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Research Report

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International Water Management Institute

Research Reports

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Generic Typology for Irrigation Systems Operation

D. Renault
and
G. G. A. Godaliyadda

International Water Management Institute
P O Box 2075, Colombo, Sri Lanka

The authors: D. Renault is Irrigation Specialist, International Water Management Institute (IWMI) and G. G. A. Godaliyadda is Irrigation Manager, Irrigation Department, Sri Lanka.

This collaborative work between the Irrigation Department of Sri Lanka and IWMI has received financial aid from France and technical support from Cemagref, Irrigation Division, Montpellier. The authors are grateful to Ian W. Makin, Design and Operation Research Leader of IWMI for his critical comments and suggestions on an earlier stage of the work and his helpful revision of the paper.

Renault, D., and G. G. A. Godaliyadda. 1999. *Generic typology for irrigation systems operation.* Research Report 29. Colombo, Sri Lanka: International Water Management Institute.

/ irrigation management / irrigation systems/ water use efficiency / canals / operations / water delivery / irrigation effects / hydraulics / gravity flow / resource management / typology / case studies / constraints / water supply / networks / Sri Lanka /

ISBN 92-9090-372-4
ISSN 1026-0862

The International Irrigation Management Institute, one of sixteen centers supported by the Consultative Group on International Agricultural Research (CGIAR), was incorporated by an Act of Parliament in Sri Lanka. The Act is currently under amendment to read as International Water Management Institute (IWMI).

Contents

Summary

With respect to operations, irrigation systems are heterogeneous both at large scale (variations between schemes) and at local level (variations within a scheme). If operational decision making and resources allocations can take such heterogeneity into consideration, the cost-effectiveness of operations will be improved.

This report presents a methodology for identifying the main characteristic features (constraints and opportunities) of gravity-fed irrigation systems, which influence management and operation of the system for the purpose of water delivery. The methodology is applicable for analysis of entire irrigation systems or for subsystems. The proposed typology analyzes activities related to system operation at four levels.

The first level of analysis is the System and Structures of the irrigation system and are shown to be analogous to *factory* and *machines* in the industrial sector. At this level, the utilization of resources for manipulation of the irrigation system to achieve targeted operational objectives is analyzed. At the second level the hydraulic networks that control known and unknown perturbations to water entering the system are considered. These boundary networks influence the behavior of the system and consequently the operation of regulating structures. The third level considers the hydrological context of the system, i.e., availability and quality of water, which impact on the operation of regulators and canals. The concern is to identify the constraints imposed on operations by the quantity and quality of water resources available to the system. The final level considers the outputs of system operations in terms of allocation of priorities amongst different users and uses; and the specification of performance objectives. The analysis focuses on rules for distribution and the socio-institutional context of the system. This level is labeled as the *consumer*.

At each level of analysis relevant criteria are identified and then subdivided into classes based on their management-related properties. The resulting matrix of characteristics can be used to characterize irrigation systems. This matrix enables system managers to identify key properties that determine performance of canal operations.

A case study of 64 irrigation systems in Sri Lanka is presented illustrating the practical application of the proposed typology. The typology is shown to differentiate four major types of systems with significant differences in terms of constraints (perturbation occurrence) and opportunities for operation.

Generic Typology for Irrigation Systems Operation

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Introduction

Irrigation is under increasing pressure to improve the productivity of water and to become more sustainable. These pressures are a result of increasing demands for food and the evermore limited possibilities for extension of irrigation to new areas due to land and water scarcities, and increasing costs of development (Shanan 1992). Increased inter-sectoral competition for water, particularly from the municipal and industrial sectors, is also affecting irrigation.

Increasing water productivity is not an easy task because of the complexity of the hydrologic cycle in the watershed context. For instance, despite apparently low water use efficiency at the local level, it can be shown that water use efficiency of irrigation at the larger scale can be much higher. This is due to the recycling process of water during its downward course within the watershed (Seckler 1996). Systems operation is the process that ultimately determines whether irrigation achieves, or fails to achieve, the objectives of providing a water service to users and controlling the impacts of irrigation on the water basin.

Irrigation operations require the mobilization of a range of resources—human, transportation, and hardware and software—to manipulate the system. These resources must be allocated and used in the most efficient way for implementing scheduled changes to the system status and to respond to unscheduled perturbations.[1] In addition, resources must be allocated for data collection and data processing to support decision making.

The current process for allocation of resources and the definition of strategies and rules for operation are generally based on the assumption that irrigation systems are homogeneous. This implies that generic rules for operation can be derived and would lead to the equivalent levels of performance whatever systems or subsystems are considered. This assumption is implicit in technical guide documents, such as *Plan of Operation and Maintenance* (POM), which are increasingly recommended by external agencies. In some irrigation departments the completion of irrigation development projects, for both new and rehabilitated schemes, is defined as the adoption of an operational procedure based on these documents.

In this report we argue that the assumption of homogeneity of irrigation systems is not valid at either the large scale or at the local level. Therefore, a heterogeneous approach to operations is required to deal with the spatial variability of irrigation system properties, which should result in a more cost-effective allocation of resources. The heterogeneity of irrigation systems has two major consequences for operations. First, the quality of service and, therefore, the performance targets that operations should achieve, have to be differentiated. For instance, some zones of a scheme may be more sensitive to variations in deliveries and, therefore, should be operated with more precise targets. Second, the allocation of resources for operations should be differentiated on the basis of the spatial variation of the

[1]Perturbation is understood here as a slight variation of the input conditions, i.e., a variation of water depth and/or discharge.

difficulty of the task. For instance, structures that are more hydraulically sensitive require more frequent operational inputs to avoid propagation of perturbations to their zone of influence, and hence require additional resources for effective operation.

For managers to be able to reengineer the process of operations, a systematic procedure is required to identify the main determinants of system behavior. Once identified, the manager would be able to develop specific operational strategies and rules to improve the reliability of the irrigation service and ultimately the overall efficiency of water management.

The reasons for reengineering irrigation operations, are numerous. As a result of recent institutional reforms, particularly irrigation transfer, users are becoming increasingly responsible for setting of irrigation service standards and for meeting the costs of providing that level of service. Therefore, system managers may, in future, have to adjust the cost of operating irrigation systems, i.e., mobilization of resources, to match the required level of service at the local level. Furthermore, recent advances in the hardware and software for irrigation system operation are spectacular but their implementation on-site is quite slow. Many reasons can be put forward for the slow adoption of modern techniques in irrigation (cost of investment, absence of trained staff, maintenance issues, etc.). Here again, it is proposed that a more selective approach to investment and allocation of resources, which considers the spatial distribution of system characteristics, is likely to be more cost-effective than a blanket application of advanced technologies.

A clear and adaptable methodology for development of operational strategies is missing. Several initiatives have been taken to define strategies and rules for operation and maintenance of irrigation systems. For example, the World Bank and the International Commission on Irrigation and Drainage published a technical guide for the preparation of operational strategies and manuals (ICID 1989). In India, the Indian National Committee on Irrigation and Drainage published a national guide for preparing the POM (INCID 1994). At system level, a manual of specifications for operation and maintenance, is given to managers when irrigation systems are handed over to them. These types of documents are usually exhaustive in listing the tasks that managers should undertake for operation and maintenance. Although these documents must be considered as steps to improve operational procedures they are usually rigid and, due to the assumption of homogeneity described previously, are not adapted to fit the local context. Two extreme attitudes are evident at scheme level: either the rules are applied bureaucratically or the POM is completely neglected and other, generally, simpler rules adopted. In many irrigation systems, it is still common not to be able to find any O&M manual at all.

Perhaps a major step towards improvement would be to realize that the operational framework cannot be fully determined at the design stage and that fine-tuning after some years of practice is fundamental (Uittenbogaard and Kuiper 1993). It is seen that an adaptive process or a learning process or both are generally preferable to a strictly prescriptive approach (Skogerboe and Merkley 1996) as found in POM manuals.

This study is an attempt to bridge the gap between generic approaches, loose by nature, and site-specific methodologies based on rule of thumb, which are not transferable. The goal is to derive a framework for building new strategies in operating irrigation systems on the basis of a comprehensive analysis of the key determinants of water management in the context of water basins and irrigation systems. This framework is based on the assumption that irrigation systems can be grouped into classes with characteristics of operational behavior, for which specific guidelines can be proposed for management of systems.

This report presents the development of a generic typology for improving irrigation systems operations. The resulting typology has been applied to irrigation systems in Sri Lanka, and discriminates four main types. Finally, strategies for improving system operations of each type are discussed.

Review of Irrigation System Classification and Partitioning Schemes

Numerous typologies or classifications for irrigation systems have been proposed recently. This illustrates the current level of interest in the characterization of existing or projected irrigation systems; however, the proposed classifications in the literature vary significantly. Malaterre (1995), reviewing several proposed classifications, observes that they are not only not clearly structured, but also based *"on misleading terminologies."* He then suggests that the rules for governing the division of categories should be clearly defined and should not overlap one another.

A basic irrigation system typology is found in a paper by Bos and Nugteren (1974). The importance of the canal in the system or its position in the irrigation network or both are the criteria used for the characterization. This classification divides the canal network into primary, secondary, tertiary, and quaternary canals. Although in some cases there is a clear relation between the above classification and the different management operational units, this typology is not intended to define characteristics of canal operation within each management unit. Manz (1987a) proposes a similar classification but puts greater emphasis on the specific functions of canals with regard to the water delivery. He divides irrigation systems into quaternary, distributary, and first-order laterals. Another contribution by Manz (1987b), proposes classification of components on the basis of their water management functions: diversion, depth control, transfer, and storage.

Clemmens (1987) proposes a terminology to suit different delivery scheduling methods. Paudyal and Loof (1988) state the need for a classification, and list several criteria to be taken into account in the typology of main systems (size, climate, crop, management, ownership, storage). A classification by Ankum (1992a) combines traditional flow criteria (fixed flow, intermittent flow, varied discharge flow) with considerations of supply policy (arranged, semi-demand, on-demand) in relation to the type of irrigation (protective or productive). Water availability compared to demand is the main criterion that Sagardoy, Botrall, and Uittenbogaard (1982) use. They distinguish, among irrigation schemes, those having a supply greater than or equal to the demand, those having a moderate water deficit, and those having a large water deficit.

The domain of irrigation for which classifications have been mainly developed is canal regulation. Burt (1987) presents a practical taxonomy of water delivery control with some features not commonly used such as flow versus water level control and intermediate storage. Ankum (1992b) proposes a flow control classification based on a management criterion. Malaterre (1995) gives an updated review of several existing classifications, with some comments on their strengths and limitations, and presents a more comprehensive and consistent analysis applied to 27 regulation methods. His classification is based on four criteria (considered variables, logic of control, design method, field implementation).

The classification developed by Shanan, Uppal, and Albinson (1986) combines hydraulic features defining control characteristics along the main canal with the physical properties of the outlets. The physical and hydraulic characteristics used are: undershot, overshot, free-flow, and submerged structures. The approach is developed as a sensitivity analysis to perturbations within the irrigation system. Plusquellec, Burt, and Wolter (1994) give a comprehensive description of the factors to be taken into account to promote modern water control. Kosuth (1996) reviews the main characteristics of irrigation canals (size, time dependent-behavior, interactions in operation) and operational constraints (variety of perturbations and targets) illustrating the complexity of canal operation. He then suggests improvements that could be derived from modern methodologies such as information system, simulation models, and automatic control.

This review of classification systems found that most of those applied to irrigation are generic and descriptive but in general only consider internal factors. Externally imposed constraints such as water availability, and institutional and sociological factors are left aside. Further, although these classifications address important aspects of irrigation, the application of the typologies is not always clear, except for those focusing on flow regulation.

A Typology for Canal Operation

The management of irrigation involves a complex mixture of activities, involving those related to institutional and technical constraints. The objective of the typology proposed here is to assist irrigation system managers to analyze the complex domain of irrigation system operations.

From the generic framework presented below it is possible to identify the major constraints to, and opportunities for, improved system operations. Practical guidelines for improving canal operation at a specific scheme can be developed from the analysis.

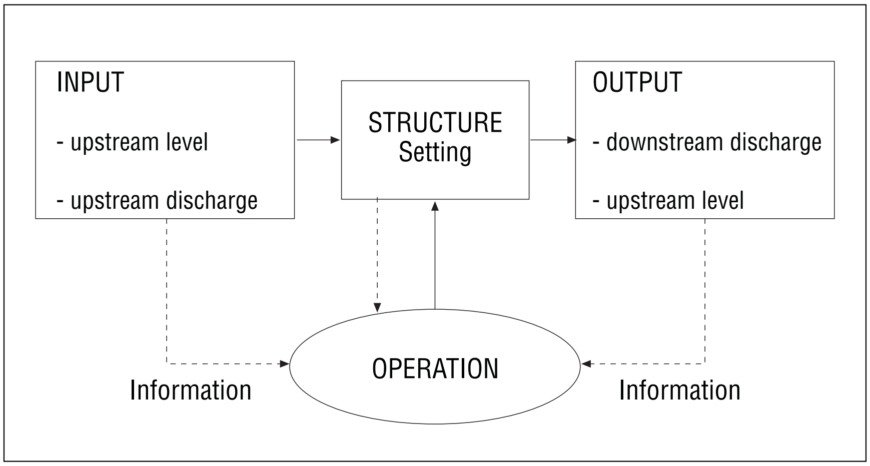
This typology defines a set of pertinent criteria for analysis of canal operations and develops a class structure for each criterion. The matrix of criteria and subdivisions can be used for application at different levels of irrigation infrastructure, for example:

- in evaluation of system properties of importance in canal operations to assist irrigation managers' decision making (local management)
- for partition of systems into subsystems with homogeneous operational characteristics (local management)
- for comparison of the difficulties of operations between irrigation systems to enable improved allocation of resources (national/regional level)
- for comparison of irrigation system performance in relation to the physical, agricultural, and institutional contexts (policy makers and research and development institutes)

Irrespective of the level of irrigation infrastructure at which the typology is applied, the operation of a canal is analogous to an industrial process in that inputs are transformed by operations of machines (canals and structures) into outputs (fig. 1). In classifying the "process" of canal operations four aspects are considered.

First, the internal and external *constraints*, which affect the variability of inputs to the system

FIGURE 1.
Canal operation: Basic process.



and hence modify the status of the system. Second, the characteristics of the *machines* involved in the process. The characteristics of canal reaches and regulating structures determine how the system will react to perturbations of the input and how perturbations caused by the operation of the “machine” will propagate through the system. Third, the *impact* of the quality of irrigation service on the system, which enables the manager to determine what level of performance should be achieved. Finally, the *means* or resources (inputs and efforts) required to achieve the required level of performance, given the internal and external constraints.

Keeping in mind the four areas of consideration, the canal operation typology is developed with four levels of analysis (fig. 2). The first level of analysis considers the technological aspects of the irrigation system, seeking to differentiate the control process; the degree of operation; characteristics of the *‘process’ machines;* and the canal reaches and the structures that are analogous to “factory and machines” from industrial processes (Rey, Renault, and Lamacq 1996). This level is referred to as *“system and structures.”*

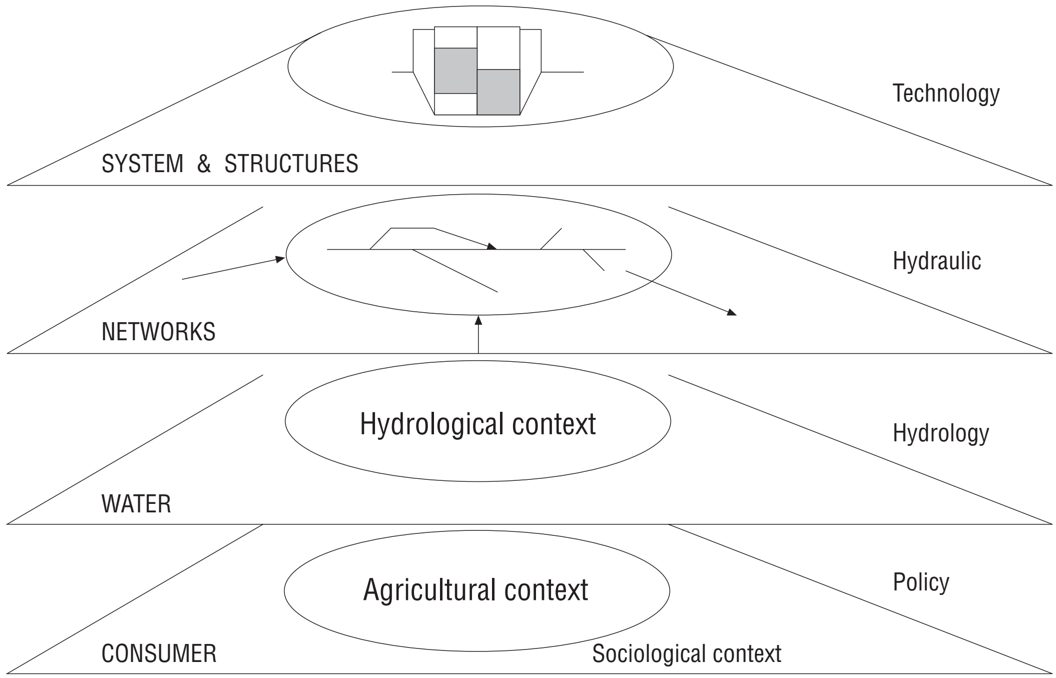
The second level focuses on the interface at the boundaries of the considered system, with particular regard to the characteristics of water flows at the boundaries. The system network being considered joins with a number of other networks including irrigation, drainage, return-flows, runoff, natural streams, and rivers. This level is therefore referred to as *“networks.”*

The third level, *“water”* considers the opportunities and constraints presented by the hydrological context of the system considered, with particular focus on the constraints imposed on canal operations by the relative availability and quality of water resources.

At the fourth level, the service provided to users of the system is analyzed. Again taking the analogy with the industry, irrigation operations ‘add value’ to water by processing water through the irrigation system to transform lower-value water, in rivers or storages, to higher-value water at the point of delivery to the user. The quality of the delivery to the user will, to a large extent, affect the potential of the user to make effective use of the irrigation delivery and therefore the perceived value of the water. This level is referred to as the *“consumer.”*

In the following sections the generic typology matrix is developed through an analysis of the constraints, characteristics, impacts, and resources applicable at each level of analysis discussed above.

FIGURE 2.
Framework for canal operation approach.



Considerations on Level of System and Structures

This level is divided into two sublevels. The sublevel, *system* addresses the overall physical characteristics of the irrigation system, and the sublevel, *structures* focuses on the local characteristics of structures.

System Sublevel

The matrix of criteria developed for this sublevel is displayed in table 1A, where criteria of characterization are identified, related properties

TABLE 1A.
Matrix of criteria: Level of system and structures (system sublevel).

Criterion of characterization	Properties related to operation	Classes Partition of the criterion		
Controlled variable	• Flexibility in deliveries • Regulation of water balance	Discharge	Volume	Composite
Type of control	• Supply- or demand-driven	Upstream	Downstream	
Type of operation	• Amount of effort • Hydraulic stability • Adjustability	Manual • Manual and gated	Automatic • Automatic • Semi-automatic	Fixed • Structured

for operation listed, and classes defined. The criteria considered are: controlled variable, type of control, and type of operation.

Controlled variable

Operation of irrigation systems may seek to control discharge, volume or a combination of discharge and volume. Discharge control is most common.

Discharge control may be direct or, more commonly, indirect through control of water level. Other systems are designed and operated to control volume in canal reaches. This latter technique requires the availability of storage, either on-line storage capacity in the canal itself or in intermediate reservoirs. Available storage is dependent on variation of water depth in the system and therefore offtake discharge should be somewhat independent of upstream water level, i.e., outlet structures should have a low sensitivity.

Dynamic regulation (Rogier, Coeuret, and Brémond 1987) is one example of volume control methodology applicable to irrigation canals without intermediate storage reservoirs. The main advantages of using a volume control technique is the ability to deliver instantaneous discharges greater than the actual transport capacity of the system. This property is of great importance to match peak flows in nonrotational distribution, e.g., on-demand or free access delivery pattern. Volume control techniques are receiving increased attention. For example, in India, several examples of new or modernization projects are implementing volume control techniques including the Sardar Sarovar Irrigation Project in Gujarat (Frederiksen 1985), the Majalgaon Project in Maharashtra (Rousset 1990), and the Krishna Project in Karnataka (Lele and Patil 1993).

For systems with intermediate storage within the canal, the control objectives applied may be composite, i.e., discharge control for the canal reaches and volume control for intermediate reservoirs with closed loop feedback linked to the supply.

Type of control

Most gravity irrigation systems are based on upstream control. With this technique, all irrigation control structures are set according to the discharge imposed from the main intake structure. The objective is to maintain the water level upstream of each cross-regulator to control the backwater profile in the upstream reach. The backwater profile determines the head at offtakes in the upstream reach. The alternative technique, i.e., downstream control, has attracted the attention of engineers and irrigation managers because of the potential advantages (Burt 1987; Plusquellec 1988; Plusquellec, Burt, and Wolter 1994; Malaterre 1995). Downstream control automatically responds to fluctuating downstream demands from users and can minimize water losses. However, the technique requires horizontal canal banks and some automated control structures.

Type of operation

This parameter combines the adjustability of the control structures and the level of automation of operations. Some systems are fully adjustable, i.e., every structure has movable parts that can be set according to the current situation and a large range of defined operational targets. Other systems have no provision for any manipulation at all, such as the so-called ‘structured’ systems based on fixed proportional distribution. The requirements for operation of these systems are significantly different. Similarly, there is a range of systems where the degree of automation varies from zero to 100 percent, from fully automated to entirely manual operation. Both aspects, i.e., the demand and the response, partition irrigation systems into different types of operation.

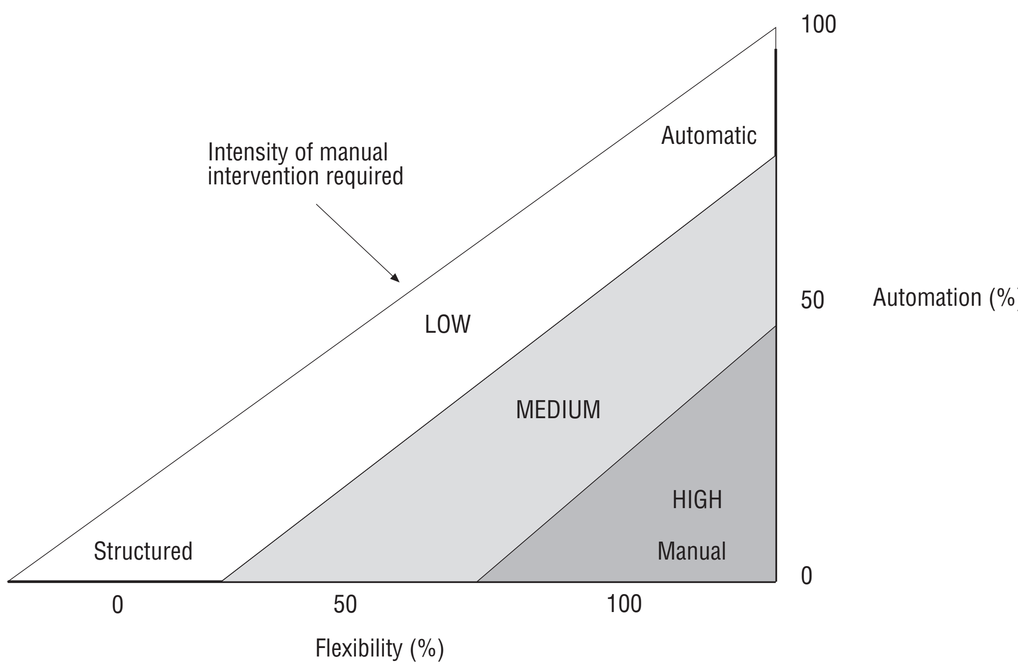
The amount of effort that the agency has to put into the operation of a system is illustrated in figure 3, and the performance that can be achieved and the hydraulic stability are the dependent variables of the type of operation. Systems with fixed structures are stable, require little effort but, by definition, are also less flexible. A fully adjustable and fully automated system does not require more effort than a fixed structure system; however it is more flexible. Fully adjustable systems can become unstable if improperly operated (manually or automatically).

Partition of this criterion is finally made considering three classes: manually operated gated systems, fixed systems, and automatic/semiautomatic systems.

Manually operated gated systems. An intensive manually operated system is one in which all offtakes and control regulators (the irrigation structures) are gradually adjustable. Each structure has to be manipulated by irrigation staff when a change in the flow regime is scheduled or occurs due to an unscheduled perturbation. The difficulty in operating these systems results from the numerous structures to be adjusted simultaneously when the flow regime is changing. A large number of structures implies the mobilization of correspondingly large amounts of resources from the agency (human and/or transport) for checking and fine-tuning of control settings. The greater the density and sensitivity of structures, the greater the difficulty of the control task resulting from unsteady flow conditions.

Fixed systems. These systems known as 'structured systems,' have been largely developed in India, Pakistan, and Nepal (Shanan 1992). Water delivery is organized around pulses of constant discharge with a varied frequency. Distribution is proportional and structures are fixed permanently at the construction stage (no movable parts).

FIGURE 3.
Intensity of efforts for operation as a combination of adjustability and automation.



Although the nonadjustable section of structured systems is limited to minor canals with the main/branch canals remaining fully operated, the savings in resources for manipulation of structures can be important as shown by Shanan (1992).

Automatic/semiautomatic systems. Hydraulically automated systems are equipped with control structures that control water levels in canals over a wide range of discharges. These structures may be either downstream or upstream control devices. Most commonly, control of water level is achieved by mechanical movements of regulator gates, driven by hydraulic forces without an external source of energy or human intervention. These types of gates include AMIL and AVIS/AVIO gates (Goussard 1987), DACL (Clemmens and Replogle 1987), and Danaidean gates (Burt and Plusquellec 1990). Variations of water level must still be expected to occur at locations remote from the control regulator. Hence, hydraulically automatic cross-regulator structures are frequently associated with constant discharge distributors, such as baffles (Burt and Plusquellec 1990), to enhance the overall performance.

Semi-fixed systems are connected to fixed structures with adjustable ones. A good example of this type of system is combining long crested weirs with constant discharge distributors (Walker 1987). In these systems on-line discharge fluctuations are converted to limited variations of water level at the cross-regulator weir. Furthermore, discharge variation through the offtake is minimized by selection of low sensitivity offtake structures. Operations are limited to the opening and closing of offtake gates and regulation of main intake discharge. Hence, they also can be referred to as semiautomatic systems.

Structures Sublevel

Irrigation systems can be considered to consist of two types of components, those for conveyance and storage of water *(canal reaches);* and those for control of water depth and deliveries *(structures).* The matrix of criteria for the structures sublevel is given in table 1B.

TABLE 1B.
Matrix of criteria: Level of system and structures (structures sublevel).

Criterion of characterization	*Properties related to operation*	*Classes Partition of the criterion*			
Adjustment of the structure	• Freedom and precision of control	Fixed	Open or closed	Stepwise	Gradual
Manipulation of the structure	• Amount of efforts	Manual	Hydraulically automatic		Motorized
Control of the structure	• Amount of efforts	In situ controlled	Remotely controlled		
Sensitivity of the structure	• Accuracy in control	Low	Medium		High
Physical condition of the structure	• Deviation from design	Low	Medium		High
Storage in the reach	• Responsiveness • Regulation of water balance	No Storage	Distributed storage		Localized storage (Intermediate reservoir)
Control along the reach	• Depth control	Under backwater effect	Under normal depth		Under free flow
Bed material in the reach	• Seepage losses • Roughness	Lined			Unlined

Control and delivery structures

The properties of irrigation structures of significance to the operation process are: first, the freedom and precision that can be exerted in the adjustment of the output; second, the effort required for manipulation and control; and finally, the hydraulic stability based on the sensitivity of the structures. These properties lead to the identification of the following criteria in the typology.

Adjustment. The properties, freedom of adjustment, and precision of control can be analyzed through the classification of structures that Horst (1983) proposes:

1. Fixed:
   no adjustment is possible, e.g., weirs, orifices, dividers
2. Open/closed:
   generally, gates for minor canal either fully open or closed
3. Stepwise adjustment:
   regulation by steps, modules, or stoplogs
4. Gradual adjustment:
   gated orifices, movable weirs
5. Automatic:
   hydraulically adjusted gates

   - For fixed structures, freedom of adjustment is nil, since output is directly imposed by ongoing discharge (input), and precision is meaningless.
   - For open/closed structures, freedom and precision are not relevant.
   - For stepwise adjustment, freedom and precision are limited by the number of discrete steps in the adjustment between zero and full capacity.
   - For gradually adjustable structures, the degree of freedom is usually high in that it is generally possible to choose any setting between zero and the maximum value. However, in practice, the actual setting will be imposed by the *input* value. Precision will depend on the increment of the mechanical adjustment.
   - For hydraulically automatic structures flow conditions are the governing factors. In general, these structures cannot be adjusted in normal use and, therefore, the degree of freedom is zero. However, the operational objective is to maintain constant output, and precision is determined by the range of variations of output resulting from variations of input.

Manipulation and control. The operational property characterized by the *manipulation* and *control* criteria is related to the amounts of effort required to operate the adjustable structures in the canal network. The *manipulation* criterion distinguishes between manual, hydraulical, and motorized control structures. The *control* criterion separates in situ and remotely controlled structures.

Sensitivity. The *sensitivity* criterion characterizes the hydraulic stability of the control structures. For example, when considering discharge control, overshot structures are three times more sensitive than undershot structures (assuming head losses are equal). The difference is due to the exponent of the head loss variable in the discharge equation, $3/2$ and $1/2$, respectively. Due to the effects of feedback from the downstream side of the structure, the sensitivity is not always simply related to the available head loss (Renault and Hemakumara 1999).

For water depth control, overshot structures are less sensitive than undershot structures, i.e., the same perturbation in discharge will result in a smaller change in water depth, three times less for overshot structure (weir type) than for an equivalent undershot structure (orifice type).

Physical condition. The current physical condition of structures greatly influences the capabilities for adjustment, manipulation and control, and the sensitivity of the structures to perturbations, irrespective of the properties at the design stage.

This property is site-specific and is largely dependent on the maintenance of the system and the discipline of the users. The physical conditions of structures are highly variable.

Conveyance and storage structures: Reach

Canal reaches are considered here as structures for conveyance and/or storage of water. The criteria of significance for operation of these structures are storage, control, and bed material.

Storage. Storage in the canal reach has a direct impact on the speed at which the system can respond to changes in flow conditions. The response of a reach to any scheduled or unscheduled perturbation to the input is related to the topography of the canal section. *Double Bank Canals (DBK), Single Bank Canals (SBK),* and canal reaches with *Intermediate Reservoirs* respond differently to such perturbations.

On-line storage acts in two contradictory fashions that are important in terms of the time lag involved in operations. On the one hand, storage increases the time lag between issue and delivery by lowering the velocity and increasing attenuation of the transition wave, and on the other, it allows local adjustment of discharge in advance of the wave, considerably reducing operational time lags. The second property related to this criterion is the regulation of water balance at subsystem level. Intermediate or on-line storage along a canal can be utilized as a partition point to separate different units for operation as they mitigate fluctuations from the upstream operations.

Control. Canal water depth is controlled by backwater effects from cross-regulators. Depth decreases with distance upstream and reaches a constant depth when normal flow depth is attained. Backwater control is interrupted wherever super-critical flow velocities occur. Super-critical flow is commonly found at cross-regulators with free-flow conditions downstream. This criterion considers reaches in three situations: within the backwater effect, operating at normal depth, and free-flow or super-critical flow.

Bed material. Seepage losses from canal reaches can be a significant factor in system operations. Bed material is selected as an indicator of seepage losses. It separates unlined canals having higher and more variable seepage losses from lined canals having lower and, generally, almost constant losses.

Considerations on Level of Networks

Irrigation systems do not operate in isolation, but rather within the context of surrounding hydraulic systems. This level of the typology identifies the boundary conditions for irrigation systems. It considers perturbations and conditions for water flows at the upstream, internal (lateral), and downstream boundaries of the system or subsystem. The characteristics evaluated are related to the different networks that impact the scheme, i.e., water sources, irrigation, drainage, runoff, and return flow. The matrix of criteria for this level is given in table 2.

TABLE 2.
Matrix of criteria: Level of networks.

Criterion of characterization	*Properties related to operation*	*Classes: Partition of the criterion*				
		Reservoir		Diversion		
Source of supply	• Variability • Degree of control	Surface water reservoir	Groundwater reservoir	River	Canal series	Branch canal
Layout of lateral flows	• Variability of on-line discharge	Return flow (RF)		Non-return flow (NRF)		
		Single bank canal (SBK) with runoff		Double bank canal (DBK) without runoff		
		Runoff ditches		No ditches		

Type of Supply

The first criterion is the type of supply, and considers the properties of variability and the degree of control of the *source of supply.* Two types of supply are considered first: reservoir and diversion. Second, each type is subdivided into surface water and groundwater reservoirs, and river and canal diversion, respectively.

In the case of a surface reservoir, freedom of control and stability of supply are generally high because, at least in the short term, water availability is not limited and the depth of water in the reservoir is steady. For groundwater reservoir, a similar statement can be made although the instant available discharge may be sometimes more influenced by locally variable hydraulic properties than by the capacity of the reservoir. For river diversion, the freedom of control is generally lower as discharge to be diverted depends on instantaneous water availability. Furthermore, short-term changes in the river level can lead to high variations in the discharge entering the system, unless the diversion is equipped with regulation facilities; hence, the degree of freedom and stability of flows diverted from a river are considered as low.

Systems with significant on-line storage capacity (intermediate storages or large canal sections), can also be classified under the category ‘reservoir,’ provided the available storage can compensate for fluctuations in upstream discharge entering the system while continuing to meet downstream requirements.

Diversions may also be considered when canal subsystems are analyzed. Two types of subsystem diversions can be considered: series and branch diversions. In a series subsystem, the discharge coming from the upstream subsystem must be accepted without modification and, therefore, the degree of control is low, unless there is a storage in the upstream reach. In the case of branch subsystems, the degree of control is generally moderate. The discharge at branch diversion points can vary to some extent without disrupting the flow of other downstream subsystems.

Layout

The occurrence of *lateral flows* to the canal system has a direct impact on the variability of on-line discharge. To capture this effect *the layout of lateral flows* criteria are used to distinguish networks which have return-flow and/or runoff from those which do not. Return-flow occurs along irrigation systems when overtopping from spill along laterals and from fields is returning to the main canal or into other laterals. Direct runoff to the canal typically occurs in the case of single bank canals and where runoff ditches are present.

Considerations on Level of Water

Operation of a canal system is largely controlled by the hydrological context of the scheme. In this typology this context is described in the *water* characteristic. Three criteria of characterization are considered: upstream context, downstream context, and impacts. The matrix of criteria for this level is given in table 3.

Upstream Context

Two characteristics are considered in this level, water availability and water quality.

Water availability

The abundance or shortage of water can make a large difference in the performance targets that managers should aim to achieve. Where water is abundant, relative to demand, the distribution targets may include a factor of oversupply to simplify operations. Operations may accept oversupply and excess losses, depending on the ability of downstream systems to accommodate them. When water is insufficient to meet demands, operations have to be more precise. Operational targets have to be defined more accurately and implementation of distribution correspondingly more accurate. In the Valencia scheme (Plusquellec 1988), three levels of water availability are considered: abundance; ordinary or low; and extraordinary drought. Depending on the situation, distribution rules vary.

In this typology, three water availability conditions are considered: abundance; shortages; and seasonal variability.

The notion of abundance in water must also be relativized in the light of a water basin perspective. Where any complacency for operation may lead to depriving downstream users from getting enough water, 'abundance' may be simply suppressed from the vocabulary.

Water quality

Two aspects of water quality are of concern, the presence of solids; and the presence of chemical pollutants.

Sediments in water entering the canal system are a serious problem affecting the physical

TABLE 3.
Matrix of criteria: Level of water.

Criterion of characterization	*Properties related to operation*	*Classes: Partition of the criterion*		
Upstream context (hydrological context)	• Water availability	Abundance	Shortage	Varying (seasonally)
	• Water quality	Sedimentation	No sedimentation	
		Salinity	No salinity	
Downstream context	• Additional water availability	Recycling systems		No recycling
		Conjunctive use		No conjunctive use
Impacts	• Environmental impacts	Salinity hazard		No salinity hazard
		Logging hazard		No logging hazard
	• Health impacts	Stable flow		Fluctuating flow

characteristics of the conveyance system and control structures. The impacts of sedimentation normally become apparent in the long term. Therefore, sedimentation is normally a concern for maintenance rather than for operations. However, sedimentation influences the design of some systems that are equipped with special structures designed to limit sediments entering the system, control sedimentation at sensitive points, and/or to share the sedimentation equitably. In some systems, operations are suspended during periods of high sediment load in the river system.

Chemical pollutants may be significant where industrial or municipal water use is high upstream of the irrigation system. Salinity of the water source may be of concern where return flows of upstream irrigation systems are a high proportion of the available resource.

Downstream Context

Reuse of water

Reuse of water draining from irrigated areas can be an important factor in determining water management objectives. In Sri Lanka, for example, cascade systems consist of several tanks and command areas, which are highly interconnected through both surface water and groundwater return flows. Losses in one place become inputs at some downstream location. The recycling of water in this way substantially eases the upstream operational task by accommodating any excess distribution.

Conjunctive use of water

As pumping technology has become more accessible (O'Mara 1988), conjunctive use of surface water and groundwater has become more popular. In India, the annual growth of pumping equipment use is about 13 percent (Moench 1996). In Pakistan Punjab, the use of pumping equipment is fast increasing. The number of shallow tube wells was estimated to have reached 300,000 in 1992 (Vander Velde and Kijne 1992). The density of wells is inversely related to the reliability of the surface network in delivering water to farmers (Strosser and Kuper 1994) and groundwater was found to contribute above 50 percent of the crop water requirement for some watercourses located at the tail end of distributary canals.

Conjunctive use provides flexibility in irrigation timing, and groundwater is frequently used to compensate for the rigidity of operations and/or poor performance of surface delivery systems. Where additional supplies from groundwater are limited, because of high pumping cost or low quality of water, more attention to supplying surface water is required than in areas where pumping can compensate for unreliable supply.

Impacts

Environmental impacts

Increases in soil and water salinity and waterlogging of areas are serious environmental hazards related to irrigation in arid regions. Clearly, operation of irrigation systems has to take into consideration the spatial distribution of areas prone to salinization and waterlogging and should provide an adapted water service. Partitioning of the irrigated area to identify areas where additional fresh surface water should be provided to leach salts from the soil, areas in which percolation should be minimized to prevent saline groundwater from rising into root zones, etc., is part of an effective water management.

Health impacts

It is well known that irrigation, despite its positive effects on the economy and income of farmers, has also brought some negative impacts on health through vector-borne diseases. The continuous presence of water in canals over long periods modifies the reproductive cycle and prevalence of disease vectors. The link between systems operation and impacts on health can be strong.

Fluctuations in canal water depth and flow are considered by many to comprise a highly positive measure to reduce vector breeding (Hunter et al. 1993). There is a clear conflict between the desirable operations from health considerations and the needs of irrigation management in terms of operational fluctuations in the system. Fluctuations of flows for health are generally in conflict with the desire for steady flow conditions in the canals to simplify operations. Methods to resolve this conflict require further investigations to test new techniques of operation.

Considerations on Level of Consumer

This level of the typology, *consumer,* focuses on the user and the intended water service. Five criteria for characterization are considered: use of water, distribution policy, performance of distribution, sociological aspects, and institutional aspects. The matrix of criteria for this level is given in table 4.

Use of Water

In many irrigation systems water is used for many other purposes as well. The multiple uses of water are increasingly integrated in irrigation management objectives, whether or not these other uses had been considered at the design stage. Domestic uses, fisheries, environment and recreation, and hydropower and industrial uses are some of the more important other uses of water.

Rules for operation of multipurpose systems should be based on clearly defined priorities and sharing between users. However, this can be complex as conflicts arise when setting targets for the different uses.

Distribution Policy

The distribution policy, whether supply is to be fully flexible, highly rigid, or some intermediate strategy, is the main determinant of the quality of service provided. Fully flexible and rigid patterns

TABLE 4.
Matrix of criteria: Level of consumer.

Criterion of characterization	*Properties related to operation*	*Classes: Partition of the criterion*		
Use of water	Priorities and sharing between users	Single use	Multiple use	
Distribution policy	Distribution mode	Supply-based	On-request (arranged)	Free access
Performance of distribution	Performance of operation	High	Medium	Low
Sociological aspects	Hydraulic stability	Discipline	No discipline	
Institutional aspects	Management setup	Headworks	Main system	Distribution system

are the extremes of a wide range (Clemmens 1987). Where cropping patterns and climatic conditions or any other important agricultural aspects are highly variable, greater flexibility in the delivery pattern is required (Steiner and Walter 1993). For farmers, the most desirable policy would be to provide a highly flexible supply (free access); however, this requires the most expensive infrastructure. Therefore, it is generally necessary to agree with a standard of service, which is affordable by the consumers. Three major classifications of distribution strategies are considered here, supply-based, on-request, and free access or on-demand.

The water delivery pattern has a major impact on the efforts to be taken by managers for operation of the irrigation system. Flexibility without automatic facilities implies large numbers of manual manipulations of regulator settings. Furthermore, flexible deliveries result in creating effectively continuous unsteady flow conditions in the distribution network. Too great a flexibility can have negative impacts on the stability of deliveries and may even negate the benefits of flexible scheduling (Palmer, Clemmens, and Dedrick 1989). The application of higher technology control systems can overcome such problems.

For rice cultivation, or for mono-cropped systems, irrigation systems operate with a more stable pattern of demands and are, therefore, less complex to operate. However, the progressive diversification to cash crops, other than rice, is likely to result in increasing demands for more flexibility in operation of irrigation systems allowing for more fluctuations of deliveries.

Performance of Distribution

A set of priorities for allocation and distribution of water is identified for many irrigation systems. These priorities are usually based on a comparison between the available water supply (hydrological context) and the demand for irrigation (agricultural context). For instance, changes in allocation and distribution priorities can be related to water shortages when the set of priorities defines the policy for sharing the available water among consumers. Some systems define priorities on the basis of crop values (high /low), or water-holding capacity of the soil, or on variable water rights.

For this typology the performance of distribution is classified and is spatially distributed on the basis of the water service, i.e., the agreed allocation policy. The performance of distribution is classified as high, medium, and low.

Sociological Aspect

Numerous sociological factors are important for irrigation system management. However, for this typology for system operations, only one aspect is considered, namely, the level of discipline displayed by consumers with respect to unauthorized operation of the system. Unscheduled operations by undisciplined consumers result in modification of the system settings, generally penalize other consumers, and may even jeopardize the safety of the system.

Two classes of discipline are included in the typology, medium to high, and low to none.

Institutional Aspect

Among the many institutional aspects of relevance to irrigation management, this typology considers only the conceptual framework for water management. Several different organizations may be involved with water management at various levels of the water delivery system, from the main water source down to the application in farmers' fields. The water management framework is subject to modification. For instance, the recent trend for transfer of management responsibilities to user organizations has modified the conceptual framework for water management, as in Mexico (Johnson 1997) and elsewhere. The balance between agency and user responsibilities is an important aspect, which must be considered when organizing operational procedures.

The typology distinguishes three levels of the irrigation network for analysis of management institutions, namely: main source and headworks, main conveyance system, and distribution system.

Application of the Generic Typology

The generic typology, defined above, includes a total of 21 criteria proposed for consideration when reengineering the process of irrigation system operations. Although the partitioning of each criterion has been kept minimal to avoid too great a number of classes, it is clear that a strict application of the typology, as defined, leads to the identification of huge numbers of potential types of systems, which is of no practical value. However, the practical significance of each criterion has to be considered with reference to the context of each application. Although this study strongly promotes the need to recognize the heterogeneity of irrigation systems it is necessary to recognize that for many of the criteria, systems may be considered as being homogeneous. And furthermore, some criteria may be totally irrelevant in a particular context. Therefore, to be useful for a specific application a typology should result in a very limited number of types of irrigation systems.

In Sri Lanka, the generic typology has been applied to the classification of 64 major/medium irrigation systems maintained by the Irrigation Department. This application has shown that in this context the irrigation systems are homogeneous for the large majority of the documented criteria (18 out of the 21 criteria). Only three criteria were sufficient to enable a clear distinction of the operational characteristics of the studied systems. Table 5 summarizes the results of the classification and identifies the main partitioning criteria, namely: storage, type of supply, and layout of lateral flows. The latter criterion is further subdivided into two sub-criteria: return flow (yes/no) and runoff (yes/no) linked mainly to the type of canal (single/double bank canals).

However, it must be pointed out that if subsystems had been studied, rather than entire schemes, greater variability of some criteria would have been identified, for example recycling facilities and double bank canals appear as more variable and, therefore, more significant at subsystem level than at system level.

Thus with a total of 4 criteria and sub-criteria selected at system level, and two classes each, 16 theoretical system types can be defined. No instances of five of the defined types were found in the survey of systems in Sri Lanka. Furthermore, after elimination of classes with a few instances, all 64 systems were classified into four main types. These types appear to be quite different with respect to the probability of perturbations occurring, the likely behavior in response to perturbations, and finally the difficulty in operating the distribution systems. They are:

- Reservoir and localized storage system: The main source of supply is a reservoir; it has a localized storage (intermediate reservoirs), single bank canals, without return flow entering the system.
- Reservoir without localized storage system: The main source of supply is a reservoir; no

TABLE 5.
Typology matrix application to Sri Lankan irrigation systems (in gray characteristics).

Level of typology	*Criterion of characterization*	*Identified classes*			
System and structures	Controlled variable	Discharge	Volume	Composite	
	Type of control	Upstream	Downstream		
	Type of operation	Manual Manual and gated	Automatic • Automatic • Semiautomatic	Fixed Structured	
	Adjustment (structure)	Fixed	Open or closed	Stepwise	Gradual
	Manipulation	Manual	Hydraulically automatic	Motorized	
	Control	In situ controlled	Remotely controlled		
	Sensitivity	No information			
	Physical condition	Low	Medium	High	
	Storage	No storage (DBK)	Distributed storage (SBK)	Localized storage (Intermediate reservoir)	
	Control	Variable			
		Backwater - normal depth - free-flow			
	Bed material	Lined	Unlined		
Networks	Type of supply (*)	Surface reservoir(**)	River diversion		
		Return flow (RF)	Non-return flow (NRF)		
	Layout of lateral flows	(SBK) with runoff	(DBK) without runoff		
		Runoff ditches	No ditches		
Water	Upstream context	Abundance	Shortage	Varying (seasonally)	
		Concern about sedimentation and salinity	Low concern about sedimentation and salinity		
	Downstream context	Variable Recycling systems (***)			
		Conjunctive use	No conjunctive use		
		Salinity hazard	No salinity hazard		
	Impacts	Waterlogging hazard	Minimum waterlogging		
		Stable flow	Fluctuating flow		
Consumer	Use of water	Single use	Multiple use		
	Distribution policy	Supply-based type for rice field	On-request (arranged)	Free-access	
	Performance of distribution	High	Medium	Low	
	Sociological aspect	Medium to high/discipline	No discipline		
	Institutional aspect	State agency for headworks and main systems Participatory management for distribution system			

(*) Canal branch and series diversion apply to the subsystem; thus they are not considered in the survey.

(**) No groundwater supply for irrigation.

(***) Recycling criterion applies to the subsystem; thus it is not considered in the survey.

SBK = Single Bank Canals.
DBK = Double Bank Canals.

localized storage (intermediate reservoir), with single bank canals, and without any return flow entering the system.

- Diversion river system: Main source of supply is from a diversion (river), it has single bank canals, with or without localized storage and return flows.

- Return flow system: This type groups irrigation systems with return flows coming back into the system, having single bank main canals, fed by reservoir or diversion, and with or without localized storage.

The first type is the least complex system for operation. The occurrence of perturbation on discharge is low as this type of system is fed by a reservoir, and has little or no lateral inflows. The opportunities for operation are good as on-line storage increases the efficiency and the reliability of operation (minimize fluctuations and water losses). On the other hand, systems with a river diversion supply, with lateral inflows from return flow and surface runoff, and with no on-line storage capacity are much more complex to operate. Perturbation occurrence and magnitude are high, and the canal has little flexibility to cope with these. More detailed descriptions of the application of this typology and the development of revised operational strategies will be reported in forthcoming papers.

Summary and Perspectives

The analysis presented in this paper defines a typology of irrigation systems specifically oriented to analysis of system operations. The typology is organized in four conceptual levels defined as: *system and structures, networks, water,* and *consumer.* Each level includes a consistent set of criteria for differentiating system characteristics. Some criteria are global, i.e., they can be applied to a system as a whole. Some criteria are spatially distributed and the aggregation of the criteria depends on the spatial variability within the system analyzed. Other criteria are intermediate and can be used to partition a particular irrigation domain into homogeneous units.

The application of the proposed typology should be seen as an approach similar to the use of Geographical Information System (GIS). For each criterion, a layer of information displays the partitioning of the considered domain with respect to the criteria. Some criteria result in classification of spatial units such as command areas, drained basins, etc., whereas others define points along the irrigation network, e.g., break points in water depth control. Layers of information within each of the four conceptual levels can be overlaid to identify units with effectively homogeneous operational characteristics. However, the overlay process has to be context-specific and local or regional features of special interest must be taken into consideration when determining the weightage to be given to each criterion.

Literature Cited

Ankum, P. 1992a. Desired behaviour of irrigation systems. In *Advances in planning, design and management of irrigation systems as related to sustainable land use,* ed. Jan Feyen, Emmanuel Mwendera, and Moussa Badji, 1:245-254. Proceedings of an International Conference held in Belgium. September 14-17, 1992. Belgium: Center for Irrigation Engineering (CIE).

Ankum, P. 1992b. Classification of flow control systems for irrigation. In *Advances in planning, design and management of irrigation systems as related to sustainable land use,* ed. Jan Feyen, Emmanuel Mwendera, and Moussa Badji, 1:265-274. Proceedings of an International Conference held in Belgium. September 14-17, 1992. Belgium: Center for Irrigation Engineering (CIE).

Bos, M. G., and J. Nugteren. 1974. *On irrigation efficiencies.* Publication 19. Wageningen: International Livestock Research Institute.

Burt, C. M. 1987. Overview of canal control concepts. In *Planning, operation, rehabilitation and automation of irrigation water delivery systems,* ed. Darell D. Zimbelman, 81-109. Proceedings of a Symposium sponsored by the Irrigation and Drainage Division of the American Society of Civil Engineers (ASCE) and the Oregon Section, July 28-30, 1987. Portland, Oregon: ASCE.

Burt, C. M., and H. L. Plusquellec. 1990. Water delivery control. In *Management of farm irrigation systems,* ed. G.J. Hoffman, T. A. Howell, and K.H. Solomon, 373-423. USA: American Society of Agricultural Engineers.

Clemmens, A. J. 1987. Delivery system schedules and required capacities. In *Planning, operation, rehabilitation and automation of irrigation water delivery systems,* ed. Darell D. Zimbelman, 18-34. Proceedings of a Symposium sponsored by the Irrigation and Drainage Division of the American Society of Civil Engineers and the Oregon Section, July 28-30, 1987. Portland, Oregon: ASCE.

Clemmens Albert J., and John A. Replogle. 1987. Controlled-leak methods for water level control. In *Planning, operation, rehabilitation and automation of irrigation water delivery systems,* ed. Darell D. Zimbelman,133-154. Proceedings of a Symposium sponsored by the Irrigation and Drainage Division of the American Society of Civil Engineers and the Oregon Section, July 28-30, 1987. Portland, Oregon: ASCE.

Frederiksen, H. D. 1985. Design for operation and maintenance: A case study. Sardar Sarovar Irrigation Project. Gujarat, India. Paper presented at World Bank Irrigation Seminar, January 1985.

Goussard, Jean. 1987. Neyrtec automatic equipment for irrigation canals. In *Planning, operation, rehabilitation and automation of irrigation water delivery systems,* ed. Darell D. Zimbelman,121-132. Proceedings of a Symposium sponsored by the Irrigation and Drainage Division of the American Society of Civil Engineers and the Oregon Section, July 28-30, 1987. Portland, Oregon: ASCE.

Horst, L. 1983. *Irrigation systems. Internal report.* The Netherlands: Wageningen Agricultural University.

Hunter J. M., L. Rey., K. Y. Chu., E. O. Adekolu-John, and K. E. Mot. 1993. *Parasitic diseases in water resources development. The need for intersectoral negotiation.* Geneva: World Health Organization.

Indian National Committee on Irrigation and Drainage (INCID). 1994. *Guide for preparation of plans of operation and maintenance of irrigation systems in India.* India: INCID.

International Commission on Irrigation and Drainage (ICID). 1989. *Planning the management, operation, and maintenance of irrigation and drainage systems.* A guide for the preparation of strategies and manuals. World Bank Technical Paper No.99. USA: The World Bank.

Johnson S.H. III. 1997. Irrigation management transfer: Decentralizing public irrigation in Mexico. In Deregulation, decentralization and privatization in irrigation: State functions move to the free market, 40-63. Eleventh International Irrigation Symposium, 1997. *DVWK Bulletin* No. 20.

Kosuth, Pascal. 1996. Remote control and management of irrigation delivery systems. In *Sustainability of irrigated agriculture,* ed. L. S. Pereira, 493-512. The Netherlands: Kluwer Academic Publishers.

Lele, S. N., and R. K. Patil. 1993. Promoting participation in ecosystem management, Pune, India. Innovations in canal management and operation for better water deliveries. In Maintenance and operation of irrigation/drainage schemes for improved performance, 7-1 to 7-18. Paper presented to the Asian Regional Symposium held in Beijing, China. 24-27 May, 1993.

Malaterre, Pierre-Olivier. 1995. Regulation of irrigation canals, characterization and classification. *Irrigation and Drainage Systems* 9: 297-327.

Manz, David H. 1987a. Terminology for describing irrigation conveyance systems. *Journal of Irrigation and Drainage Engineering* 113(2):142-154. (May 1987)

Manz, David H. 1987b. Classification of irrigation water conveyance system components. *Journal of Irrigation and Drainage Engineering* 113(4):479-496. (November 1987)

Moench, M. 1996. *Groundwater policy: Issues and alternatives in India.* IIMI Country Paper, India 2. Colombo, Sri Lanka: International Irrigation Management Institute.

O'Mara, Gerald T. 1988. The efficient use of surface water and groundwater in irrigation: An overview of the issues. In *Efficiency in irrigation. The conjunctive use of surface and groundwater resources,* ed. Gerald T. O'Mara 1-17. A World Bank Symposium. USA: The World Bank.

Palmer, Joel D., Albert J. Clemmens, and Allen R. Dedrick. 1989. Several sources of nonuniformity in irrigation delivery flows. *Journal of Irrigation and Drainage Engineering* 115(6):920-937. (December 1989)

Paudyal G. N., and R. Loof. 1988. *Improvement of irrigation system operation.* Research Report 211. Bangkok, Thailand: Agricultural, Land and Water Development Program, Division of Water Resources and Engineering, Asian Institute of Technology.

Plusquellec, Hervé. 1988. *Improving the operation of canal irrigation systems. An audiovisual presentation.* USA: The World Bank.

Plusquellec, H. L., C. M. Burt, and H. W. Wolter. 1994. *Modern water control in irrigation. Concepts, issues, and applications.* World Bank Technical Paper 246. Irrigation and Drainage Series. USA: The World Bank.

Renault, Daniel, and H. M. Hemakumara. 1997. Irrigation offtakes sensitivity. *Journal of Irrigation and Drainage Engineering: ASCE* (In press).

Rey, J., D. Renault, and S. Lamacq. 1996. Vision "industrielle" de la gestion de l'eau sur un périmètre irrigué. *Houille Blanche* 339:70-75.

Rogier, Daniel, Charles Coeuret, and Jean Brémond. 1987. Dynamic regulation on the Canal De Provence. In *Planning, operation, rehabilitation and automation of irrigation water delivery systems,* ed. Darell D. Zimbelman, 180-191. Proceedings of a Symposium sponsored by the Irrigation and Drainage Division of the American Society of Civil Engineers and the Oregon Section, July 28-30, 1987. Portland, Oregon: ASCE.

Rousset, Pierre. 1990. Majalgaon Irrigation Project (Maharashtra): Implementation of volumetric allocation and rotational delivery. Washington D.C.: The World Bank. Duplicated.

Sagardoy, J. A., A. Botrall, and G. O. Uittenbogaard. 1982. *Organization, operation and maintenance of irrigation schemes.* FAO Irrigation & Drainage Paper 40. Rome: FAO.

Seckler, David. 1996. *The new era of water resources management: From "dry" to "wet" water savings.* Research Report 1. Sri Lanka: International Irrigation Management Institute.

Shanan, Leslie. 1992. *Planning and management of irrigation systems in developing countries.* Agricultural Water Management (October 1992) 22(1+2). The Netherlands: Elsevier.

Shanan L., B. K. Uppal, and B. Albinson. 1986. Guideline 5: Layout and design. In Design and operating guidelines for structured irrigation networks. Fourth Draft. Irrigation II Division, South Asia Projects Department. Duplicated.

Skogerboe, Gaylord V. and Gary P. Merkley. 1996. *Irrigation maintenance and operations learning process.* Highlands Ranch, Colorado, USA: Water Resources Publications, LLC.

Steiner, Roy A., and Michael F. Walter. 1993. The effect of allocation schedules on the performance of irrigation systems with different levels of spatial diversity and temporal variability. *Agricultural Water Management* 23: 213-224. Elsevier Science Publishers B. V.

Strosser, Pierre, and Marcel Kuper. 1994. *Water markets in the Fordwah/Eastern Sadiqia area: An answer to perceived deficiencies in canal water supplies?* Working Paper No.30. Colombo, Sri Lanka: International Irrigation Management Institute.

Uittenbogaard, G. O., and N. R. Kuiper. 1993. Improved operation strategies in India. Paper presented to the Asian Regional Symposium on Maintenance and Operation of Irrigation/Drainage Schemes for Improved Performance held in Beijing, People's Republic of China, 24-27 May 1993. HR Wallingford.

Vander Velde, Edward J., and Jacob W. Kijne. 1992. Salinity and irrigation operations in Punjab, Pakistan: Are there management options? Paper presented at the Workshop on IIMI-India Collaborative Research in Irrigation Management. 13-14 February, 1992. New Delhi, India. Pakistan: International Irrigation Management Institute.

Walker, Robert E. 1987. Long crested weirs. In *Planning, operation, rehabilitation and automation of irrigation water delivery systems,* ed. Darell D. Zimbelman, 110-120. Proceedings of a Symposium sponsored by the Irrigation and Drainage Division of the American Society of Civil Engineers and the Oregon Section, July 28-30, 1987. Portland, Oregon: ASCE.

16. *Irrigation Management Transfer in Mexico: A Strategy to Achieve Irrigation District Sustainability.* Sam H. Johnson III, 1997.

17. *Design and Practice of Water Allocation Rules: Lessons from Warabandi in Pakistan's Punjab.* D. J. Bandaragoda, 1998.

18. *Impact Assessment of Rehabilitation Intervention in the Gal Oya Left Bank.* Upali A. Amarasinghe, R. Sakthivadivel, and Hammond Murray-Rust, 1998.

19. *World Water Demand and Supply, 1990 to 2025: Scenarios and Issues.* David Seckler, Upali Amarasinghe, David Molden, Rhadika de Silva, and Randolph Barker, 1998.

20. *Indicators for Comparing Performance of Irrigated Agricultural Systems.* David J. Molden, R. Sakthivadivel, Christopher J. Perry, Charlotte de Fraiture, and Wim H. Kloezen, 1998.

21. *Need for Institutional Impact Assessment in Planning Irrigation System Modernization.* D. J. Bandaragoda, 1998.

22. *Assessing Irrigation Performance with Comparative Indicators: The Case of the Alto Rio Lerma Irrigation District, Mexico.* Wim H. Kloezen and Carlos Garcés-Restrepo, 1998.

23. *Performance of Two Transferred Modules in the Lagunera Region: Water Relations.* G. Levine, A. Cruz, D. Garcia, C. Garcés-Restrepo, and S. Johnson III, 1998.

24. *Farmer Response to Rationed and Uncertain Irrigation Supplies.* C. J. Perry and S. G. Narayanamurthy, 1998.

25. *Impacts of Colombia's Current Irrigation Management Transfer Program.* Douglas L. Vermillion and Carlos Garcés-Restrepo, 1998.

26. *Use of Historical Data as a Decision Support Tool in Watershed Management: A Case Study of the Upper Nilwala Basin in Sri Lanka.* W. K. B. Elkaduwa and R. Sakthivadivel, 1998

27. *Performance Evaluation of the Bhakra Irrigation System, India, Using Advanced Information Technologies.* Wim Bastiaanssen and D. Molden, 1998.

28. *Performance Evaluation of the Bhakra Irrigation System, India, Using Remote Sensing and GIS Techniques.* R. Sakthivadivel, S. Thiruvengadachari, Upali Amerasinghe, W.G.M. Bastiaanssen, and David Molden, 1999.

29. *Generic Typology for Irrigation Systems Operation.* D. Renault and G.G.A. Godaliyadda, 1999.

INTERNATIONAL WATER MANAGEMENT INSTITUTE
P O Box 2075, Colombo, Sri Lanka
Tel (94-1) 867404 • Fax (94-1) 866854 • E-mail iimi@cgiar.org
Internet Home Page http://www.cgiar.org/iimi

ISBN 92-9090-372-4

ISSN 1026-0862