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Research Report

Modernizing Irrigation Operations: Spatially Differentiated Resource Allocations

D. Renault and I.W. Makin

International Water Management Institute

Research Reports

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Modernizing Irrigation Operations: Spatially Differentiated Resource Allocations

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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

Modernization of irrigation implies interventions in different components of system management. This report focuses on operations and proposes a methodology for improved assessment of irrigation canal behavior and the environment in which operations take place. An underlying assumption is that irrigation systems are generally heterogeneous and, therefore, the allocation of operational resources should be matched to the spatial distribution of management requirements.

A descriptive model of irrigation systems is presented based on consideration of three domains. First, the cause, frequency of occurrence, and magnitude of perturbations to the flow regime are considered as the *perturbation* domain. Second, the behavior of the physical system when subjected to perturbations is considered the *sensitivity* domain. Last, the impact of system operations on agricultural yields is examined in the *vulnerability* domain, which enables the specifications for a required "water service."

Combining the vulnerability and sensitivity domains enables the definition of the precision with which systems must be operated. The inclusion of the perturbation domain allows specification of the mode of operation required to achieve the desired water service, including specification of the required frequency of intervention. All of this enables the demand for operating at a spatially disaggregated level to be defined.

Modernizing Irrigation Operations: Spatially Differentiated Resource Allocations

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Introduction

Irrigation modernization is increasingly recognized as a fundamental transformation in the management of water resources within agricultural areas. Such transformation may include improvements to physical and/or institutional structures, rules and water rights, water delivery services, accountability mechanisms, and incentives. This report discusses how modernization provides an opportunity to redefine and update operational procedures within irrigation schemes. By incorporating broader perspectives and taking more consideration of the spatial distribution of significant variables, this report defines new approaches for the allocation of operational resources.

The objective of this report is to present an improved methodology for evaluating the resource demands for effective canal operations to enable more cost-effective operational management. The fundamental basis of the proposed approach is whether or not operational requirements are homogeneously distributed throughout a given scheme. If not, operations require differential responses in different sections of the scheme.

Determining the demand for operational resources consists primarily of answering the following questions:

- What service to the users?
- What mode of operation?
- At what precision?
- With what frequency of checking and intervention?
- What monitoring system is required?

The need to reevaluate and update approaches to operations is given impetus by the tremendous changes that have occurred in the irrigation sector over the last few decades. These are the consequences of increasing competition for water and financial resources, as well as of growing concerns about the environmental and health impacts of irrigation. Water management is no longer narrowly focused, but must embrace a broader perspective including water quality, conjunctive management, multiple uses of water, a watershed perspective, new water rights, and priorities for distribution. A traditional quantitative and rather uniform management system on irrigation schemes is no longer sufficient to address current issues. Further, these trends will continue and system operators will have to develop more cost-effective operational plans to satisfy the increasingly influential user-payers. The service of irrigation will be—more than in the past—the result of negotiations between the service provider and the service user and a trade-off between costs and benefits.

As opportunities to develop new areas for irrigation are increasingly restricted, many existing irrigation schemes are, or in the near future will be, undergoing major changes, either physical or institutional or both. There is a crucial need to scrutinize the basic irrigation activities, operation, and maintenance, to ensure that systems become economically sustainable.

Background on Canal Operation

Canal Operation in Technical Literature

Canal operation and flow control techniques are well documented, particularly for system design analysis, e.g., by Zimbelman (1987), Paudyal and Loof (1988), Plusquellec (1988), Plusquellec, Burt, and Wolter (1994), and RIC (1997). However, there are few published studies addressing how managers should operate existing systems, evaluate the operational requirements, or allocate resources; or describing the efforts required to optimize system performance. In many schemes, a mixture of rule-of-thumb and local experience is the basis for operational decision making. There is no standardized base for retention of operational experience while, due to staff rotation, there is a risk of permanent loss of knowledge if such information is not formally recorded in an understandable form.

Any new approach to canal operations must bridge the gap between actual on-site management and the official Plan for Operation and Maintenance (POM), and other such operational guides. These guide manuals are increasingly required by authorities and funding agencies at the completion of structural works (new projects or rehabilitation). However, the fact that the operational framework cannot be fully planned at the design stage must be recognized, so that fine-tuning over some years of practice is a fundamental requirement (Uittenbogaard and Kuiper 1993). Thus, it is proposed that an adaptive or learning process is more preferable to strictly prescriptive approaches (LBII and WPCS 1990; Skogerboe and Merkley 1996).

Operation in the Irrigation Process

The word *operations* refers to both the manipulations of physical structures in the irrigation system to implement management decisions about water allocation and schedules of delivery and distribution. Operations are also the routine actions to minimize the impacts of perturbations by maintaining steady or quasi-steady-state water profiles in the system, in addition to preventing overtopping at peak discharges.

Operations are routinely required to implement distribution decisions and, as a consequence, the terms are sometimes confused even though they are fundamentally different. To clarify the thinking, technical irrigation management implies three levels of decisions: allocation, scheduling, and distribution, and one level of implementation: operations.

Operation and Type of Irrigation Systems

Operational requirements of irrigation systems are not identical. Some are highly automated and, although requiring larger investments in construction, often require fewer resources (human and financial) for day-to-day operation. Other systems are manually controlled and require full and intensive operations during irrigation. Irrigation systems may be classified as:

- *Fully operated systems* where all structures (intake, outlets, cross-regulators) require regular and routine operation during irrigation (setting on/off, setting, and monitoring).

- *Nonoperated systems* that generally operate on the proportional distribution principle, and are common in India and Pakistan. Fixed dividing structures ensure an equitable distribution of water. No operations are required to adjust ongoing flows within the "structured system" (Shanan 1992).

- *Minimal operation systems,* such as those equipped with modules and combined with automatic or fixed regulators. Interventions are generally limited to on/off operations and flow regulation is achieved by control modules or baffles.

This classification of control systems is essentially valid only for intermediate level canals, such as distributaries. Main canal systems and field canals are generally fully regulated. Therefore, a logical conclusion would be that whatever control technique is used in the intermediate distribution system, major irrigation systems include (at least partly) portions with gates that must be operated.

The Basic Assumption of Heterogeneity and the Spatial Analysis

In general, technical manuals for irrigation operations, implicitly assume homogeneity: first, homogeneity in the requirements for operation and, therefore, homogeneity in the distribution of operational efforts. In many cases, this assumption simply does not hold true. Rather, the basic assumption in operating an irrigation system should be that the scheme is heterogeneous, unless it can be clearly shown to be homogeneous.

There is limited literature on heterogeneity in irrigation systems. Poh-Kok (1987) presented a noteworthy approach for design of an irrigation system proposing the concept of irrigation *form* and its *context.* Poh-Kok proposed that both form and context must match in order to achieve success. He considered the assumption of "heterogeneity" a generic term regrouping variability, uncertainty, diversity, and complexity before presenting a conceptual model of irrigation as a consistent aggregation of elementary homogeneous units. These elementary units were defined as a Socio-Geographic Unit (SGU), homogeneous in "form" and "context."

Steiner and Walter (1993) considered the spatial variability of all factors influencing irrigation management, such as the physical characteristics of the context, the quality of infrastructure, etc. These authors later focused exclusively on spatial variability of climate and simulated the consequences of different allocation schedules.

Consideration of heterogeneity also underpinned the methodology developed by Schakel and Bastiaanssen (1997) for water management at a large scale for the Bhakra system in Haryana, India. Irrigation management throughout an area of 1.2 million hectares was disaggregated into 67 homogeneous geohydrological regions.

The authors fully support the assumption of heterogeneity in system physical characteristics, in social and environmental contexts and, therefore, in the demands for operation. It is proposed that this assumption is valid not only for large-scale systems, but also for smaller ones, of say, one thousand hectares. Therefore, determination of demands for operational resources should be based on *spatial analysis* leading to partitioning systems into elementary units with homogeneous characteristics, for convenience called "subsystems."

An important consideration is the link between heterogeneity and equity. It is clear that the justification for the widespread application of the homogeneity assumption was partly related to the goal of achieving equity within a system. This goal should not be ignored in any new approach to operations. Without care, the introduction of the heterogeneity concept may conflict with equity; for example, considering the value of a crop per unit area could lead to reinforcing existing inequity by providing better service to already well-served users.

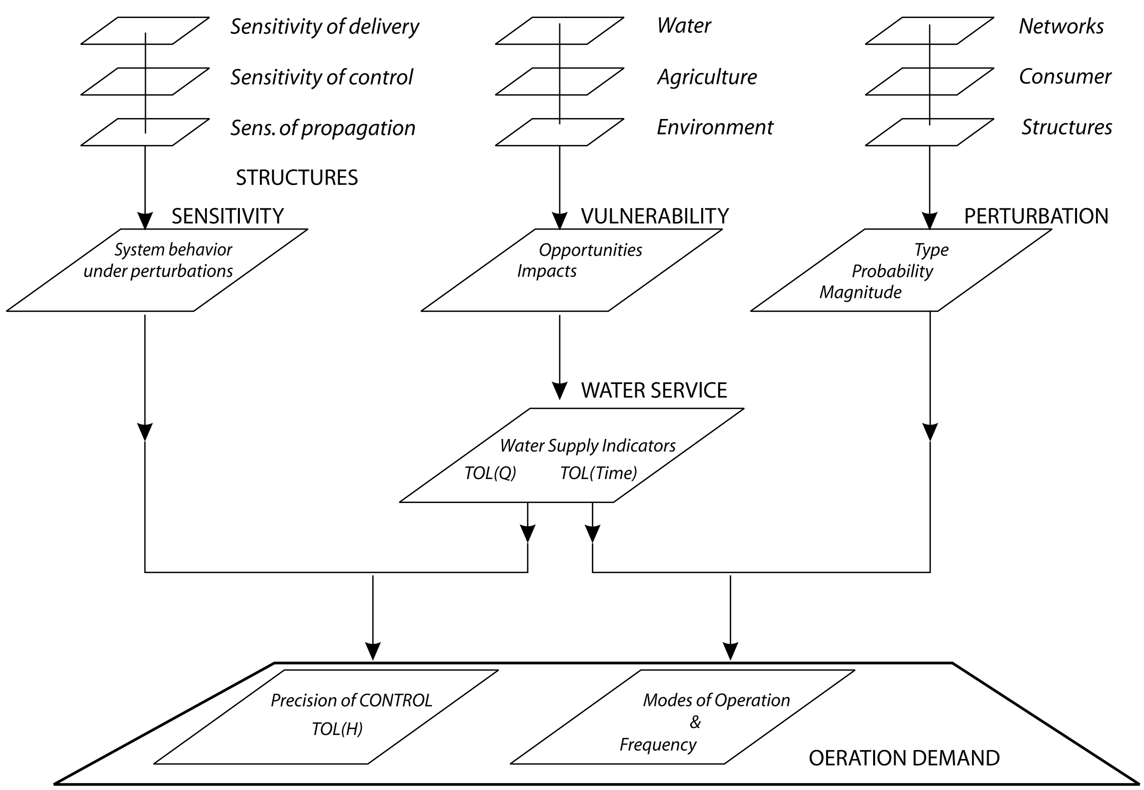
The Methodology

Open-surface canals are subject to modification of flow characteristics (discharge-water depth) resulting from scheduled and unscheduled events. In the usual operational mode, the management objective is to maintain steady state conditions when such events occur. The methodology developed here aims to characterize the frequency and magnitude of perturbation events likely to occur in a subsystem. The frequency of change in the distribution pattern defines the *perturbation domain.* By characterizing the physical properties of the irrigation structures and evaluating the behavior of canal systems when operated or affected by perturbations, the *sensitivity domain* is defined. Finally, the analysis of the impacts of operation on agricultural yields, on the environment, and on the watershed enables definition of the *vulnerability domain.*

Analysis of the vulnerability domain enables the definition of a global demand for "water services" for the multiples uses within the scheme. This may be seen as a basis on which specific agreements defining the level of service have to be found between the service provider and the users, particularly when the latter are bearing the cost of the service. The concept of service in irrigation is receiving more and more attention within the irrigation community (Huppert 1993; Hofwegen and Malano 1997) and is generally perceived as much broader than water delivery. In this report though, the concept of water service is restricted to water delivery, and is analyzed through classical performance indicators (adequacy-efficiency…).

Considering the required water service performance, and then combining this with sensitivity analysis of the infrastructure, enable the specification of the precision of water depth control required (figure 1). The mode of canal operation required is defined by the combination of the vulnerability and perturbation

FIGURE 1.
Overlay process for mapping distribution of efforts for canal operation.



domains. Finally, the perturbation domain determines the required minimum frequency of system observation and regulation.

The approach can be viewed as a series of overlays of spatially distributed variables, illustrated in figure 1. Although defined by technical considerations, the process must be sociologically acceptable and also fit the objectives of the irrigation scheme in terms of agricultural development.

Opportunities and Constraints in Water Service

The Vulnerability Domain

Vulnerability is a generic term used here to describe opportunities and constraints and/or impacts of operation at different scales of space and time. Vulnerability of an irrigated area can be seen as the propensity to be positively or negatively affected by irrigation operations. For instance, a highly vulnerable area would be a unit in which impacts and side effects of low-quality operation are high (sensitive crops, areas without drainage facilities). Inversely, areas of low vulnerability are those in which impacts and consequences of low quality operation are either temporally or permanently dampened (rice fields are more tolerant to interruption of water supply than other crops). "Vulnerability" extends beyond the confines of water for crops and includes consideration of larger-scale *water management impacts.*

Some of the wider aspects of water management that define the vulnerability domain include:

Water quality. Modern agricultural methods and the scarcity of freshwater result in irrigation having to deal with water loaded with chemicals (pesticides, nutrients) and other pollutants. Acknowledgement of the importance of water quality is one of the main challenges for current irrigated agriculture, with implications for both surface water and groundwater. Many shallow aquifers are important for domestic supply. These often receive some recharge from dry-season percolation from irrigated areas representing simultaneously a gift: an additional source, and a threat: pollution. In these situations, managers will have to consider both uses and arrive at an effective compromise.

Recycling of irrigation water. Drainage flows from irrigated areas can be important assets in water management. Losses in one place become inputs for other areas. The presence of such recycling can substantially ease the upstream management problem by allowing less precision in distribution, knowing any surplus will not be lost. Return-flow systems represent an opportunity for managers to store positive perturbations, for example to harvest rainfall, as both drainage and surplus irrigation are channeled back to the irrigation network itself.

Water harvesting and conjunctive management. Water harvesting during rainfall periods is an important opportunity for water management. Specific operational procedures may be designed to maximize harvesting while preventing canal overtopping. Conjunctive use of water (surface water, groundwater, and rainfall) can provide additional flexibility to farmers. Groundwater is frequently used to compensate for rigidity or low performance in the surface water delivery system. Areas lacking access to additional supplies from groundwater should be considered for greater management attention than areas where pumping facilities can compensate for inadequate and/or unreliable deliveries.

Soil and water salinity and waterlogging. The rise in soil and water salinity, and the increase in waterlogged areas are environmental hazards of great importance in arid regions. They represent a severe threat to irrigation schemes. It is clear that operation of irrigation systems must take into consideration the spatial distribution of these hazards in order to provide a selective and locally adapted water service. In practice, solutions are largely site-specific and generic guidelines are difficult to derive. But, as a principle, partitioning of the irrigated area should distinguish areas where freshwater has to be provided from areas in which excessive percolation should be avoided to prevent saline groundwater from rising.

Multiple uses of water. In many irrigation schemes, water is used not only for crops but also for many other purposes including domestic water supply, environmental uses, fisheries, perennial vegetation, and hydropower, amongst others. Rules for multipurpose system operations are complex because of potential conflicts in setting targets for the different uses and also, on occasions, because of the lack of suitable accounting procedures. Multiple uses of water may have to be increasingly integrated in management concerns, whether or not these uses were considered at the design time. A first step in the management of multiple uses is to define a consistent set of water and productivity accounting procedures (e.g., Molden 1997).

Water rights, equity, and priorities in distribution. Water distribution priorities may be based on long-term rights and established uses. However, in systems experiencing water shortages, these priorities should define a policy to share limited water among shareholders. Priorities may be defined based on the value of crops (high/low), soil- and water-holding capacity, etc. As the mission of irrigated agriculture changes from subsistence to more highly productive agriculture, it may sometimes be necessary to revise previous policies. There may be a necessity to avoid damage to highly sensitive or high-value crops in case of water shortage. In many cases, distribution policies should be reexamined and, where appropriate, changed to enable new operational objectives.

Health impacts. Despite the positive effects of irrigation on the rural economy and income of farmers there is no doubt that, in some circumstances, it has also brought negative impacts on the health of communities through vector-borne diseases. The maintenance of water in canals for long periods of time can affect the reproductive cycle of disease vectors. The link between system operations and community health can be strong. The recommendations from health experts are converging towards a requirement for more variability in canal flow regimes to, for example, reduce the breeding of mosquitoes (Hunter et al. 1993). However, there is a clear conflict between these requirements for vector control and the irrigation management objective of stable water profiles. New techniques of operation may be required where mosquito breeding is related to irrigation practices (Matsuno et al. 1999).

Location within the system. The impact of operations on the command area is evidently greater for structures located towards the head of the canal system. Therefore, location is included in the analysis of vulnerability.

Finally, the study of each aspect of the vulnerability domain leads to a basis on which the provider of service can further analyze the requirements for water service. The rationale here is that a highly vulnerable command area requires a high water service and vice versa. In modern management, a further important step towards the definition of service is the negotiation with the users of service (farmers, associations, cities, environmentalists, industrials, etc.) with the idea of reaching an “agreed service” compatible with the hydrological constraints at scheme level and the users' willingness to pay.

Vulnerability, Water Service, and Irrigation Performance Indicators

The spatial characteristics of the vulnerability domain can be converted into specific "water service" targets and measured with Water Supply Performance Indicators (WSPI) (Bos et al. 1994) such as adequacy, efficiency, dependability, timeliness, and equity, the common performance indicators (Molden and Gates 1990). Flexibility of access to water and reliability of deliveries are important criteria of performance that should also be considered (Renault and Vehmeyer 1999).

Performance indicators for operation can be derived from the vulnerability domain considering both water deliveries for irrigated crops and water management in a broad perspective. In the analysis presented here only the primary indicators, adequacy, efficiency, and timeliness, are considered. Performance targets are expressed as tolerances with respect to the target discharge rate as shown in equation 1.

$$\mathrm{Tol(Q)} = \begin{Bmatrix} +y\% \\ -z\% \end{Bmatrix} \qquad (1)$$

Equation 1 shows that discharge at a given location should be maintained within the two limits, -z% or +y%, which constitute the tolerable range for the target discharge.

The lower limit, z, is the tolerance factor related to adequacy, reflecting the capacity of the command area to accommodate water shortage and incorporates concerns about deliveries. This factor, z, will vary as the period considered changes: a relatively high tolerance may be stipulated for a short period (days, weeks); however, the tolerance becomes smaller as the period considered is extended (months, seasons).

The upper limit, y, is the tolerance factor for efficiency and reflects the capacity of a subsystem to accept surplus water (positive perturbation). As for the z factor, the permissible tolerance y is a function of time and the physical characteristics of the subsystem, such as the opportunities for return flows, reuse, etc.

A similar relationship can be developed considering the time of delivery, as described in equation 2.

$$\mathrm{Tol(Time)} = \begin{Bmatrix} +u \\ -v \end{Bmatrix} \qquad (2)$$

where, u reflects the maximum acceptable delay in water delivery; and v expresses the maximum allowable advance in delivery without water loss.

The Perturbation Domain

Open channel irrigation systems are hydraulically complex. In general, system operations are reduced to controlling water levels at cross-regulators in an attempt to maintain stable water levels and hence discharges at offtake structures. However, steady water level profiles seldom occur in irrigation systems due to both variations at the upstream boundaries of the system (perturbations of intake flow rate) and the effects of operational interventions themselves. Hence, operation is a never-ending challenge as gate adjustments are made to bring the system to the intended steady state conditions; but under the influence of perturbations, resulting from variable discharges entering the system and the multiplicity of gate operations, frequent adjustment are required.

A perturbation at a given location is defined as a change to the ongoing discharge. Such changes arise from two sources: first, planned changes in the delivery; and second, unexpected or transient changes. Unexpected or transient perturbations are more difficult to manage precisely because they cannot be anticipated and therefore effective control depends on early detection (degree of information).

Management of Unexpected Perturbations

When a perturbation occurs in a canal, the effects travel both upstream and downstream from the location where the perturbation was created. However, the main impacts are noticed downstream. For analysis, the perturbation domain is divided, first, into *generation* and, second, into *propagation,* which are also expressed as the “active” and “reactive” processes.

The active process can be analyzed in three constituent parts: (1) the *causes* of perturbations, such as return flows, illicit operation of structures, and drift in the setting of regulators; (2) the frequency of *occurrence;* and (3) the *magnitude* of perturbations experienced.

Causes, frequency of occurrence, and magnitude of perturbations. Causes of perturbations are to a large extent determined by the “network” properties of the system (source of supply, hydraulic layout, interconnections with other networks, such as drainage, unregulated return flows, etc.). Renault and Godaliyadda (1999) describe these properties more fully. However, a second source of perturbations is the operation of the irrigation regulation system itself. Offtake and regulator operations generate transient conditions in the network, which may be translated upstream to the parent canal from the dependant canal if submerged flow occurs at the division from the main canal. In such cases, the sensitivity of offtakes is the major determinant of the propagation of the transient (Renault and Hemakumara 1999). Perturbations may also be generated at the offtake due to deliberate or accidental modification of the flow section, either due to changes in gate settings (illicit operations) or by trapped debris (drift). Perturbations are also generated by unscheduled operation of structures for unauthorized withdrawals, flow rejection, or overtapping. Table 1 summarizes the major components and properties causing the generation of perturbations.

The position in the network controls the frequency of occurrence of transients and partially explains the notorious “head/tail” issue in irrigation. In this analysis, the occurrence and magnitude of perturbations at any given point are dependent on the numbers and the operational characteristics of upstream structures (cross-regulators and offtakes). Generally, the more numerous and the

TABLE 1.
Components and properties significant for unexpected generation of perturbations (adapted from Renault and Godaliyadda 1999).

Components	Related properties for operation	Classes for partitioning			
Source Supply	Fluctuations of source Degree of control	Reservoir	River diversion	Canal branch diversion	Canal series diversion
		Return flow (RF)		Non-return flow (NRF)	
Layout Lateral flows	Variability of on-line discharge	Single bank canal (SBK) with runoff		Double bank canal (DBK) without runoff	
		Runoff ditches		No ditches	
Offtakes	Upward sensitivity for conveyance	Low	Medium		High
	Sensitivity to setting				
Regulators	Sensitivity to setting	Low	Medium		High
User	Illicit operation	Discipline		No discipline	

greater the sensitivity of upstream cross-regulators, the greater the magnitude and frequency of perturbations. Inversely, for systems with sensitive offtake structures, perturbations generated in the head reaches will be attenuated by upstream offtakes and the downstream offtakes will experience smaller transients.

Perturbations are expected whenever a change in the distribution takes place and therefore *distribution policy* (on-demand, supply-based, free-access) is a key determinant of the frequency of occurrence of perturbations. The greater the flexibility of delivery service provided the greater the frequency of changes in discharges in the canal system. Proper consideration of the impacts of service flexibility is essential to identify the specific operational modes and structure characteristics required for acceptable performance.

The Sensitivity Domain

Sensitivity describes the ratio of output to input of a particular process. In the context of irrigation, sensitivity analysis describes the behavior of structures during the propagation of transient conditions (the reactive process). The behavior of regulation structures, such as offtakes and outlets, in response to water level perturbations in the parent canal, is the delivery sensitivity, described by the ratio of the relative offtake discharge (dq/q) to the change in upstream water level (ΔH_{US}), as described in equation 3.

$$S = \frac{dq/q}{\Delta H_{US}} \qquad (3)$$

All irrigation structures (offtakes, regulators, canal reaches) have a distinct sensitivity. A comprehensive analysis of the sensitivity of irrigation offtakes leads to the identification of several indicators defining delivery and conveyance impacts, including upstream and downstream translation of transients, as well as water-level changes due to hydraulic conditions and adjustment of structures (Renault and Hemakumara 1999). Albinson (1986) has done an in-depth study of the relative sensitivity of regulator and offtake combinations. The rationale for sensitivity analysis is that more-sensitive structure groups must be monitored and operated with greater care than less-sensitive groups.

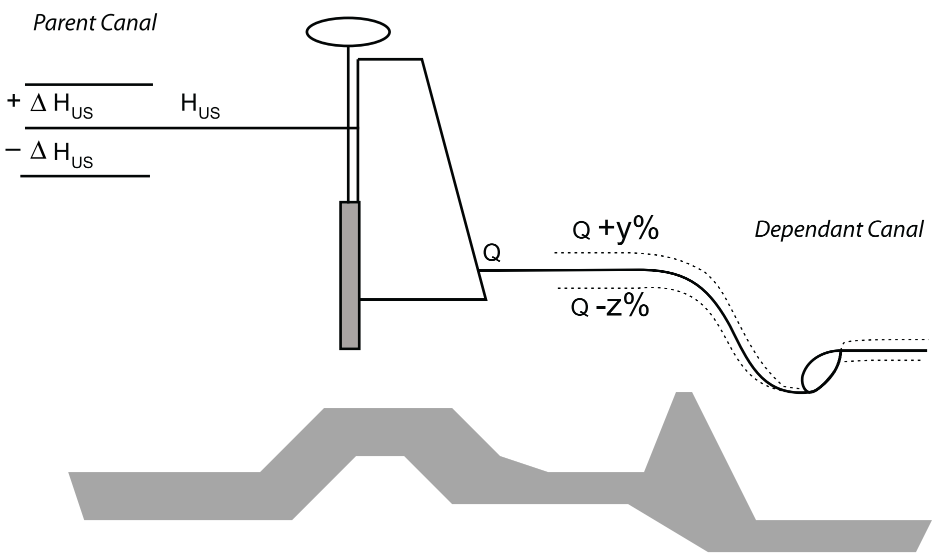
An important consideration for canal operations is the sensitivity of structures and their impact on the propagation or attenuation of transient flows that enter the canal system. In the absence of operational interventions the evolution of perturbations through the subsystem defines a decay curve integrating the conveyance sensitivity of the reaches and associated regulators and offtakes. Systems with sensitive offtake structures tend to attenuate the transient flows by diverting surplus water through offtakes, while less-sensitive structures propagate the perturbation downstream (Renault 1999a).

Determining the Demand for Operation

The study of the domains discussed above provides the basis for the specification of requirements for operational interventions in a specific subsystem. Before presenting a case study of the irrigation system let us consider a simple analysis of the operational requirements for a typical structure. For this simple case, a delivery structure (figure 2) links the parent canal, in which control is implemented, and the dependent canal, in which service is specified.

The vulnerability in the command area of the dependent canal defines the tolerance on the discharge (here no consideration is paid to timeliness). For instance, if crops grown in the command area are sensitive to water deficit, then lower tolerance, i.e., z in equation 1 should be minimized. On the other hand, if the drainage water from the command area is recycled downstream then the upper tolerance, y, can be larger. Having defined both tolerances (y and z),

FIGURE 2.
Linking service and control through a delivery structure.



they are converted to precision of operation and control through the sensitivity of the structure. Inverting equation 3, the precision required for control in the parent canal (ΔH_{US}) is computed as:

$$\Delta H_{US} = \frac{\alpha}{S} \qquad (4)$$

where, y or z is substituted for α when considering adequacy or efficiency. In this case y and z are specified as a tolerance in a linear dimension rather than a percentage deviation; S is the sensitivity of the structure; and ΔH_{US} is the required precision of control of water level in the parent canal.

Equation 4 expresses the target for the control in the parent canal at this particular structure, which has to be converted into control targets at the nearest downstream regulator. Control of water levels along the canal is the result of the combined effects of the hydraulic properties of the canal section, regulator characteristics, and periodic operation of cross-regulator structures. The precision with which target water levels are controlled at cross-regulators (ΔH) is an indicator of operational performance directly influenced by management. Conversely, the extension of the influence of cross-regulators on canal water level is determined by the physical characteristics of the reach and discharge rate defined by the backwater curve.

The required operational precision is proportional to the specified tolerance and inversely proportional to the delivery sensitivity. Examples are given in table 2.

Equation 4 is valid for a single structure; however, similar relationships can be determined at the system level by linking system sensitivity indicators, the required precision of control, and operational performance (Renault 1999b).

The relationship between water service, irrigation performance indicators, and operational targets illustrated above for a simple case, can be generalized, as shown in figure 3.

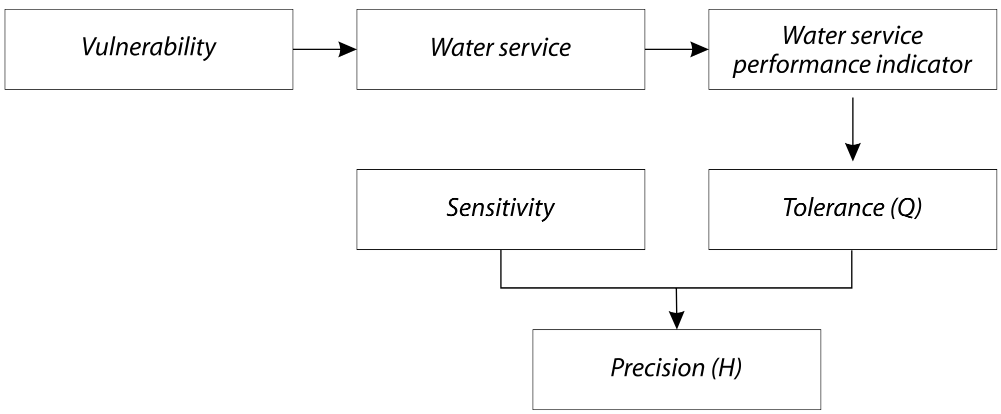
This relationship indicates that the required precision of structure operations is the product of the tolerance on delivery and the sensitivity of the structure. This relationship deals with the objective to achieve the specified service to the user.

Another important aspect of canal operation deals with the management of perturbations (fluctuations of flows), with the objective of

TABLE 2.
Examples of sensitivity, tolerance, and control precision.

Sensitivity of the structures S (m^{-1})	Tolerance for discharge α (%)	Precision of control (ΔH_{US}) (m)
0.5	± 10%	± 0.2
Low sensitive	± 20%	± 0.4
1	± 10%	± 0.1
Medium sensitive	± 20%	± 0.2
2	± 10%	± 0.05
High sensitive	± 20%	± 0.1

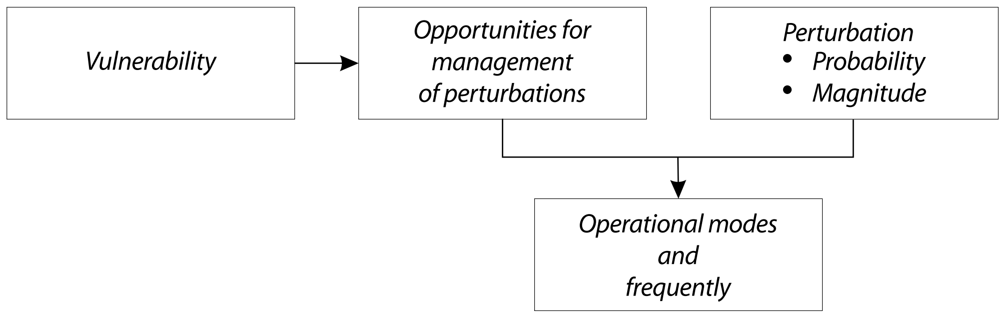
FIGURE 3.
Functional relationships between the vulnerability, sensitivity, and the characteristic of the service.



increasing water management efficiency (for instance rainfall harvesting) while minimizing the effect of perturbations on the deliveries. This combines the opportunities for perturbation management (storage facilities or efficient use of water surplus) and the probability and magnitude of occurrence. This allows the determination of the appropriate mode and frequency of operation, depending on the expected frequency of perturbations as illustrated in figure 4.

Ultimately, the determination of the demand for operation is a mixture of both quantitative and qualitative approaches. With the qualitative approach, the goal is to identify the significant properties strongly influencing potential operational strategies in each subsystem. These properties may include, for example, the presence and opportunities for recycling losses and the vulnerability within the system. These properties can be combined to classify the demand for operation as low, medium, or high and lead to a more appropriate distribution of efforts for operation within the scheme. With the quantitative approach, formalized through equation 4, the goal is to specify the operational targets that will have to be used for control to achieve the agreed service.

FIGURE 4.
Functional relationships between the vulnerability, perturbation, and operational modes.



Case Study of Kirindi Oya Irrigation Settlement Project, Sri Lanka

The proposed methodology has been applied to the Kirindi Oya Irrigation and Settlement Project (KOISP), one of the largest agricultural development programs in Sri Lanka completed in 1987 (figure 5).

Scheme Summary

Kirindi Oya has two command areas with markedly different characteristics:

- ***The Old Ellegala command area*** existed prior to the development of the new system. The Ellegala zone is in a flat alluvial area of about 4,000 hectares. Water is delivered to the area through an old system of five interconnected tanks receiving water from a diversion structure (anicut) across the Kirindi Oya (river). Water is released from the new reservoir to supply this anicut system. The Ellagala command area has the first priority in water allocations. The area is subdivided into two subsystems, designated as:

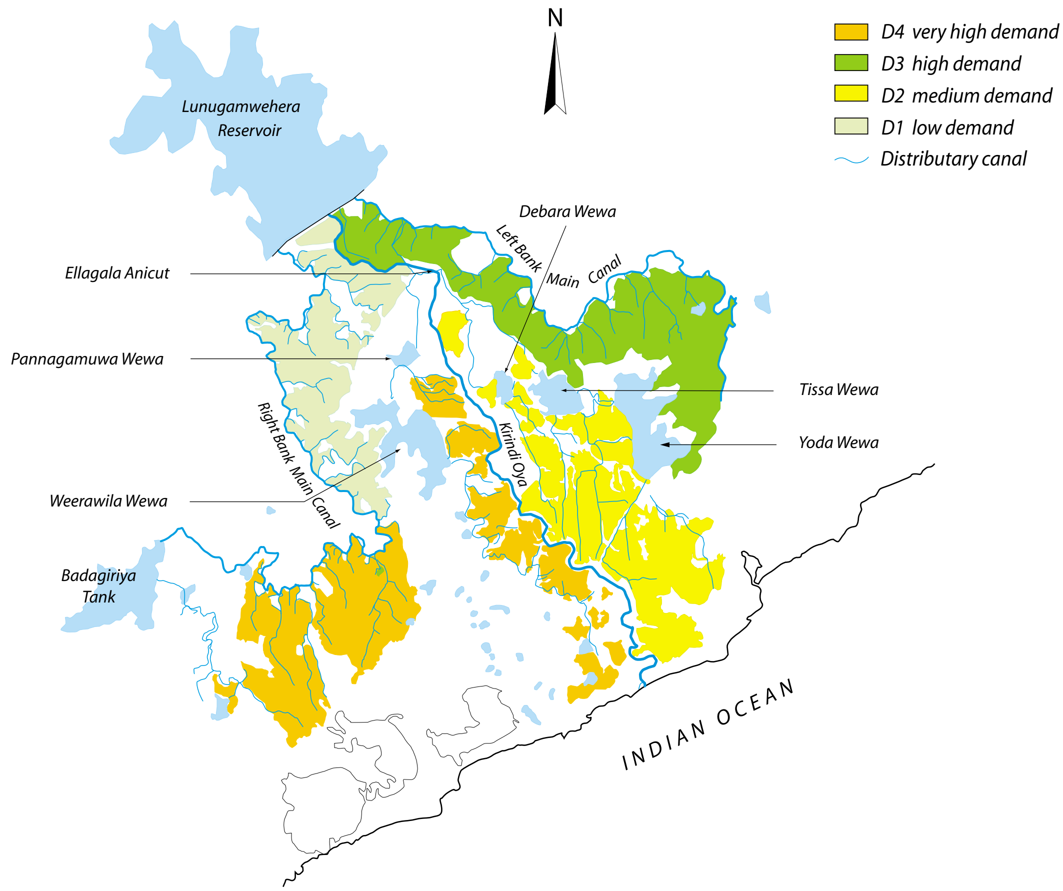
    - Left Bank Old (LBO) 2,850 hectares, and
    - Right Bank Old (RBO) 1,150 hectares.

- ***The new command area*** was completed in 1987. This command has a slightly undulating topography and is located upstream on both sides of the alluvial plain of the Ellegala system. The new command is served by two subsystems:

    - Right Bank New (RBN) delivering to five newly developed sub-commands (Tracts 1, 2 5, 6, and 7), totaling 3,300 hectares and a reservoir (Badagiriya) with an associated command area at the tail of the main canal. The Badagiriya command receives scheduled deliveries from KOISP plus surplus flows from the tail of the main canal.
    - Left Bank New (LBN) canal command area, which is fully developed in Tracts 1 and 2, and partly developed in Tract 3, with a command area totaling 1835 hectares.

Climate. The climate is classified as tropical humid with two seasons: *maha* (a wet season between October and February/March); and *yala* (a dry season from April to September). The average seasonal rainfall is 750 mm in the maha season

FIGURE 5.
Spatial evaluation of the demand for operation (KOISP).



and 240 mm in the yala season. The annual evapotranspiration (ET_{ref}) is approximately 1,500 mm.

Water resources and water management. Water for agriculture is derived from direct rainfall on rice fields and supplemented by releases from the system reservoirs. The main reservoir (Lunugamwehera, 200 MCM) was developed to extend irrigation to the new command areas and to secure irrigation double-cropping in the old Ellegala command. An important characteristic is the *cascade of tanks* in the system that enables capture of runoff, overflows, and drainage from upstream areas to be used for irrigation at a later stage of the season.

With limited commitments to downstream uses (bathing and lagoon supply), KOISP can be considered as the last water user before the river discharges to the ocean; therefore, water savings in this scheme are “real savings” as defined by Seckler (1996).

Crops. High-yielding varieties of rice are grown throughout the project area during the maha season. However, during the yala season, only the Ellegala area is routinely cultivated for rice with the new command areas cultivating rice only when water availability is high. Other field crops are grown in limited parts of the new command area on uplands during most yala seasons.

Institutional arrangements. The responsibility for operations of the main and branch canals is vested with the Irrigation Department of Sri Lanka, a national public agency in charge of medium and major schemes in the country. The responsibility for operations of distributary canals was transferred to farmers and/or associations of farmers in the beginning of the nineties as part of an institutional reform. Farmers do not pay for water and the activities (operation and maintenance) carried out by the Irrigation Department are funded directly by the government. Decisions about allocation of water are taken before the crop season begins, by a cultivation committee with representatives of farmers, state agencies, and other stakeholders. Decisions are based on available resources in the reservoirs and rotating priorities. In practice, the equity is maintained fairly high within each subsystem (new and old) but it is low between the two subsystems, the old area receiving *de facto* a higher share than the new area.

Improving System Performance

Due to a perceived mismatch between available resources and potential uses of water the full extent of the new command has not been developed. Even though development is not complete, the cropping intensity in the irrigated areas has not reached the expected levels and has remained at about 178 percent (increased from 140% before Lunugamwehera reservoir came into operation) in the Ellegala area and at only 108 percent in the new commands. Current on-field operational strategies are largely based on “overflow” or paddy-to-paddy practices, which result in large outflows from the command areas and losses where recycling is not feasible.

Located in the coastal strip, KOISP should seek to maximize effective water use as any unused water is lost to the sea. It can be shown that the irrigation intensity at KOISP can be raised to 200 percent in both new and old areas provided an efficiency of 43 percent is obtained at scheme level (Renault 1997). In 1998, a water balance study showed that water losses to the sea are about equivalent to the crop consumption through evapotranspiration (Renault, Hemakumara, and Molden 1999). To achieve a high level of efficiency, operational resources (human, transport, energy, communication) must be allocated effectively, which depends on an accurate assessment of the required levels of operational control. The analysis of operational requirements at KOISP addresses two aspects: first, the water service required in the command and, second, the management of reservoir operations. In addition, specific operational procedures should be tested to improve the utilization of rainfall, aiming to harvest and store as much rainfall in reservoirs and rice fields as possible.

An analysis of the demand for operation at KOISP is presented, based on the framework proposed above, examining the vulnerability, perturbation, and sensitivity domains of the system.

Vulnerability Domain

Water is relatively abundant and annual average resources (local rainfall + reservoir inflows) are sufficient to sustain two crops a year provided the system is operated effectively (Renault 1997). Maha rainfall is reasonably dependable; however, yala rainfall is less so. The start of irrigation in the new areas generated some concerns in the early nineties related to the leaching of salt that drained to the downstream area (old system). However, the phenomenon has not persisted and, apart from some limited areas very close to the sea, no major salinity or waterlogging problems are found in the area.

The existence of a cascade system, with several tanks in succession, makes it possible for the scheme to be very efficient in harvesting rainfall by operating the tanks at the lowest level possible to maximize storage capacity.

Single bank or contour canals (SBK) are common in Sri Lanka giving the potential to capture runoff from lateral watersheds. The Right Bank Old (RBO) canal is a single bank contour canal and this, combined with the storage capacity of three intermediate reservoirs, provides opportunities to capture water during rainy periods. Some parts of the Left Bank New (LBN) canal are also single bank.

Water management. The potential for recycling drainage or spilled water from the command areas divides the scheme into two operational categories. All tracts in the LBN canal and Tracts 1 and 2 of the RBN canal drain to tanks that supply the Ellegala area. Tracts 5, 6, and 7 of the RBN canal drain to a lagoon and ultimately to the sea, resulting in large water losses. Drainage flows from the RBO subsystem return directly to the main river canal and then to the ocean with little opportunity for recycling these losses except through pumping facilities.

The Left Bank Old command area is characterized by extensive interconnections between drainage and irrigation networks due to the flat topography. It is almost impossible to define precise command areas for individual outlets (Mallet 1996) or to uniquely characterize the hydraulic characteristics of channels or structures. Surplus flows at one point become inputs elsewhere; therefore, in the terminology developed by Renault and Godaliyadda (1999), this area is classified as a return-flow system. The LBO subsystem must, therefore, be managed as a single unit considering several entry points to the network such as tank outlets and canal inlets and a number of drainage outlets to the river and the ocean. To increase the efficiency of water use, all drainage outlets require monitoring to avoid excessive losses. An effective feedback control system is essential to enable effective control of the inlets into the subsystem. There is no conjunctive use in the area and pumping from the river and drainage or irrigation canals is restricted to small-scale gardening enterprises.

Multiple uses of water are important in the KOISP area. However, there are no major conflicts between irrigation and the other uses of water, including domestic water supply, bathing, homesteads, gardens and perennial vegetation, environmental uses (wetlands, wildlife habitat), tourism (lagoons and national parks), and fisheries. Irrigation is the major user of water, representing more than 90 percent of water use in the basin; and water for irrigation ensures availability for other uses. There are no specific health-related issues.

Agriculture. Rice cultivation is relatively less vulnerable to variations in water supply than other field crops due to the buffer effect of the flooded rice field. As the area is mainly cultivated for rice in both seasons, the cropping system can be considered as homogeneous and of low vulnerability. This is an important characteristic for tracts where recycling is not feasible as it may allow implementation of strategies to reduce overflows. Special consideration may be required for the new areas, where some farmers cultivate other field crops that are more vulnerable to water shortages.

Soils in the Ellegala area are heavier than those in the new command areas. Percolation rates in these two areas are estimated at 3 mm/day and 6 mm/day, respectively (IIMI 1994). Although this has some implications for water allocation and drainage flows it has little impact on operational strategy or on system efficiency, as the dominant criterion is the ability to recycle water.

Water rights and equity. In theory, all farmers at KOISP have equal water rights. However in practice, farmers of the old areas have established a powerful position and have been able to establish preferential allocations of water in their favor. The Ellegala area also obtains irrigation supplies in advance of the new areas, directly contrary to effective water savings strategies. Under these conditions, any attempt to improve water management must assure 200 percent irrigation intensity to farmers in the Ellegala subsystem before attempting to implement any changes of supply to the new areas.

Environment. The area surrounding KOISP has several facets of environmental and wildlife importance: The entire area is a recognized wetland sanctuary of importance to migrating birds and the Bundala National Park is to the southwest of the scheme (Matsuno, van der Hoek, and Ranawake 1998). The lagoons in the park are partly supplied by water draining from the RBN area. Fortunately, there are no conflicts between improved irrigation management and existing environmental concerns. Improved water management in irrigated areas will extend the period of water in the tanks and will reduce freshwater inflows to the lagoons, currently considered a potential hazard.

Water service and performance indicators. In subsystems with no opportunities for recycling of excess flows, the water service must be much more accurate than elsewhere. Therefore, tolerance on deliveries (equation 1) must be minimized and a feedback link between drainage outflows and system inlet settings should be established. In areas where recycling is possible, the water service can be less precise and delivery tolerance can be less strict in terms of discharge provided that, in the long term, the volumes are roughly adequate. A feedback loop control is recommended to maximize storage potential in downstream tanks during the wet season.

Perturbation Domain

Analysis of this domain focuses on the occurrence and magnitude of externally and internally generated perturbations. The upstream boundary conditions of each subsystem are homogeneous as all systems are supplied from the main reservoir or tanks and have manually operated gates.

Lateral flows. The RBN and LBO canals are double bank canals and as such not greatly influenced by rainfall. Parts of the LBN and the entire RBO canals are Single Bank Canals (SBK) and, therefore, susceptible to large perturbations during periods of rainfall.

Position in system. Field observations have confirmed that the LBN and RBN canals were subjected to an increasing range of water-level fluctuations from head to tail locations, increasing from 65 mm at the head to 90 mm in the middle reaches, and then to 110 mm at the tail during maha 1993 in the LBN. Observations on the RBN show a similar trend; records over six seasons indicate that the average water level fluctuations range from 75 mm at the head to 120 mm at the tail.

Users. Discipline is variable between the systems. In the old system there are few disciplinary problems, probably as a result of the relatively reliable water supply. In the new system, farmers must contend with shortages of water to the extent that some have not been able to establish themselves as farmers and have had to seek other employment. Even those who have been able to establish themselves as farmers have less influence in decision making over water allocations. As a result, unauthorized operations of gates and harmful interventions at cross-regulators do occur. System managers have responded by issuing more water to the main canal than is theoretically required. The lack of discipline may be a serious constraint to increased precision in operations aimed at improved efficiency and therefore intervention strategies should be aimed at achieving highly reliable water supplies in all areas.

Operational procedures. To improve economy of water use in command areas with no opportunity to recycle drainage flows, managers will have to encourage farmers to adopt field procedures that are more effective than the existing lot-to-lot irrigation. Two alternative main canal operational procedures might be considered: first, a strategy of progressive reduction of deliveries; and second, the introduction of rotational delivery. *Progressive adjustments* (PA) would impose permanent and progressive modifications of inflows (deliveries) to continually reduce downstream drainage discharges. This option would require precise operation and methods to fine-tune deliveries to minimize inflows, while avoiding drying-up of downstream field units. Ultimately, this method would result in a minimum steady state discharge. *Rotational operations* (RO), either with an *on/off* schedule, or with alternating *high* and *low* discharges, will result in frequent fluctuations in canal discharges, requiring greater supervision of the canal system.

The Sensitivity Domain

Offtake sensitivity. The sensitivity of offtakes distinguishes the RBN canal (medium sensitivity, average S=1.3) from LBN and RBO that are classified as highly sensitive (respectively average = 2.4 and 2.2). This means that the same level of precision in water depth will generate discharge deviations twice as large in LBN and RBO than in RBN.

Regulators and reaches. Three different situations can be distinguished with regard to the regulation of water levels in the main canals as listed below:

Not regulated: for example, the RBO canal is not regulated effectively as the density of regulators is very low and most existing structures are no longer functional.

Poorly regulated: the LBN canal has adequate provision of regulators, but the existing condition is poor, with gates generally missing or otherwise inoperable.

Well-regulated: the RBN canal is well-equipped for regulation and the regulators are in good condition.

Spatial Variation of Operational Demands at KOISP

The operational requirements to achieve specified levels of water delivery service and acceptable levels of water use economy at KOISP are analyzed for daily regulation of water releases and for control of the canal system. Requirements for improved scheme operations related to the scheduling and tank management to impose rainfall-harvesting tasks are not addressed here.

Considering four classifications of operational requirements, varying from *low demand* to *very high demand* (D1, D2, D3, and D4), five subsystems were identified. An evaluation of the characteristics of the demand for operations in each is summarized in table 3. Although the ranking used here may be subject to discussion, the identification of significant operational differences at each subsystem allows a spatially differentiated allocation of management resources as shown in figure 5.

The next step would be to determine what allocation of resources would be required to match the demand. Clearly, the number of operators required will vary from area to area to match the operational demand that would, in turn, improve the overall efficiency of the system.

TABLE 3.
Evaluation of the demand for operation per subsystem in KOISP.

Subsystem	Tracts 1 and 2 of RBN	LBO	LBN	RBO	Tracts 5, 6, and 7 of RBN
Vulnerability	*Low* Recycled	*Low* Return-flow RF	*Low* Recycled	*Very high* Non-recycled	*Very high* Non-recycled
Water service*	*Low* TOL Q = ± 20%	*Low* TOL Q = ± 20%	*Low* TOL Q = ± 20%	*Very high* TOL Q = ± 5%	*Very high* Option PA*** TOL Q = ± 5% High Option RO**** TOL Q = ± 10%
Sensitivity of structures	*High* 1.3	*Very high* (not measured)	*Very high* (2.4)	*Very high* 2.2	*High* 1.3
Precision	*Low* ± 15 cm	*High* 10 cm as an indication	*High* ± 10 cm	*Extremely high* ± 2.2 cm *Unrealistic*	*High* ± 4 cm for option PA *Medium* ± 8 cm for option RO
Perturbations	*Low* probability *Low* magnitude	*Low* probability *Low* magnitude	*Medium* probability (High sensitive offtakes and Single Bank Canal sections)	*High* probability and magnitude (No water depth control; single bank; improved operational procedures)	*High* probability and magnitude (Improved operational procedures)
Operational mode and frequency	*Low* frequency FBC** from downstream tank	*Medium* frequency FBC from drainage outlets	*High* frequency checking of sensitive offtakes *Low* frequency FBC from downstream tanks	*Note:* A specific control project will have to be designed for RBO including some rehabilitation and/or modernization works.	*High* frequency FBC from drainage outlets Precise control of level (Improved operational procedures)
Class of demand	D1 *Low*	D2 *Medium*	D3 *High*	D4 *Very high*	D4 *Very high*

*The tolerance for time is irrelevant here as deliveries are continuous.

**FBC: Feedback control: monitoring downstream discharge or variation of volume and operating upstream issues.

***PA: Progressive adjustments.

****RO: Rotational operation.

Conclusions

The case study of Kirindi Oya illustrates the existence of heterogeneity of requirements for operational resources, even within a medium-sized mono-cropped irrigation system, based on an analysis of three operational domains: vulnerability, sensitivity, and perturbation.

System managers can address heterogeneity of operational demands through two different strategies. They may accept the reality of spatially variable operational requirements and allocate resources accordingly. Alternatively, the effects of spatial variability can be minimized by interventions in the physical system. In either case, it is expected that the improved evaluation of the spatial variability of demands for operation will be useful in the design of:

- more cost-effective strategies and procedures for operation, and
- priorities for rehabilitation or modernization of physical infrastructure.

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