Closing the First Cross-regulator on Canal 'Da' on the Flows and Water Levels in the Virtual System

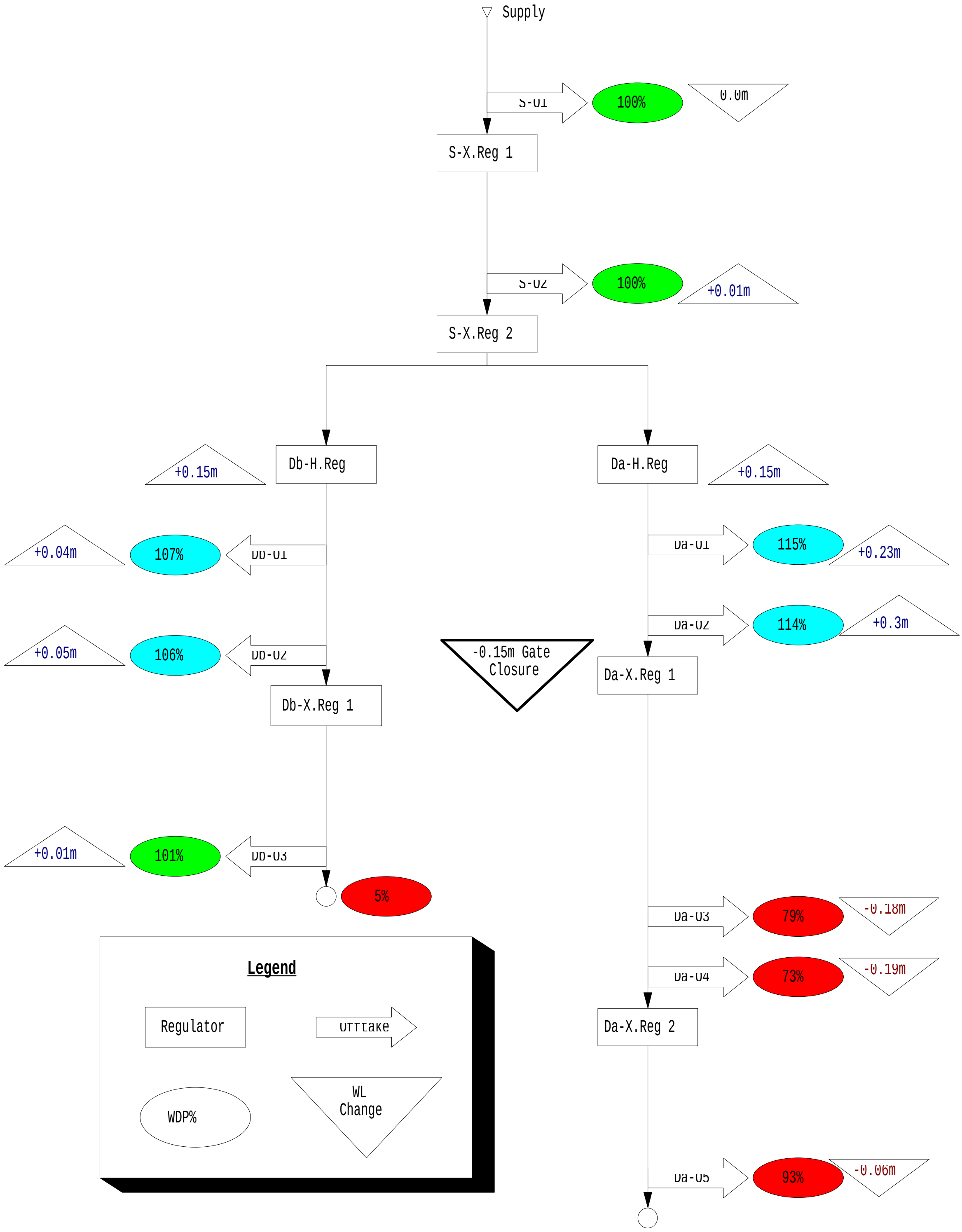


Figure 8.17 Impact of Partly Closing the First Cross-regulator on Canal ‘Da’ on the Flows Diverted to Canals ‘Da’ and ‘Db’

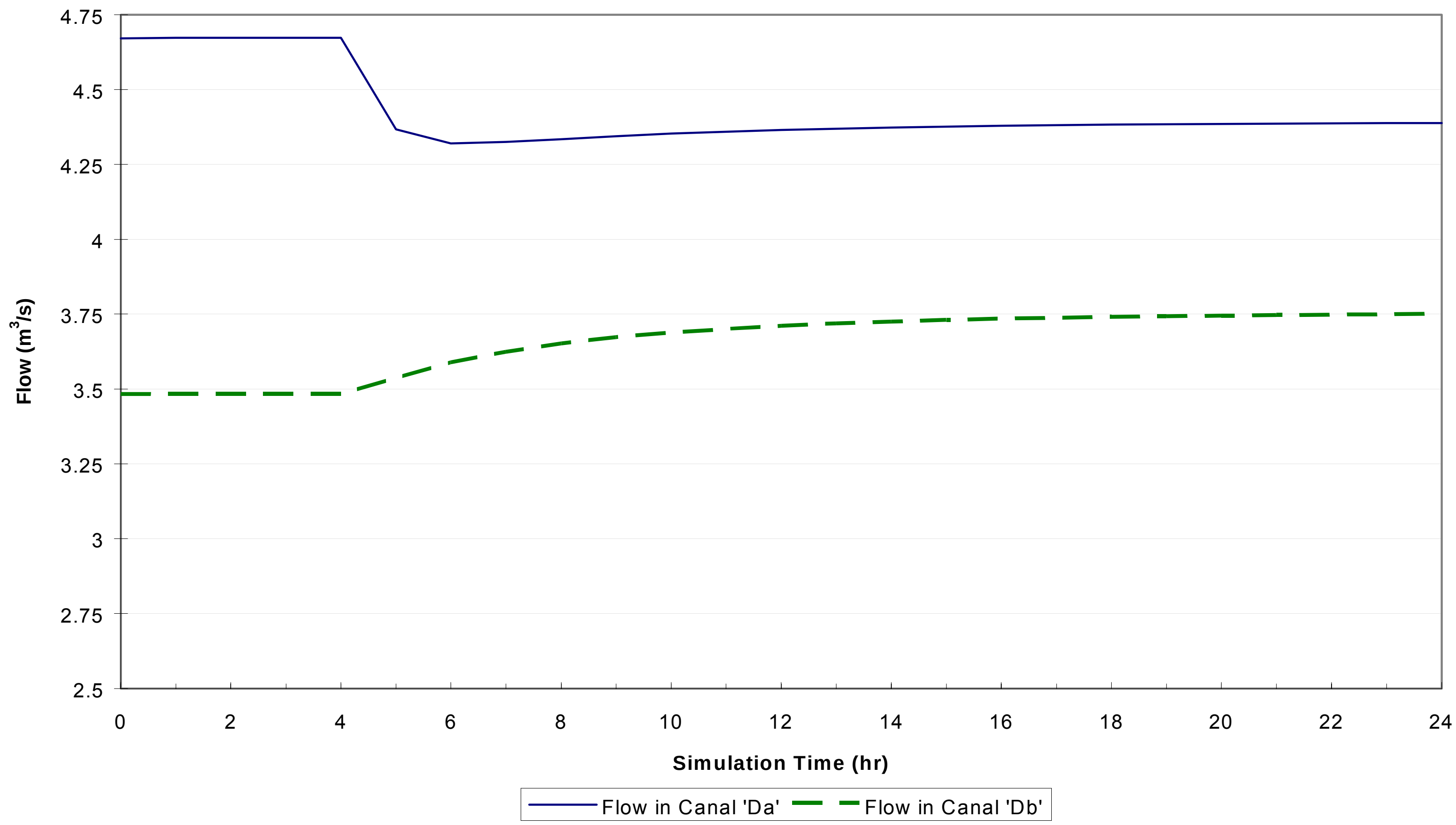
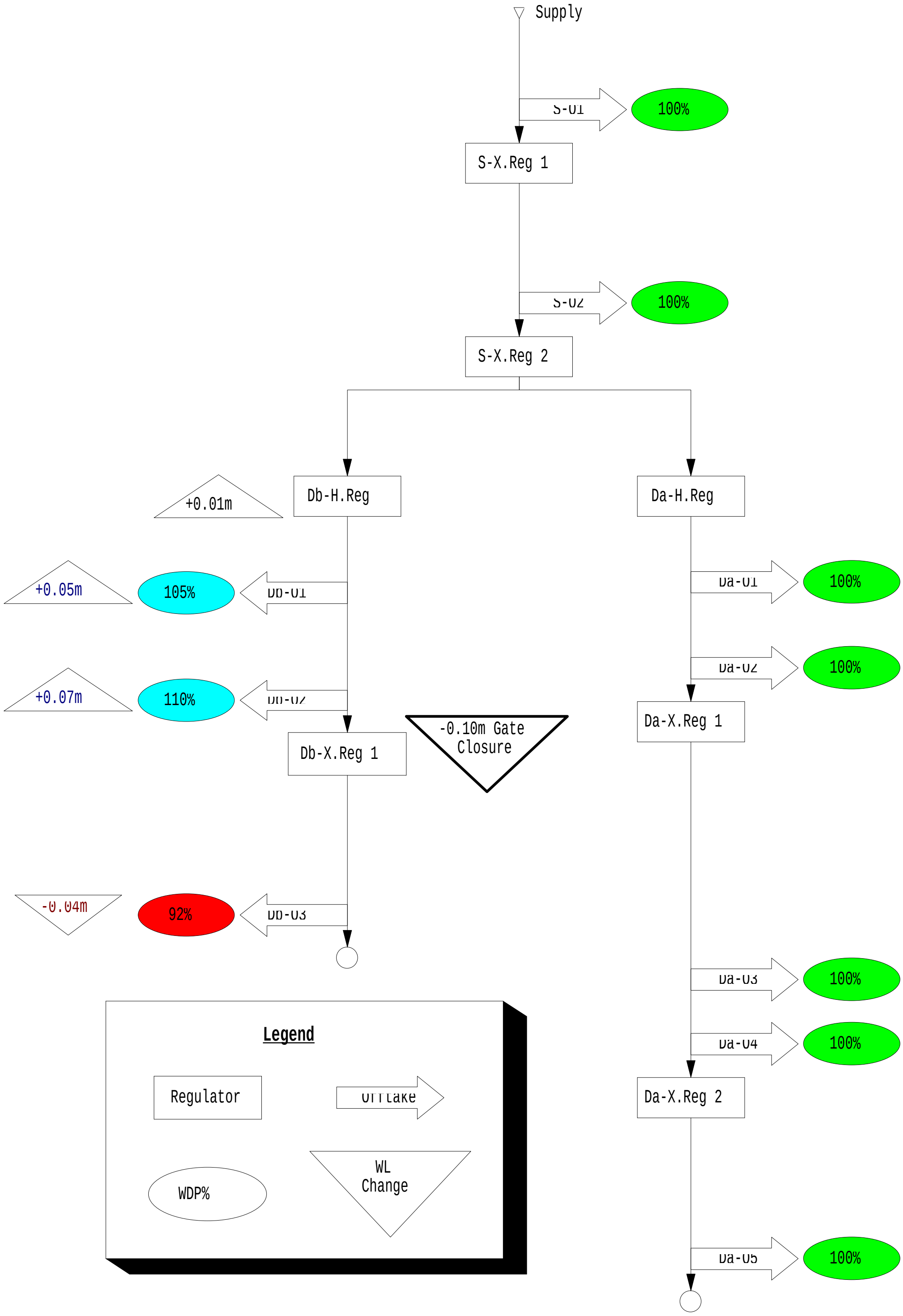


Figure 8.18 Impact of Partly Closing the First Cross-regulator on Canal 'Db' on the Flows and Water Levels in the Virtual System



Closing the cross-regulator causes the upstream water level to rise interfering with the water level downstream from the head-regulator ‘Da-H.Reg’. Consequently the rise in the water level downstream from the head-regulator affected the water levels at the upstream junction causing more discharge to be diverted to canal ‘Db’ and decreasing the flow diverted to canal ‘Da’, Figure 8.17. The increase in the flow diverted to canal ‘Db’ resulted in water wastage as rejection flow at the tail-end of the canal. This output emphasises that the interference between control structures is a feature that should not be neglected and must be acknowledged in real-time system operation.

The same exercise was repeated by partly closing the gate of the first cross-regulator on distributary canal ‘Db’ (Db-X.Reg 1) instead of that on canal ‘Da’ and keeping the settings of the rest of the regulators unaltered. The results of this exercise are depicted in Figure 8.18 from which it is clear that the impact of the change in the setting of the cross-regulator was confined within the same ‘Db’ canal. The flow split between canals ‘Da’ and ‘Db’ remained the same and all the offtakes except those on canal ‘Db’ abstracted their full supply targets. In other words, the first cross-regulator on canal ‘Db’ did not interfere with the head regulator of the canal.

The fact that the first cross-regulator on canal ‘Da’ interfered with the canal's head-regulator while that on canal ‘Db’ did not is related to the characteristics and the design of each canal. Firstly canal ‘Da’ is larger and carries more flow than ‘Db’ so the backwater curve from a cross-regulator on canal ‘Da’ will usually extend further than that of a cross-regulator on canal ‘Db’. The length of the backwater curve is also dependent on the longitudinal slope of the canal and on the heading up at the cross-regulators. However, these latter aspects were kept similar in the two canals when designing the virtual system.

8.3.3 Conclusions and Guidelines

- Interference between control structures is undesirable in systems under upstream water level control[3] as it complicates system operation.
- The interference between control structures may be minimised or eliminated by:
  - (a) providing sufficient spacing between control structures although it is not recommended to have offtakes located at too great a distance from the commanding cross-regulators because commanding such offtakes at low flows is often difficult;
  - (b) increasing canal slope when possible;
  - (c) providing critical flow sections between controls by installing critical-depth flow-measurement structures such as broad crested weirs and flumes downstream from gated regulators. The structures must be designed to maintain critical flow at

[3] Note that the interference between control structures in systems which operate under **downstream** control is an **essential** feature in the design of those systems.

all times (design for situations that create minimum head on the structures). The advantage of this alternative is that it allows for flow measurement besides isolating control structures. The results could be significant improvements in control (Clemmens et al., 1989).

- The most critical locations where interference should be minimised are canal head reaches. The interference between canal head-regulator and any subsequent control structures is most likely to affect the flow into the canal and therefore causes large negative impact on the performance of the system, as demonstrated by the results of the hydraulic modelling simulations discussed above.

- Simple backwater curve calculations can be used to estimate the possible interference between control structures under steady flow conditions. Hydraulic modelling on the other hand is an essential tool for assessing the actual interference that might occur under unsteady flow conditions along with the impact on the different parts of the system.

8.4 Isolating Control

Clemmens et al. (1989) deal with the problem of control structure interference from a broader perspective and discuss the isolation of different control structures in the same irrigation network. They explain control isolation as isolating the control of adjoining canals from each other or isolating the control of a lateral canal from that of its parent. Although in essence isolating controls can be achieved by eliminating the interference between the head regulator of a canal and the downstream structures, other measures can be utilised to isolate control structures:

(a) Flow control and downstream control on a lateral canal can effectively isolate the control of the canal from the upstream network.

(b) Using regulating reservoirs at the head of laterals or farm reservoirs at the field level. The reservoirs collect the water from the source according to the water delivery schedule and supply it to the users at will. They therefore isolate the downstream service areas from the rest of the project upstream and offer higher flexibility.

8.5 Control Structure Automation

Traditional upstream control structures can either be manually or automatically operated (refer to Section 4, **CANAL CONTROL METHODS** for more details). Structure automation will be desirable when the structures need to be adjusted very frequently. The frequency of control structure adjustment is dependent on the variability in the water supply and the demand patterns. High variability requires more structure adjustments in order to maintain relatively stable water levels in the canals.

The variability in the flow usually increases in the low-level canals as we get closer to the water use points (farmer offtakes). It is common therefore that the automation of control structures on low-level canals is considered first before the automation of structures on higher canals. Combined upstream and downstream control is one of the canal control methods which balance a medium system cost and an automated, thus improved, downstream control at the lower parts of the system (see Section 4, **CANAL CONTROL METHODS**).

Studying the automation of upstream water level control structures on large canals using hydraulic modelling showed that it is possible to reduce the cost of automation of large structures. Control structures on large canals usually comprise many parallel bays such that the gate(s) used in one bay are neither too large nor too small for structural and hydraulic purposes. When adjusting the gates in such structures, the number of gates to be operated depends on the variation in the flow. When the flow varies by less than 20% only one third of the gates in the structure need to be adjusted to regulate the water levels. Higher flow variations will require more gates to be adjusted. It is possible therefore to automate only one third of the gates in a large structure such that it can automatically handle flow variations up to 20%. Since the flow in most large canals is regulated to be relatively steady, the flow variations which are bigger than 20% (and hence the need for manual gate adjustments) will be required only a few times per season/year thus achieving better water control at a much lower cost.

9 ROTATIONAL FLOW

9.1 Introduction

The capacity of an irrigation delivery and distribution system is usually related to the requirements during the peak demand or use period (Clemmens, 1987). Under such operating condition the flows and water levels at different key locations in the system are called "design flows" and "design water levels (DWL)" respectively. The operational procedures of manually operated upstream-oriented systems call for maintaining design water levels at offtake points regardless of the actual water supply by manipulating cross regulation structures. While this procedure might be possible for a wide range of supply flows, it may be difficult to achieve at very low flows.

Two options are available for operating upstream-oriented systems in periods of low flows: one is to maintain continuous supply to all demand points in the system trying to achieve equitable distribution, and the second is to rotate the supply between groups of users (rotational flow). The selection of the procedure to follow is dependent on many factors (Clemmens, 1987), these are primarily:

- the objectives of the scheme such as to achieve equitable water distribution at all times;
- the method of water control and available control structures;
- the level of technology and staffing required to operate the system;
- existing social aspects and water rights;
- the types of crops grown.

The two options described above for operating upstream-oriented systems at low flows should not be confused with similar water delivery schedules to the farm offtakes. The focus in this discussion is on the irrigation distribution system, typically secondary and distributary canals. It must be noticed however that the method of water distribution can influence the delivery schedule. When water is available in tertiary canals continuously for example, the options of delivering this water continuously to all the offtakes on the canal or rotating it among them will still be available. While if the water is rotated among the tertiary or secondary canals, it will not be possible to supply it continuously to the offtakes unless storage is available.

The types of crops cultivated may also influence the choice of the water distribution method that should be adopted. Crops vary in their tolerance to drought, salt levels, needs for water at particular growth stages, and required frequency of irrigation. Although it may be difficult to satisfy the needs of all the crops in a scheme, it is essential that the requirements of the main crops are met. For instance attempts to introduce a rotational schedule in rice schemes in Madagascar have failed (Plusquellec et al., 1994) because farmers traditionally prefer continuous supply to their paddy fields which enables them to pond water on the fields.

Reddy (1988) reports on one of the advantages of rotational flow in India by making a comparison between the performance of two outlets in the same irrigation system which have different water delivery schedules. It was found in the study that the farmers on the outlet with rotational flow practiced night irrigation while those on the outlet with continuous flow hardly practiced irrigation at night. There are many reasons for this, one of which is the rotation schedule itself which starts from the farmer at the tail end and then proceeds upstream. The duration of the rotation turn is divided among the farmers considering 24-hour irrigation. Farmers whose irrigation time is at night must irrigate at night or miss their turn.

Farmers on the outlet with continuous flow, on the other hand, did not practice irrigation at night allowing large quantities of water to be lost. Also because all the farmers in the scheme wanted to irrigate during the daytime, competition for the limited water resource was very high.

Although irrigation at night is regarded as an advantage by Reddy, Chambers (1988) reviews the different opinions of experts in the field. It is envisaged that water savings by irrigating at night due to the low evaporation losses at night and using the water that would be otherwise lost to the tail escapes of the canals may be offset by the very low efficiency of water distribution and application at the field level. The final conclusion is that if water is to be used efficiently farmers should not be forced to practice irrigation at night (by enforcing rotation schedules which cover 24 hours a day for example). Instead, daytime irrigation should be planned for in the design and operation of irrigation systems.

9.2 The Rotation Level

There are different possibilities for the level of the system at which rotational flow can be practiced during periods of low supply. Some of those possibilities are:

- Rotation between groups of farm units (offtakes) along tertiary or secondary canals which will be running continuously.
- Rotation between groups of tertiary canals on a secondary canal.
- Rotation between groups of secondary canals.

No specific factors can be identified for governing the level at which rotational flow should be employed (Plusquellec et al., 1994). However, the following guidelines may provide a framework for decision making:

- Rotating the flow between groups of farm units (offtakes) is usually arranged by manipulating the gates of the offtakes while the water levels in the supply canals are kept reasonably high. This situation tempts farmers at the top-ends of the canals to (illegally) open their offtakes when they are in the "off" turn and take extra water. The efficient application of this rotation system therefore requires a very well organised operation organization and water user groups to prevent such actions.
- Rotation between canals has an advantage in terms of saving water losses through canal seepage for two reasons: The scale effect and the reduced time of exposure (Shanan et al., 1985).
- The scale effect refers to the increase in the wetted perimeter of a canal section as the flow in the canal is increased in rotation. Doubling the flow in a canal for example will not double the wetted perimeter in most cases and hence will not double the seepage

losses. Adding the factor of the reduced time of exposure (canals in rotation run full only part of the time) it can be expected that the total seepage losses from canals under rotation will be much less than when the canals are running continuously.

- Nevertheless, some experts in the field support a totally opposite opinion. They envisage that in hot climates the soil at the sides of earth canals can become relatively dry when the canals are empty in the "off" turns. Depending on the weather, soil types, and the duration of the rotation turn; the soil can become dry enough for cracks and holes to form. Filling the canals in the "on" turns will require that all the cracks and holes are filled in first which might need extra quantities of water offsetting the savings from reduced seepage losses.

- There is a trade-off between the ease of operation and system performance with reference to the level at which rotational flow is practised. As we move higher in the system the operation effort is reduced while the likelihood of a lower performance level is increased. Practising rotational flow between groups of canals will require the head regulators of those canals to be opened and closed in the different turns of the rotation. Since normally the number of canals of the same level decreases as we move higher in the system (typically there are fewer secondary canals than tertiary canals in irrigation systems, and so on), the operation effort decreases as well.

- The concern of the impact of the rotation level on system performance originates from the necessity for filling the canals when starting the "on" turns (usually when a canal is in the "off" turn, farmers still try to abstract all the water stored in the canal). This task can be problematic when the canals are long such that they take a very long time to completely fill. The situation can be very severe to the extent that the whole duration of the "on" turn may not be sufficient for the canals to fully fill. In such a case the offtakes at the top-ends of the canals will easily abstract more water than those at the tail-ends, lowering the efficiency of the system in terms of equitable water distribution.

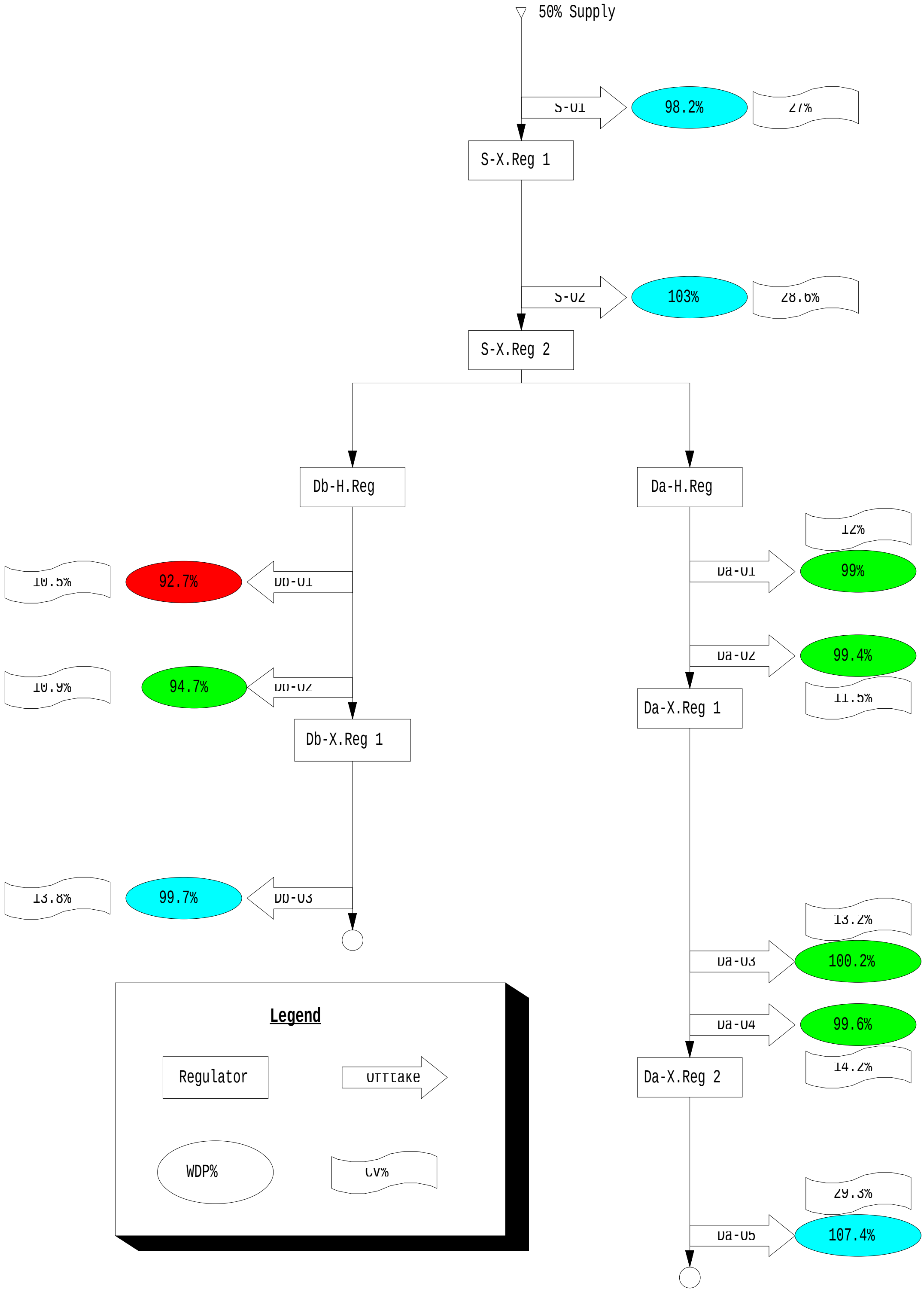
- As will be shown below, the results of hydraulic modelling tests have shown that rotating water supply between canals of up to 5.0 km long can be achieved with high distribution equity. These results indicate that it is more advantageous to apply rotational flow at the tertiary level, and not at the secondary level as secondary canals will be much longer in most cases. The figure of 5.0 km as the maximum length of canals in rotation should be regarded as an approximate limit and should not be taken as definitive - rotation may still be practised on longer canals while achieving reasonable performance levels, according to circumstances.

- The travel and response times of canals with weir cross-regulators are much shorter than those of similar canals with gated undershot cross-regulators (see Section 8.1.4). This important feature can be utilised in rotational flow by allowing rotation between relatively long canals when they have weir cross-regulators and limiting it to relatively short canals when they have gated cross-regulators.

9.3 Rotation between Short Canals

Rotational flow has been investigated using the hydraulic model of the virtual system developed in this study, Appendix C.3. The objective of this modelling work was to study the performance of rotational flow when practised between short canals. The offtakes in the virtual system were divided into two groups: Group "A" which includes all the five offtakes on distributary canal 'Da', and Group "B" which includes the three offtakes on distributary canal 'Db' and the two direct offtakes on canal 'S' (Figure 9.1). A 5-day two-turn rotation was simulated by maintaining a constant flow of 50% design supply at the head of the system and applying the rotation by opening/closing the gates of the head regulators of distributary canals 'Da' and 'Db' ('Da-H.Reg' and 'Db-H.Reg' respectively) and offtakes 'S-O1' and 'S-O2'. The gates of the cross-regulators and the rest of the offtakes were set for 100% design flow without any alteration during the simulation.

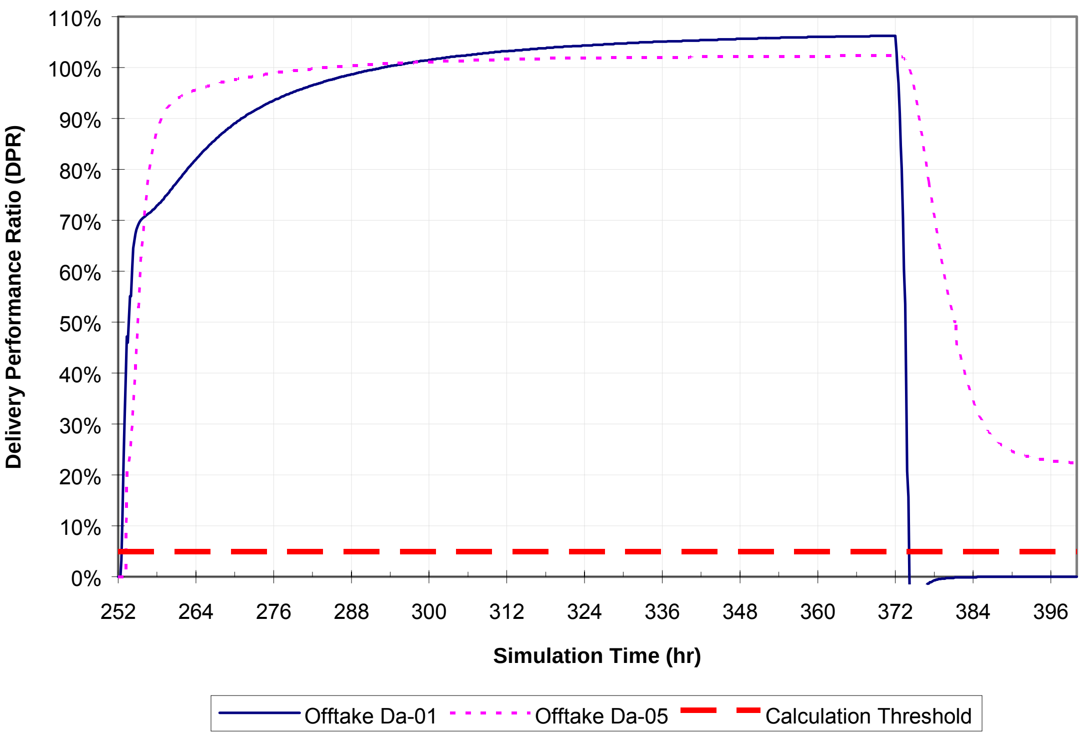
Figure 9.1 Performance of Rotational Flow between Short Canals 'Da' and 'Db'



Model Results and Performance Assessment

Before evaluating the performance of this rotation scenario it is worthwhile studying the pattern of the flow abstracted by the offtakes as depicted in Figures 9.2 & 9.3. The general trend of the flow can be defined by three distinctive patterns: first, there is a rapid increase in the flow which occurs usually within the first six hours of starting the "on" turn of the rotation schedule; then the flow remains relatively steady during most of the duration of the turn; and finally a rapid decrease in the flow occurs as the "on" rotation turn is over. The figures also show what is defined as "*calculation threshold*" which corresponds to 5% Delivery Performance Ratio (DPR). This *calculation threshold* means that any flow that is less than 5% of the target flow of the offtakes was neglected in the calculation of the performance indicators adopted in this study. It is believed that such small flow will not in practice be beneficial to the users and therefore was not taken into consideration when evaluating the performance. For consistency, this criterion was maintained in all the calculations presented in this report.

Figure 9.2 Evaluation of the Delivery Performance Ratios of Selected Offtakes on Canal 'Da' Under Rotational Flow – The Virtual System



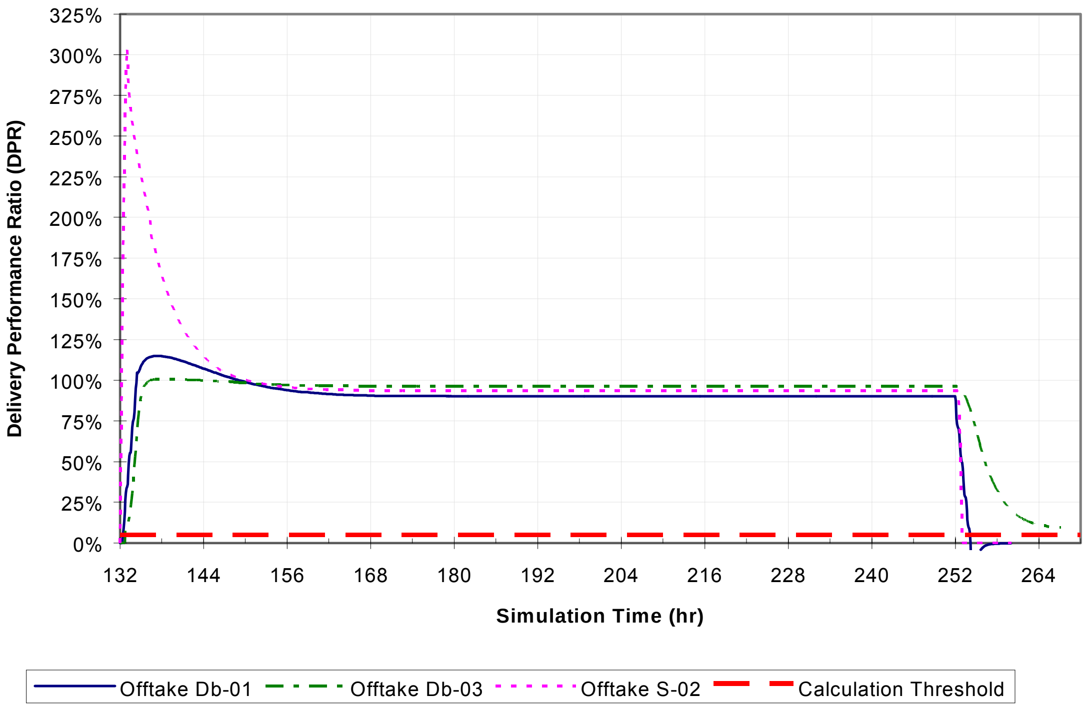
The results of the hydraulic simulation are presented on the schematic diagram of the system, Figure 9.1. The figure shows the actual volumes of water abstracted by the offtakes during their 5-day "on" turn as percentages of the 100% target volumes (Water Delivery Performance, WDP). The points that should be noticed are:

- The flow distribution between the offtakes is generally highly equitable which indicates that the travel and response times did not have strong impact on the performance of the system during canal filling and emptying periods - a consequence of the relatively short length of the canals (up to 5.0 km).

- The Water Delivery Performance of the offtakes on distributary canal 'Db' was slightly less than 100% because the 50% supply at the head of the system was less than the 100% demand of group "B"[4].

- The offtakes immediately upstream from the tail escapes of the canals *benefited from their location* and abstracted more water than the rest of the offtakes from the water ponds at the tail-ends of the canals during the "off" turns (notice the slow decay of the Delivery Performance Ratios of the tail offtakes 'Da-05' and 'Db-03' at the ends of the "on" turns, Figures 9.2 & 9.3).

Figure 9.3 Evaluation of the Delivery Performance Ratios of Selected Offtakes on Canal 'Db' Under Rotational Flow – The Virtual System



[4] This situation is realistic as it is very difficult to split a system into two groups of exactly identical demands. In this case the target demand of group B was greater than group A.

- The variability in the flow delivered to the offtakes during the "on" turns was within the acceptable range. Generally, it could be seen in Figure 9.1 that the variability increases as we move down the system (from top to tail). However, the high variability in the flow diverted to the two offtakes on secondary canal ‘S’ (‘S-O1’ & ‘S-O2’) is attributed to a highly variable flow immediately after the gates of the offtakes are opened at the beginning of the "on" turn. This highly variable flow lasts for a few hours only after which the flow becomes reasonably stable (Figure 9.2).

A summary of the evaluation of the performance indicators from the output of this hydraulic model is presented in Table 9.1.

Table 9.1 Evaluation of the Performance of the Offtakes in the Virtual System Under Rotational Flow

Performance Indicator	Maximum	Minimum	Average	IQR
Water Delivery Performance (WDP)	107.4%	92.7%	99.4%	1.08
Flow Variability (C_v)	29.3%	12.5%	20.4%	2.14
Delivery Duration Ratio (DDR)	122%	99%	104%	1.1
Management Input Index (MII)	4 structures every 5 days			

9.4 Rotation between Long Canals

9.4.1 The First Scenario

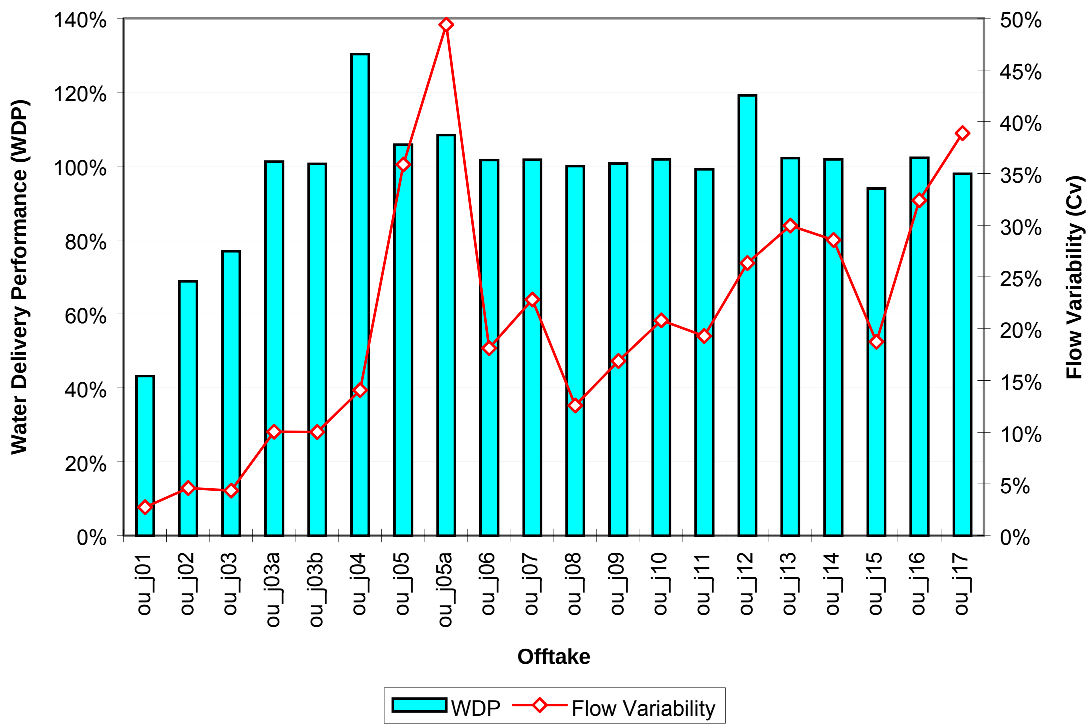
To study the effect of canal length on the performance of rotational flow, a similar investigation to that described above was carried out using the hydraulic model of system *A*, Appendix C.1. The average length of canal *A1* and *A2* is about 30 km, that is almost six times the length of canal ‘Da’ in the virtual system.

The demands of the offtakes on canal *A1* are substantially the same as those on canal *A2*. It is thus possible to practice rotational flow between the two canals in periods of low water supply. Again, a 5-day, two-turn rotation scenario was modelled. The head regulator of canal *A2* and the first cross-regulator on canal *A1* (‘tr.r’ & ‘jr.1u’ respectively, Appendix C.1) were operated to allow all the supply (50% design flow) to either of the canals according to the rotation schedule. In the mean time, the rest of the cross-regulators on both canals and the gates of the offtakes were set for 100% design flow and were kept unaltered during the whole simulation run.

Model Results and Performance Assessment

clearly see in Figure 9.4 that the water distribution equity was not high (IQR = 1.18) and that some offtakes suffered from a highly variable flow during the 5-day "on" turn. As expected, the variability in the flow increases dramatically as we move down the canal. Identifying the reasons for this low performance must be made after considering all the factors that affect the actual flow abstracted by an offtake. Bearing in mind that the gates of the offtakes had fixed openings throughout the simulation run, the remaining important factors to consider are shown in Figure 9.5, namely the travel time and the supply duration (Delivery Duration Ratio, DDR).

Figure 9.4 Water Delivery Performance of the Offtakes on Canal *A1* Under Rotational Flow – Scenario 1

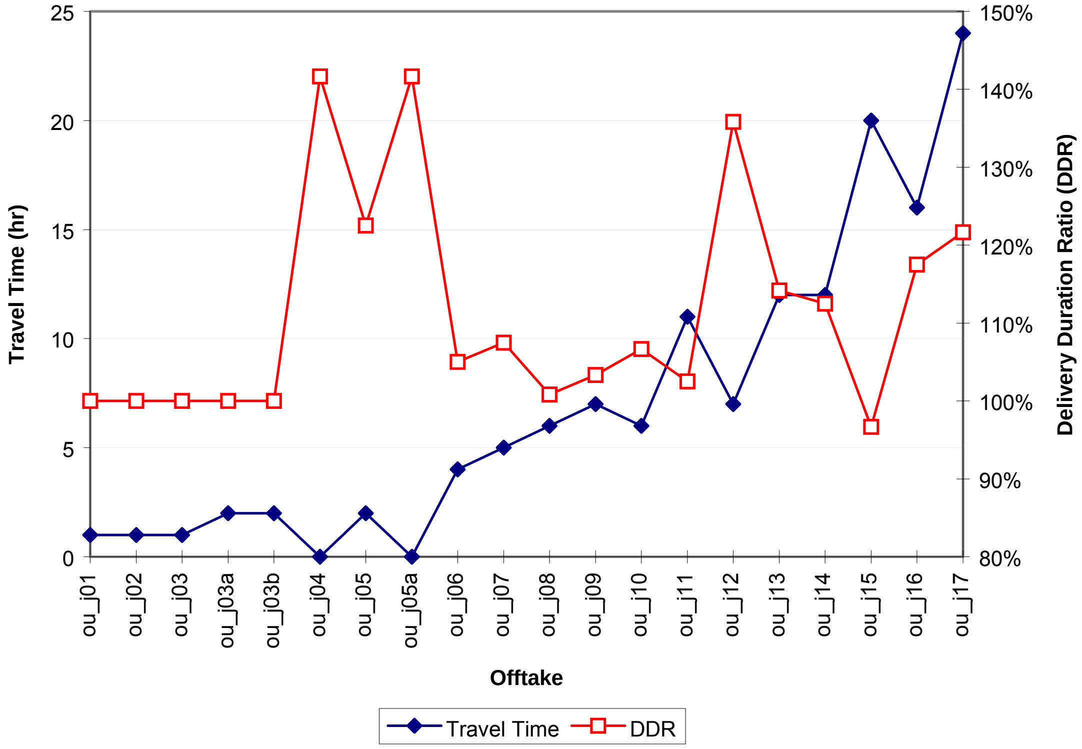


The travel time for an offtake is the time period it takes the flow released at the head of the canal to arrive at the offtake. The travel time shown in Figure 9.5 was calculated as the time lag between the start of the "on" turn of the rotation (opening of canal head regulator) and the time at which the Delivery Performance Ratio (DPR) of an offtake was equal to or greater than 5% (calculation threshold). Figure 9.5 shows a very strong correlation between the location of an offtake on the canal and the travel time. Typically, the travel time is longer as we move down the canal. In fact, a thorough inspection of Figures 9.4 and 9.5 shows that the Flow Variability (Cv) and the Travel Time have very similar patterns for this canal network.

The other factor is the Delivery Duration Ratio (Figure 9.5). In a 5-day rotation schedule, the target supply duration would be around 120 hours. Considering factors such as the travel time, the hydraulic characteristics of the canal and the offtakes, the Delivery Duration Ratio varied as shown in Figure 9.3. No specific trend for the Delivery Duration Ratio could be observed.

Two other points need to be highlighted here: The first is that the design of an offtake can greatly affect its performance. As an example, although offtakes 'ou_j04' and 'ou_j05' on canal *A1* are about 2.3 km apart (Appendix C.1), the Water Delivery Performance of offtake 'ou_j04' in this model run is 130% while that of offtake 'ou_j05' is just 106% (Figure 9.4). This large difference in the Water Delivery Performance of the two offtakes is mainly attributed to their design; while the bed level of the field canal downstream from offtake 'ou_j04' is about 0.2 m *below* the bed level of canal *A1*, the bed level of the field canal downstream from offtake 'ou_j05' is about 1.2 m *above* the bed level of canal *A1*. Consequently, offtake 'ou_j04' can abstract water from canal *A1* no matter the water level in the canal is, while the water depth in canal *A1* must be at least 1.2 m before offtake 'ou_j05' can abstract any water. The impact is very vivid on the Delivery Duration Ratio of both offtakes (Figure 9.5).

Figure 9.5 Delivery Duration Ratio of the Offtakes on Canal *A1* Under Rotational Flow – Scenario 1



The other point to be made is the very low Water Delivery Performance of the first three offtakes on canal *A1* (offtakes 'ou_j01', 'ou_j02', and 'ou_j03'), Figure 9.4. The reason for the very low Water Delivery Performance of these offtakes is that although the full supply level upstream from the cross-regulator commanding the offtakes was achieved during the "on" turn of the rotation, the corresponding water levels at the locations of the offtakes were lower than the design full supply levels because they are located some way upstream from the cross-regulator. This observation leads to an important conclusion: to practice rotational flow on a canal, the offtakes on that canal should be located close enough to the commanding cross-regulators, otherwise, maintaining the command required for the offtakes at low water supplies will be very difficult.

A summary of the evaluation of the performance indicators from the output of this hydraulic model is presented in Table 9.2.

Table 9.2 Evaluation of the Performance of the Offtakes in System *A* Under Rotational Flow - Scenario 1

Performance Indicator	Maximum	Minimum	Average	IQR
Canal *A1*				
Water Delivery Performance (WDP)*	130%	94%	104%	1.18
Flow Variability (C_v)	49.4%	2.7%	20.8%	5.87
Delivery Duration Ratio (DDR)	142%	97%	112%	1.34
Management Input Index (MII)	4 structures every 5 days			
Canal *A2*				
Water Delivery Performance (WDP)	166%	101%	112%	1.3
Flow Variability (C_v)	52%	8.5%	24.6%	3.28
Delivery Duration Ratio (DDR)	140%	99%	117%	1.38
Management Input Index (MII)	1 structure every 5 days			

* Excluding the first three offtakes on canal *A1*.

9.4.2 The Second Scenario

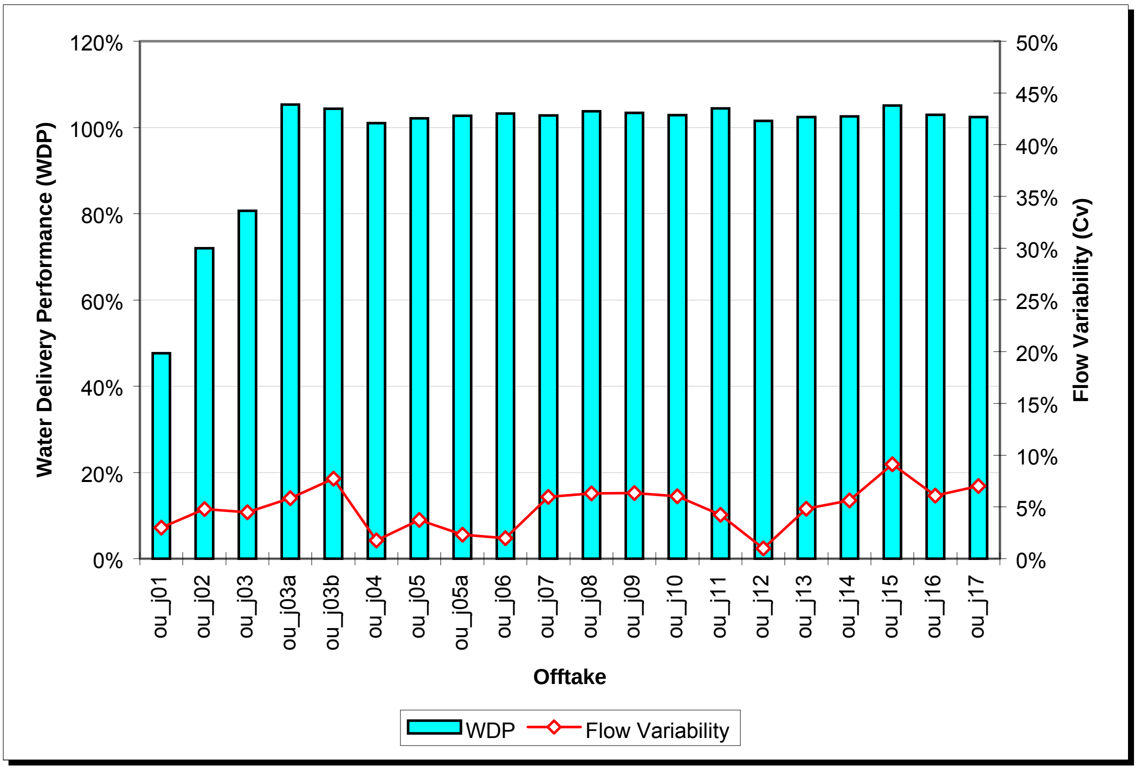
The previous scenario simulated what is believed to be the most common operational procedure for rotational flow by operating only the head structures which control the flow to the canals. Although the advantage of this procedure is clear in its very simple and easy operation, this advantage is offset by low performance levels as shown by the results of the previous scenario. To overcome those shortfalls, a different operational procedure is proposed and tested in this scenario using the hydraulic model of system *A*. The difference in this scenario is mainly in the way in which the control structures are operated to carry out the rotation schedule. In this scenario, all the structures on both canals (the head-regulators, cross-regulators, and offtake gates) are operated. When the rotation turn of a canal is over (start of "off" turn) all the cross-regulators and offtake gates on the canal are closed to prevent the water stored in the canal reaches from being depleted by the offtakes. This will in turn speed up the process of starting the system again when the following "on" turn commences and all the structures are opened again.

Due allowance has been made in the simulation to allow for leakage from the gates of the regulators in the "closed" position.

Model Results and Performance Assessment

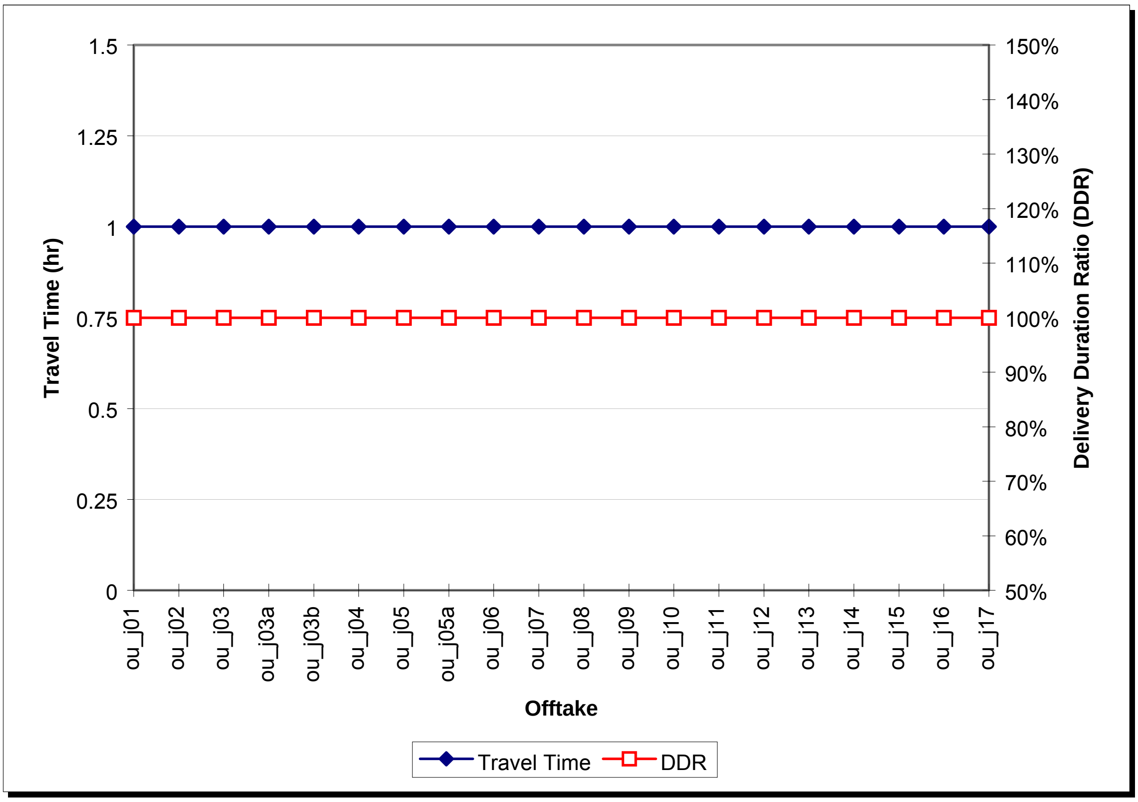
Figures 9.6 & 9.7 show the output from this model run. The figures have the same format as Figures 9.4 & 9.5 to enable a comparison between the results of the two scenarios. It is noticeable how the performance of the system has improved in this scenario. Apart from the first three offtakes on canal *A1*, the water distribution equity is almost ideal, the variability in the flow is much lower, and the travel time and the Delivery Duration Ratio (DDR) are the same for all the offtakes. The one hour travel time is actually the time allowed for the operation of the structures when the "on" turn of the rotation starts (Figure 9.7).

Figure 9.6 Water Delivery Performance of the Offtakes on Canal *A1* Under Rotational Flow – Scenario 2



The main disadvantages of this scenario are the very high operation input required for setting the structures and the potential for siltation in the canals as water is stored during the "off" turns. The evaluation of the Management Input Index (MII) highlights the difference between this scenario and the previous one: while the Management Input Index in the previous scenario was an overall number of five structures to be operated once every five days (duration of rotation turn), the Management Input Index in this scenario is 57 structures to be operated once every five days; some 11 times the input required in the previous scenario!

Figure 9.7 **Delivery Duration Ratio of the Offtakes on Canal *A1* Under Rotational Flow – Scenario 2**



A summary of the evaluation of the performance indicators from the output of this hydraulic model is presented in Table 9.3.

9.5 Conclusions and Guidelines

- Rotational flow is an effective operational procedure to practice in source-oriented systems at low water supply. Rotating the limited supply between users allows it to be fully diverted to a small number of users at a time thus delivering flows that are still near design targets. Delivering flows that are near design targets to farmers enables them, in turn, to make the best use of the flow because it is then within the optimum range of flow that can be efficiently handled by farmers.

- A number of possibilities exist for the level of the system at which rotational flow can be practiced at low water supply: rotation between groups of farm units along canals and/or rotation between groups of canals.

Table 9.3 Evaluation of the Performance of the Offtakes in System *A* Under Rotational Flow - Scenario 2

Performance Indicator	Maximum	Minimum	Average	IQR
Canal *A1*				
Water Delivery Performance (WDP)*	105%	101%	103%	1.03
Flow Variability (C_v)	9%	1.0%	4.9%	3.64
Delivery Duration Ratio (DDR)	100%	100%	100%	1.0
Management Input Index (MII)	29 structures every 5 days			
Canal *A2*				
Water Delivery Performance (WDP)	143%	102%	109%	1.17
Flow Variability (C_v)	7%	1.7%	5%	2.04
Delivery Duration Ratio (DDR)	100%	100%	100%	1.0
Management Input Index (MII)	28 structures every 5 days			

* Excluding the first three offtakes on canal *A1*.

- Every possibility has its advantages and disadvantages, especially in terms of the management input required and the performance levels that can be achieved. Rotating the flow between groups of farm offtakes will require strong discipline to prevent farmers from illegally abstracting water in the "off" rotation turns. The formulation of water user groups is highly recommended in such situations because it will make them share the responsibility of policing the offtakes to make sure that the rotation schedule is carried out correctly.

- The results of the hydraulic models presented in this section proved that there is a direct relationship between the management input and the achieved levels of performance. When rotating the flow between canals by operating their head regulators only, the performance of the system is relatively low, especially when the canals are long. The performance levels can be significantly increased by operating all the cross-regulators and gates of the offtakes on the canals to be fully closed when the rotation turn is "off" to maintain the water levels and volumes stored in the different reaches of the canals. This operation procedure, however, increases the management input significantly and has the potential for silt deposition in the canals if the silt load in the water is high. Sediment transport must be studied in such a case to evaluate the volume of siltation that is likely to take place.

- An analysis of the costs and benefits of the operation procedure suggested here needs to be carried out before the procedure is adopted. The benefit/cost ratio needs to be about 1.5 or higher for the procedure to be worthwhile. Such analysis is highly dependant on the situation in each scheme and therefore must be carried out separately for each one.

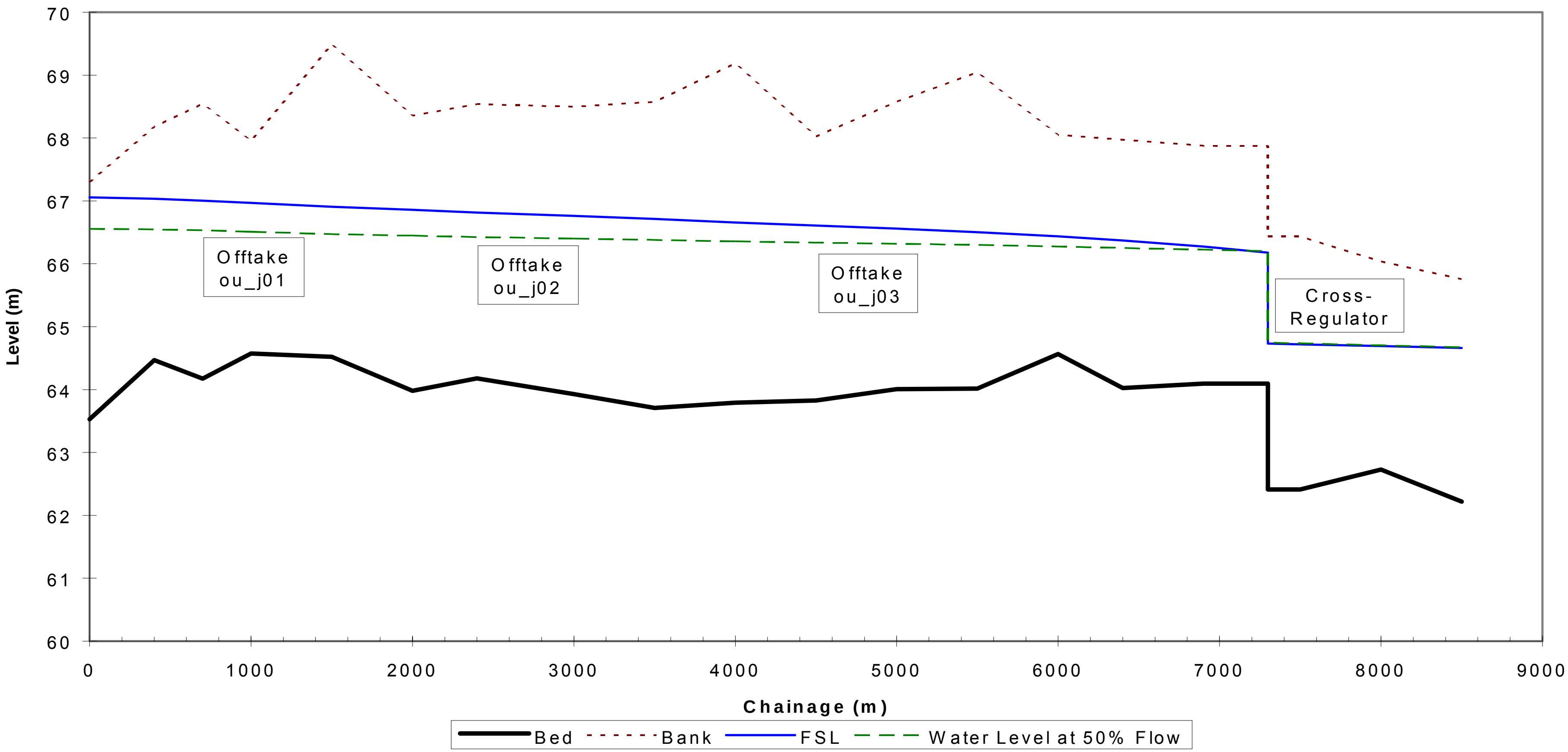
- In the case of weir cross-regulators on a canal whose supply is to be rotated, it might be necessary to install additional gates to the weir structures. The gates will be used to totally close the cross-regulator structures in the "off" turns of the rotation to store the water in the canal reaches (to simulate the second operational scenario presented in Section 9.4.2). In the "on" turns, the gates will be fully open such that they will not interfere with the flow to restore the functionality of the weir structures.

- If the canal is not long, this provision might not be necessary and operating the head regulator of the canal could prove to be sufficient because the travel time of the flow in a canal with weir cross-regulators is much shorter than with undershot gated cross-regulators.

- With respect to the design of offtakes in systems where rotational flow is to be practised, the main points arising from these studies relate to the locations of the offtakes and the hydraulic dimensions of each offtake.

the offtakes located some distance from their commanding cross-regulators are very difficult to command at low water supplies (for example the first three offtakes on canal *A1*). Such offtakes are usually designed based on normal depth and/or backwater curve calculations. The calculations are made for the design flow in a canal with design cross-sections. Under low flows and deteriorated canal sections, maintaining the required command at the distant offtakes by simply maintaining the full supply levels upstream from the commanding cross-regulators will not be possible. Figure 9.8 presents the output from two simulation runs of the hydraulic model of canal *A1* in which it is evident that although the design water level at the first cross-regulator on the canal was maintained when the flow in the canal was 50% of the design flow (by lowering the gates of the regulators), the required command at the first three offtakes upstream from the cross-regulator could not be achieved. Consequently, the offtakes were not able to abstract their fair share of water. Such a design forces farmers to tamper with the system. Under these circumstances, farmers tend to increase the dimensions of the "official" offtakes or install new "illegal" ones to increase the flow diverted to their fields probably to a higher flow than that of the target.

Figure 9.8 Difficulty in Achieving Command of Distant Offtakes at Low Flows



The other point to be considered in the design of the offtakes is their relative hydraulic dimensions. The areas served by the offtakes on a canal, and thus their demands, are most likely to be unequal. However, to keep the cost of construction down, the dimensions of the offtake gates are usually standardised. To control the flow to each offtake, either an orifice plate is fitted to the offtake or the opening of the offtake gate is changed. Although this design might be economical it is prone to abuse and difficult to understand by farmers. A better design from the perspectives of farmers understanding and ease of operation is to proportion the widths of the offtakes (or pipe areas) relative to the design flows (similar to the design of fixed proportional control structures). This design is easier for the farmers to understand and for the operation staff to operate because the offtakes can be designed such that the gates are fully open to deliver the design discharges. Similarly, the heights of the offtake crests above the bed of the supply canals should be constant or proportional to the design flows of the offtakes when topography and canal layout permit. This feature will refine the equity of water distribution at low water supplies when full supply levels in the feeding canals are not maintained.

In all cases, hydraulic modelling is a very effective tool for testing the efficiency and the performance of a system with different offtake designs.

10 WATER STORAGE IN SURFACE RESERVOIRS

10.1 Why is Water Storage Required?

The optimum and most efficient use of irrigation water requires there to be a careful match between supply and demand. When the supply exceeds the demand, excess water is wasted and may in some cases cause environmental damage due to water logging and soil salinity. A shortfall in water supply, on the other hand, will not satisfy all the demands causing adverse impacts on the yield of crops.

Matching supply with demand is a very difficult task in upstream-oriented irrigation systems. The cycle of the variation in the demands, and hence the required regulation of the supply, can be as long as several months (seasonal variation in the requirements of a scheme due to changes in the weather, stage of crop growth, water table fluctuation, etc.), and can be as short as a few hours (variation in demand between day and night times when farmers do not practice irrigation at night).

Water storage is a very effective method to overcome this and other problems. Storing water in surface reservoirs has proved to be the most effective method of water saving in most irrigation projects (Zimmerman, 1966). Providing for water storage in irrigation systems has the following benefits:

(a) Allows greater scope for water regulation and thus promotes efficient water use and water saving by minimising water losses which might otherwise result because of the following:

- in supply-oriented systems water supply is not based on actual demands but on prearranged schedules
- sudden or regular changes in the demands due to rainfall and during night time when farmers do not practice irrigation at night.

(b) Increases the flexibility of the system to respond to changes in water demand and hence improves performance.

10.2 Methods of Irrigation Water Storage

Storage can be provided in three main ways: in surface reservoirs, on fields, and in the ground as groundwater. Storing water on fields and as groundwater has been briefly dealt with in Section 4.2.5 (b) of this report. This section focuses on storing water in surface reservoirs.

Surface water storage can be classified into two general categories: in-line storage and off-line storage. In-line storage can be either by storing water in the freeboard area of carrier and distribution canals or by using on-line reservoirs which are basically canals with enlarged cross-sections. Off-line storage is always in separate reservoirs connected to the irrigation network by means of additional channels and control structures.

10.3 Storage in Canals

10.3.1 Background

It is very important that the basics of water storage in canals are understood by both system designers and operators. Let us consider a simple case of a canal with one cross-regulator somewhere near its middle; thus dividing it into two reaches. Consider also that the cross-regulator has vertical manually operated undershot gates.

When the water level downstream from the cross-regulator is higher than the invert level of the gates, the gates are said to be submerged and the submerged orifice flow equation can be applied to the structure. Recalling the basic form of the equation of flow through submerged orifices;

$Q = C_d \, A \, \sqrt{2g} \, h^{1/2}$

where Q = flow through the orifice (m^3/s)

C_d = coefficient of discharge

A = cross-sectional area of the orifice (m^2)

g = acceleration of gravity (9.81 m/s^2)

h = head on the orifice (m)

Applying this equation to the gates of the control structure in our example, then:

A = function of the gate opening

h = function of the water levels upstream and downstream from the gate.

It is clear then that in the case of an increased flow into the canal, in order to satisfy the orifice equation either the area (gate opening) or the differential head (h) must be increased. Considering the latter option (gate opening not changed), and knowing that the water levels downstream the structure are mainly governed by the downstream conditions and therefore do not change markedly with a small change in the flow, it is evident that the increase in the differential head on the gates will have to come from an increase in the upstream water levels; thus introducing some water storage in the upstream reach of the canal.

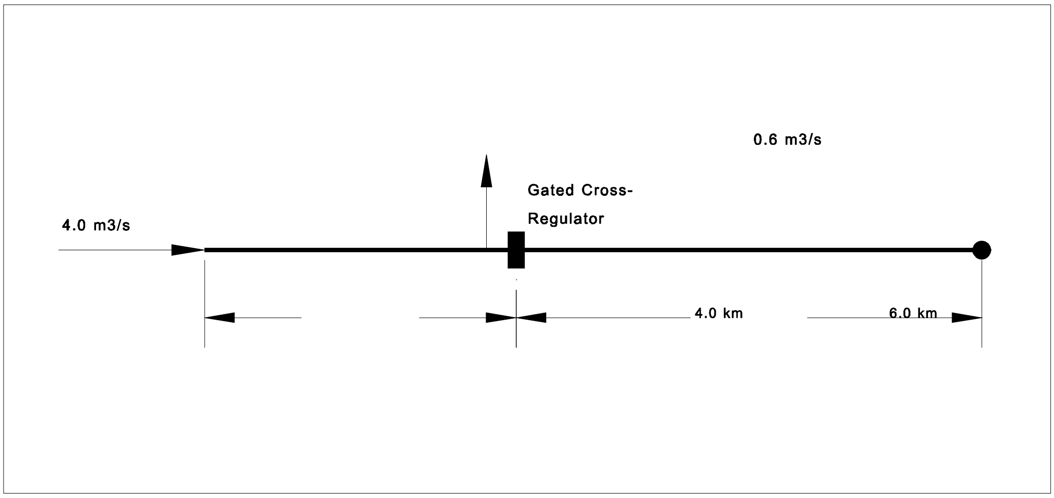
10.3.2 Factors Affecting In-line Storage in Canals

To demonstrate the characteristics of in-line storage in canals and to study some of the factors which affect that storage, a simple hydraulic model was set up. The features of this model are:

- a single canal 10 km long with rectangular cross sections 7.0 m wide and 4.0 m deep
- a cross-regulator with a vertical undershot gate 4.0 km downstream from the canal intake
- an offtake that abstracts water upstream from the cross-regulator

- the flow into the canal was fixed of 4.0m^3/s and the gate of the cross-regulator had a fixed opening throughout the simulation run while the flow abstracted by the offtake varied between 0.6m^3/s for 14 hours and 0.1m^3/s for the remaining 10 hours of the day. The lower abstraction for 10 hours simulates a case of no irrigation at night.

A schematic presentation of the model is shown in Figure 10.1.



Several simulation runs were carried out in order to study the effect of different factors on the quantities of water stored in the canal due to the flow rejected from the offtake during night time. The factors studied were: cross-regulator gate opening, ratio of flow rejected from the offtake to canal flow, and canal longitudinal bed slope. The choice of rectangular cross-sections for the canal was to isolate the effect of the change in the storage area with water level change in cross-sections with sloping sides.

Table 10.1 summarises the key features of the different models studied and the output from their simulation runs. The first three runs listed in the table were meant to study the effect of changing the opening of the cross-regulator gate on the storage in the canal (notice that both canal bed slope and flow in the canal were the same in these three runs). In the next three runs the effect of the canal bed slope was studied (bed slope increased to 0.0004 m/m), and then finally the effect of changing the flow in the canal was studied in the last two runs (gate opening of the cross-regulator was also changed to maintain the same upstream water level under each flow).

The "U/S Storage" in Table 10.1 is the storage in the upstream reach of the canal (4.0 km long) while the "D/S Storage" is the storage in the downstream reach of the canal (6.0 km long) that occurred during the 10 hours of low abstraction by the offtake (rejected flow).

The conclusions that can be drawn from the results presented in Table 10.1 are:

- There is an inverse relation between the storage in a canal and its longitudinal bed slope (storage decreases as canal slope increases).

Table 10.1 Summary of the Results of Studying the Factors Affecting Storage in Canals

Bed Slope (m/m)	Flow In (m3/s)	Cross-regulator Values				U/S Storage* (%)	D/S Storage* (%)	Total Storage* (%)
		Gate Opening (m)	Max Head (m)	Min Head (m)	Head Range (m)			
0.0001	4.00	0.5	0.197	0.15	0.047	17.8%	18.2%	36.0%
0.0001	4.00	0.4	0.307	0.236	0.071	21.9%	17.8%	39.7%
0.0001	4.00	0.3	0.542	0.42	0.122	30.2%	16.9%	47.0%
0.0004	4.00	0.5	0.111	0.078	0.033	3.6%	18.2%	21.9%
0.0004	4.00	0.4	0.209	0.145	0.064	5.8%	18.2%	24.0%
0.0004	4.00	0.3	0.486	0.336	0.15	13.8%	18.0%	31.8%
0.0001	6.00	0.65	0.267	0.224	0.043	16.9%	16.5%	33.3%
0.0001	5.00	0.4	0.485	0.395	0.09	24.8%	16.6%	41.4%

* Percentage of a maximum potential storage of 0.5 m^3/s * 10 h * 3600 = 18,000 m^3/day

- the openings of the gates of the structure controlling that reach (cross-regulator at the end of the reach) as shown in Figure 10.2. This point is very important to consider in the design of gated control structures: if water storage in the canal reach upstream from a gated control structure is to be kept as large as possible, the gates of the structure should be designed to operate in drowned condition for the widest possible range of operation flows. Structures that operate like weirs should be avoided as they reduce the capacity of the canal to store extra water.

- Regardless of the capacity of a canal, there is a maximum limit for the quantity of water that can be stored in it. In the models investigated in this exercise, the maximum storage achieved was around 55% of the potential storage (results not shown in Table 10.1) although the canal was designed with extra capacity. Notice in Figure 10.3 that the maximum water level in the canal was far below its bank level. The excess water was lost through the tail escape of the canal.

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Figure 10.2 Impact of the Gate Opening and the Head on Undershot Gate on the Storage in Test Canal

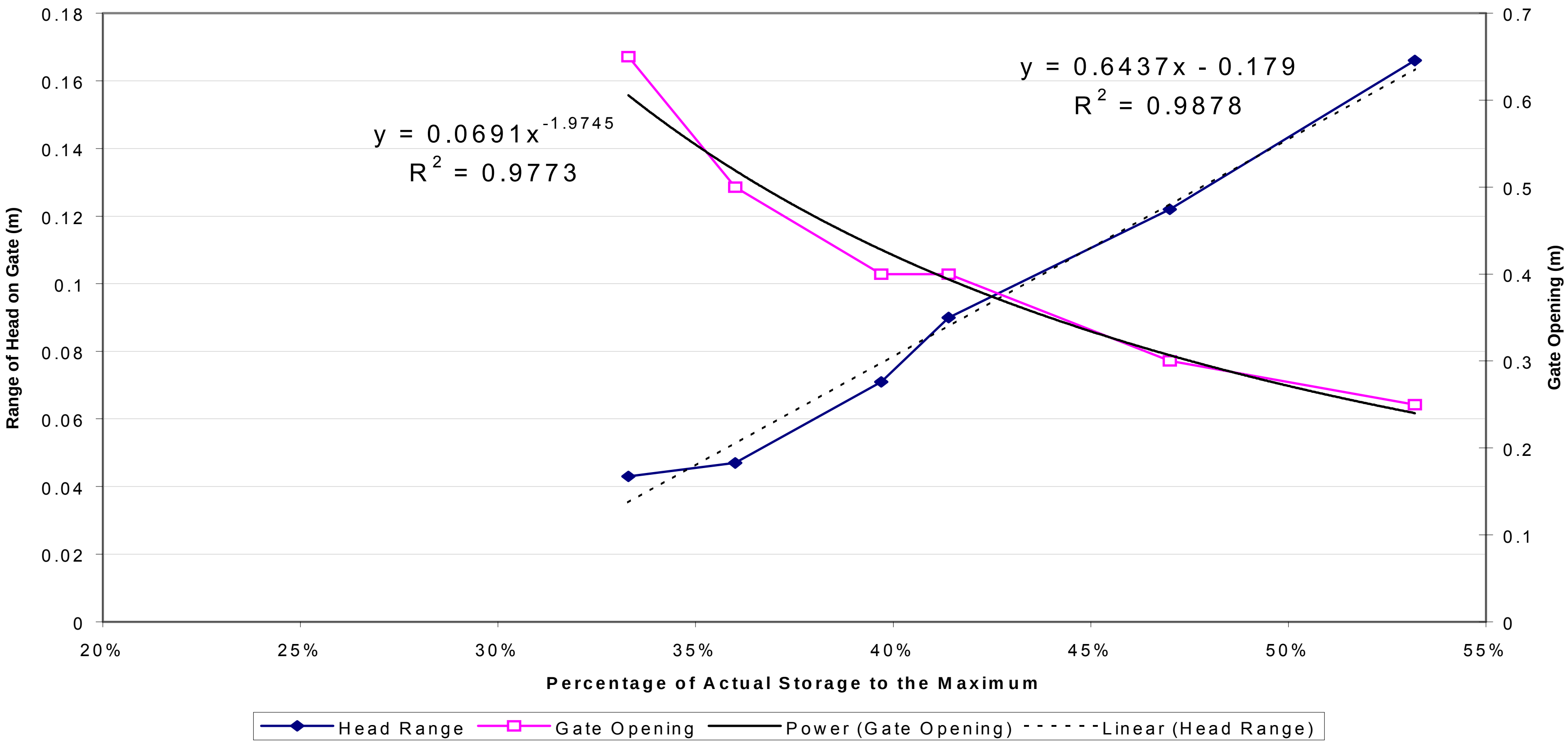
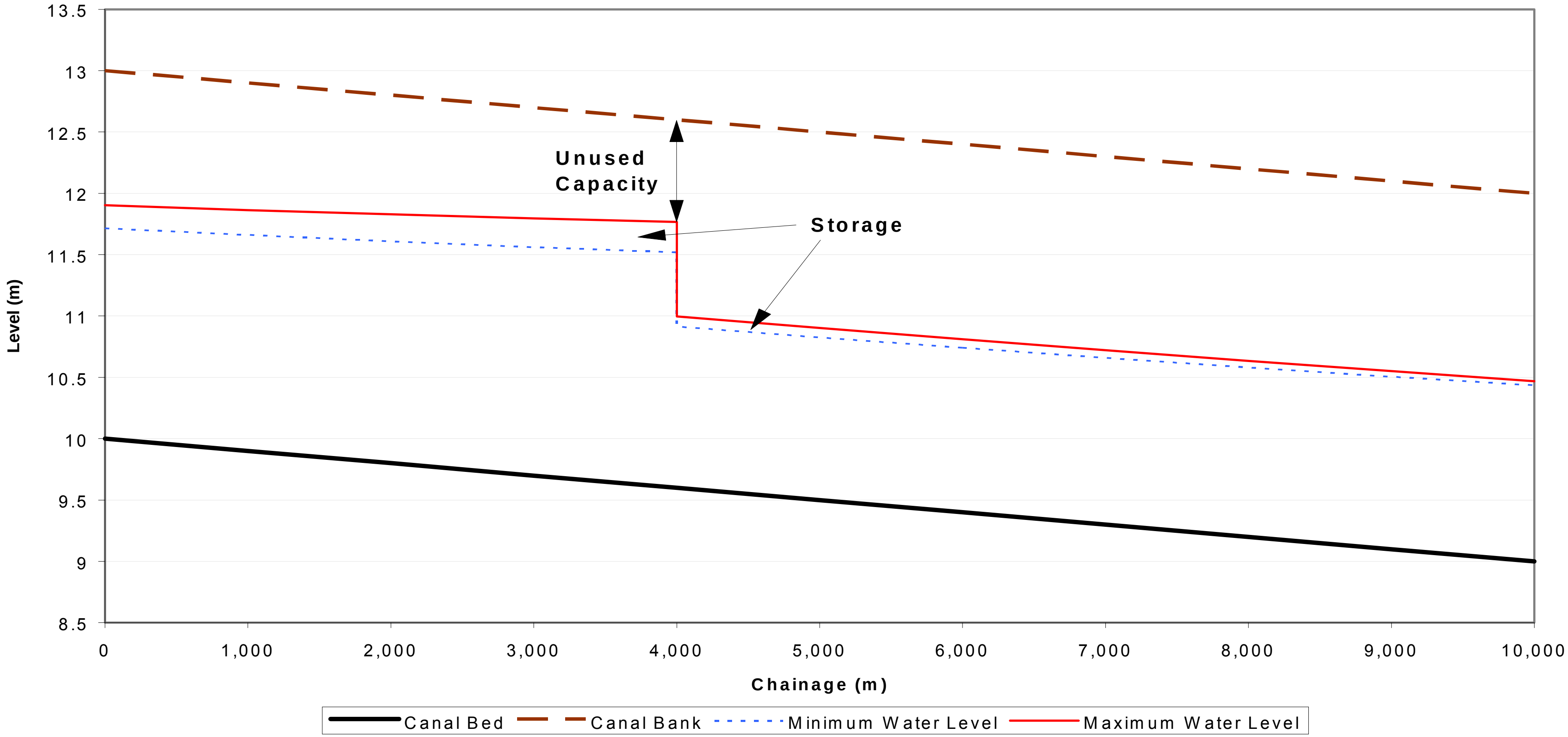


Figure 10.3 Maximum Storage in Test Canal



- Because of the fact that not all the flow rejected in a canal reach is stored in that reach, there is always excess water flowing to downstream reaches. The ratio of the quantity of the water stored in a reach to the quantity flowing to downstream reaches is dependent on many factors, especially the length of the reach, the slope of the canal bed, and the opening of the gate(s) at the downstream end of the reach. It is essential therefore to ensure that emergency facilities and ample freeboard are provided at downstream reaches to prevent canal breaches and over-topping.

10.3.3 In-line Storage in Long Canals

Schuurmans et al. (1992) studied in-line storage in a long canal to cater for no irrigation at night. The lined canal was 100 km long with a capacity of 15 m^3/s only, had trapezoidal uniform cross-sections, and bed slopes that varied between $18x10^{-5}$ to $28x10^{-5}$. Water control was achieved via 36 cross-regulators, each comprising a central gate 3.6m wide and symmetrical weirs at the sides for emergency situations. The canal was used to convey water to 22 irrigation offtakes located along its length and to supply municipal water to a city. The offtakes abstracted water for only eight hours a day while the municipal water was required 24 hours a day.

The study investigated the applicability of three control methods namely upstream, downstream, and mixed control; and the operation strategy accompanying each method. Hydraulic modelling was used to test the different alternatives and to reach a satisfactory operation strategy.

The results of the study showed that it is possible to achieve in-line storage with either of the three control methods investigated. However, some methods have advantages over the others. Downstream control was found to be the most suitable method to control a canal with in-line storage. On the other hand, mixed control is most suitable if the canal is to respond to events at its upstream end such as conveying floods.

Whatever control method used, it was found that it was very difficult to achieve high performance if the cross-regulators were operated to maintain fixed water levels (fixed set points). Instead, varying the target water levels maintained by the cross-regulators during daytime operation was indispensable. This requirement in the operation strategy of the system signifies that control structure automation is virtually a necessity. It also limits the selection of the automation technology as for example the hydraulic gates which control upstream and/or downstream water levels (like AMIL and AVIS gates) have fixed target water levels and therefore cannot be used in such a case.

The other point that must be considered in the results of the study is that it was clearly stated that the variable settings of the cross-regulators were derived heuristically (by trial and error). Using hydraulic modelling in the trial and error process is indispensable. There is a concern that the trial and error process cannot be carried out in the field because of the consequences on the safety of the system. Thus, the proper and efficient operation of the system under conditions which are different from those tested using hydraulic modelling will be very difficult for operation staff to achieve.

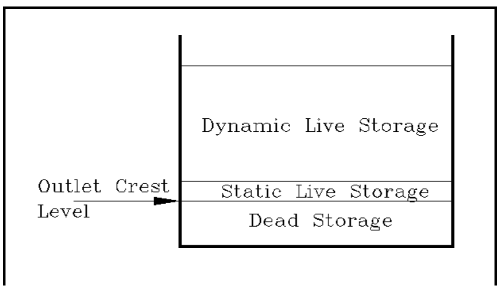
10.4 Off-line Storage

When the canal slope is relatively steep or when the capacity of an existing canal is based on a uniform demand throughout the day, in-line storage is not a feasible option for water storage. Off-line storage in such cases is a possible alternative. Considering water storage that caters for the differences in the demand patterns during day and night times when farmers do not practice irrigation at night, different options for the arrangement of off-line storage exist. One option is to use one main reservoir at the heads of secondary, distributary, or tertiary canals. A second option is to distribute many off-line reservoirs along the canals. And a third option of locating the reservoirs further down in the system at the heads of minor canals or on the fields may also be possible. An investigation into these different options is presented below.

10.4.1 Sizing Off-line Reservoirs

Sizing off-line reservoirs based on the volumes of water to be stored and the estimation of the quantities of sediment that are likely to be deposited in the reservoirs should be a straight forward task. There may be a limitation on the surface area of a reservoir from topographic conditions, the existence of obstacles, the economic value of the water to be stored compared with land value, and social and political issues. If no constraints are imposed on the surface area of a reservoir it is desirable to size it such that the water depth is as small as practicable. Although it is recommended that off-line reservoirs should be at least 3.0 m deep to avoid sunlight penetration encouraging vegetation growth (Burt, 1987), it can be argued that shallower reservoirs are advantageous. Besides the merits of shallow reservoirs in terms of the ease of operation as will be further explained below, they are also easier to maintain, the small water depth means less pressure on the reservoir lining material thus reducing the cost of lining, and shallow reservoirs reduce the danger to people and animals of drowning if they fall into the reservoirs. However, to make reservoirs shallow their surface areas must be increased thus increasing evaporation losses from the water stored.

The total storage volume in a reservoir may be divided into three categories: 1) *Dead storage*; 2) *Static live storage*; and 3) *Dynamic live storage* (Figure 10.4). The *dead storage* is the volume between the bed of a reservoir and the minimum crest level of the reservoir's outlet structure. It should be provided to allow for the possible siltation in the reservoir as water velocity almost approaches zero. The size of *dead storage* is therefore related to the silt load in the water. Although silt traps can be provided at reservoir inlets it is always recommended to allow for *dead storage* rather than losing some of the *live storage* if unexpected deposition takes place.



The *static live storage* is defined as that part of the *live storage* which is required to provide the head loss required through the outlet structure of a reservoir to pass its design flow. The term *static* in the name highlights that this storage volume, although live, should not be used in the daily operation of reservoirs, i.e. the water level in a reservoir should not be allowed to drop below the top of the *static live* *storage*. The term *live* in the name denotes that no siltation should be allowed in this storage volume.

And finally the *dynamic live storage* is the area of a reservoir where daily operation should take place. It is the volume of water that can be stored in a reservoir during the night and the maximum volume of water that should be released during daytime. The recommended depth of *dynamic live storage* is between 0.5 and 1.0 m with more emphasis on the smaller depth. The need to minimise the depth of *dynamic live storage* is to reduce the fluctuation in the head on the reservoir outlet structure that occurs as flow is released. In this way a fairly constant discharge can be maintained through the structure without the need for frequent resetting of the structure.

The provision of *static live storage* with minimum reservoir depth will only be necessary if water is to be released from the reservoir by gravity. If water is pumped then it might be more economical to increase the depth of water in the reservoir such that its surface area is decreased in order to minimise evaporation losses.

10.4.2 Off-line Reservoir Location

The location of off-line reservoirs is usually governed by topographic, hydraulic, and economic factors. From the topographic and economic aspects it is desirable to locate the reservoirs in areas where drops in canal beds exist such that the inlet of a reservoir is located upstream from the drop and the outlet at the downstream thus allowing water into and out the reservoir by gravity and eliminating the need for pumping. It is also desirable to locate the reservoirs in areas of low soil permeability to reduce seepage losses from the reservoirs which not only reduce the volume of water stored but also may have an adverse impact on surrounding land by raising the water table.

From a hydraulic point of view if off-line reservoirs are located along a canal, it is better to distribute them on the canal such that the volumes of water to be stored in each reservoir is similar. The magnitude of the flow into and out of a reservoir should not be excessive in order to prevent large flow concentrations in the canals at the locations of the reservoirs.

10.4.3 Water Storage in Head Reservoirs

This alternative of using off-line storage at the head of irrigation canals is probably the most commonly used arrangement for water storage. In fact, a dam, whether large or small, which stores water from a catchment for the use of an irrigation scheme is in essence an off-line storage reservoir that is located at the very top of the system. This type of major storage is suitable for regulating the variation in the seasonal water requirements of a scheme. It is apparent that off-line reservoirs that can regulate the variation in demand patterns between day and night times should be located further down in the system. One can easily establish the relationship between the possible location of an off-line reservoir and the time span over which flow should be regulated: as the time span gets shorter, the reservoir should be located further down in the system, i.e. closer to the locations whose demands are to be satisfied by the flow from the reservoir. If the reservoir is located higher in the system, the response time required for the water to arrive from the location of the reservoir to the demand points might be longer than the time period during which the flow from the reservoir is required.

Testing the Scenario Using Hydraulic Modelling

Investigating the efficiency of head reservoirs in storing the flow rejected during night time if farmers do not practice irrigation during that period of the day has been carried out using the hydraulic model of the virtual system developed in this study, Appendix C.3. It was assumed in the model runs that farmers will irrigate for 14 hours during the daytime only and hence water will not be required for irrigation in the remaining 10 hours of the day. To simulate this situation in the hydraulic model, the gates of the offtakes were kept open for 14 hours every day and then fully closed for 10 hours. One main off-line reservoir was located at the head of the system (top-end of canal 'S', Figure 10.5). The flow into the system was totally diverted to the reservoir at night for storage. During the daytime, the flow into the system was the sum of the flow from the source plus the flow from the off-line reservoir.

The First Scenario. In this scenario, the sluice gates of the cross-regulators on all the canals were kept with fixed openings during the whole simulation run time. The gates were set to achieve full supply levels upstream from the cross-regulators at the high flows during the daytime.

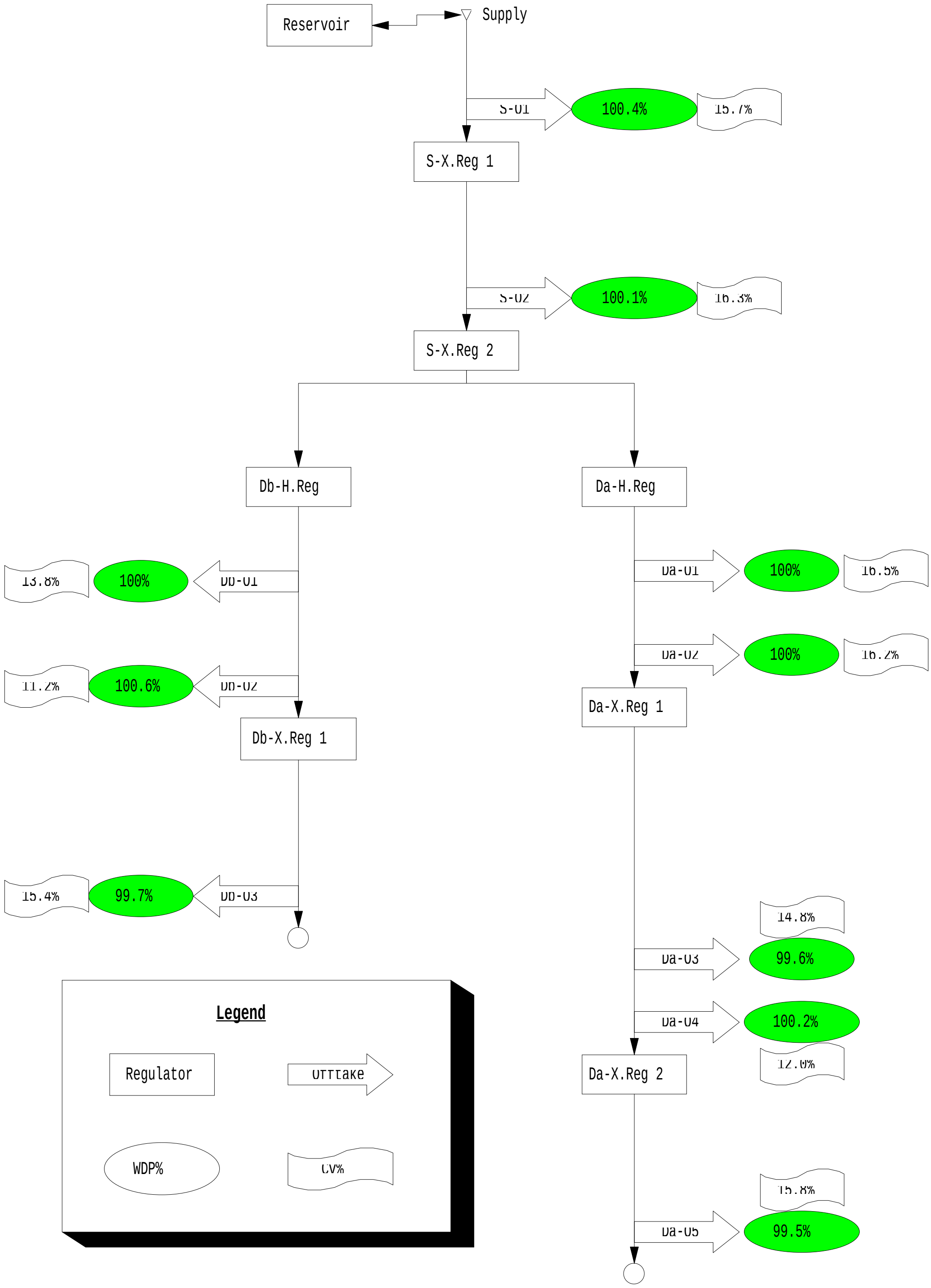
The results of this scenario showed that it was not successful in achieving equitable water distribution or saving water from being lost through the tail escapes of the canals. It was very clear from this run that the problem was related to the operation of the cross-regulators: as water supply in the system ceased during the night time, because the gates of the cross-regulators were kept open the water stored in the upstream pools of the system escaped to the downstream reaches depleting the storage in the upstream canal reaches and flooding the downstream ones. When the supply was increased again during the daytime, it was required to fill up the upstream reaches first before the offtakes could abstract any water. The consequence was a very poor water distribution equity with more flow being abstracted by the downstream offtakes.

A summary of the evaluation of the performance indicators from the output of this hydraulic model is presented in Table 10.2.

Table 10.2 Evaluation of the Performance of the Offtakes in the Virtual System When Using Main Head Off-line Reservoir - Scenario 1

Performance Indicator	Maximum	Minimum	Average	IQR
Water Delivery Performance (WDP)	119.7%	82.2%	94.5%	1.36
Flow Variability (C_v)	52.3%	15.6%	35.4%	2.57
Delivery Duration Ratio (DDR)	195.4%	93.1%	137.7%	1.98
Management Input Index (MII)	12 structures twice a day			

Figure 10.5 Performance of the Virtual Model When Using Main Head Off-line Reservoir



The Second Scenario. In a trial to improve the low performance achieved in the previous scenario a modified operational procedure is proposed here. In this scenario, the gates of the cross-regulators were all closed during the night time simultaneously as water supply in the system ceased. Closing the gates of the cross-regulators almost maintained the full supply levels in all the reaches of the canals in the system. Starting the system again during the daytime by opening the gates of the cross-regulators as the supply increased did not pose problems. All the offtakes were able to abstract water as soon as daytime operation started since command was maintained in the canals. The water distribution equity achieved in this scenario was very high as depicted schematically in Figure 10.5 (notice that all the offtakes abstracted almost 100% of their target water volumes). The evaluation of the variability of the flow abstracted by the offtakes during daytime operation showed that the variability was much lower than in the previous scenario (Figure 10.5).

A summary of the evaluation of the performance indicators from the output of this hydraulic model is presented in Table 10.3.

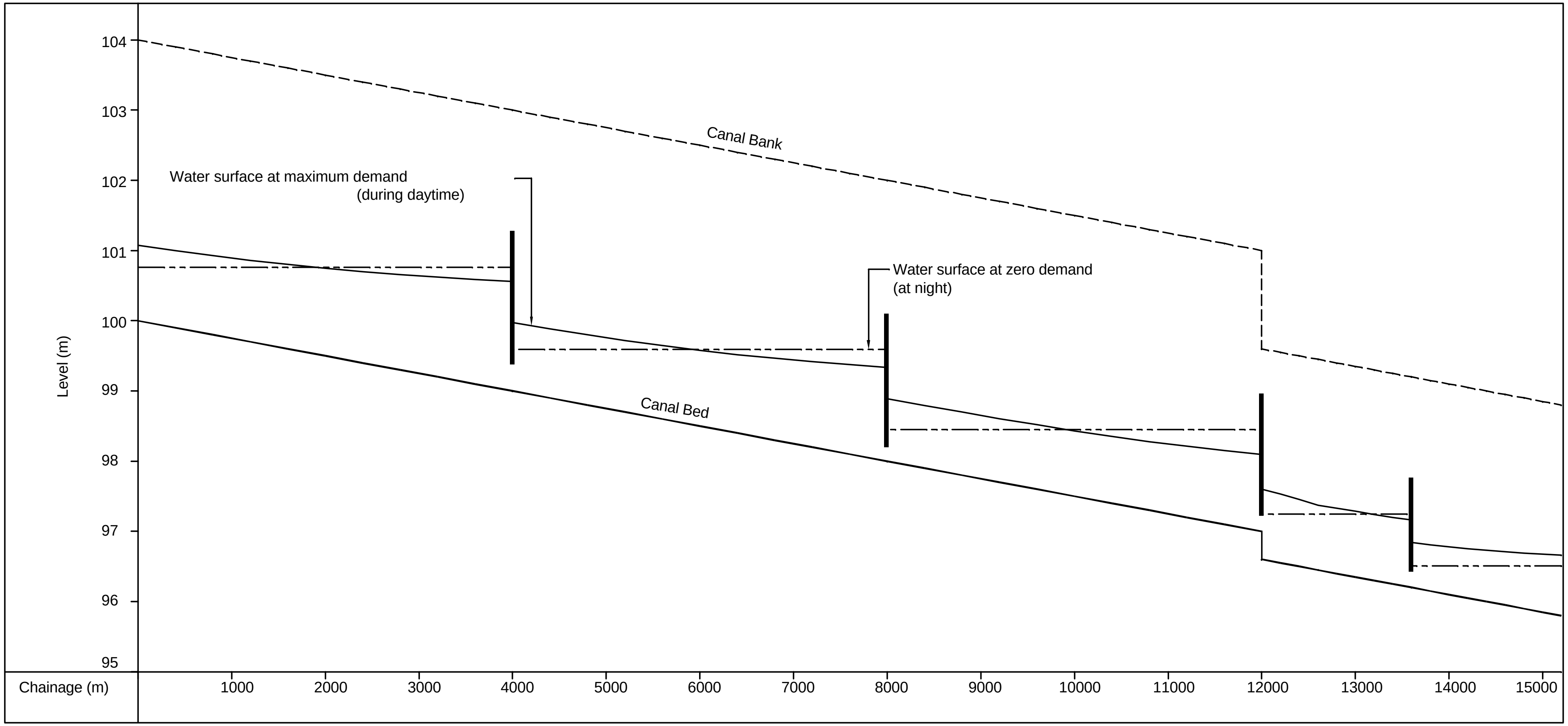
Table 10.3 Evaluation of the Performance of the Offtakes in the Virtual System When Using Main Head Off-line Reservoir - Scenario 2

Performance Indicator	Maximum	Minimum	Average	IQR
Water Delivery Performance (WDP)	100.6%	99.5%	100%	1.0
Flow Variability (C_v)	16.5%	11.2%	14.8%	1.32
Delivery Duration Ratio (DDR)	100%	100%	100%	1.0
Management Input Index (MII)	19 structures twice a day			

The points that must be highlighted are:

- Although off-line storage is used to store water during low or zero demand times (at night), the irrigation network must have sufficient capacity to accommodate the high flows during high demand times (almost double the flows that will pass if the system is to be operated continuously without storage). This extra capacity must also allow for the rise in the water levels upstream from the cross-regulators which occurs as water is stored in the canal reaches during zero demand periods (Figure 10.6).

Figure 10.6 Water Surface Profiles in the Virtual System When Storing Night Water in Head Off-line Reservoir



- The operational procedure that should be followed for the proper operation of a system with off-line storage at the head of the canals should not present major problems. Obviously, the input of the operation staff will be higher than that which will be required if the system is to be operated continuously, as regulator and offtake gates will have to be opened and closed daily with some further adjustments during daytime operation. Established water user groups can play an important role in the daily operation of offtake gates to relieve the work load on operation staff.

- It is interesting to compare the results of the hydraulic modelling runs presented in this section with those from the runs used to investigate rotational flow between short canals (refer to Section 9.3 - **Rotation between Short Canals**). In fact the idea of off-line storage at the head of a canal system is very analogous to rotational flow; in both cases the flow is rotated between two water bodies, a canal and an off-line reservoir in the case of night storage, and two groups of canals in the case of rotational flow. The main difference between the two cases is the duration of the process; the duration is very short in the case of night storage and is much longer in the case of rotational flow. This difference is in fact the main reason for the success of rotational flow between two groups of short canals without having to change the settings of the cross-regulators on the canals and the failure of this same operational procedure in the case of night storage as discussed above. In the case of rotational flow, the time required for filling the short canals at the beginning of the "on" turns is not significant compared to the duration of the turns (a few hours compared to five or more days). In the case of night storage this canal filling time becomes significant since the duration of the "on" turn is only a few hours.

10.4.4 Water Storage in Intermediate Reservoirs

When a canal, where storage is considered, is relatively long, using one main reservoir at the top of the canal will not be an optimum solution to employ, as explained in the previous section. To reduce the response time of the flow from the reservoirs, some reservoirs should be located along the canal such that each reservoir is located close to its service area and hence the flow required by a reach near the tail-end of the canal does not have to travel down the canal starting from its top-end.

Testing the Scenario Using Hydraulic Modelling

A Study of employing intermediate off-line reservoirs along secondary canals was carried out using the hydraulic model of canal *B1* in irrigation system *B* (Appendix C.2). The canal is ideal for using intermediate off-line reservoirs as it has many drops in the bed distributed along its whole length. Five off-line reservoirs were proposed as shown in Figure 10.7. They were located at the drops in the canal bed such that water pumping was not required. Every reservoir was connected to the canal via an inlet and an outlet structure. The structures had undershot gates which were automated to maintain certain flows to pass through. The inlet structures to the reservoirs were opened for 10 hours every day during the night time during which time the offtakes to the fields were closed. The reservoirs' outlet structures were opened for 14 hours every day during daytime operation to supply water to the offtakes which were also then opened.

In this study the cross-regulators on canal *B1* were manually operated as in the original design of the system. Also the settings of the cross-regulator gates were kept constant during the whole simulation run time.

Model Results and Performance Assessment

The results obtained from the hydraulic simulation models show that:

- Because of the way this operation scenario is designed, unsteady flow occurs in the canal most of the time - a situation that most system operators would normally try to avoid. In fact, managing a system that experiences unsteady flow for long periods is not an easy task even if aided by hydraulic modelling. Because of the frequent changes in the water levels in the canal, setting the gates of the cross-regulators was not straightforward. The new settings were obtained by trial and error with a target to achieve equitable water distribution between all offtakes as far as possible. The process was very lengthy and cumbersome and therefore can never be followed in the field. Setting the cross-regulators to just maintain full supply levels did not achieve equitable water distribution. The final settings reached caused the water levels to be higher than the design water levels, in some cases encroaching on the free board of the canal.

- The implications of the great difficulty in managing the system in this scenario on the its performance are presented graphically in Figures 10.8 & 10.9. Notice that the flow distribution equity is not even, Figure 10.8. The offtakes located in the middle of canal reaches (not in the immediate vicinity of cross-regulators) are the worst in terms of water adequacy. The variability in the flow diverted to the offtakes dramatically increases as we move down the system.

Additionally, some operational losses still took place and could not be avoided. Those operational losses must be accounted for in such an operational scenario otherwise water shortage might occur in some locations.

- To allow for canal filling and emptying times the inlet and outlet structures of the reservoirs had to be opened and closed one hour earlier than the offtake gates.

- The excess water resulting from the operational losses that occur at the times of highly transient flows when offtake and reservoir gates were opened and closed accumulated at the tail-end of the canal. This fact highlights the necessity of providing extra capacity in the canal reaches and the off-line reservoirs near the tail end where such operational scenario is to be employed.

Figure 10.7 Testing Intermediate Off-line Reservoirs on Canal B1 - Irrigation System B

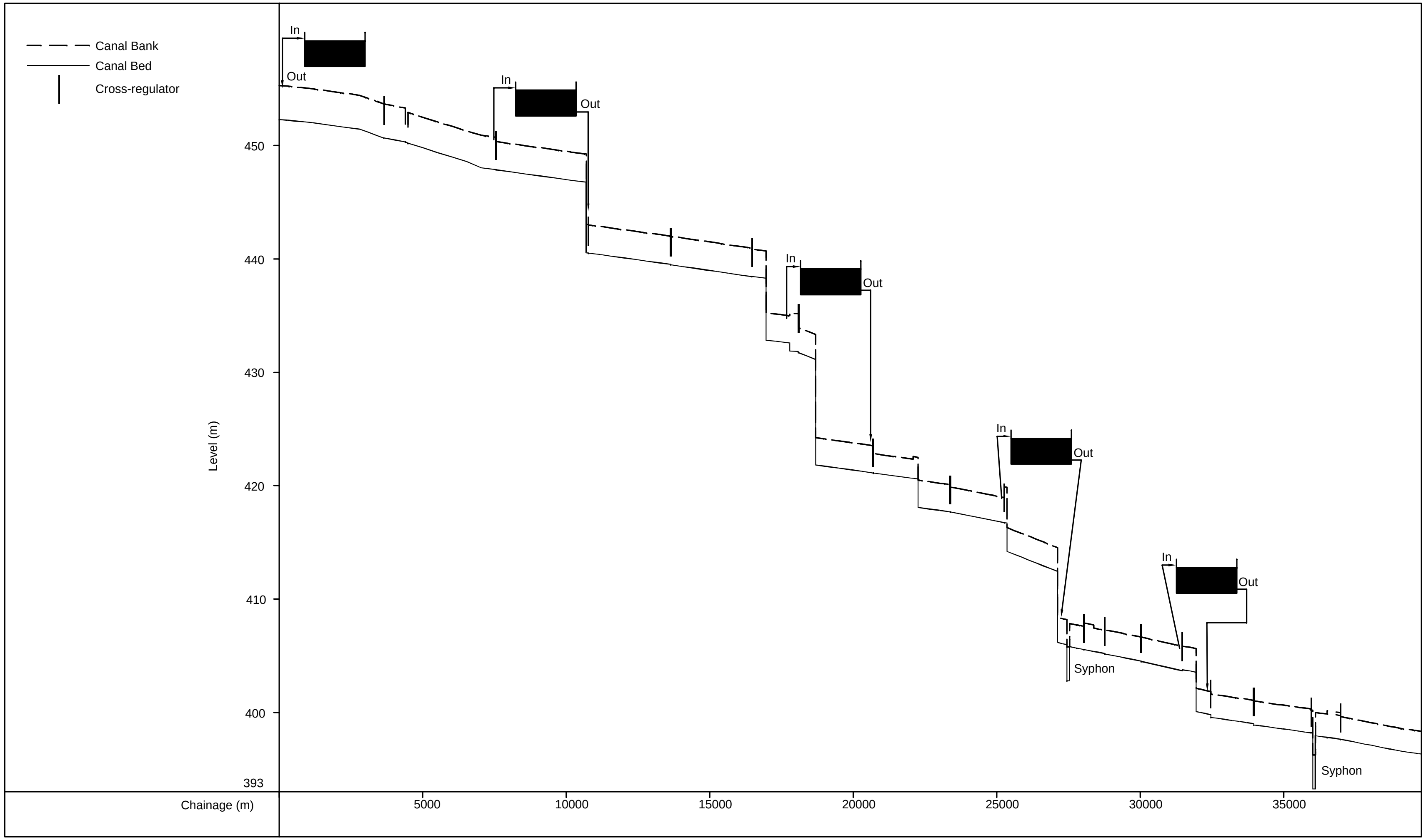


Figure 10.8 Water Delivery performance of the Offtakes on Canal *B1* When Using Intermediate Off-line Reservoirs

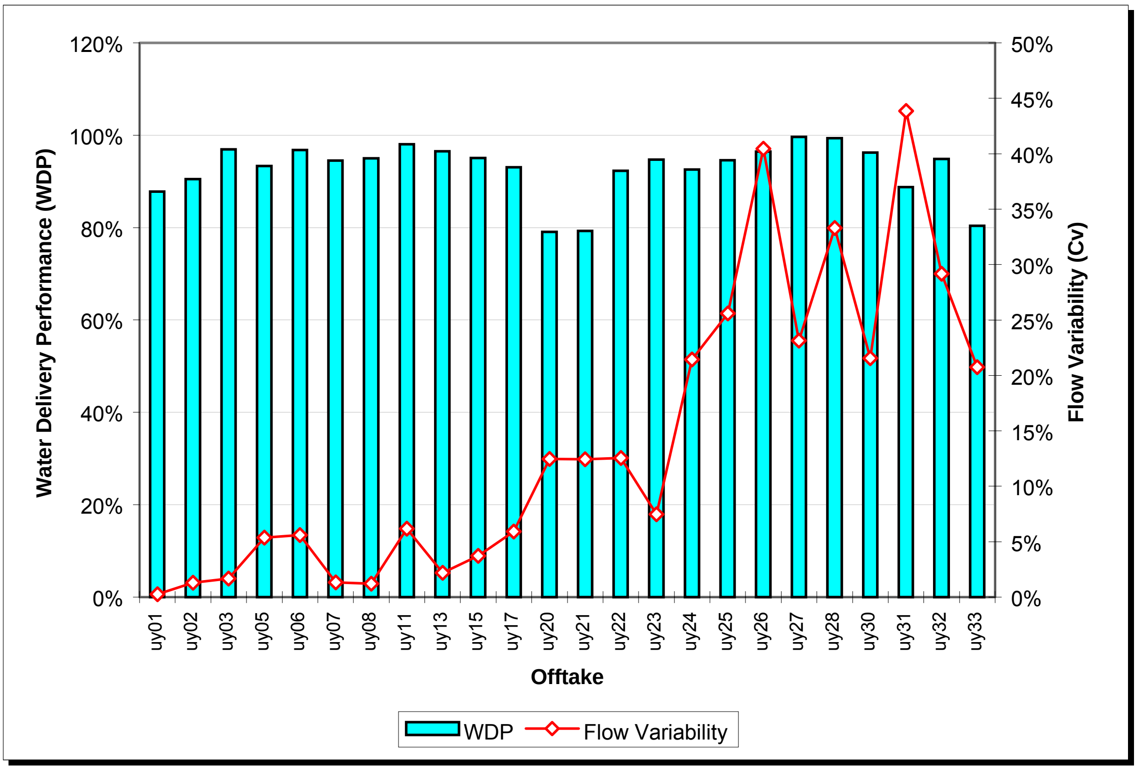
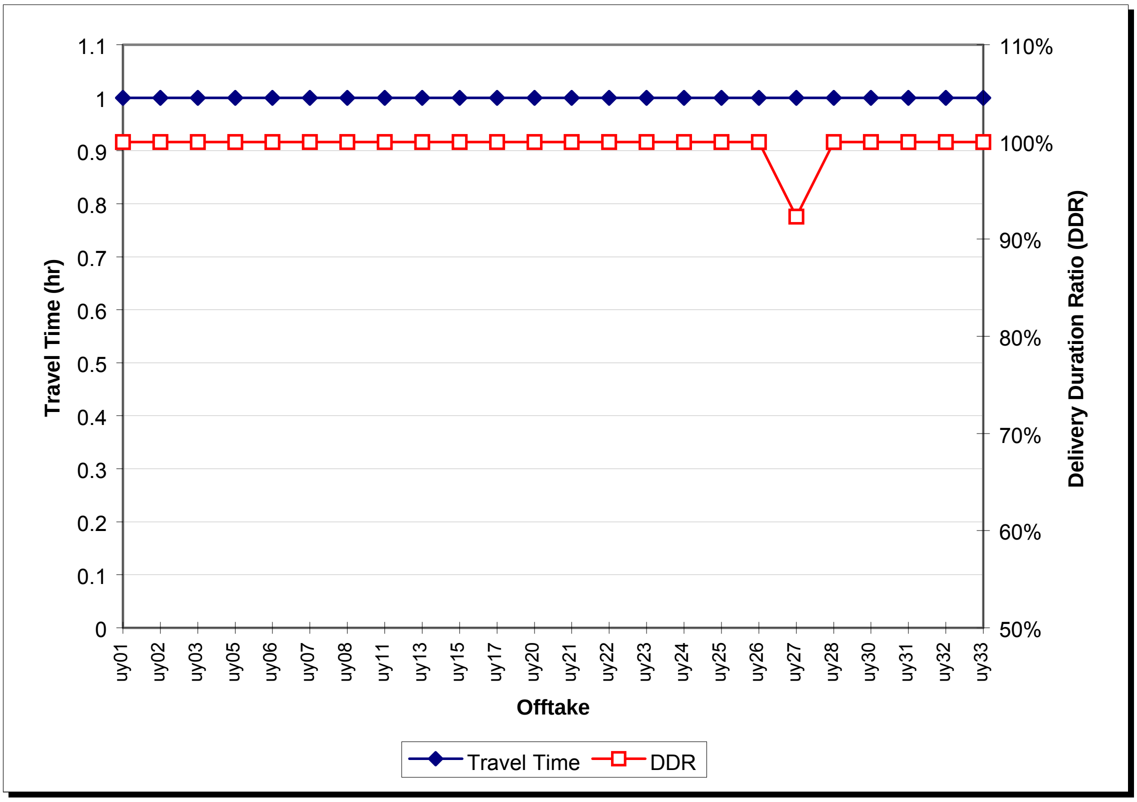


Figure 10.9 Delivery Duration Ratio of the Offtakes on Canal *B1* When Using Intermediate Off-line Reservoirs



- Considering the previous point regarding the operational losses and taking into account the possibility of the failure of any of the automated inlet and outlet reservoir structures, it is essential that emergency facilities are provided to cope with such situations. Generous free board must be provided along canals, emergency side weirs/escapes are to be provided in all cross-regulator structures, all canals must have tail escapes, etc. One of the emergency procedures that can be followed if a reservoir inlet structure fails to collect the excess water in the canal during night time is to open the gates of the offtakes downstream from the faulty structure and let the water escape to the drains.

A summary of the evaluation of the performance indicators from the output of this hydraulic model is presented in Table 10.4. Notice that the variability in the flow is extremely high.

Table 10.4 Evaluation of the Performance of the Offtakes on Canal *B1* When Using Intermediate Off-line Reservoirs

Performance Indicator	Maximum	Minimum	Average	IQR
Water Delivery Performance (WDP)	99.6%	79%	92.7%	1.16
Flow Variability (C_v)	43.8%	0.3%	14.1%	24.4
Delivery Duration Ratio (DDR)	100%	92.3%	99.7%	1.01
Management Input Index (MII)	34 structures twice a day			

10.4.5 Off-line Reservoirs' Inlet and Outlet Structures

Control structures are required to control the water to and from off-line reservoirs. The hydraulic characteristics desired in these structures are:

(i) to allow water to and from the reservoirs at certain times as set up in the operation plan of the system

(ii) to allow certain design flows to pass to and from the reservoirs at relatively steady rates for a wide range of operating heads.

In their basic principle, the structures will either be weirs or orifices (undershot gates). Some points to be considered in the selection of the structures are:

- weirs have higher *flow sensitivity* than undershot gates (response to water level changes in terms of the flow passing them). This feature is obviously contradictory to the second desired hydraulic characteristic given above

- fixed-crest weirs cannot be totally closed unless the structure is provided with additional gates

Because of the disadvantages of weirs as flow control structures it is recommended that undershot gates are used for reservoir inlet and outlet structures. To satisfy the requirements of the hydraulic design of the structures the gates should be automated to control the flow passing through. To control the flow through the structure a flow measuring device (for example a broad crested weir) might be required downstream from the gates. The water level above the crest of the weir can be automatically measured by a float and then the flow can be calculated. A motor will then change the openings of the gates to adjust the flow passing the structure as required.

Despite the fact that the technology might not be available or justifiable in some schemes, it is not advisable to replace it with manual control. Although the frequency of setting the gates might not be so high as to preclude manual operation and, there is a high risk of mismanaged structures, especially at night because of unfavourable conditions like cold weather, darkness, animal and reptile attacks, etc. If the reservoirs' inlet gates are not properly operated during night time to store the water rejected from the offtakes the negative impacts can be as little as just an inequitable water distribution and some water losses from the system, but can also be as severe as causing canal over-topping with the possible consequences of land flooding, canal breaching, structure failure, etc. The risk of the failure of the proper operation of reservoir inlet structures can alone justify the expenses of automation.

10.5 Conclusions and Guidelines

- Water storage in surface reservoirs is a very effective water saving measure which can greatly increase the water use efficiency, the flexibility and response of system operation. Water can be stored in the irrigation canals themselves (in-line storage) or in separate reservoirs (off-line storage).

Off-line storage can in relative terms relieve the dependency of downstream users on upstream users, but cannot totally isolate them. If for example the users at the top end of the system abstract a greater quantity of water during daytime irrigation or do not stop the water from running into their farms during the night, the rejected flow available for storage by all subsequent reservoirs will be less than the requirements of the downstream users. According to the hydraulics of the canal network, the deficit in storage may occur at any location; most likely at the tail-end. The water distribution and water use efficiencies will be low.

The formulation of water user groups at the level of distributary canals will be crucial for the success of such an operational scenario. Farmers at the upper parts of the system must understand the need for storing the unused water during the night for it to be used by their downstream neighbours.

The role of the operation staff and the organization running the scheme cannot be neglected as a key element for the success of system operation.

- Implementing in-line storage with upstream water level control is not the optimum solution. Operating such a system will not be easy due to the widely fluctuating water levels in the canals. Also, some operational losses will still occur at the tail-end of the system which lowers its efficiency. Downstream control is better suited for in-line storage.

- Off-line storage is preferred to in-line storage for the following reasons:

(i) In-line storage has the disadvantage of storing water in the canals with the additional possibilities of siltation and excessive seepage. Siltation in off-line reservoirs, on the other hand, should be accounted for in the design of the reservoirs by providing for dead storage. The frequency of maintaining the reservoir will depend on the silt load in the water and the frequency of using the reservoir.

(ii) All canal flows have to pass through in-line reservoirs which means that the reservoir must be continuously operated whether there is a need for water storage or not. Achieving command at low water supplies will be problematic because of the large cross-sections of the canals at the locations of the in-line reservoirs. The response of the system to changes will be very slow unless the in-line reservoirs are distributed between different locations in the system.

- Depending on the topography and land use, off-line reservoirs may be located where drops exist in the canal bed. Water can then be allowed to and out of the reservoirs by gravity, otherwise, pumping will be required. In-line storage always operates by gravity.

- When an off-line reservoir is located such that water can be discharged from the reservoir by gravity, the reservoir should be designed such that the depth of water to be stored is as small as possible by enlarging its surface area. This feature minimises the change in the head on the reservoir outlet structure and hence helps to release steady flow from the reservoir with minimum adjustments to the outlet structure.

If water is to be pumped, the design criteria should be changed such that the surface area of the off-line reservoir is minimised to reduce water losses by evaporation and the area of agricultural land lost.

- When water storage is utilised to cater for the changes in the demand when irrigation at night is not practiced, the canal network and the offtakes must be designed to allow for the higher flows that will be required during daytime operation.

- It is advantageous to locate one off-line reservoir at the top of a canal where water storage is to be provided instead of using intermediate reservoirs distributed along the canal. The advantages being in terms of ease of operation and minimising the number of control structures required for the reservoirs. For optimum performance, off-line reservoirs should be located at the lowest level of the system possible. Locating the reservoirs close to the water users minimises the response time of the system and leaves the higher canals with steady flows.

- To achieve high performance levels for a system with night storage, the proposed operational procedure is to operate the gates of all the cross-regulators and offtakes such that they are fully closed at night when no water is needed for irrigation. The drawback of this method is the possibility for siltation in the canals when water is stored during the night. If this concern is not relevant, this operational procedure should achieve very high performance.

- In order to safeguard irrigation systems where storage is implemented, automation of reservoir control structures is highly recommended, if not essential. The risk of the consequences of a mismanaged storage system will most probably justify the cost of automation. However, automation of canal control structures is not required.

- Emergency facilities like side weirs and canal tail escapes must be provided in any system where water storage is used to store rejected water. It is most likely that the downstream reaches of such irrigation systems will experience higher flows than anticipated in the design which therefore necessitates the existence of emergency facilities.

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