Chapter 7
Mapping perturbations

CANAL OPERATION FOR CONTAINING INSTABILITIES

Steady-flow conditions are often the targeted status for canal operation, at least this is quite often the written rule in the plan for O&M. This status may occur in a very well-isolated and well-controlled system. However, in common practice, it is seldom achieved. This is often because, by the time the system is converging after the implementation of major changes and further fine tuning, new changes and numerous perturbations (disturbances) are already beginning to be reflected on flow conditions throughout the system.

The complexity of canal operation stems from the fact that it is necessary to deal with numerous physical components and individuals, and the process is fraught with uncertainties.

During an irrigation period, for example of one week or ten days, canal operation entails thousands of individual actions that have to be coordinated, sequenced (keeping in mind the time lag), checked and adjusted. The time lag, which is the water travel time between any two points, is a key factor that needs to be taken into account when operations are coordinated and implemented.

Therefore, it is much safer to consider permanent unsteady-flow conditions rather than a hypothetical steady flow.

The focus on steady flow also generates confusion in management interventions. It is quite common to see managers trying to stabilize both water levels and discharges through the operation of regulators, which is practically impossible. This confusion leads to chaos and increasing instability. It is preferable to consider unsteady conditions (variation in discharge) for canal operation and to focus the control of water levels at controlled points.

HOW INSTABILITY INCREASES DOWNWARDS

Perturbations of water variables (level and discharge) along an open-channel network are the norm not the exception. Thus, perturbation is a permanent feature of irrigation canals owing to the upstream setting of structures and compounded by intended or unpredicted changes in inflows/outflows at key nodes.

An example of amplification of discharge variation has been reported along the GLBC (Karnataka, India), as shown in Figure 37. Discharge is recorded every two hours at different locations along the main canal, and the graph displays the average variation recorded between two measurements, showing a sharp increase in variability reaching a high value of 3 percent of change every two hours at km 100. The bihourly increasing variation in discharge moving downwards also comes with variations and deficits in a longer period (Figure 38). This is an

FIGURE 37
Average variation in discharge every two hours along the GLBC, kharif 2006

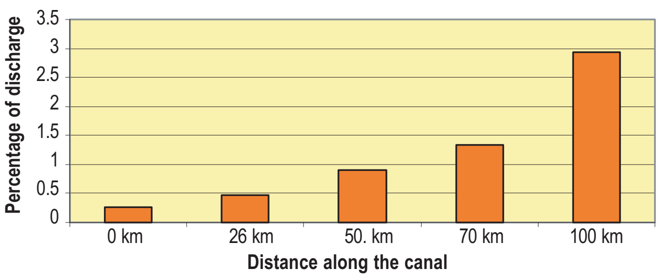
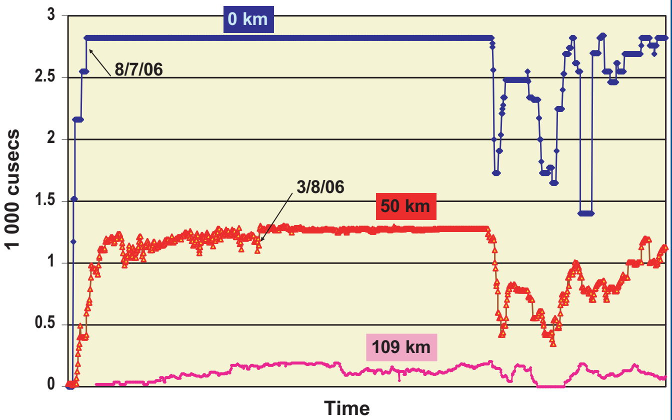


FIGURE 38
Hydrograph at various locations along the GLBC, kharif 2006 (July–October)



example of the well-known situation of increased instability penalizing downstream users.

THE CHALLENGES OF INACCURACY, UNCERTAINTY AND INSTABILITY

Imprecision and uncertainty plague the process of canal operation. The main issues that exacerbate imprecision, and thus contribute to the complexity of canal operations, are:

- Accuracy:
  - inaccuracy of data for water demand and main sources of water (inflows);
  - imprecision in anticipating the impact of the downward propagation of waves caused by operation itself;
  - imprecision in action or gate settings.
- Interventions:
  - inappropriate reactions to scheduled and unscheduled perturbations;
  - incorrect operation procedures;
  - illicit interventions.
- Unscheduled external perturbations:
  - from the source upstream – or unexpected runoff along the canal;
  - unexpected rainfall causing perturbations – may require closure of canals and disposal of additional water.

THE UNAVOIDABLE NATURE OF PERTURBATIONS

In many contexts especially in tropical areas, variability in both inflows and outflows is often a major characteristic of irrigation systems. For example, in the MUDA Scheme, Malaysia, the regulated supply accounts for only 35 percent (controlled supply from a remote reservoir [29 percent] and recycled drainage water [6 percent]) of the annual total water supply to the area (ITIS, 1996). Other components are direct rainfall (52 percent) and uncontrolled river flows (13 percent). In this context, fluctuations in inflows are as important as fluctuations in the demand as far as operational decisions are concerned.

In general irrigation systems might experience inflow fluctuations caused by:

- Return flow: overflows from distributary channels or from fields that return to the irrigation system – these vary over time.
- River diversion supply: run-of-the-river systems are subjected to greater variability in inflows than are reservoir types.
- Upstream canal operations: for a canal branching out of a main canal there is a certain control on the supply rate, whereas for a serial diversion – section of the main canal fed by the upstream reaches – control is low, i.e. the flow from upstream must be accepted at the supplied rate. Fluctuations at this point are the consequences of upstream operations.
- Single-bank: single-bank canals, i.e. canals without a built bank on the uphill side, also called contour canals, are quite common in slightly undulating topography. Large inflow fluctuations are the results of unregulated runoff entering the canal system during rainfall events (Plate 24).

Some systems however are not so much concerned by inflow perturbations, these are in particular the ones fed by a well regulated reservoir and serving a double bank canal network where intrusion is limited if not nil.

Features that are worth considering for inflow variations management are

- Localized storage: the presence of an intermediate reservoir within the system is an opportunity to damp perturbations.
- Return flow: diverting positive perturbations towards areas with return flow enables implementation of efficient reactions.
- Reuse system: positive perturbations can be diverted preferentially towards areas where it is known that water can be recycled downstream.

Plate 24
Single-bank canal experiencing runoff during wet season, KOISP, Sri Lanka.

OPERATION FOR SCHEDULED CHANGES AND UNSCHEDULED PERTURBATIONS

The strategy of management and canal operation is a twofold one: a strategy for implementing the scheduled changes (known and planned); and a strategy for dealing with perturbations resulting from imprecision and unscheduled changes.

In facing and managing scheduled changes and the imponderables (perturbations), a logical sequence would be to:

- implement, in the best way possible, the scheduled operation and distribution plan;
- deal with perturbations, both external and internal, generated by imprecision in the water plan and by the operations themselves.

If a perturbation is to be managed, it must first be detected in order to trigger a sequence of interventions that operators must be ready to implement. In the case of unscheduled perturbations, this implies that the managers and operators have to:

- check water variables (water levels, discharges, water demand, inflow, outflow, etc.) and compensate;
- manage the perturbation or let the system react without any intervention (diversion);
- increase the flow of information, both upwards and downwards.

WHERE UNAVOIDABLE ERRORS GO

Even with the better controlled gated system using modules (baffles), the best flow control that can be achieved is ±5 percent of the set value. Therefore, on a branch canal with 1 m^3/s at head, serving 10 modules of 100 litres/s each, the discharge can vary as follows:

- at the head: between 950 and 1 050 litres/s;
- at each offtake: between 95 and 105 litres/s.

As a consequence, the first nine offtakes of the branch withdraw a total flow varying between 855 and 945 litres/s. Hence, the remaining flow for the downstream offtake may vary between 55 and 145 litres/s. Consequently, the last offtake may face

Plate 25
Tail-end spill on a canal equipped with rigid offtakes (baffles), Tadla, Morocco.

Plate 26
Uncontrolled direct outlets on the main canal as sources of perturbations, Sindh, Pakistan.

a high shortage of water (-45 litres/s) or a high surplus (+45 litres/s). For the latter, a spill is needed in order to evacuate the water in excess (Plate 25). This illustrates the tail-ender concept in irrigation systems – the last offtakes have to compensate for the errors further upstream in the system.

OTHER SOURCES OF PERTURBATIONS

Illicit operations

Operations carried out by users without permission/authorization are an important source of perturbations in a CA. Illicit operations are usually attempts by users to divert more discharge than they are entitled to or that the running conditions allowed. This phenomenon aggravates rapidly further downstream as more people try to compensate for the propagating deficit. It ultimately results in large portions of the downstream CA receiving little if any supply.

Illicit operation can also be a problem during the intermediate season in the event of unexpected rain. The unauthorized closure of offtakes can generate a surplus of flow within the system that may create some physical damage if the canal is not well protected.

Direct outlets

Errors are not all generated by operation and management or by external variation in flows. Outlets offtaking directly from the main canal without any effective control mechanism (Plate 26) are common in many irrigation systems.

The issue of direct outlets is socially critical because it always results in extra pressure on irrigation managers. The consequence is that sometimes a large fraction of the available flow entering the system cannot be managed effectively by operators. In one system in Pakistan, about 40 percent of the flow was not under the control of the managers. This is not only an issue of equity. Uncontrolled outlets on the main canal can generate high discharge variations. This has consequences on the performance and resulting service to users served by the controlled outlets.

PROPORTIONAL SYSTEMS

In proportional systems, the service is proportional by design and this is achieved no matter what the inflows are and what the variation in internal flows are (where the structures are properly set and installed). This is why the proportional systems, also called structured systems, are easy to operate, they have the lowest O&M costs.

However, these systems have other constraints, in particular with regard to service to users. Historically, they have been widely used in traditional irrigation systems, e.g. in Indonesia, and in more structured multilayered irrigation systems, e.g. in the Indo-Gangetic Plains, as an inexpensive technique for distributing water to the maximum numbers of farmers and area of land. The proportional system is reliable where the sharing of the flow is ensured by a single proportional division structure. Where proportionality results from two separate structures, then there is a high risk of seeing the proportionality "drifting" because of changes in hydraulic conditions (sedimentation and erosion).

DIMENSIONS OF PERTURBATIONS

As mentioned above, perturbations have different origins. For mapping perturbations, it is important to know their origin, timing or frequency of occurrence, amplitude, and then how the system reacts to them. It is important to know whether the system is self-reacting or whether specific interventions need to be carried out.

LINKING SENSITIVITY AND PERTURBATIONS IN A CONSISTENT WAY

Sensitive regulators are good points at which to detect perturbations. A small variation in discharge will generate a noticeable variation in water level at these structures.

At the subsystem or reach level, it is critical to know whether the system absorbs or propagates the perturbations. Figure 39 presents two different systems in terms of their capacity in propagating/absorbing perturbations. A discharge change was generated at the head of each canal (Regulator 1 in Figure 39). Then, measurements were made at each reach in order to estimate how much of the change was retrieved downstream when no operation was carried out to change the setting of the irrigation structures.

The two systems presented indicate very different behaviours. The Kirindi Oya Irrigation System Project (KOISP) propagates the change regularly. In absolute terms, it declines regularly, but in relative terms the change remains steady. This means that the system is more or less proportional.

The Mahaweli-B system is heterogeneous, either fully propagating or highly absorbing. The initial change is absorbed significantly in two reaches (the first reach downstream of Regulator 1, and the reach downstream of Regulator 5). Reaches 2, 3 and 4 propagate the full change downstream. After Reach 5, only 20 percent of the initial perturbation remains in the main canal, 80 percent of the water surplus being diverted through sensitive offtakes.

The strategy for canal operation and water management will differ in these two systems. Without going into great detail:

- The KOISP propagates and shares the perturbations: For scheduled changes, it is necessary to operate all the regulators with the same care. No specific action is required in the event of unscheduled perturbations.
- Mahaweli-B either propagates or absorbs perturbations. Operation for scheduled changes should focus primarily on Reaches 2 and 6 in order to ensure that they do not divert the input variation. For unscheduled changes, the offtakes

FIGURE 39
Analysis of perturbation absorption along two canal systems

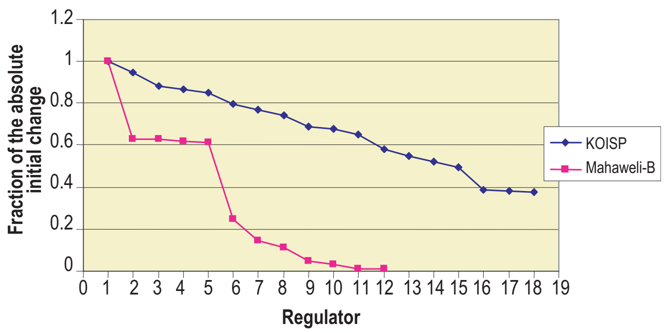


TABLE 19

Perturbations – summary of meaningful characteristics for operation and possible responses

Type of perturbations	Solutions (options for managing perturbations)
Positive perturbations:	Share the surplus among users, particularly relevant where the system is proportional. Divert and store the surplus into storage capacity.
Nature (inflow-outflow – internal)	
Magnitude (water-level fluctuation – relative discharge variation)	
Frequency	
Negative perturbations:	Compensate from storage.
Nature (inflow–outflow – internal)	Check for immediate correction.
Magnitude (water-level fluctuation – relative discharge variation)	Reduce delivery to some offtakes with compensation later on (less sensitive/vulnerable areas, delivery points with storage facilities, with alternatives source of water).
Frequency	

of these reaches have to be operated carefully in order to distribute equitably the changes in the inflows.

An illustration of how this information can be used to organize control at subsystem level in Mahaweli-B is as follows:

- Downstream of Reach 1, the precision of flow control for a scheduled operation depends considerably on upstream headworks setting, but also on the first reach setting. If Regulator 2 is not properly adjusted, then the scheduled change in flow implemented at the headworks will be reduced significantly within the first reach (40 percent).
- Unscheduled perturbations in the first reaches are mostly absorbed in Reaches 1 and 5, after Regulator 6 only 20 percent of the perturbation remains in the main canal.
- Between Regulators 2 and 5, perturbations are transferred without change. Therefore, Point 5 should receive a lot of attention and should be checked very often in order to control the three upstream reaches.

MAPPING AND MANAGING PERTURBATIONS

Mapping perturbations means identifying and characterizing their dimensions (Table 19) as described previously:

- origin;
- frequency and timing;
- location;
- sign and amplitude;
- options for coping.

Example from the SMIS – Step 3. Perturbation

Main supply

There is only one source of surface supply, the Koshi River. The supply ranges from 60 m^3/s in the monsoon period to 15–25 m^3/s in winter and spring. However, the supply is stable on a weekly basis. Variations in the supply are generated by the necessity to close the intake and flush out the sediment trap upstream at monsoon time. This can take two hours a day during periods of high sediment load in the river. This generates perturbations at the main intake.

The hydropower plant downstream of the trap reach is also a potential source of perturbation of the flow during the low-peak season, when the main entrance flow is cut in order to raise the water level in the desilting basin, and when discharge is reduced as a consequence of this.

FIGURE 40
Variation in water level at CR4, Jhumka Minor, monsoon season

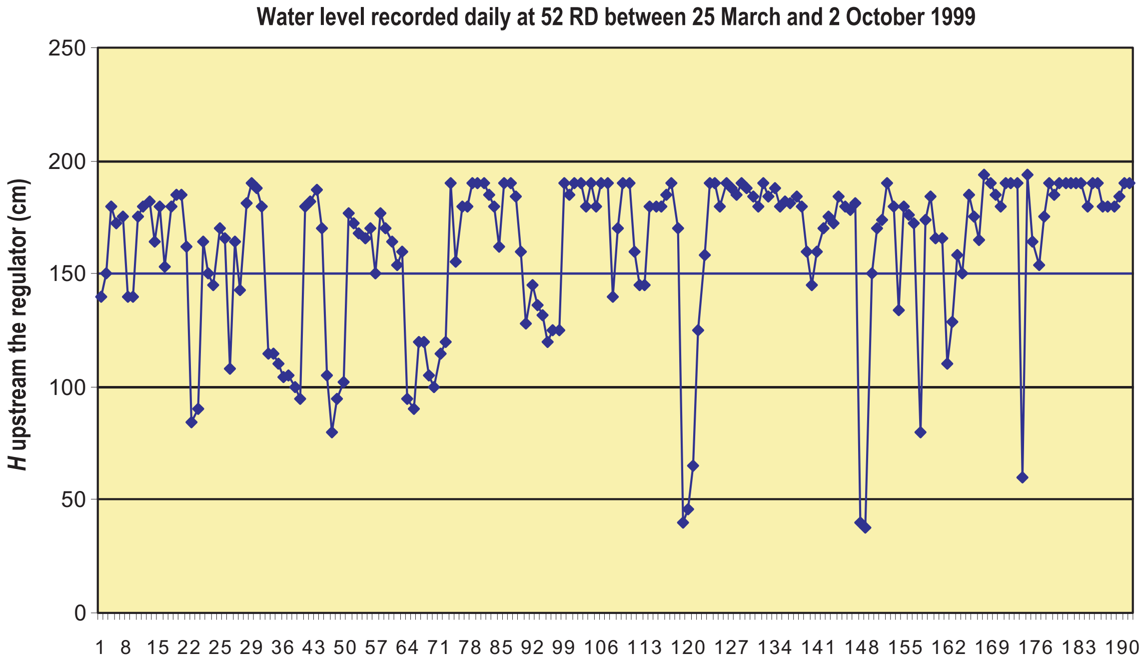
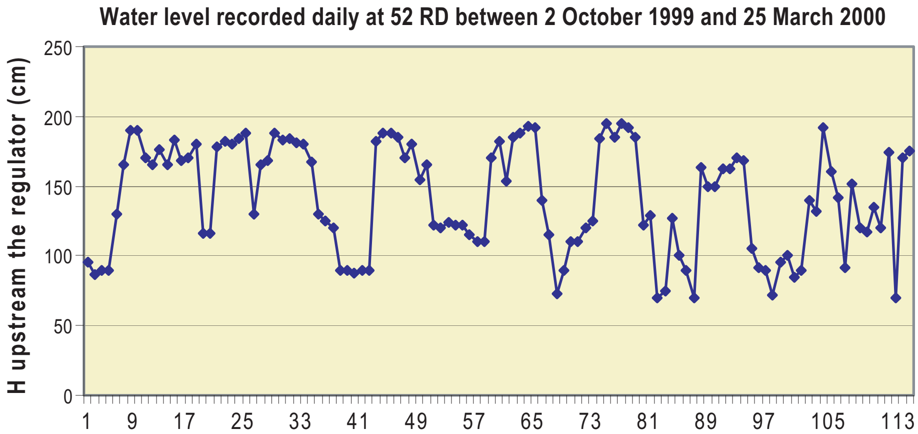


FIGURE 41
Variation in water level at CR4, Jhumka Minor, winter season



Supply to secondary canals

The supply to secondary systems has been reported as varying significantly (Figures 40 and 41). This may be the consequence of the low control on water level. Throughout the year, water-level variations of up to 25–30 cm occur on a regular basis. Although lower, daily variations can reach 9–17 cm. These variations, associated with sensitive diversion structures offtaking at CR2, CR4, CR6 and CR7, are one of the two main causes of the significant variation in supply (the other being illegal direct interventions on diversion structures).

TABLE 20
Recorded precision of control along the CMC and related discharge variation

Cross-regulator	Day-to-day average variation in water level upstream the CR (not including major changes) (cm)	Sensitivity of the CR	Sensitivity of the offtake (head of secondary canal)	Discharge variation at secondary canal intake, in ± target (%)
CR1		2.0	0.60	
CR2	12	0.5	2.00	± 24.0
CR3	15	3.0	0.80	± 12.0
CR4	17	1.0	1.60	± 27.0
CR5	9	1.5	1.00	± 9.0
CR6	11	0.5	4.30	± 47.0
CR7		1.0	3.40	
CR8		1.5	0.35	
CR9	13	0.5	0.50	± 6.5
CR10		0.1	0.70	
CR11	11	0.5	1.50	± 16.5
CR12		n.a.	n.a.	

However, even with the existing structures, the control of the water flow can be improved easily. The physical condition of the cross-regulators is fine, and each secondary canal is equipped with a measurement weir. This all allows for good control of supply to the secondary canals. Therefore, the issue is one of organization of operation rather than being about the physical infrastructure itself.

Table 20 shows measured daily variations in water level (day-to-day difference after having excluded the high variation corresponding to a temporary disruption or closure of the canal) for 7 of the 12 regulators. The values express the precision (or tolerance) with which the control is exercised. Multiplying the value by the sensitivity of the nearby offtakes leads to an estimation of the control on discharge exercised.

The higher variation in water level recorded at CR4 is not explained. CR3 has a higher sensitivity than CR4 and still exhibits a much lower variation.

The high variation at CR11, having a low sensitivity indicator (0.5), results from the high variation in discharge reaching the end of the system.

The records on water-level variation do not show any particular trend. This means that there is no increase in perturbations along the CMC.

Three of the six secondary canals evaluated have discharge variations of more than 20 percent as a consequence of the variation in water level.

Chapter 8
Water networks and water accounting

The canal and drainage systems within the service area need to be properly understood in order to develop appropriate and workable water management and operational strategies, ones that fully consider constraints as well as opportunities. In order to achieve this objective, it is necessary to map the flow routes (network) and specify (as much as possible) the flows in terms of timing, flow rates and volumes (water balance).

Water accounting, also called water balance, refers to the accounting of all the influxes and outfluxes of water in a given space and time. It must consider all water (surface water and groundwater streams, conjunctive use, storage and recharge, etc.) that enters and leaves a defined area in a particular span of time. Thus any recycled water within the spatial boundaries is not included in the water balance. It should take into account quantity and also water quality aspects, the use of lower quality water, and the impacts of agriculture practices on water resources.

Although the concept of conjunctive use of irrigation water has been around for many decades, it is only in the last decade or so that systematic and comprehensive water balances have been carried out in major canal systems in order to gain a better understanding of the flows and water resources.

This chapter briefly describes mapping of water network and then introduces the concept of water accounting and its use as a powerful decision-making tool for the operation and management of an irrigation system at different levels of management setup. The RAP includes a water balance at the project or scheme level, which is done with the available data and is useful for making decision about water conservation. In addition to the water balance done as part of the RAP, MASSCOTE recommends making water accounting a part of routine management.

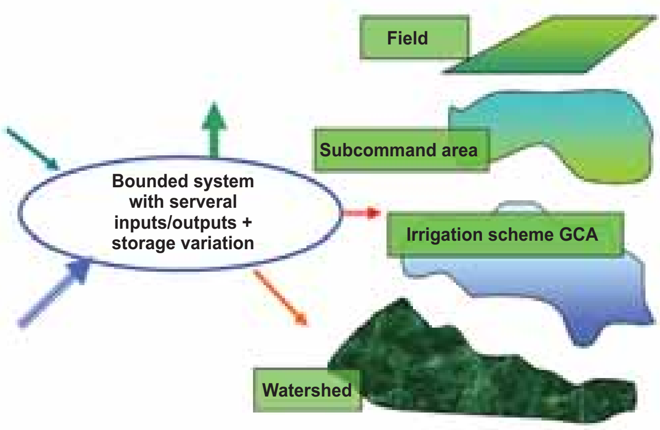
MAPPING WATER NETWORKS

A thorough knowledge of all existing and potential sources of inflows and outflows in service area is required for efficient canal operation and good water management practices. This is done, in MASSCOTE, by assessing the hierarchical structure and the main features of the irrigation and drainage networks, natural surface streams and groundwater, and the mapping of the opportunities and constraints, including drainage and recycling facilities. Thus mapping of water network includes not only irrigation canal and drainage network but also any stream and/or natural channel and drain that crosses the service area and which interacts (or may interact in future) with the canal and drainage network and storage facilities. This also includes escapes that evacuate water to the drainage network.

The geographical distribution of the canal system and infrastructure within the service area is usually quite well known. However, this is often not the case for the drainage system, which typically has not been developed fully or has been developed in various phases, often with no reliable record of precise locations and of what has been maintained and is functional. Information on where and how much water is drained may help managers and decision makers in assessing the potential of recycling this water.

Also information regarding the layout and the (dry) discharges of streams that could be used for irrigation, if the topography allows, in water short system is often

Figure 42
The water accounting system approach and the physical scales at which accounting might apply



not available, thus managers do not consider water from these streams in allocation and distribution plan.

Mapping of water network is particularly important for developing practical water management strategies and effective water resource allocation, in particular in (seasonal) water short system.

WATER ACCOUNTING FOR WATER MANAGEMENT

Water accounting should be considered as the foundation of water management and operation in the sense that it defines the requirements (demand) for surface water service. Through a spatially disaggregated water balance it is possible to identify: (i) various flows within the service area; (ii) the needs that the managers must satisfy; and (iii) opportunities for sharing the cost of operation among more users than only the farmers. It also gives a good indication of the efficiencies of water management and allows the identification of environmental problems, such as waterlogging.

Where done properly, a water balance can be used by managers to assess the conditions under which canal operations take place.

A comprehensive water balance is critical:

- at the initial project stage, for setting water services, designing appropriate management strategies and operational procedures;
- later, for appraising modernization strategies to achieving updated performance targets.

Three important features for water balances are:

- Delineation of the physical boundaries: upper limit, lower limit and horizontal limit. Figure 42 presents the components of the water balance for spatial boundaries.
- Time frame: year, season, month, fortnight or ten-day period.
- Focus: water quantity and water quality.

Water quantities must account for all inflows and outflows, plus changes in internal storage. For water quality, the process is more complex and depends considerably on the biochemical and physical properties with time of the parameter under consideration. Along their paths through the water cycle, chemicals are absorbed, degraded, transformed, lost through aerial reaction, etc. Therefore, mass conservation applies to water but does not always apply easily to chemical constituents.

Depending on the purpose, water accounting could be done on a seasonal or yearly basis at the entire scheme level and for submanagement units in order to facilitate management decisions.

DELINEATION OF THE PHYSICAL UNITS WITHIN THE SERVICE AREA

There are many criteria to consider in defining the physical boundaries for an irrigation water balance. A water balance can be conducted for a field, a farm, a submanagement unit, an entire irrigation service area, and a river basin. Whatever the unit of evaluation, it is necessary to define upper, lower and horizontal boundaries of space. Table 21 presents an example of defining spatial limits for water balance. It shows that

TABLE 21
Spatial boundaries of various areas

Space	Upper boundary	Lower boundary	Horizontal boundary
Farm	Crop canopy	Bottom of rootzone	Farm fields
Conveyance system	Water surface	Canal bottom	All diversions, spills and discharge points
Water district without groundwater pumping	Crop canopy	Bottom of rootzone	District
Water district with groundwater pumping	Crop canopy	Bottom of aquifer	District
Water district without groundwater pumping, but with a high water table	Crop canopy	Bottom of aquifer that is tied into the high water table	District

Source: Burt, 1999.

groundwater use or a high water table can have a significant influence on the lower limits of the water balance.

Spatial boundaries for a water balance to assist decisions regarding system management and operation would include:

- the gross service area of the project: often used as the first approach to examine a global water balance;
- canal hierarchy: main, secondary, tertiary and quaternary;
- institutional management: federation of WUAs, WUA, farmers organization.

The above criteria can be included in the definition of the water balance. However, one of the more important aspects is pragmatism. Units for the water balance should be based on realistic boundaries for which flows can be either measured or estimated with reasonable accuracy. In an ideal situation, a water balance is conducted for the entire irrigation service area and each management subunit in order to allow the managers and operators to make decisions within their own subunits as well as at the entire project/system level. However, whatever unit is chosen for the analysis, the boundaries must be clearly set and understood.

Setting the spatial as well as the temporal boundaries for a water balance is very important. The failure to set these limits properly is often a main reason for errors made in computing water balances.

SETTING TEMPORAL BOUNDARIES

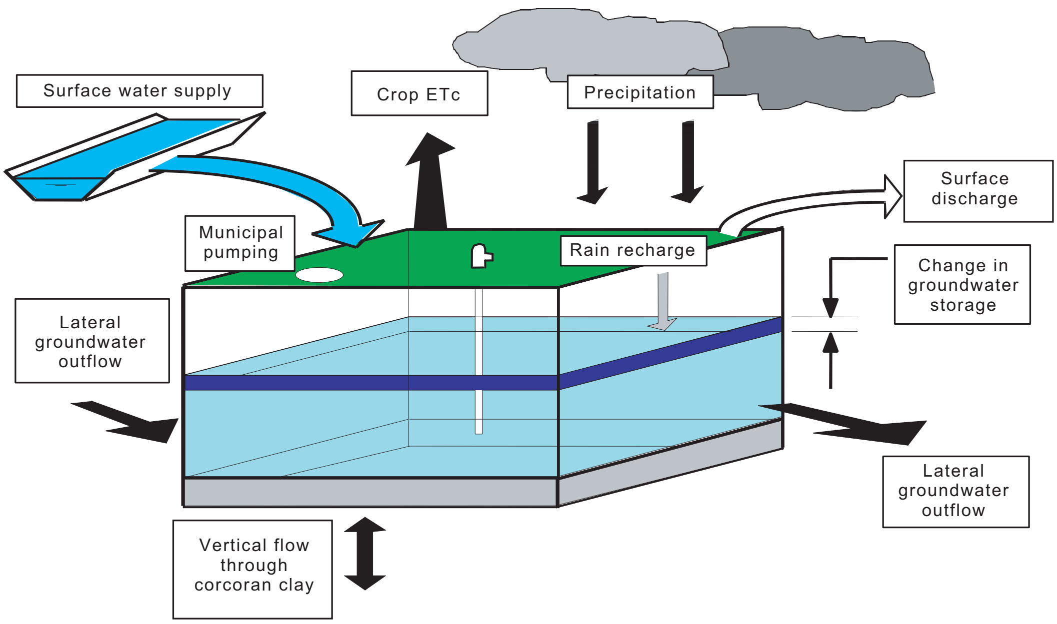
Temporal boundaries are critical when computing a water balance. Depending on the objectives for which the water balance is conducted, temporal limits can be set as multiple years, one year, six months, an irrigation season, monthly or fortnightly. For example, making long-term recommendations on the basis of only a one-year water balance is not recommended because such data are often not representative of normal conditions. The values of most of the water balance inputs, such as rain, surface allocations, and evapotranspiration vary from year to year. For the purpose of making long-term recommendations, 4–5-year average values from water balances done on a yearly basis must be considered.

For the purpose of evaluating modernization strategies, a time frame of a year, six months or a single irrigation season is advisable. Monthly or fortnightly water balances are required where the objective is to use the values for real-time management decisions. However, it is often difficult to assess changes in the groundwater storage on a scale smaller than one year. Nevertheless, it is necessary for managers and operators of the irrigation system to keep an account of where water is coming from and where is it going to within the management units in order to be able to make efficient decisions regarding water conservation, allocation and distribution.

WATER BALANCE TERMS

Whatever the spatial unit under consideration, a number of basic flow parameters need to be evaluated (Figure 43):

FIGURE 43
Water flows relevant for water accounting in agriculture



Source: Style and Burt, 1999.

- irrigation diversions;
- surface runoff into and out of the spatial boundary;
- evapotranspiration (ET) from fields and other areas such as canals, drains and other non-irrigated areas;
- rainfall within the spatial boundaries;
- surface drainage, lateral groundwater flows and vertical drainage within the lower boundary limit.

Irrigation Diversions

Irrigation diversions are often measured through measurement devices at bifurcations. For a water balance, irrigation diversions entering the spatial boundary must be known.

Rainfall

Rainfall should be measured with sufficient density of points to account for the spatial variability of precipitation, especially if the time frame of events is short. It is common to see large irrigation projects covering dozens of square kilometres that have only one rainfall gauge despite a high variability of rainfall during storm episodes. In practice, the number of rainfall gauges should be adjusted to the local spatial variability of the precipitation. A reasonable distribution is one gauge every 5 km in a medium-size system, and one every 10 km in a large system.

Evapotranspiration

Evapotranspiration or crop water use is usually the largest and the most important component of water balance. It is obtained as the product of crop area and the estimation of crop evapotranspiration (ETc). However, where non-crop vegetation (trees, bushes, etc.) covers a non negligible part of the CA, its evapotranspiration also constitute a significant part of the water balance.

Crop evapotranspiration or crop water requirement can be assessed by multiplying the reference evapotranspiration and the crop coefficient: ETc = *Kc* × ETo; where: ETc is crop evapotranspiration; ETo is the reference evapotranspiration; and *Kc* is the crop coefficient.

The reference crop evapotranspiration represents the evapotranspiration from a standardized vegetated surface. The only factors affecting ETo are climate parameters. Thus, ETo can be computed from weather data. There are a number of methods for calculating ETo, but FAO recommends using the FAO Penman-Monteith method (FAO, 1998). Alternatively, the FAO CROPWAT program can be used to assess both ETo and Etc (see CD-ROM attached).

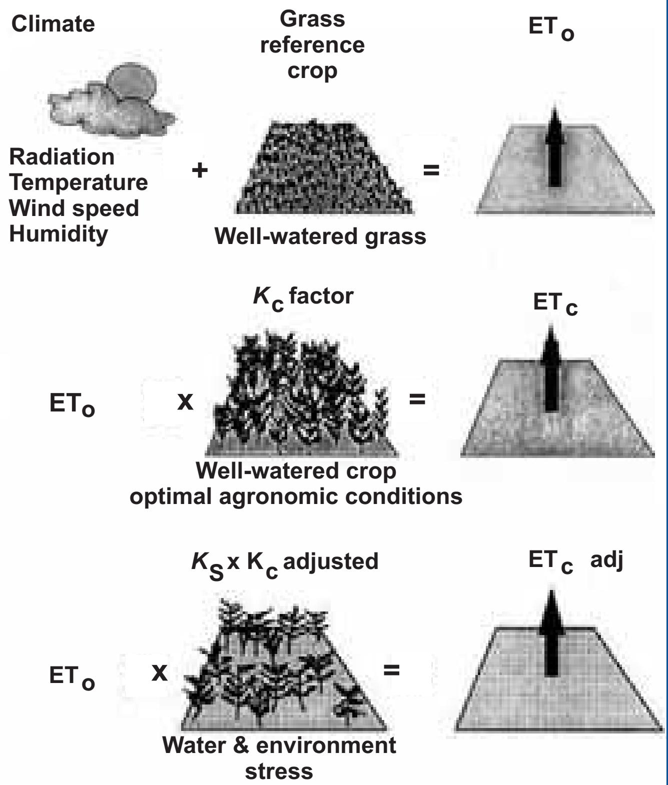
Some weather data (temperature, solar radiation, relative humidity, and wind speed) are required in order to calculate ETo irrespective of the method used for its calculation. However, it is not always easy to obtain these data from the nearest meteorological station. Where no data are readily available, climate databases such as CLIMWAT (FAO) or the Climate Atlas of the International Water Management Institute (IWMI) provides values for weather parameters needed for ETo calculations. These source also provide good estimates of ETo.

The crop coefficient, *Kc*, is basically the ratio of ETc to ETo, and it depends mainly on the crop variety and the growth stages of the crop. FAO (1998) provides *Kc* values for different crops and their growth stages, which are used widely throughout the world for estimating ETc.

The ETc calculated through above equation is the evapotranspiration from crops grown under optimal management and environmental conditions, with good water availability and no limitations of any other input. In most cases, actual crop water use differs from this potential ETc because of non-optimal conditions, such as the presence of soil salinity, water shortage, waterlogging, pests, etc. These conditions may reduce the evapotranspiration rate below ETc. In order to address this problem, a water stress coefficient, *Ks*, is introduced into the equation (Figure 44). *Ks* is dependent on the available soil moisture and ranges between 0 and 1. When the rootzone depletion is lower than water that is readily available to the crop, *Ks* = 1, meaning that water uptake to plants is equal to ETc where the soil is wet: ETc adj = *Ks* × *Kc* × ETo.

FAO (1998) and Annex 3 provide more information on evapotranspiration calculations.

FIGURE 44
Reference ET, crop evaporation under standard (ETc) and non-standard (ETc adj) conditions

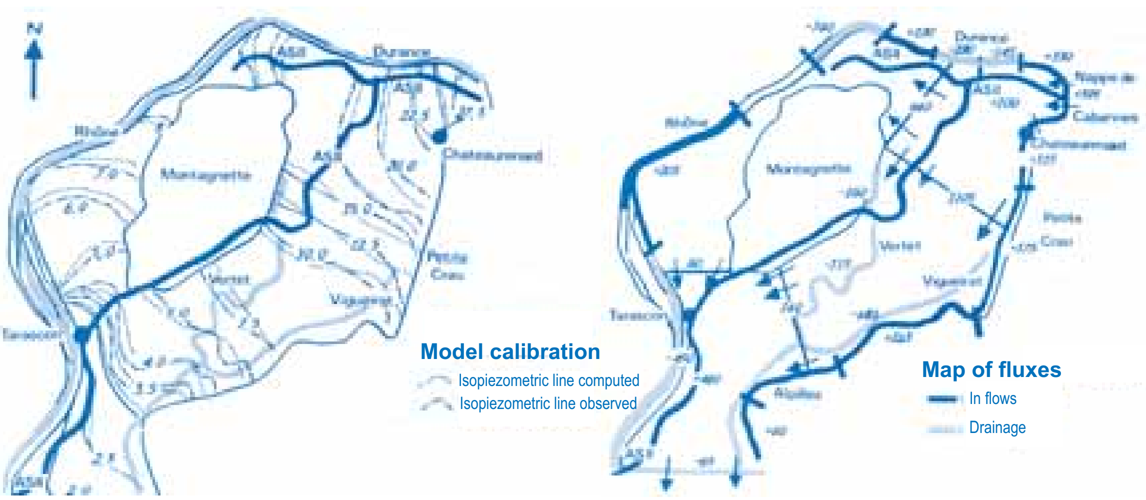


Source: FAO, 1998.

Drainage

Drainage should be measured at key points, particularly when it leaves the spatial boundary set for water balance, and possibly monitored for water quality if necessary. Water quality monitoring of drainage water from

FIGURE 45
Example of use of hydromodelling to simulate groundwater flows (right) after calibration with water-table levels (left), Tarascon, France



irrigated areas is important, in particular where this water is to be used for irrigation downstream, in order to keep a check on the safe levels of agrochemical loads.

Groundwater

Groundwater fluxes, i.e. lateral flows and vertical drainage, are often the most difficult aspects to handle in a water balance. While direct measurements of groundwater flows are not possible, water-table levels can be measured, and groundwater or hydrological modelling (Figure 45) can be used to reconstruct the flows using trial and error and comparison with field data. However, it is not always easy to calibrate these models owing to a lack of empirical data. An easier way of monitoring the changes in groundwater is to install monitoring wells, which could be made locally.

Groundwater is an important component of water accounting. The setting of the lower spatial boundary usually determines whether the use of (shallow and/or deep) groundwater is considered a supply or a mere recirculation of surface water supply and rainfall. However, a distinction between shallow groundwater and deep groundwater should be made in the water accounting procedures if they are to be conducted for assisting in management decisions, particularly in semi-arid and arid regions.

In case shallow groundwater (less than 20 m) is incorporated in the lower spatial limits of the water accounting system, there is no need to take account of additional water supply from the tubewells fed by the shallow groundwater. Only lateral sub-surface flows entering and leaving the limits of the system should be considered.

Generally, water extracted from deep groundwater (more than 20 m), is considered beyond the limits of the system. Therefore, the specific water supply from deep ground water is usually added to the inflow.

In order to avoid double-counting of water entering into the spatial boundary of the water balance area, it is necessary to clearly identify the groundwater that is pumped within the spatial boundary and which may be considered as the recirculation of surface water and rainwater entering the spatial boundary. This groundwater should not be accounted for whereas groundwater that is pumped outside the spatial boundary but is used for irrigation within the boundaries of water balance should be taken into account as inflow/supply.

CONFIDENCE INTERVALS

A certain amount of error or uncertainty is inherent in all measurement or estimation processes. Therefore, the true or correct values for the water volumes needed to calculate terms such as "irrigation efficiency" are unknown. Estimates must be made of the component volumes, based on measurements or calculations.

One method of expressing the uncertainty (Annex 3) is to specify the confidence interval (CI) that is associated to the estimate of one value. If it is believed that a reasonable evaluation of data indicates that the correct value lies within 5 units of 70, then it should be stated that the quantity equals 70±5. More specifically, when discussing an estimated quantity, the meaning of a CI should be illustrated, e.g.: "The investigators are 95-percent confident that their estimate of the irrigated area in the project is within ±7 percent of 500 000 ha (between 465 000 ha and 535 000 ha)."

Statistically, a CI is related to the coefficient of variation (CV), where: CV = (mean) / (standard deviation); CV has no units. In addition, CI = ±2 × CV, where the CI is expressed as a fraction (%/100) of the estimated value. Stated differently, if the CI is declared to be 0.10, this means that the ±2 standard deviations cover a range of ±10 percent of the stated value.

Assuming a normal distribution of data, then in about 68 percent of cases the true value is found within plus or minus one standard deviation of the estimated value. Similarly, in about 95 percent of cases (from which comes the "95-percent confident" statement), the true value is found within plus or minus two standard deviations of the estimated value.

Combination of independent parameters

Many terms in a water balance are the result of the addition or multiplication of individual terms and parameters. There are methods for calculating the CI of such aggregated parameters, such as $m = m_1 + m_2$ or $m = m_1 \times m_2$ when these parameters and terms are independent.

Clemmens and Burt (1997) provide more detail on CIs.

HIGH UNCERTAINTY ON THE CLOSURE OF WATER BALANCE

The closure of a water balance is a term or a set of terms of the balance that cannot be measured but have to be estimated from the assessment of the other terms. The closure of water balance is always computed with a high uncertainty because it accumulates all the uncertainties of the other terms. This aspect can be illustrated with three cases: perennial vegetation, groundwater, and seepages.

Non-crop vegetation of the gross command area

Non-crop vegetation in the CA might be an important term of the water balance as many trees thrive on water made available from surface irrigation. This phenomenon can be assessed visually by looking at areas within and outside the CA. In dry zones of the tropics, there is often a clear difference in terms of type of vegetation and foliar development, and, as a consequence, in terms of water consumption. However, it is not easy to estimate the areas covered and the unit consumption.

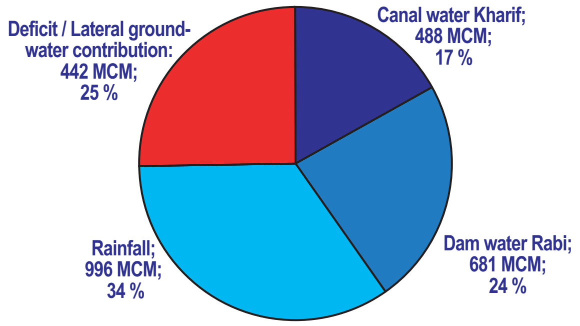
The value of the perennial vegetation water consumption can be computed as the closure of the balance after having estimated all the other terms.

Net lateral groundwater contribution

The lateral net contribution of groundwater (not including recharge from the canals and surface of the CAs) can be estimated as the closure of the other terms, and as such known with high uncertainty.

In the case of the GLBC (Figure 46), with high inaccuracy on the other terms of the balance, the initial estimation is that the closure is probably known at ±55 percent.

FIGURE 46
Closure of the balance for lateral groundwater in the gross command area of the GLBC



Thus, the groundwater lateral flows might be between 238 MCM and 732 MCM per year. Some further investigations need to be made in order to reduce this uncertainty by improving the assessment of the other terms.

Seepage measurement

Seepage measurement is also a good example of how a closure of a water balance is fraught with uncertainty. Most experts recommend measuring seepage using ponding tests, from the records of drop in water level in an isolated reach (no inflow and no outflow) taking into account the evaporation.

The other possible method, the inflow–outflow method is much less precise. It consists of measuring the flow in the canal at two locations and deducting all the inflows and outflows occurring between the two sections considered: Seepage = Inflow - Outflow.

In order to provide an accurate estimate of seepage, the water lost should be significantly greater than the error in measuring the flows.

The problem of accuracy can be illustrated through the case of the main canal in the GLBC project. A measurement campaign was done to assess the seepage. Discharge was measured at 0 km and 50 km in order to estimate the losses through seepage. Inflow was 78.90 m^3/s, total outflow was 73.36 m^3/s, leading to a seepage estimate of 5.6 m^3/s for 50 km, i.e. 0.11 litres/s/ml. The problem is that the uncertainty about the inflows and outflows is such that this result is probably known plus or minus 200 percent.

Even with an ideal situation where inflows and outflows are known in the field at 2.5-percent accuracy, the inflow is known thus ±1.97 m^3/s and the outflow ±1.83 m^3/s. In these circumstances, the seepage estimator is know at ±3.8 m^3/s, and thus lies between 1.8 m^3/s and 9.4 m^3/s. This kind of figure cannot be conclusive on seepage losses and related water savings from canal lining.

THE RISK OF DOUBLE-COUNTING

The risk of double-counting in a water balance is real and it is always necessary to ensure that only the fluxes through the boundary of the system are accounted for.

A typical example of this is groundwater pumping or recycling from drainage. While it is important to have an estimate of their value, they should not be counted in the water balance if this water has already been accounted for as inputs either from the rain or from the irrigation supply. Only external water to the system should be counted, which can be deep groundwater and lateral water from aquifers. The same applies for the surface recycling facilities.

USE OF WATER BALANCES AT MANAGEMENT LEVEL

The rationale behind water balances may differ depending on whether the goal is to use the overall water balance within the gross service area or to evaluate the management and operations of potential modernization strategies. Water balances can be useful to the management of a canal system in several ways:

- to set up an efficient and user-oriented water management strategy;
- to manage water in real time during the season and operate the system accordingly;

- to assess performance in water management as well as in delivering the service by providing an estimate of external indicators.

Water balances for assessing water management strategies

Water balances are vital to understanding issues such as the potential for improvement (e.g. water savings), the different uses of water within the service area, and, particularly, non-crop water use.

In Cabannes, France, a modernization project early in the 1980s was designed explicitly on the basis of a water balance. The scheme was divided into two sections:

- The upstream part, devoted mainly to cereals and field crops, was modernized using modern surface irrigation technologies (mainly furrow irrigation) to maintain high the recharge of groundwater for the downstream part of the system as well as for some domestic supply.
- The downstream part, devoted mainly to orchards, was modernized with drip irrigation using shallow groundwater pumping stations.

The water balance of the whole system was checked carefully in order to ensure a sustainable supply for both sections, in the knowledge that the modernized downstream part would need to divert much less water with localized irrigation technique compared with the earlier surface techniques.

Water accounting for institutional arrangements among users

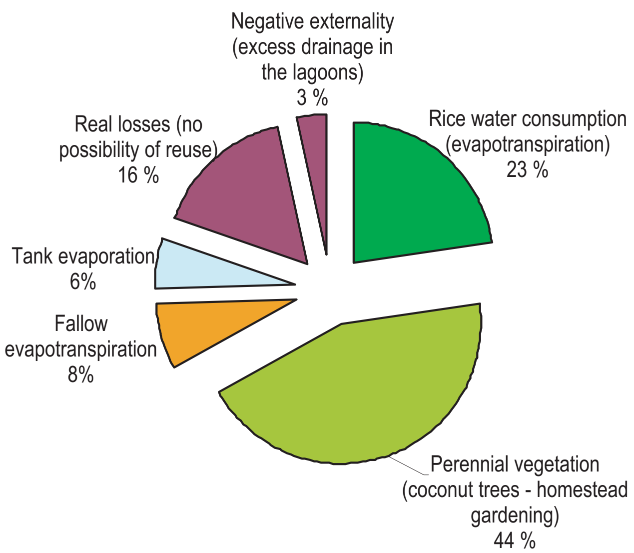
In many cases, canal systems provide water services to different types of users, regardless of the fact that the main objective is to supply water to crops. Multiple uses of water are the common rule and not an exception.

Water for crop use and water for other uses

Although most irrigation systems have been built solely to supply water to crops during dry periods, in practice some of them have been feeding other uses of water, from the management losses or natural seepages. This is often the case for rice systems, where water ponding generates high shallow groundwater flows that might be tapped by others users.

In old, gravity-fed systems in southeast France, figures of less than 25 percent of annual surface water supply for irrigated crops are not unusual, the remaining fraction being shared by groundwater recharge and surface-stream supply. This phenomenon is not well documented in the irrigation systems in developing countries. However, one such example is the Kirindi Oya irrigation system in Sri Lanka, where water for natural vegetation and homestead gardens in tropical humid areas takes an important fraction of the irrigation water input (Figure 47).

FIGURE 47
Water balance in the Kirindi Oya Project, Sri Lanka



Source: Renault *et al.*2000.

In these types of systems, water accounting may have a strong impact on the identification of different uses of water, and to a lesser extent on the qualification of users or beneficiaries that take advantage of water management. It is the basis on which managers, users and beneficiaries can discuss management strategies within the project. This can assist in initiating a discussion on how the cost of operating the system should be borne by all stakeholders and not only irrigators.

Water accounting for performance assessment

Water accounting for canal operation is also useful for performance assessment within a period of time (ten days, month, season and year). In particular, it is useful in comparing water deliveries with water uses. Figure 47 shows the water balance of the Kirindi Oya system (for one full year (1998), considering the two crop seasons as well as the fallow period. This water balance was carried out because of the presumed poor performance of irrigation management. The fact was that the water duty (water delivered for irrigation from the main reservoirs divided by the CA) was dramatically high, values of 3 000–4 000 mm/season were not unusual, this was the initial motivation for investigating the matter.

The water balance has changed completely the way of looking at performance in this project. The striking facts that were brought to light in 1998 were:

- Crop evapotranspiration accounts only for 23 percent of the total water supply (irrigation plus rainfall).
- The bulk of the consumption lies in homestead gardens and coconut trees, fed mostly by lateral flows from the irrigated areas, and which are very beneficial for the people.
- Other users are those who fish in the tanks, and cattle growers for their use of the fallow period on paddy-fields.
- A win–win situation was identified for the lagoon, where excessive freshwater from irrigated areas are generating negative impacts for a total of 3 percent of the total water volume.
- The real water losses (at the sea mouth, where no more value can be assigned to freshwater in the project) account for 16 percent.
- The potential for water savings (16 percent + 3 percent) is significant compared with crop use (23 percent) although it is necessary to consider that part of these water losses occur at flood times and would be difficult to value.

A water balance can also provide estimates of external indicators, such as irrigation efficiencies, ratio of relative water supply (water required vs total water available), and crop yield per unit of water supplied (Chapter 4 and Annex 3).

Water accounting for canal operation

Water accounting can also be important for real-time decision-making for adjusting operation and upstream deliveries. On this short time scale, it is more a combination of indicator assessment and water accounting.

For example, the presence of excessive drainage flows downstream from a subarea can indicate that there is too much water entering the CA compared with the current use. Observing this can be a trigger for action. The managers need to know: (i) by how much to reduce the inflow to the CA in order to reduce significantly the drainage without creating a water shortage in the downstream part of the CA; and (ii) how long it takes for an inflow change to be reflected in the drainage flow. These parameters of the reaction to the presence of drainage flow can be adjusted by trial and error, and simple water accounting.

IMPROVING THE WATER ACCOUNTING PROCESS

The uncertainty relating to water accounting within a gross command area can be reduced progressively with time. The compilation of data over long periods of time allows the uncertainty on some parameters to be reduced, and some inconsistencies to be detected and corrected. This improves water balance data and helps to narrow the gap between estimations and actual values.

Improvements in water balance data require good measurement devices and efficient information management systems, which cost resources in terms of time and money.

The intelligent use of the memory of water accounting enables improved decision-taking in the followings seasons and years.

WATER QUALITY

The quality of water in irrigation is also an important issue for the environment, resource management, and the health of the local population. A separate account of quality of water entering into and leaving out of a physical boundary helps in identifying water related environmental hazards. This information then could lead to the identification of appropriate mitigation strategies. The main issues of water quality in an irrigation system are related to:

- salinity – reduced crop yield, reduced soil quality;
- environmental pollution – disposal of industrial and municipal wastes into irrigation canals;
- drainage water from irrigated area with agrochemical loads;
- health – water related diseases, arsenic and heavy-metal contamination.

Use of marginal quality water in irrigation

There are various impacts to consider in relation to the use of marginal quality irrigation water.

- Soil pollution/contamination: Marginal quality irrigation water can affect crop yields severely and damage soils. In particular, in semi-arid and arid countries (e.g. Egypt and Pakistan), soil salinity and sodicity are major problems that have been exacerbated by irrigation from saline groundwater because of unreliable surface water supplies. High levels of heavy metals in the water are likely to accumulate in the topsoil and then enter the food chain.
- Conflict with other uses: Wastewater from small industries as well as municipal waste is frequently discharged into the canals and surface water streams. This creates pollution and health hazards as these canals often provide water for drinking purposes and domestic use. Moreover, use of un-treated waste water for irrigation in urban and peri-urban agriculture is a major source of concern to human health.

Urban areas

Canals running through settlements, villages and urban areas are also frequently used as dumping grounds for refuse. This creates pollution and health hazards for the adjacent communities. It also causes problems of water conveyance by blocking the canals, and eventually disrupts water distribution downstream.

Health issues

While water-borne diseases are caused by consuming contaminated water, stagnant water in waterbodies, canals and fields are major sources of vector-borne diseases as they become breeding grounds for insect vectors, especially mosquitoes.

The uptake by plants of heavy metals and arsenic through direct contact with irrigation water or through accumulation in the soil also poses a threat to human health as these elements can enter the food chain.

Monitoring and evaluation of water quality

Water quality requires its own M&E system, which is not always possible for irrigation managers to organize and handle because of the lack of technical and financial resources.

However, a minimum dataset of water quality indicators needs to be developed and monitored in canal systems, in particular for those providing water for multiple uses and where water quality is a major issue, e.g. where the water is known to be saline/sodic, or contaminated with high levels of arsenic and/or heavy metals.

Chapter 9
Mapping the cost of operation against services

In order to produce the service that has been decided/agreed upon with users, managers need to mobilize a set of various resources or inputs (water, staff, energy, office, communication and transport). These resources/inputs all have a cost. This chapter clarifies the issue of inputs/costs for operation vs outputs/services as part of the overall management activities and as a fundamental element of the elaboration of a modernization process.

On the one hand, analysing the current cost of operation provides a clear idea about the cost-effectiveness of current operation and, thus, helps in identifying changes in different inputs (increases or decreases) for improving the cost-effectiveness of operation. On the other hand, it provides a good basis for a cost analysis of any improvements. Thus investigating inputs and costs is important for:

- setting the service levels, in particular in exploring options for different types of services and associated costs;
- water pricing to users, in order to propose a set of charging procedures that takes into account the real cost of service production;
- improving performance and cost-effectiveness, by investigating technical options for maximizing operation effectiveness (better allocation of existing resources, automation, etc.).

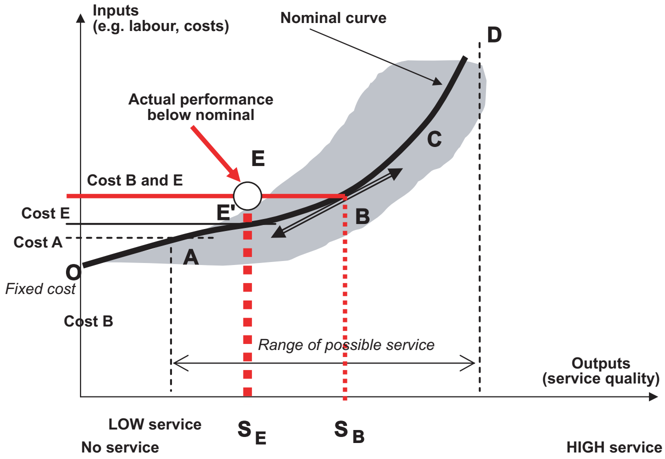
MAPPING THE INPUT–OUTPUT CHARACTERISTIC

The objective of this step of MASSCOTE (i.e. mapping the cost of operation/service) is to provide some meaningful information about the input–output relationship even in an approximate format. Figure 48 presents nominal service-cost curve. It is assumed that this theoretical curve linking service (outputs) and cost (inputs) is of the general shape, with an initial fixed cost at service nil (point O) and a progressively increasing cost (inputs) with the quality of service provided to users.

In Figure 48:

- Point O corresponds to no service at all for any reason, such as lack of water in the reservoir. However, there are always operating costs as some maintenance, safety and financial costs are incompressible. Thus, even if users do not ask for a service, or ask for it and do not receive it, costs are incurred.
- Point A refers to the situation where the quality of service to users is low, e.g. inadequate or unreliable or inflexible deliveries.

FIGURE 48
The nominal service–cost curve (input–output)



For example, point A could be a service based on fixed rotation of irrigation and proportional deliveries.
- Point B indicates that with a limited increase in inputs the service is much improved. This could be the typical situation for many large-scale irrigation systems in the world. Inputs are low, and a medium level of service should theoretically be expected.
- Point C could correspond to a highly reliable and flexible service of water on a gated system. Moving towards better service (C) becomes increasingly costly with the same system, and the stage may be reached (D) where the service can no longer be reasonably improved with the same physical system. Any further improvement would have to be obtained by drastically changing the type of system, e.g. shifting towards downstream controlled canals or to a pressurized system or utilizing another source of water (groundwater supply) from a shallow groundwater well (highly reliable, flexible, adequate, timely, etc.).
- Point E corresponds to a performance of management below nominal; actual performance is below what could be obtained with the same level of inputs (resources) when the management of resources is more focused. Many large irrigation systems in the world are "point E" type.

This curve is central in SOM when there are discussions with users about deciding on the irrigation service that managers should target and that the users are willing to pay for. Users need to have a good knowledge of what the cost should be for the service they want. They need to know:
- what a low-service cost is (point A of the curve), what a high-service cost (point C) or any intermediate type of service (B) is;
- what the expected potential gains in service quality are by refocusing inputs (from E to B);
- what the expected reductions in costs are by reducing inputs for the same level of service S_E (from E to E').

CHALLENGES IN MAPPING THE COST OF OPERATION

The inputs and costs of a canal system are seldom transparent to the users. Indeed, they are sometimes not transparent to the management either. For many reasons, there is a dramatic lack of references on the real cost of irrigation services, although the concept of water charging has been debated thoroughly in the water sector in recent years.

Information and knowledge about the costs of management and O&M are usually fragmentary and often not enough to estimate cost of operation. Further analysis is mostly required in order to produce reliable figures on what should be considered a reasonable cost for a given service, and what the maintenance should entail.

The challenges are manifold:
- a basic lack of information;
- difficulties in interpreting the information where it is available;
- difficulties in separating operation from the other activities;
- identifying the proportionality between services and inputs.

Critical issues

The critical question here is about the proportionality of management, operation and maintenance (MOM) to the service. This can be captured through a set of questions, and ultimately it is necessary to document the proportionality, as shown in Table 22. Some specific questions are:
- What are the fixed costs of MOM?
- What part of maintenance is proportional to the service? What part is fixed?
- What part of management is proportional to the service?

- What is needed in terms of input changes in order to modify the service to users?
- What will be the cost (gain or additional) associated with this change?
- What are the options for reducing input yet with the same level of service?

This chapter does not attempt to provide references but to give some directions that should be investigated by managers, as well as local and national stakeholders, in order to determine more reliable, locally specific information about the cost of operation as a function of service.

TABLE 22
Proportionality of MOM with services, indicative values

Activity	Fraction of the activity that is: fixed or independent of service	Fraction of the activity that is: proportional to service
	(%)	(%)
Management	80	20
Maintenance	100[1]	0
Operation	0	100

[1] Assuming that 100 percent of maintenance is fixed or not proportional to service is an extreme assumption. In many cases, it might be correct but not in all. In canal systems, the nature of maintenance work might change with the level of service but the total cost might remain the same. With a lift system, maintenance is related more closely to the service (volume and pressure).

Sources of information

Where clear information on cost of operation is lacking, other available sources should be utilised to acquire cost estimates. Some such sources of information and knowledge on the input–output relationship are listed in Table 23.

TARIFF ANALYSIS

The assumption here is that the tariff for services should normally reflect the intensity of efforts deployed to produce the service. This assumption is not always nor fully verified on the ground as other considerations engender some explicit and/or implicit distortions.

Crop-based tariff

Irrigation fees are often crop-based. As water needs (volume, frequency, and season duration) vary with the crop, the service to users and, therefore, the fees they should pay are different. To a certain extent, the set fees recognize the fact that the service is different for each crop. However, part of the tariff may also reflect the added value of the crops. This is the case in Maharashtra (India), where the fees for perennial cash crops (e.g. sugar cane and bananas), are much higher than for any other sequence of three crops throughout the year (Table 24). Thus, a crop-based tariff is one source of information about service cost as a function of crop, but it is necessary to double-check what is really reflected in the composition of the fees.

Energy-based tariff

In irrigation systems where energy is an important component of the cost, a differentiation is to be expected depending on the energy input in the service. This

TABLE 23
Sources of information and knowledge on the input–output relationship

Sources of information	Assumption	Outcomes
Tariff analysis	Tariffs are based on service	General shape
Survey of actual service and fees	Fees are related to actual delivery of service	General shape
Budget analysis of the management agency	Breakdown between operation and maintenance	One point of the curve
Cost analysis (macro)	Breakdown between operation and maintenance	One point of the curve
Groundwater services	Groundwater individual services provides the best service	One point along the curve and the general shape

TABLE 24
Irrigation fees according to crops, Maharashtra, India, 2004–05

Crop	Surface canal water (US$/ha)
Kharif	
Seasonals & paddy	5.2
Groundnut, hy. seeds, etc..	10.4
Rabi	
Seasonals (except wheat and groundnut)	7.8
Wheat	10.4
Cotton, groundnut, paddy, etc.	15.8
Hot-weather season	
Seasonals	15.8
Perennial	
Sugar cane and banana	137.0

FIGURE 49
Example of charging for different services in irrigation offices in Morocco (Ait Kadi 2002)

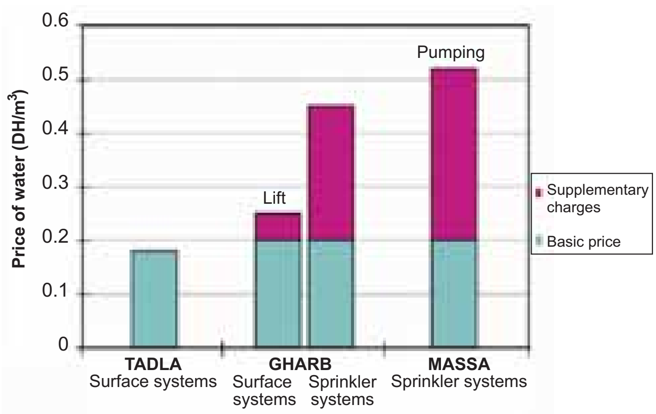
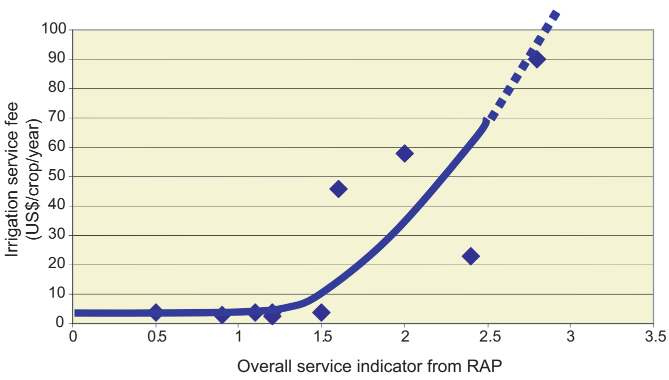


FIGURE 50
Irrigation service fee vs water delivery service in different irrigation projects



is the case for surface and pressurized irrigation services. Figure 49 presents water charges in three different situations in Morocco: surface irrigation in Tadla; sprinkler irrigation in Massa; and disaggregated surface irrigation lift and sprinkler systems in the Gharb irrigation projects. The figure shows water prices per cubic metre of water based on the Agricultural Investment Code. This code provides the legal and institutional framework for significant recovery of both investment and operating costs in irrigation (full recovery of O&M costs and up to 40 percent of initial investment costs).

SERVICE–FEE RELATIONSHIPS FROM VARIOUS RAPS IN ASIA

Water charges reflect both the level of service provided and the constraints influencing the costs associated with it. This is illustrated in Figure 50, which plots the irrigation service fee of 11 irrigation projects against the overall service indicator (which embedded in itself individual service indicators of flexibility, equity and adequacy) from RAPs conducted of these projects between 1995 and 2005.

Figure 50 shows that, although the O&M of most of these irrigation systems are subsidized (especially the ones at the lower end of the service indicators), the overall service indicator increases with the irrigation service fee or water charges. Lower water charges are mainly in the irrigation systems, which are designed for staple crops such as rice and wheat as major crops. Systems with high water charges are designed more for cash crops such as cotton and tobacco. The main reasons for low water delivery service indicators included deferred maintenance and improper operations, which in turn were related to the budget constraints. This shows that considerable increases in water charges (and improvements in their collection) are required in order to improve overall water delivery service. For water users, improved water delivery service (meaning improved reliability, adequacy and flexibility) would result not only in better yields and in improved planning and undertaking of on-farm irrigation activities, but also in more freedom to choose which crops to grow. Thus, their decisions on investing in improved water delivery service (one or more components) will depend on their choice of crops to cultivate. For example, rice growers may well opt only for improved reliability rather than flexibility, whereas farmers who want to diversify would opt for improvements in all components of the water delivery service.

Even within the same basic type of canal system, the inputs for operation will depend on the land distribution pattern, planting/harvest schedules, frequency of changes, etc. Another factor that influences input cost is the water charging method (not discussed in detail in this paper). For example, if a WUA (or water user) is charged on the basis of volume delivered during a season instead of a fixed charge depending on the area and crop irrigated, then: (i) the volume of water delivered must be known for billing, which requires good measurement structures at the point of delivery; (ii) better planning and very careful operations (gate settings, perturbation management, etc.) are required; and (iii) better communication and mobility of the personnel is also required. All these factors have implications for the inputs and, thus, for the cost.

Although fee analysis and general tariffs provide indications about inputs and costs, they are too approximate and vague to yield useful insights such as to enable full understanding of the elements contributing to the cost of services.

BUDGET ANALYSIS OF MANAGEMENT AGENCIES

The analysis of the budget of the management agency is a source of information on cost associated to operation. The budget information of irrigation projects collected in the RAP (MASSCOTE Step 1) gives a first indication of the cost of operation. However, detailed information on different inputs is required in order to evaluate the cost of different options for improvements. For example, in systems where labour is expensive, the number of staff can be reduced and vehicles provided to the remaining staff in order to increase mobility. In such a case, it is important to know the unit cost of keeping a vehicle (price, insurance, fuel, maintenance, etc.).

For proposing improvements and analysing the cost-effectiveness of operation, it is useful to disaggregate the total budget into activities related to MOM. The cost of O&M often refers to the sum of all costs related to distribution of water and maintenance of irrigation infrastructures. However, some differences exist in different projects about what is included in the irrigation (and drainage) infrastructure and O&M activities. Disaggregating this cost into operation and maintenance (and other relevant components) is important when making decisions regarding the improvements and cost-effectiveness of both operation and maintenance activities.

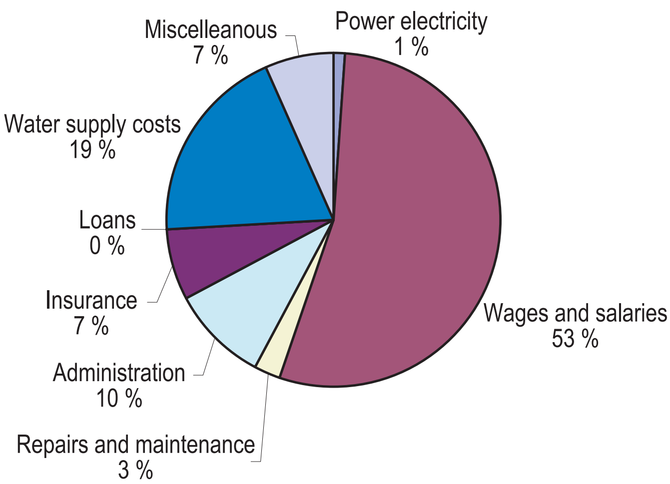
Personnel cost is usually by far the largest component of operations as staff is a main input for canal operation. Staff costs are rarely less than 50 percent of the total annual cost, often as high as 70 percent (FAO, 1986). The cost of equipment is usually the lowest item. However, some of the costs related to equipment use, e.g. of the staff who operate it, are included in personnel and salaries. Table 25 presents an example of

TABLE 25
Breakdown of the annual budget, Canal St. Julien, France, 2004

Item	Budget allocation (EUR)
Electricity	35 460
Small equipment, stationery, clothing	12 906
Contracts for canal maintenance	193 926
Vehicles (insurances, fuel & maintenance)	26 191
Communication (post & telephone)	13 306
Land tax	7 720
Water agency (tax)	46 508
Personnel (salary, charges & training)	646 605
Miscellaneous	113 620
Total	1 096 242

Note: EUR1 = US$1.28.

FIGURE 51
Budget breakdown for the Cu Chi Irrigation Management Company, Viet Nam



Source: Davidson, Malano and George, 2004.

budget breakdown from the Canal St Julien system in France (5000 ha). The personnel costs represented about 60 percent of the annual budget of the association in 2004. In the past, this cost was even higher when all maintenance was done by the staff instead of being subcontracted (as is done now).

The Canal St Julien system is managed by an irrigation bureau or WUA with some degree of state control. The WUA provides water and collects the water fee from individual owners. The O&M is covered by the water charges. The 2004 budget was EUR1.096 million (about US$1.4 million) with salaries and contracts for canal maintenance as the two major items in terms of budget allocation (Table 25). In 2006, the O&M budget of the WUA was EUR1.2 million, about EUR250 (about US$300) per hectare per year payable by the water users. The investment budget of the WUA for 2006 was EUR1.4 million, to be paid by state subsidies, the river basin agency, and some loans taken out by the WUA.

Figure 51 shows a similar budget breakdown for the Cu Chi Irrigation Management Company in Viet Nam. The annual MOM cost of the company is about US$38/ha for a scheme area of 8 500 ha. Again, wages and salaries represent more than 50 percent of the total budget.

The cases of the Canal St Julien system and Cu Chi Irrigation Management Company are examples and these in no way suggest that every irrigation project or WUA needs to have the same categories for budget allocation. However, it is important for a WUA to have different categories and a detailed account of the budget, rather than putting everything under O&M. The minimum information required for a cost analysis of operation is:

- salaries and personnel benefits;
- energy cost for pumps (if there are pumps in the project);
- communication – telephone bills, etc.;
- transport, including fuel, insurance and maintenance of the vehicles;
- equipment – depreciation, operating cost, and repairs;
- miscellaneous/others (operators' quarters, administrative costs, etc).
- investments

GENERIC ANALYSIS OF THE COST OF MOM

Another source of information about cost and service is the national or project surveys that are sometimes produced by the national irrigation departments. This generally provides figures for one of the two complementary sources of information about cost analysis:

- national and/or regional references on costing of operation;
- accounts of the project.

The ideal case is where both sources can be tapped, combining local figures with national references. However, the information on project accounts and the budget is often not readily available for this analysis, and where it is, it is not always easy to separate the budget for operation from other activities. Moreover, in many cases, the budget for operation is underestimated, which is one of the causes of low performance of many irrigation schemes. Therefore, it is sometimes important to compare these costs with the cost of operation at national and regional level.

TABLE 26
Breakdown of operation costs per level of the infrastructure in the SMIS, Nepal

Component	Operation Nr/ha	Percentage of the total cost for operation (%)
Headworks	35	10
Main canal	50	15
Secondary & subsecondary canals	120	35
Tertiary canals & watercourses	125	40
Total	260	100

Source: S. Sijapati, personal communication, 1999.

Cost of O&M: an example from Nepal

In the 1990s, the Irrigation Department of Nepal estimated that the annual O&M cost for most large projects in the Terai was more than Nr400/ha (US$1 = Nr72), with operation costs as per Table 26. At that time, the project operation plan for the SMIS then assumed an annual maintenance budget of Nr770/ha (DOI, 2001). These figures have decreased since canals serving less than 1 000 ha were transferred to users.

In the project operation plan for the Narayani Zone Irrigation Development Project, the annual incremental O&M cost for surface irrigation schemes was Nr950/ha (Pradhan *et al.*, 1998).

According to the current managers, the O&M cost in the SMIS should be Nr1 500/ha, with Nr500 for operation and Nr1 000 for maintenance. This amount would correspond to about 3.3 percent of the gross product in the CA for 2005. According to Pradhan *et al.* (1998), it would correspond to about 10 percent of the net income per hectare provided.

Part of the differences in the figures for O&M costs can be explained by inflation and by the increase in cropping intensity from one irrigated crop per year (rice) to more than two on average (the cropping intensity is currently 215 percent). With year-round irrigation, the service is provided for a much longer period of time and the cost of O&M increases. Therefore, a figure of Nr1 500/year for irrigation should be considered for O&M.

This figure should be compared with the cost to individual farmers of pumping groundwater. The RAP estimated this cost at Nr2 000–3 000 per crop/season, meaning that two crops per year would cost Nr4 000–6 000 with this type of supply (even more expensive where the farmer has to rent the equipment).

This O&M cost corresponds to the current service, which in many regards is not able to satisfy demand in winter and spring. Responding to the users' demand with more flexible service, assuming that water availability from the Koshi River has been secured, would increase the inputs again and, as a consequence, the cost per year (Figure 52).

Therefore, it seems reasonable to consider a cost for an upgraded service from surface supply allowing two crops at about Nr1 800/ha/year (the increase being mainly due to operation). This cost should be

FIGURE 52
Evaluation of different cost/services, SMIS, Nepal

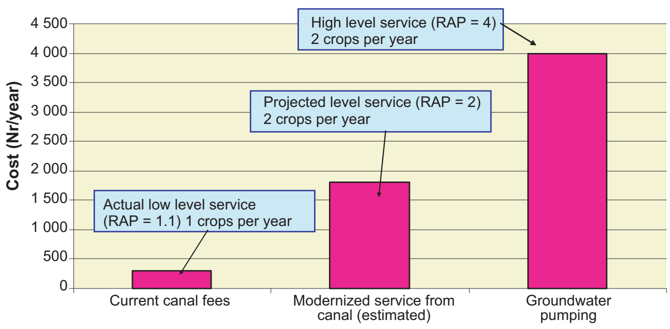


Plate 27
Supplying a paddy-field with shallow groundwater, Nepal.

TABLE 27
Energy requirement when water is supplied by groundwater, Ghataprabha project, India

Crop	Sugar cane
Crop water requirement	2 000 mm as evapotranspiration per year
Field efficiency	66 percent
Water supply at field inlet	30 000 m^3/ha
Bore well	80 m, with submersible pump at 40 m
Water lift (head)	24 m (12 m static + 12 m dynamic)
Pump efficiency	75 percent
Energy demand	(Volume × Head)/(367 × Efficiency)
Annual energy demand	2 600 kWh spent for 1 ha sugar cane
Energy per cubic metre	0.086 kWh/m^3
Electricity rates	
Agriculture (average)	Rs0.5/kWh
Industrial	Rs7/kWh
Cost of energy for pumping	Rs9 150/ha (at Rs3.5/kWh).

Note: The fixed cost for pumping equipment was estimated at Rs2 000/ha/year. This includes the capital cost for wells and pump equipment, and routine maintenance.

acceptable to users provided that the service really improves.

GROUNDWATER SERVICES

Many farmers that have poor service from a canal, or none at all, have moved to groundwater pumping wherever it is accessible at a reasonable cost. Thus, they usually pay a high cost for an adequate, reliable and flexible service. The cost of pumping varies with the context. In Terai, Nepal, farmers spend Nr3 000 per season for rice (Plate 27).

Table 27 summarizes the information on energy requirement and related cost for water extraction from shallow groundwater in Ghataprabha irrigation project in India. The average cost of energy for pumping groundwater to cultivate sugarcane in one hectare is about US$ 210, which is much higher than the canal water fee of sugarcane in the project.

COST ANALYSIS FOR OPTIONS FOR IMPROVEMENTS IN COST-EFFECTIVENESS AND SERVICE

Cost analysis of operations for different options is done for two reasons: (i) to reduce the cost of operation without jeopardizing the existing level of service; and (ii) to improve the level of service. Analysing current costs should allow identification of potential cost-saving items and answer questions such as what the most expensive items are and where money can be saved.

Improving the level of service of an existing irrigation system by taking measures to improve the operation will add a certain cost to the existing operation costs. Being able to estimate the costs associated with such an improvement project is important in order to evaluate whether the expected benefit of a project is reasonable in relation to the expected costs and whether the users can afford these costs.

Estimating costs is commonly done using the standard methods of cost–benefit analysis. These methods help evaluate the financial costs and returns associated with certain projects, and they provide guidance for decisions on the changes in service charges that are needed to recover the costs associated with these projects. In these types of economic analyses, it is important to make a distinction between two different types of costs, each of which is known under different labels:

- Capital or fixed costs are the costs that have to be paid, usually at the beginning of a project, in order to buy new equipment and materials, to modify irrigation structures and to set up new information and communication systems. Usually, such capital costs have to be incurred once and then benefits are provided for a long time, 5, 10, 20 years or longer, depending on the equipment or structures.

TABLE 28
Estimation of inputs for operation and for improved service in Narayani Irrigation System, Nepal

		Actual service	Option 1	Option 2
		Blocks 13–15 not served at all. Actual delivery from the main canal 0.4 (Blocks 1–12) (From the RAP)	Operation improvements aim at providing a slightly improved service to all local agencies, including downstream part of the CA	Serving the entire CA with an improved service to all users (2 crops/year).
		Inputs (Nr million)		
Level 1	Staff	1.250	2.000	2.500
Main system	Office	0.250	0.500	0.500
25%	Transport & communication	0.175	0.500	0.500
Level 2	Staff	3.750	4.100	6.000
Secondary and tertiary canals – local agencies	Office	0.750	1.000	2.000
75%	Transport & communication	0.525	1.050	2.000
Total operation		6.700	9.150	13.500
Cost per hectare served		Nr233	Nr244	Nr360

- Recurrent or variable costs are costs that recur, e.g. on a daily, weekly or monthly basis, and they are the costs associated with providing the service, once all the equipment and infrastructure is in place. They include fuel costs for transportation, labour costs, electricity costs, and general maintenance costs for equipment (e.g. regular servicing for vehicles, pumping stations and diversion structures).

Table 28 shows the breakdown of cost of operation for the Narayani Irrigation System (NIS), Terai, Nepal, with an actual service from the main canal to secondary canals ranked at 0.4 (very low) by the RAP. This value corresponds to water delivery service to 12 blocks (covering about 80 percent of the official CA of the irrigation scheme). The last three blocks do not receive any surface water. With reference to the irrigated area, the cost of operating the system is Nr233/ha.

From the breakdown of the actual cost for different levels and items, a rough estimation of the service cost has been determined for two options.

Option 1 aims mainly at improving water management and deliveries along the main canal through tapping additional water from natural surface streams, an improved information system and better operation. This option does not target much improvement within the secondary CAs. The service (in terms of reliability and equity) to farmers is only slightly improved.

The main system level inputs are increased significantly to face these challenges while some new allocation is made in order to develop the local management capacity in Block 13–15. Under this option, the cost of operating the system would be about Nr244/ha.

Option 2 targets Option 1 plus significant improvements in the service delivery to farmers, which basically means two crops a year and improved reliability and equity. In order to realize this option, an increase in the staff capacity at main canal level and increases in many more inputs at the secondary canal level are required. For this option, the cost of operating the system would be about Nr360/ha.

Chapter 10
Mapping the service to users

Promoting Service Oriented Management (SOM) is the central goal of irrigation modernization. It means that service to users is central at management level and has many implications for the designing, agreeing upon, producing, monitoring and evaluating the service. In irrigation systems, the primary historical focus has been on agriculture. However, consideration also needs to be given to other users. Within an irrigated service area, the provision of different services to multiple users is a constraint for managers; it increases the complexity of the task of controlling and delivering water. However, it is also an opportunity for sharing the cost of management among a larger number of stakeholders.

This chapter attempts to qualify and characterize (mapping) the service to users, starting with the primary service to farmers. In addition, it also seeks to map the services to other types of users.

A preliminary vision for the future of irrigation scheme should emerge at the end of this step of MASSCOTE.

FEATURES OF SERVICE-ORIENTED MANAGEMENT

As stated in the definition of SOM (Box 1): An SOM solution supervises and controls the delivery of a service from a service provider to a service requester. In irrigation management, the latter is called a service receiver. The three pillars of SOM are the service itself and the two actors – the provider and the receiver (or user or beneficiary) – as illustrated in Figure 3.

The actors of the service

In business language, receivers are considered customers or clients. In an irrigation system, receivers are these but also actors or stakeholders of the management through effective participation in the governance of the scheme. For example, in a WUA, farmers are not only the customers of the service, they also are involved in making the decisions about it. In this sense, the farmers are also actors.

The elements of the service

The first element is the water. Water delivery is central in the service, but it is not the only important component. Information is also an important flow of the water service. Information flows in both directions, from providers to receivers and vice versa. Users need to have information about the allocation of water, the scheduling of supply, and about measurements of deliveries.

Indeed, the service consists of three main flows: service = water + information + money (Table 29). These three flows are intrinsically linked to each other, and this can be captured through the following phrases:

- No water, no money.
- Water needs information.
- Information is money for the users.
- Money needs information.
- Money must pay for water, information and money.

TABLE 29
Service flows

Provider	Service	Receiver
Operates the system to produce water deliveries.	Water flows	
Should inform receivers beforehand about the service they can anticipate for a given period of time (season, year), about the scheduling of deliveries. Information on actual service must be collected.	Information flows	Information on the demand for services from the receiver should be conveyed to the provider. Information on actual service must be checked/collected.
Should charge for the actual service and ensure the long-term sustainability of the infrastructure.	Money	Should pay the service according to the volume used or benefit obtained.

Information and services

Information is a critical part of the service in SOM. Reliable and accurate information about the service of water is crucial for farmers when they need to make strategic decision about their cropping pattern and cropping calendar. They need to know in advance if the amount of water will be enough for the crops they are planning to grow, and if this water will be available at the water-sensitive growth stages of these crops.

Information on the demand for water services is critical for the managers before and during a season.

Information is also needed in order to assess the actual service and charge the users accordingly.

Money and services

Money is essential for the sustainability of the scheme. Numerous irrigation systems were and still are underfunded by the state, whereas the management transfer to users has not been completed (or even started) in many cases.

The bill for the irrigation management services has to be paid by someone, now or later, for own use and for someone else. It is common to see the taxpayer paying part of the entire bill for irrigation management at the investment. It is also common to see the taxpayer paying for MOM, but this modus operandi cannot last for long.

Therefore, it is a major responsibility of the management to organize effectively the flows of money for producing the services (MOM).

Defining services to users

Irrigation systems were originally built to supply farmers with water where crop requirements could not be met by natural precipitations. Thus, service to farmers has been and should still be the central focus of the management. However, with time, it has become more and more apparent that other beneficiaries are taking advantage of irrigation water supplies for other uses, which may penalize irrigated agriculture. In the extended category of services within an irrigation project, the following services can be found:

- domestic supply to villages;
- recharge to groundwater;
- environmental flows;
- health;
- industrial uses;
- fishing;
- recreational areas;

- tourism.

The services to users are today much broader than at the initial stages of irrigation development although water demands by farmers are still central.

The task of defining the service and determining the requirements for operation consists primarily of answering the following questions that address both the definition of the service and the consequent requirements for operation:

- What services are demanded by the different user groups?
- How do these relate spatially, in time and in terms of operational requirements?
- What services can be offered to the users?
- What is the possible range of services and fees to be considered?
- What mode of operation can be followed and with what precision?
- What should be the frequency of checking and intervening?
- Which setup is required in order to monitor the service?
- What are the mechanisms to ensure that services are provided and paid for?

Several possible irrigation service arrangements can usually be conceived. Even where the physical infrastructure is pre-set, there can be a number of variations in planning, flexibility and accuracy of operation. It is logical to expect that an increase in inputs (labour and money) will generally result in a higher level of service. However, it is not that simple. A key factor for successful canal operation is targeted improvements that meet a real demand of the users.

In order to meet contemporary irrigation demands on canal operations, it is useful to follow a service-oriented approach. This implies that users and service providers are jointly responsible for designing and defining the best compromise between the level and cost of service, bearing in mind that users will ultimately reap the benefits and bear the costs of operation.

SERVICE TO FARMERS

The quality of service to agricultural users can be specified through indicators similar to those used for performance assessment, e.g. adequacy, flexibility, reliability and timeliness. For other uses of water, such as fishing, environment and heath, service indicators can be very different: presence of water, fluctuations of streams, temperature, etc.

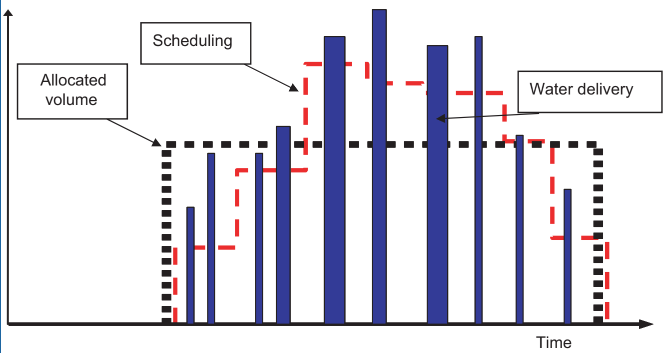
The service to farmers is usually defined with reference to three time-related aspects that are important for farming organizations:

- allocation of water for the season or year;
- irrigation delivery scheduling;
- actual water delivery.

In terms of allocation of water for the season or the year, the service includes not only the quantum (volume) of water but also the flexibility in negotiating variations around that value. This aspect is important in relation to the structural decision in matching water demand and water supply, for example, in adjusting the cropping pattern to whatever water is allocated, or in securing additional water supply to cover the cropping pattern.

Irrigation delivery scheduling is the procedure to establish a roster of irrigation turns or water applications for a specific period of time, for example an irrigation (or crop) season. The quality of service is specified by the frequency with which water will be made available, e.g. every week, fortnight or month, and again the flexibility in modifying the schedule to match unexpected changes. This aspect is important for ensuring that the water supply will prevent moisture deficit at field level, and also for the organization of the human resources and equipment at farm level. Flexibility here means that for a given allocated volume, the scheduling of supply can be adjusted. For example, some farmers may want to reduce the initial scheduled deliveries and reserve the volume for the peak or the end of the season.

FIGURE 53
Dimensions of service: allocation, scheduling and deliveries



Actual water delivery refers to the water provided to the users. Specifically, it deals primarily with discharge (instantaneous flow) and volume (quantity over a period of time) of water delivered with respect to demand at a given point in time.

Therefore, although the emphasis tends to be on the service in terms of water delivery, it is necessary to bear in mind the three dimensions of the service to farmers (Figure 53).

Water quality is also an important aspect of the service that must be considered by the managers and users. However, it is often not easily controlled, and may be more the result of given conditions.

Sizing the service: target and tolerance

The service can be assessed through hydraulic indicators attached to the deliveries similar to those used for performance assessment, e.g. adequacy, flexibility and reliability. An important indicator of service is the tolerance within which deliveries are allowed to fluctuate. Therefore, it must be specified by two variables: target and tolerance: Service = {Target; Tolerance}. For example:

- service = 100 litres/s ± 10 percent;
- service = deliveries on time ± 3 days.

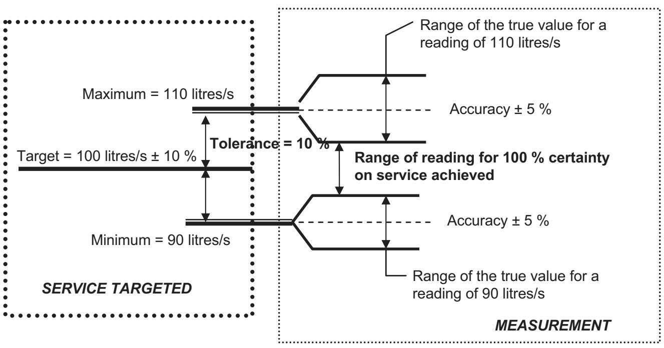
The tolerance sets the limits within which the volume is allowed to fluctuate. There is a need to define a tolerance level that is: (i) acceptable to all the stakeholders involved; and (ii) consistent with the accuracy by which service is assessed.

In theory, the previous definition allows identifying without ambiguity when the service is achieved and when it is under default. In practice, it also depends on the accuracy by which it is measured.

Accounting for inaccuracy

The inaccuracy of measurement adds ambiguity to the process. Figure 54 shows how this happens. In this example, the tolerance is set to 10 percent, which for a target of 100 litres/s means that the discharge should vary within the range of 90 to 110 litres/s. Assuming that the measurement device is capable of assessing the true value with a precision of 5 percent, it means that when the reading is 110 litres/s the true value lies between 105 and 115 litres/s. Similarly, for 90 litres/s the true value lies between 85 and 95 litres/s.

FIGURE 54
Illustration of the tolerance/accuracy compatibility for water service



As a result, the range for which there is no ambiguity about the fact that service has been reached is for readings between 95 and 105 litres/s. This range is defined by the tolerance minus the accuracy of measurements. This is why tolerance cannot theoretically be equal or lower than the measurement accuracy. It would not be consistent to set a tolerance of 5 percent in discharge with devices that can only be 10 percent accurate.

Plate 28 shows a measurement structure (weir) downstream of an offtake along the SMIS (Nepal). In this structure, the measurement accuracy is very low because of: (i) the imprecision in reading the gauge; (ii) the presence of turbulences; and (iii) the low sensitivity of the weir (too large). It is estimated that accuracy is equal to or greater than 20 percent. Therefore, in this particular case, it is not possible to target service at less than 20-percent discharge.

In short, there is no point in having a narrow tolerance for service on discharge where the measurement accuracy is low.

Plate 28
Head of secondary canal equipped with a measurement device (gauge) of very low accuracy (Nepal).

Types of service

Service targets and indicators for water delivery to farmers (rate, duration and frequency) are to a large extent dependent on the infrastructure/technologies and water-control method. For example, it is not possible to achieve flexibility in delivery rate in a proportional distribution system. The main options for service delivery are:

- pre-set;
- arranged (on-demand);
- free access (full flexibility).

Clemmens and Replogle (1987) reviewed water delivery patterns as far as the target indicators are concerned. Table 30 presents different water delivery targets, their operation parameters and the flow control systems in which these targets are often found or aimed for.

Setting service parameters

The way targets and tolerances are set during the irrigation season results in a certain level of service (Table 31). Service targets and tolerances to variation may be distinct for different users. Some can accommodate a lower service quality than others (access to groundwater); some want very timely water deliveries (vegetables); others want very low discharges over a long period (drip irrigation). Furthermore, demands can change over time. The reliability of irrigation during the transplanting of rice should be very high, whereas some variability is allowed later in the season. Last, the stakes are highest for tail-end users as they will feel the impacts of flawed service the hardest.

Other requirements of service are not so much related to the quantity of individual deliveries but more to the general setup and their influence on the operation system. An important indicator is the flexibility of the system. Delivery flexibility can be defined as the level of freedom to change the variables of water delivery (rate, duration and frequency), e.g. the possibility to request a certain volume of water at a certain discharge at a certain place and time.

In Pakistan, variable tolerances for water deliveries are found in systems managed with rotating priorities for irrigation (particularly during dry or water-short seasons). During one turn (usually a week or ten days), one set of offtakes is given the highest

TABLE 30
Definitions of delivery scheduling methods

Schedule categories / water delivery service targets	Operation parameters			Flow control methods
	Rate	Duration	Frequency	
Free access / on-demand				
Unrestricted	U	U	U	DS-auto, US-auto-cent
Limited rate demand	L	U	U	DS-auto, US-auto-cent
Limited or arranged frequency	L	U	A	DS-auto, US-auto-cent
Limited duration	U	L	U	DS-auto, US-auto-cent
On-request / arranged schedules				
Arranged	A	A	A	DS-auto, US-auto
Limited rate arranged	L	A	A	US-auto, US-man
Restricted arranged	C	C	A	US auto, US-man
Fixed duration arranged	C	F	A	US-auto, US-man
Fixed rate / restricted arranged	F	C	A	US-auto, US-man
Rigid or imposed				
Central system	V	V	V	US-auto-cent; US-man
Fixed amount	F	F	V	US-auto; US-man
Fixed rotation	F	F	F	US-auto; US-man
Varied amount rotation	F(V)	F(V)	F	US-auto; US-man, Prop.
Varied frequency rotation	F	F(V)	F(V)	US-auto; US-man, Prop.
Continuous flow	F(V)	-	-	US-man, Prop.

Note: U: unlimited, no restriction, under user control; L: limited to maximum flow rate, but still arranged; A: arranged between user and water authority; C: constant during irrigation as arranged; F: fixed by central policy; V: varied by central authority, at authority's discretion; (V): varied by central authority, seasonally by policy; DS-auto: downstream automatic; US-auto-cent: upstream automatic central; US-auto: upstream automatic (both central and local); US-man: upstream manual; Prop.: proportional.
Source: After Clemmens and Replogle (1987).

TABLE 31
Example of service targets and tolerances for a delivery to a farmer

Service component	Target	Tolerance
Discharge	100 litres/s	-10 litres/s, +20 litres/s[1]
Timeliness	At the hour	±1 day
Duration	6 hours	±30 minutes
Flow characteristics	Stable flow	20% variation in discharge
Compensation when at fault	Direct compensation in water	Max. 3 days period

[1] The tolerance for discharge might be different under target and over target as a deficit is more penalizing for farmers than is an oversupply.

priority and, therefore, the lowest tolerance of variation from targets, while the other set is fed only if there is some left over, thus with a high tolerance of deviation from target. For the following turn, the priority is reversed.

SERVICE BY TYPE OF CANAL SYSTEM

The concept of a uniform service defined once and forever and for everyone at the design stage is no longer valid. Given the diversification of crop production and marketing strategies, as well as the development of alternative sources of water (e.g. shallow groundwater pumping), the demand for service is increasingly variable within the area of the canal system and throughout the cropping season(s). The question is the extent to which the variety of demands can be accommodated, in the knowledge that more flexibility makes operation more complex and often more costly. Again, a compromise has to be found between meeting the demands of users and keeping complexity and water charges at an acceptable level. Figure 55 shows some examples of flexibility and complexity for various modes of operation and system layouts. The systems plotted in Figure 55 are:

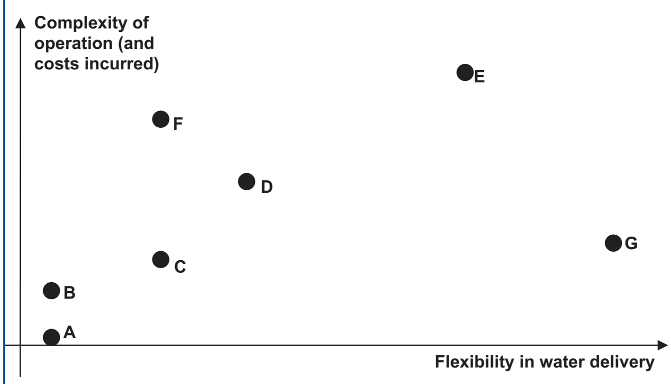
- Proportional system:
  - A: Continuous flow (sawah and many hill irrigation systems); low flexibility, but extremely low operational requirements and costs.
- Gated system:
  - B: Uniform service: fixed rotational schedule (times, discharges, frequencies, based on shares); flexibility does not increase, but operational complexity does.
  - C: Uniform service, imposed rotational schedule, crop-based on seasonal planning.
  - D: Semi-uniform service, imposed rotational schedule, based on real-time crop demands.
  - E: Diversified service, arranged scheduling and allocation; this is the most flexible situation for gated systems, but can be extremely complex and needs a strong management setup.
- Automated or semi-automated system:
  - F: Uniform service, imposed rotational schedule that is crop-based, seasonal planning; the service is similar to the situation under C, but the infrastructure is not designed for this operational mode, and it will be complex to enforce the rotation.
  - G: Diversified service, on-demand, free delivery; this system is rarely found in practice. The dream of many farmers, it resembles the service of domestic water supply. Operational complexity, where well designed, can be low and flexibility is very high.

Figure 55 compares the flexibility of the system with operational complexity and costs incurred. The operational modes are presented as points rather than as curves. Transition from one mode to another is often not a gradual, but a step-by-step or very drastic reform. There is a cloud of possibilities around each point, and many more setups are possible. However, the ones plotted are those most frequently found in practice rather than in the literature. Although complexity and level of service are related, it is not a one-dimensional curve. Infrastructure is a major determining factor in the range of possibilities. For example, point G shows that a semi-automated system can deliver high flexibility at relatively low costs, whereas a traditional gated system can perhaps never attain this level of flexibility and surely at much higher costs. However, the conclusion should not be that all systems should be automated. The reasons for this statement are:

- Water-use efficiency is not represented in Figure 55. Where water is scarce, a less uniform but highly efficient system can deliver a better service to the users than a water-consuming flexible system.
- Variability in operational modes. Throughout the season, or over the years, the required modes of operation may vary widely. For example, infrastructure and management arrangements should be capable of shifting from a strict to a more *laissez-faire* mode of operation.
- Control over the system: Can free-riders be isolated? Is the system

FIGURE 55

Flexibility vs complexity of operation for different modes of operation and system layouts



tamperproof? These questions are in the interests of both users and operators, and control can be partly exercised through the choice of infrastructure.

THE MULTIPLE USES OF WATER

Agricultural uses

Primary objective of irrigation systems is to supply water to farmers. Therefore, agricultural demands dominate in debates and negotiations over service. However, agricultural demands are not homogeneous. The demands of an organic farming community, growing vegetables and flowers, will be very different from uniform rice-based smallholder systems, which are again quite different from large cotton or sugar-cane estates. Their irrigation requirements will not only be different in terms of all performance variables, but their water demands will also be based on considerable differences in irrigation techniques, labour requirements, economic returns, vulnerability to service failures, bargaining power, status, gender divisions, etc. Crop water requirements for the different crops and varieties will be the basis of any irrigation service demand, but they are not the only rationale in farmers' irrigation strategies.

In this paper, it is not possible to deal with all considerations and specific service demands that are to be found in projects today. Water users are growing more capable of articulating their demands in debates on service provision. In addition, any debate on irrigation service demand will have to face a mosaic of demands that might be difficult to accommodate, or that may even be mutually incompatible. The final service agreements will reflect different crop water requirements, spatially different irrigation methods, established rights, local power relations, economic interests, etc. that are in line with the water resources available and O&M budgets. They may be different in time and location, with some designated critical periods per year.

In summary, it is important to remember that irrigation service demands:

- are heterogeneous in time and space and for different types of use;
- deal with delivery parameters as well as with demands on the operation and management setup.

Service to other uses/users and externalities

Water management is not confined to delivering water to crops. Increasingly, irrigation projects are seen within the larger context of basin water management as regards to both the qualitative and quantitative aspects of water. Even within a canal system, "irrigation water" may be used for many other purposes by farmers and other inhabitants of the area (Plate 29). Furthermore, the demands on the operator also include issues in the sphere of mitigation of possible negative side-effects of irrigation, e.g. salinization, waterlogging and the spread of vector-borne diseases. All these issues place more or less stringent requirements on the chosen mode of operation. For example recent studies (IWMI, 2001) have shown the positive effect of intentional water-level fluctuations on vector-borne diseases, e.g. malaria.

Plate 29
Fishing activities in a tank system (Sri Lanka).

Within a canal system, there are several common externalities that managers have to deal with:

- ➢domestic water supply to villages (Plate 30);
- ➢groundwater recharge;
- ➢streams and waterbodies for fishing activities;
- ➢water supply for livestock;
- ➢environmental needs/impacts (groundwater recharge, waterlogging, salinity, and drainage and return flow from the CA to natural streams);
- ➢recreational needs;
- ➢health and sanitation.

Energy production is sometimes another important use of water stored in multiple-use reservoirs. The routing and scheduling of water demands for generating energy is most often at the main inflow point to the project. However, in some cases, it may be within the system itself.

Plate 30
Domestic water use, natural streams recharge by the surface canal network (Ghataprabha, India).

Types of service for other uses

The above-mentioned various additional uses and specific needs related to water management require different types of water service, ones that differ from the service for crop production. These extra services are context-specific, sometimes simple and at other times complex; they need to be discussed and tackled locally. The different service issues that managers may have to deal with are outlined in the following sections.

Supplying water to a delivery point

An example might be to provide a specific delivery flow rate at a particular point. In such a case, the service is rather similar to a delivery to farmers. This is particularly the case where water is delivered to a water tank for domestic supply to villages. In this case, the quality of service is mainly about timeliness and adequacy, but it is also about water quality.

An IWMI study (Ensink *et al*., 2002) in Pakistan showed that a significant part of the CA has unpalatable groundwater and that, therefore, a large fraction of the rural population rely on irrigation surface water for their domestic supply. About 40 million people are estimated to be affected by water quality in the canal system, and this number is likely to double in the next 25 years. With a basic need of 50 litres per person per day, this represents a volume of 2 MCM/day. Some people are heavily dependent on surface irrigation water to fulfil their domestic needs, and they suffer during closure of the canal system for maintenance.

In many countries, water is treated for domestic water use, but there is no guarantee that this is the case for water in canal systems. Few options are available. One is to have water infiltrated in the soil and pump back from the water lenses on brackish water, in which case quantity is as important as quality.

Maintaining flows in local streams and waterbodies

In some low-lying areas, maintaining flows in the local drains, streams and marshes is important for preventing seawater intrusion. In other cases, maintaining water resources in wetlands is equally important for their capacity to sustain wildlife and the environment.

Maintaining water levels in local waterbodies

In some areas, water in the canals is the only source of water not only for drinking but also for other domestic uses such as bathing and for washing clothes. When the canals are closed (e.g. for canal maintenance, or when there is no irrigation demand), people living nearby can suffer owing to poor-quality groundwater – at times, it is impossible for them to access good-quality water. This issue has put pressure on managers to periodically fill portions of the canal systems in order to maintain minimum water levels (e.g. in Pakistan and Sri Lanka).

Maintaining water quality in natural streams

During dry periods, water supplies to natural streams maintain a minimum quality in local streams through the dilution of toxic wastewater drained from urban and peri-urban areas.

Maintaining the capacity for storing water and control floods

In areas and seasons where heavy rains are likely to occur, one objective of water control in the system is to maximize the ability to store precipitation. This has two positive effects: (i) it improves water resource availability; and (ii) it minimizes the impacts of the floods.

Types of operation required for different services

In theory, the basic physical operation of gates in the system is the same for providing any type of service. However, the process of decision-making and planning for these activities may differ from that of farmers and canal managers (Table 32).

An important aspect of operation for these "other uses" is planning and allocation. Canal managers need to know the water demands and requirements, as well as available resources, for these different users in order to be able to allocate water properly for these activities.

The multiple uses can sometimes conflict with one another and there is a need to compromise when the operation requirements are antagonists.

MAPPING THE DEMAND FOR SERVICE

Mapping the demand for service means identifying spatially the type of service, and then quantifying the service itself. More specifically, the demand for water service consists primarily of answering the following questions that address both the definition of the service and the consequent operation requirements:

- What type of service is demanded by the different user groups?
- What service can be offered to the users?
- What is the possible range of service and fees to be considered?

As examined in Chapter 12, service and operation are intrinsically linked. Therefore, mapping the service should not only be done from the perspective of the users but it should also be based on that of the service provider. Thus, an important question concerns how the services contemplated relate spatially, in time and in operational requirements.

The water service from the canal infrastructure has to be placed in the larger context of water management within the CA. In other words, the

TABLE 32
Type of target and service for different uses

Use	Type of service / target
Farmers	A time bound water delivery
	A share of flow
Support to natural surface streams & environment	A specific discharge
	Water quality through water dilution and/or drainage control
Tourism, fishing, groundwater recharge, recreation, wild animals & natural parks	A water presence & a given water level in waterbodies
Control of vector-born diseases in waterbodies	Water-level fluctuations
Flood control	Water storage capacity
Control of drainage return flow	Maximum discharge

BOX 5

Services and users: the case of "energy savings" in a conjunctive-use system

There are cases where considerations about the users and the service are not straightforward. For example, in a well-developed conjunctive-use system, the service from the canal is more about energy than about water.

In a conjunctive-use system, it can be assumed that the destination of canal water is to replenish soil moisture either through direct surface supply, pumping from shallow groundwater, or drainage partially or totally fed from seepages and percolation generated by the irrigation system itself. In a well-managed conjunctive-use system, there are no irrigation water losses, and, therefore, from a strict water management point of view, there is no difference whether the managers succeed in achieving a high delivery service at field level or not. The only major difference is the use of energy and the cost incurred in order to lift the water up again.

In these circumstances, the service of water to fields also comes with the notion of energy. Gravity-fed water at field level is energy saving. The real service for the irrigation system can be divided into two parts: (i) water service as a bulk of water supply to the CA; and (ii) energy savings for water delivered at field/farm level.

Savings depend on the head of the lift, for the example in Table 27, Chapter 9, the savings can be estimated at 3.6 Wh/m^3/m lifted.

Users/beneficiaries: Where the farmers pay the full cost of water pumping, they are the users for both water and energy services. Where, as in India, energy is provided almost free of charge to farmers, it is necessary to consider two users/beneficiaries: farmers receive the service of water, and state saves the energy (or funds spend on subsidising energy).

analysis of the demand for water service needs to consider the individual demand for water service as well as the specific context in which this demand is expressed (Box 5).

Agricultural demand

For agriculture, several criteria influence the nature and the characteristics of service:

- crop water requirements: function;
- source of water: rainfall, groundwater, etc.;
- soil characteristics.

Moreover, it is also necessary to consider different time scales, from the seasonal allocation of water (volume depending on the expected total needs) down to the characteristics of deliveries (discharge and volume, frequency, reliability, etc.).

Within one command, it is probable that the demand for service in irrigated agriculture varies spatially. There are some exceptions to this, for example, a small system with one single crop and no spatial variation in climate (e.g. rice paddy system during the dry season).

THE WATER MANAGEMENT CONTEXT

Irrigation systems, as stated in the previous sections, are increasingly expected to provide services for uses other than irrigation. Hence, service to users must be defined, produced, and assessed in the context of water management. This is considered vital for i) sustainability and enhanced performance of irrigation systems; and ii) mitigating negative impacts of irrigation on health and environment.

Water quality

Modern agricultural practices and the scarcity of freshwater result in some areas having to deal with water containing chemicals (pesticides and nutrients) and other pollutants.

Dealing with the wider causes and effects of water quality is a major challenge for 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 benefit (supply) and a threat (pollution). In these situations, managers will have to consider both uses and arrive at an effective compromise.

Recycling of irrigation water

Return flows from irrigated areas can be important assets in water management. Losses in one place become inputs for other areas. A good understanding of this cycle can ease the upstream management problem substantially by allowing less precision in distribution, knowing that surpluses will not be lost. Return-flow systems present an opportunity for managers to store positive perturbations, for example to harvest rainfall as both drainage and surplus irrigation are channelled 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. The 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. Groundwater recharge can be a target of canal operation. Areas lacking access to additional supplies from groundwater should be considered for greater management attention than areas where pumping facilities can compensate for inadequate or/and unreliable deliveries.

Soil and water salinity and waterlogging

Rising soil and water salinity and the increase in waterlogged areas constitute environmental hazards of great importance in arid regions. They represent a severe threat to many irrigation schemes. The 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. However, as a general principle, partitioning of the irrigated area should identify areas where freshwater has to be provided, and areas where excessive percolation should be avoided in order to prevent saline groundwater from rising.

Multiple uses of water

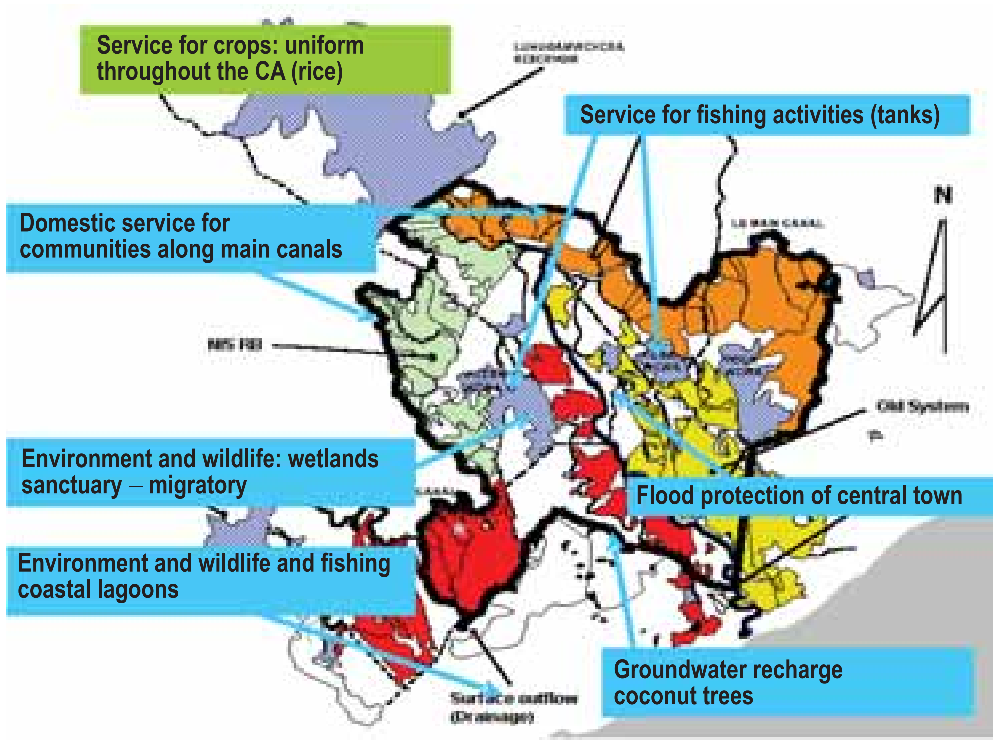
In many irrigation schemes, water is used not only for crops but also for many other purposes (Figure 56). Rules for multipurpose system operations are complex because of potential conflicts in setting targets for the different uses and also, on occasion, because of the lack of suitable accounting procedures. Multiple uses of water may have to be integrated increasingly in management concerns, whether or not these uses were considered at the design stage.

Health impacts

Despite its positive effects on the rural economy and in terms of income for farmers, irrigation has also sometimes led to negative impacts on the health of communities through vector-borne diseases. The maintaining of water in canals for long periods 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 in order

FIGURE 56

An example of highly diversified multiple water services with a homogeneous agriculture demand for a rice-based system in Sri Lanka



to, for example, reduce the breeding of mosquitoes. However, there is a clear conflict between these requirements for vector control and the irrigation management objective of stable water flows and steady deliveries. New techniques of operation are required in areas where mosquito breeding is related to irrigation practices.

Figure 57 provides an example of how service should be linked to the water context (groundwater management). The downstream part (in red) of the NIS (Nepal) has never been fed properly by canal water and, therefore, has developed extensive pumping from the groundwater. However, this practice has resulted in contamination of irrigation and domestic water supplies by arsenic. An alternative to groundwater must be found through an improvement in canal operations. On the other hand, the upstream part of the system seems to be less vulnerable to arsenic and, therefore, pumping to compensate for reduced canal service is an option that could be considered by the manegers.

MAPPING A VISION FOR THE SCHEME

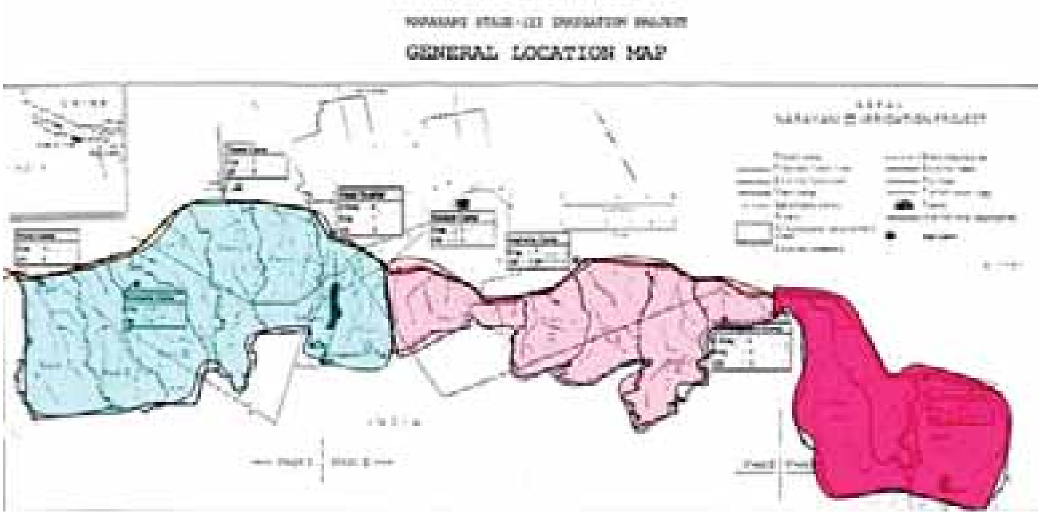
While mapping all the services, actors, users and beneficiaries of the water scheme a vision of the irrigation infrastructure in the rural society is emerging. At the end of this step it is thus critical to spell out clearly what is this vision as it will be one of the main drivers of the following steps of the MASSCOTE process.

Of course the vision of the future of the system should be agreed upon by the various stakeholders engaged in the process of modernization. Therefore at this point one can only speak of preliminary vision. This vision should cover the agriculture domain as well as the water management domain. Some example of visions that were crafted during previous RAP workshops are:

- ➢ A lively agriculture sector engaged in high-value cropping based on equity in accessing any water sources, supported by efficient and sustainable operation

FIGURE 57

Map showing three classes of demand for surface water services resulting from arsenic contamination of the Narayani Irrigation System, Nepal



Note: Blue = upstream and low demand.
Red = downstream and high demand.

and management of canal water supply, with users bearing the operational cost coverage at a 10-year horizon.

- A staple-food production agriculture supported by low-cost water services.
- A project directed towards sustainability through the modernization of hardware and management in order to improve service.
- Modernizing the irrigation systems in order to make them more efficient, functional and service-oriented by enhancing the necessary infrastructure and developing the management capacity of the local stakeholders in fulfilling their responsibilities.
- Temporal and spatial distribution of adequate, reliable and equitable irrigation water in a flexible manner so as to increase irrigation efficiency for increased agricultural production and, thus, to contribute to poverty alleviation.
- Service-oriented water management that provides equitable and reliable deliveries in order to improve the living standards of the community.