Modernization of Irrigation Systems

Canal Operation Techniques

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Modules	
Basic Knowledge Irrigation canal management	
M-I Operation Methods in Canal Delivery systems	Paul Ankum
M-II Operation Techniques in Canal Systems	Daniel Renault

Operation methods in canal irrigation delivery systems

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OPERATION METHODS

Classification of operation methods

At present, different classifications for the basic operation methods in delivery systems are used by different authors. For instance, ASAE proposes for canal control (Burt and Plusquellec, 1990):

(i) conventional upstream control;
(ii) automatic upstream control;
(iii) downstream control with level top canals;
(iv) downstream control on sloping canals.

ICID proposes for canal system operation (Goussard, 1993):

(i) upstream control;
(ii) close downstream control;
(iii) distant downstream control.

The World Bank proposes for control strategies (Plusquellec *et al.,* 1994):

(i) proportional control;
(ii) adjustable flow-rate control;
(iii) upstream control;
(iv) downstream control;
(v) remote monitoring;
(vi) remote control.

It seems more practical to adopt a classification based on the location of the water level that is maintained by gate regulation. Thus, there are five basic operation methods (Ankum, 1993b):

• **proportional control**, in which the incoming flow is split according to predefined ratios. Thus, there is no constant water level in a canal reach;

• **upstream control**, with a constant water level at the upstream side of the regulator as the operational target. The outflowing discharge from the delivery system can be changed only after an intentional change of the inflowing discharge from the river by a system manager, a subsequent diversion at the bifurcations and after a certain 'time lag'. The time lag is related to its (negative) dynamic canal storage;

• **downstream control**, also called 'downstream control on level-top canals', with a constant water level at the downstream side of the regulator as the operational target. Such a delivery system is 'responsive' and would provide immediately the requested outgoing discharge because of its (positive) dynamic canal storage. Level-top embankments are required;

• **BIVAL control**, also called **'constant volume control'**, with a constant water level in the middle of the downstream canal reach as target. Hence, there is no effective dynamic canal storage in a canal reach. BIVAL control resembles downstream control and is also 'responsive' as it provides immediately the requested outgoing discharge. However, the canal embankments can be kept at a lower level, while telemetry and electro-mechanical gates are needed;

• **ELFLO control**, also called **'downstream control on sloping canals'**, with a constant water level at the other end of the downstream canal reach as target. It requires telemetry and electromechanical gates. ELFLO control is 'responsive' to changing outgoing discharges, like in downstream and BIVAL control. On the other hand, ELFLO control resembles an upstream controlled system as the embankments are similar, and as the change in outflowing discharge will only be effective after a certain 'time lag' because of the (negative) dynamic canal storage.

It is also possible to use different control methods at one location, such as composite control, where the gate is normally regulated under downstream control, but may change to upstream control for certain conditions (Goussard, 1993). Moreover, it is often very effective to use different operation methods at different locations in the main system, e.g., downstream control in primary irrigation canals and with upstream control at secondary irrigation canals.

Delivery system management and regulation of structures

The term delivery system management refers to the management of the delivery system as a whole, and deals with matching the outgoing discharges with the inflowing discharges from the river. The main system management can be (Ankum 1993b):

• **no (day-to-day) system management**, when regulation of the structures is not possible and/or required. It is applied in delivery systems under proportional control with a fixed splitting of the discharges, and in upstream controlled systems with standing orders for the water delivery during the whole irrigation season;

• **central system management**, when a 'water operation centre' has to match the incoming discharge from the river with the required delivery schedule. It is applied in upstream controlled delivery systems;

• **responsive system management**, when the delivery system itself adjusts to the changing outflowing discharges. It is a feature of downstream, BIVAL and ELFLO control (as well as composite control).

The term regulation refers to the actions of the controller, and focuses on maintaining the water level or the discharge at the target value. Regulation can be done manually by a human operator, by the water forces on a hydro-mechanical gate, by a float with programmable logic controller (PLC) of an electro-mechanical gate, etc. Moreover, regulation can be done by a passive regulator, such as a long-crested weir.

SELECTION PROCESS FOR THE OPERATION METHOD

Procedure

The selection of the most appropriate operation method for an irrigation delivery system, such as proportional, up- and downstream control, is quite complex. Moreover, the consequences of the selected operation method are often not well understood. Therefore, the selection is usually based on past experience. A systematic selection process is recommended here.

The systematic selection process for an operation method may follow iterative steps:

• the operational objective of the delivery system has to be defined first;

• an initial selection of the operation method follows directly from the operational objective, as will be discussed below.

Certain features of the control method are already determined by this initial selection, such as the hydro-dynamic performance, the design and constructional aspects, the operation and maintenance requirements, and some other aspects;

• an evaluation has to be made whether the features of the selected operation method are acceptable. If not, the original operational objective of the delivery system has to be revised, and another operation method may follow.

Operational objective

The operational objective of a delivery system is specified by three fundamental factors:

• the decision-making procedure on the water delivery to the tertiary offtake, i.e., 'who' decides on water delivery to the tertiary unit;

• the method of water delivery to the tertiary unit, i.e., 'how' that water is delivered to the tertiary unit;

• the method of water distribution through the main system, i.e., 'how' the water is distributed through the main irrigation system.

The decision-making procedure on the water delivery to the tertiary unit has to be selected first. Three options are possible. Under 'dictated delivery', the water user associations of the tertiary unit have no say in the water delivery. Alternatively, water user associations may request a changed water delivery, which is effected after endorsement by the water operation centre, and after some time ('arranged delivery'). Thirdly, the users themselves may decide on the water delivery, which is supplied immediately or after a time-lag ('on-demand delivery').

Also, there are three options for the delivery method to the tertiary unit. The traditional delivery method to a tertiary unit is 'split flow', where the available flow is diverted equitably throughout the system by 'proportional structures'. The second delivery method, 'intermittent (on/off) flow' to the tertiary units, is often applied in schemes under dryland crops, where a 'unit flow' is rotating between the individual fields. The choice of such an intermittent delivery is irrespective as to what decision-making procedure has been selected. A third delivery method, the 'adjustable flow' to the tertiary units, is often applied in schemes under paddy, when the peak discharge is required, e.g., during land preparation, and the discharges are gradually reduced during the off-peak period.

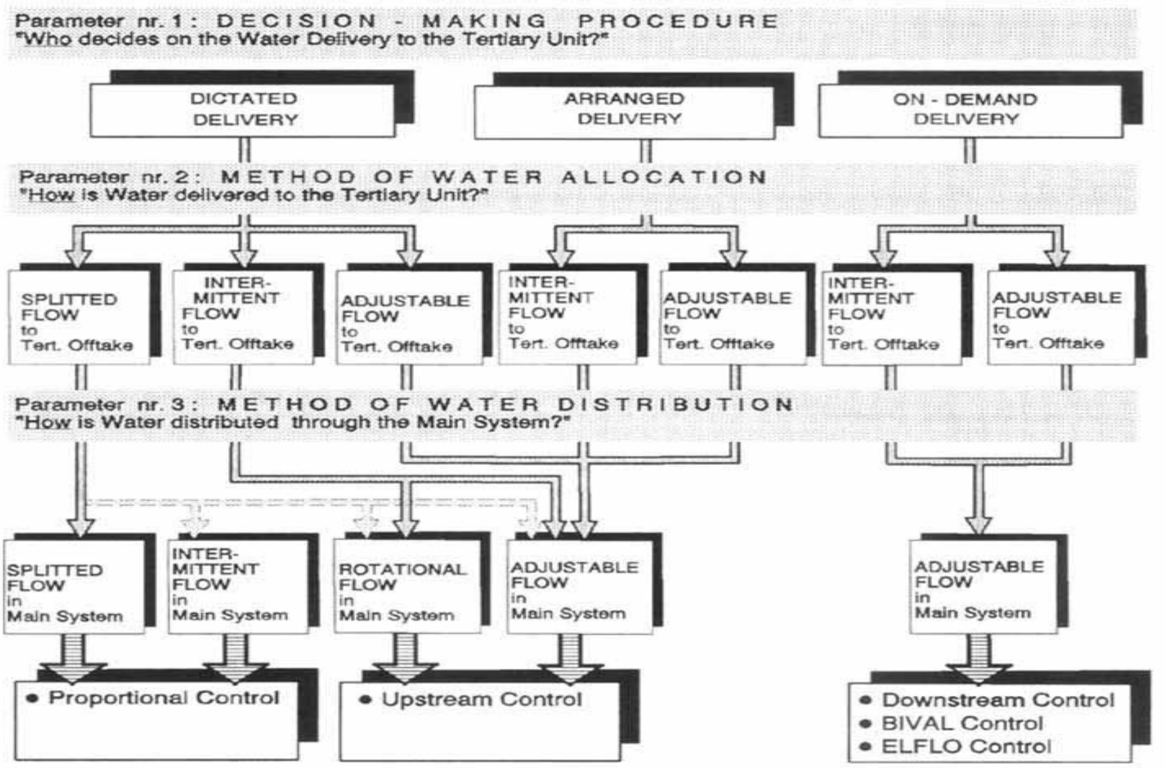

FIGURE 1. The selection of the operation method in canal irrigation delivery systems

The distribution method through the delivery system can either be based on 'split flow', 'intermittent flow' or 'adjustable flow', while also 'rotational flow' can be applied when the (sub)secondary offtakes are intermittently supplied by the same 'rotating' flow.

It is obvious that only a few options of delivery scheduling can be combined into the operational objective of a delivery system (Figure 1).

The initial selection of the operation method

The logic choices for the operation method follow from the above operational objective (see also Figure 1):

• The operation method for dictated delivery is either proportional control or upstream control. Proportional control requires only structures throughout the whole system that split the flow proportional into fixed ratios. Upstream control is required for an intermittent and adjustable flow to the tertiary units.

• The operation method for arranged delivery is upstream control with a central system management. Downstream, BIVAL and ELFLO control can also be operated on a basis of arranged delivery when the water availability is less than the accumulated water needs.

Then, the water requests from the individual tertiary units are checked first against the water availability, and the actual delivery is only done after endorsement by the O&M agency. Thus, a time-lag is introduced.

• The required operation method for on-demand delivery must be responsive. Downstream control and BIVAL control meet these requirements immediately. An alternative operation method might be ELFLO control which is also responsive, but will require a time-lag for the adjustment of the dynamic canal-storage.

EVALUATION OF THE OPERATION METHOD

Evaluation criteria

The criteria for evaluation of an initial selected operation method will vary for different irrigation projects. Also, different weighting factors may be applied. Generally, an operation method may be evaluated on aspects such as (see also Table 1): hydro-dynamic performance, hydrological and geographical setting, design and construction, operation and maintenance, economy, political and social aspects.

Evaluation on the hydro-dynamic performance

Systems with 'negative' dynamic canal storage (upstream, ELFLO control) have to adjust first the in-canal storage before a steady state is reached. The filling of the negative storage leads to a time-lag between the water release at headworks and the actual water availability at the tertiary offtake. Thus, these systems have long response time T_r during increasing discharges. The reverse will happen during decreasing discharges, as water flows out of the dynamic storage while it is not needed at the tertiary offtake. This is the operational loss.

In downstream control, the 'positive' (operational) in-canal storage provides immediately the increased discharge to an offtake, while the decreasing discharges can be saved in the canal reach for later use. In BIVAL control, the 'positive' (operational) storage always equals the 'negative' storage of the reach, so that such a canal functions like a pipeline without dynamic storage. Thus, systems under downstream control and under BIVAL control do not have time-lags nor operational losses. Efficient water use may not be a major factor in irrigation systems with re-use of drainage water, or when other systems depend on this return flow.

Irrigation systems with day irrigation only may have a low overall efficiency when the flow is not halted during the night. Systems with positive in-canal storage (downstream and BIVAL) will be suitable for an intermittent supply of 12 hours. The suitability for day irrigation only might be less relevant in run-of-the-river systems than it is for systems on storage reservoirs.

Evaluation on the hydrological and topographical setting

Operation methods under responsive management (downstream, BIVAL, ELFLO) fail during water shortages in the river. However, also upstream controlled systems may suffer from serious water problems in the tail-ends during unexpected water shortages, unless 'gate-proportional' operation is applied (Ankum 1993c).

High sediment loads prohibit operation methods with stagnant water in the canal reaches, such as downstream control and volume control. Also upstream and ELFLO control will be a less suitable choice. The application of a sandtrap at the headworks may solve these sediment problems.

TABLE 1 - **Evaluation of operation methods in irrigation**

Evaluation criteria	Proportional control	Upstream control	Downstream control	BIVAL control	ELFLO control
hydro-dynamic performance					
• short response time	na	- -	+ +	+ +	- -
• high operational efficiency	na	- -	+ +	+ +	- -
• high overall system efficiency	- -	-	+ +	+ +	-
• suitable for day irrigation only	- -	-	+ +	+ +	+
the setting					
• performance under water shortages	+ +	+	- -	- -	- -
• performance under sediment loads	+ +	+	- -	- -	+
• applicable at steep terrains	+ +	+ +	- -	-	+ +
design and construction					
• simplicity structures and regulators	+ +	+	-	- -	- -
• reliability structures and regulators	+ +	+	-	- -	- -
• application of local materials	+ +	+ +	- -	-	-
• operation without telemetric system	+ +	+ +	+ +	- -	- -
• operation without electric power	+ +	+ +	+ +	- -	- -
operation					
• without a water operation centre	+ +	- -	+ +	+ +	+ +
• without discharge measurement	+ +	- -	+ +	+ +	+ +
• no operators at secondary offtakes	+ +	- -	+ +	+ +	+ +
• no operators at tertiary offtakes	+ +	- -	-	-	-
maintenance					
• dependence on canal maintenance	+	+	- -	- -	+
• maintenance at a low technology	+ +	+ +	-	- -	- -
economy					
• low costs of earthwork	+ +	+ +	- -	-	+ +
• low costs of structures and gates	+ +	+ +	- -	- -	- -
• local currency only	+ +	+ +	- -	- -	- -
political and social aspects					
• robustness against water-theft	+ +	+	- -	- -	- -
• equity of water distribution	+ +	na	na	na	na
• equal disturbances in supply	+ +	+ +	- -	- -	- -
• flexibility of water delivery	- -	-	+ +	+ +	+ +
• use of dependable rainfall	- -	-	+ +	+	

na = not applicable
+ = good
+ + - very good
- = poor
- - = very poor

Evaluation on operation and maintenance requirements

Water operation centres are required for all upstream controlled irrigation systems where a 'flexible' supply of water should meet the changing demands. However, worldwide, it appears to be very difficult to create a well-functioning water operation centre. The question may arise whether more efforts should be made to establish water operation centres, or whether they be avoided by selecting other operation methods.

Field staff for system operation are especially required in upstream controlled systems, where they play an essential role. The flow diversion through these systems is frequently adjusted by the water operation centre, and the discharge regulators and the water level regulators have to be adjusted accordingly. The unsteady state of the system during the adjustments make proper gate settings a very time consuming activity. Discharge measurement throughout the system appears to be a burden for the day-to-day management, and is rarely well achieved.

Deferred canal maintenance on canals causes the roughness to increase, and leads to a steeper gradient of the water line in the canal reach. For proportional, upstream and ELFLO controlled systems, the tailwater level at structures becomes higher than the design water levels. This may not disturb the diversion of flow through the system as long as sufficient headloss and freeboard remain available at the regulators. Systems under downstream control and under BIVAL control may react differently. Here, the downstream water levels are kept constant, and the steeper water line 'rotates' around this target level. Thus, the upstream water level at structures becomes lower than the design levels. This causes the velocity to increase, and hence the friction losses in the canal, which leads to a further lowering of the water levels. It means that systems under downstream or BIVAL control are more vulnerable to poor canal maintenance.

Evaluation on economical, political and social aspects

The cost of the operation method will be a major determining factor in the selection. The creation of positive in-canal storage means that the embankments have to be raised above the design water level. This involves higher costs, especially for the longer distances between the regulators. The automation of the gate regulation as necessary under downstream, BIVAL and ELFLO control seems expensive in comparison with the manually operated gates. However, these incremental costs are only a minor component of the total project costs. The costs of the different control methods should be determined in the pre-design of the system, and have to be evaluated against the benefits and other aspects, such as organization, efficient water use, flexibility, and need for foreign currencies.

The political and social aspects might have an essential say in the ultimate selection of the operation method. Aspects may include: the robustness against water-theft and abuse, the equity of seasonable water distribution ('protective' irrigation), the equal distribution during disturbances in supply (upstream controlled systems), the flexibility of water delivery (downstream controlled systems), the use of 'dependable rainfall'.

THE ULTIMATE SELECTION

Observations on the ultimate selection

It is obvious that the selection of an appropriate operation method for delivery systems is not easy, and that all operation methods have their pros and cons (see also Table 1):

• Proportional control is the most simple and will suffice only in certain conditions of mono-cropping, extensive irrigation or when drainage water can be re-used. Systems under proportional control perform without system management, and react slowly to changes to supply. Equitable distribution is guaranteed for all discharges, when proportional structures with sufficient headloss are utilized.

• Upstream control is widely applied. These systems require strong central management, which is often hard to effect. The operation of the upstream controlled systems encounters difficulties because of the response time, while the operational losses may become high due frequently changing discharges.

• Downstream control does not require a central system management, and solves the above problems in response time and operational losses. However, earthwork and structures can become very expensive, while the in-canal storage, and thus the earthwork, is normally larger than required for good operation.

• BIVAL control is a good alternative to the downstream control at sloping canals. However, telemetry and electro-mechanical gates are introduced.

• ELFLO control is responsive, and needs even less earthwork than BIVAL control. However, it requires telemetry and electro-mechanical gates, while its in-canal storage behaves as in upstream control; with its response time and operational losses.

• A combination of the above control systems may sometimes lead to the optimum control method. For instance, it is possible to combine different control methods throughout the delivery system, or to apply regulating reservoirs or storage reservoirs.

Changing operational objectives

The selection of the operation method on existing systems may become quite complex when the operational objective has changed gradually. A mismatch between the changed operational objective and the operation method of the delivery system often occurs.

The objective of equitable water distribution is best obtained by proportional control. However, such a system is often not very efficient in water use. Efforts to improve the efficient use of water by applying gates in the structures will transfer the system into upstream control. The new objective of water efficiency might be obtained within the tertiary unit, but at the same time it introduces (new) operational losses in the delivery system. The original concept of equitable water distribution is deliberately eliminated and should no longer be used as a criterion to judge the performance of the central system management.

Arranged delivery in upstream control is obtained only when the central system management is active. However, it is often felt that such a water operation centre does not fit in the prevailing technical and social context. An upstream controlled system without central management can never meet an arranged delivery. It is just operated on a dictated delivery basis with standing orders, or is operated in a chaotic manner. Proportional control (dictated delivery) or ELFLO control (demand delivery with responsive system management) would often lead to better results.

Many 'supply-based' systems (dictated delivery) under proportional and upstream control have been developed for protective irrigation (e.g., India, Pakistan). These systems cannot easily be reshaped into 'crop-based' systems (arranged and on-demand delivery). Firstly, the relative capacities of these systems have to be increased substantially (e.g., from 0.3 l/s.ha to 1.2 l/s.ha), and the water availability has to be ensured. Secondly, it has to be acknowledged that upstream control for arranged delivery has to rely on a strong central management, while a slow response time and operational losses are unavoidable. Other alternative control methods with responsive management are normally not applicable. Downstream control is often prohibitive because of extensive reconstruction works on the canal banks. BIVAL control would reduce these reconstruction works, but it introduces telemetry and electro-mechanical gates. ELFLO control would even avoid any reconstruction works, but it requires telemetry and electro-mechanical gates and it performs with a time-lag and with operational losses.

CONCLUSIONS

On-farm irrigation scheduling is only possible when the delivery system provides the irrigation water at the expected time, rate and duration. The selection of the proper operation methods for these delivery systems is quite complex.

There is no ideal method of operation applicable to any delivery system anywhere. For instance, proportional control might be the best choice for irrigation scheduling focusing on equity. Upstream control might be considered for high efficiency at on-farm level. Downstream control provides a flexible irrigation scheduling at on-farm level. However, all operation methods have their weaknesses.

The selection process may follow the three iterative steps outlined above. The ultimate selection is closely related to the required irrigation scheduling. It requires inputs from all parties concerned, in a multidisciplinary approach.

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Operation Techniques in Canal Systems

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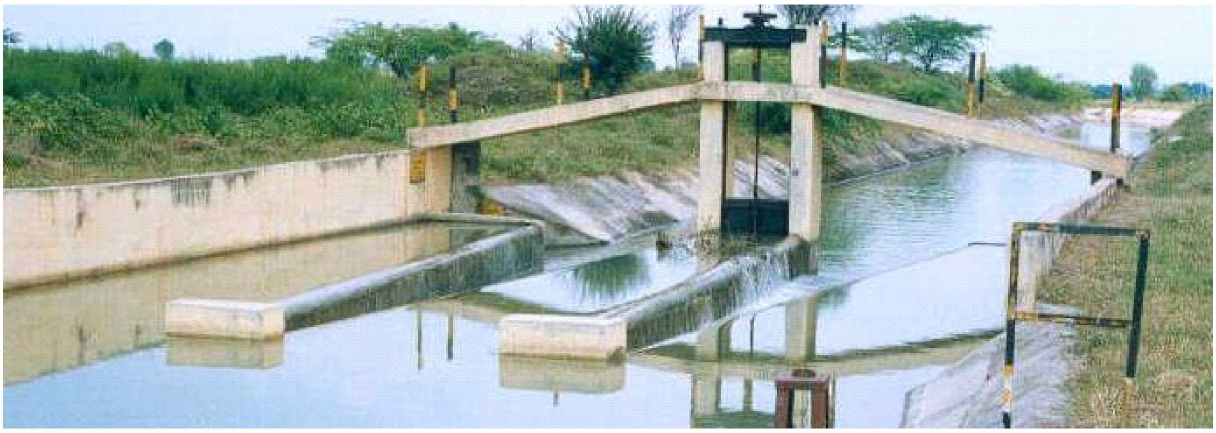

In irrigation system management, distinction must be made between the organization of the water service (distribution) and the way the structures are operated (operation).

These two aspects of management, are strongly related, operating a canal is made with the purpose to satisfy the agreed upon service, and inversely, the choice for a given service is highly dependant on the physical and managerial capacities of the existing structures.

The water service distribution.

Water service organization reflects the way users have access to water and how they deal with the service provider in agreeing for a water service. In that regards, water service can be organized in many different ways. Of course along open channel irrigation systems, the more usual practice is the rotational distribution of water. This is in fact the more cost-effective way for irrigation, as the infrastructure is designed only for the continuous flow at the peak of the season. On the other side of the spectrum, open access to water (limited rate demand schedule) is offering to the users high flexibility in accessing the water, allowing optimisation of irrigation practices and equipment. In between these two extremes, there are many variations of water distribution modes, which have adapted with time and have been locally crafted. Here we are examining only rotational, open access and arranged demand.

Rotational system - Warabandi

The main type of distribution in open channel systems is based on rotation. This is the less costly type of distribution, and it covers a large part of the world irrigation domain, particularly in the old irrigation systems. The principle is that the irrigation module circulates within one block from one user to the other, the duration of irrigation for each user depending on the irrigated area. This distribution mode leads to minimum canal capacity possible. Within one block the size of the canal is set to the module, and upstream the block it is set to the continuous flow requirement of the command area.

The modules are the discharge delivered to farmers, ranking from 30 to 100 l/s, depending on the irrigation technique at field level. This module is based on the capacity of the user in controlling efficiently water application at field level. With furrow irrigation, the module can be something between 25 l/s to 50 l/s, with basin or border irrigation it can go up to 100 l/s. The module is same whatever the size of the field, and the adjustment to water requirement is obtained by adjusting the duration of the turn to the area irrigated.

One block is designed in such a way that at the end of the cycle after last user's irrigation, the module is issued again to the first user. The size of the block results from the capacity of the module in satisfying water needs at peak. For instance if the water needs at peak are 1 l/s/ha a module of 30 l/s will circulate then within a block of 30 ha as shown in figure 1.

The periodicity of irrigation is organized to make sure that the day and night time irrigation are shared equally during the season among users. For instance the rotation can be based on a 7 days 6 hours period. A farmer who starts irrigation Monday at 16h00 will start next week at Monday 22h00.

Open access

Very few open channel system with surface irrigation at field level accommodate open access distribution. It is generally too costly:

- the size of the canals much be much bigger than for rotational system, in order to allow for peak demand.
- it must come with downstream control to allow the system to react instantaneously to the variation of the demand.

Some systems can though accommodate in some circumstances some flexibility to the users, it might be the case:

- during the early stage of irrigation when the demand is lower than the peak leaving some room for flexible adjustments.
- On some irrigation systems that presents some over capacity due to reduction of command area or reduction of water needs, i.e. change from rice system to other crop.

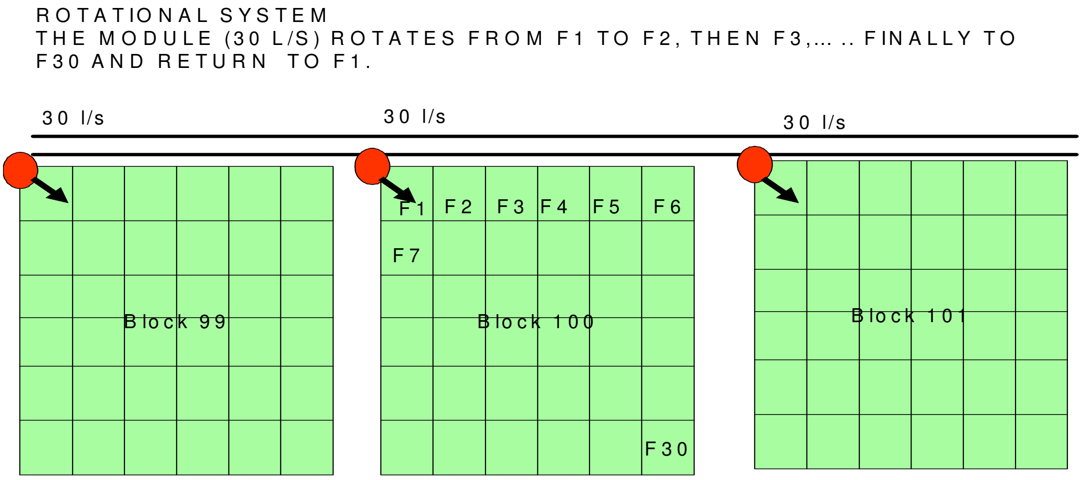

Figure 1. Organization of rotational systems per block in surface irrigation.

Arranged demand system

The arranged demand system has been developed particularly in the USA, it is a good compromise between rotational and open access. The size of the canal are designed to allow little more than the peak continuous flow. Users are expressing their demand to the manager through various means (nowadays telephone, or internet) in advance with a requested discharge (Q) and timing (start and duration).

The manager then processes all the demands and design a suitable solution for accommodating all requested flows. He then informed each user on how the distribution will reply to the initial request. Some irrigation demand can be satisfied without change some might be delayed, by one or two days.

Operational and regulation modes

Operation consists in manipulating gates and structures in order to produce the agreed upon service and deliver it to the users. There are several logic for operation, they depend on several criteria which are described briefly in this section. The first criteria we are considering for operation are: controlled variable, type of control, and degree of operation.

Controlled Variable

Operation of irrigation systems may seek to control discharge, volumes or a combination of discharge and volume. **Discharge control is the most common control procedure**. To be very precise it means the **control of distributed discharge** along the main canal.

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

UPSTREAM CONTROL

Most gravity irrigation systems are based on upstream control. With this technique, all irrigation control structures (structures) are set according to the discharge imposed from the main intake structure. The objective is to maintain the water level upstream of each cross-regulator to control the backwater profile in the upstream reach. The backwater profile determines the head at offtakes in the upstream reach.

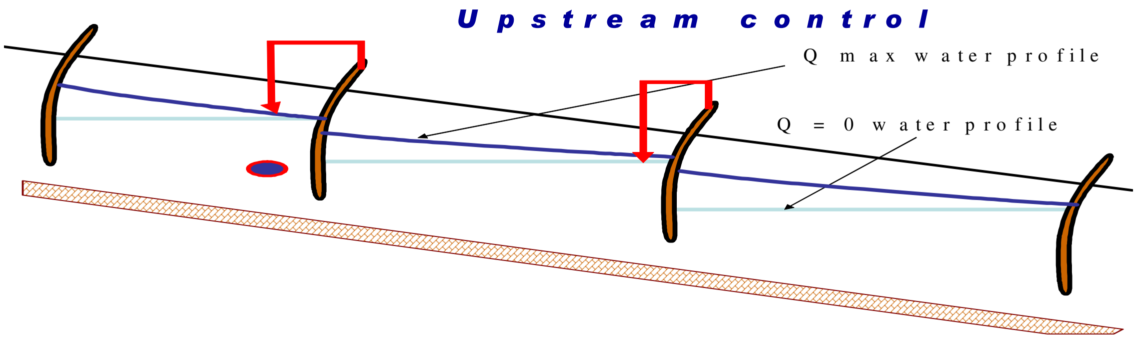

Figure 2. Sketch of upstream control technique at X-regs

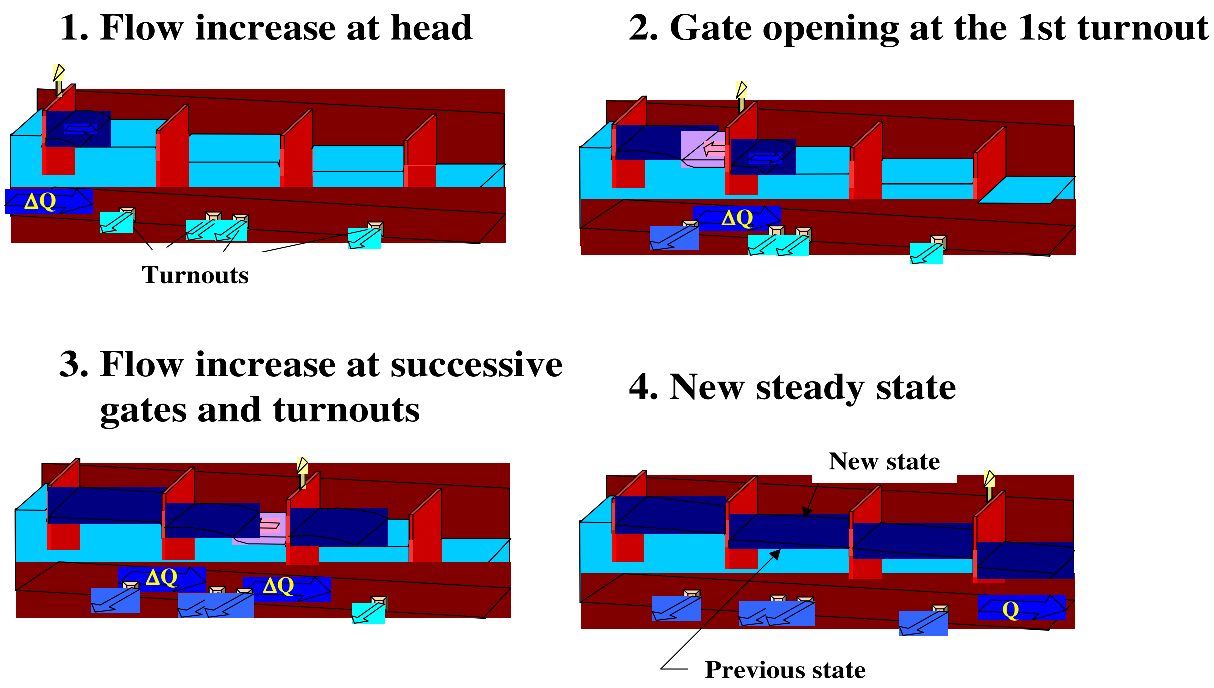

Figure 3. Upstream control dynamic

DOWNSTREAM CONTROL

The alternative technique, i.e. downstream control, has attracted the attention of engineers and irrigation managers because of the potential advantages. Downstream control automatically responds to fluctuating downstream demands from users and can minimize water losses. However the technique requires horizontal canal banks and some automated control structures.

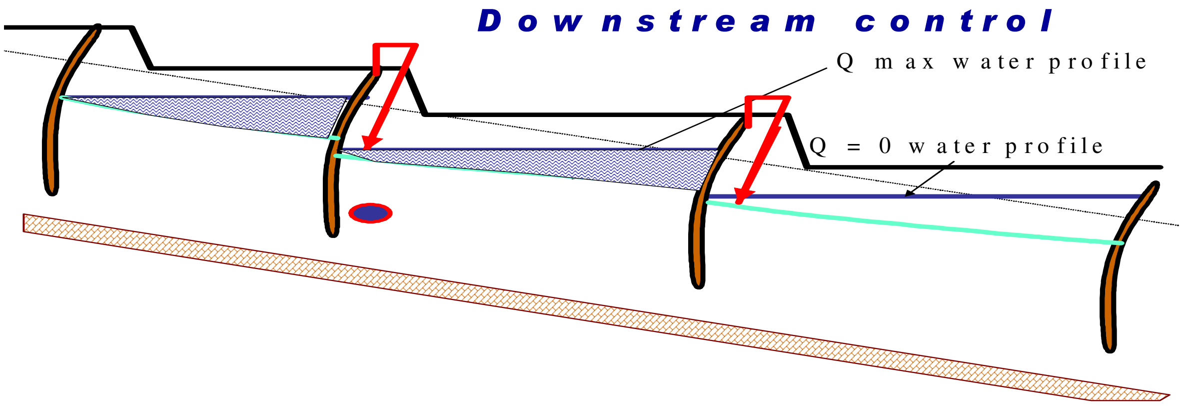

Figure 4. Sketch of downstream control principle.

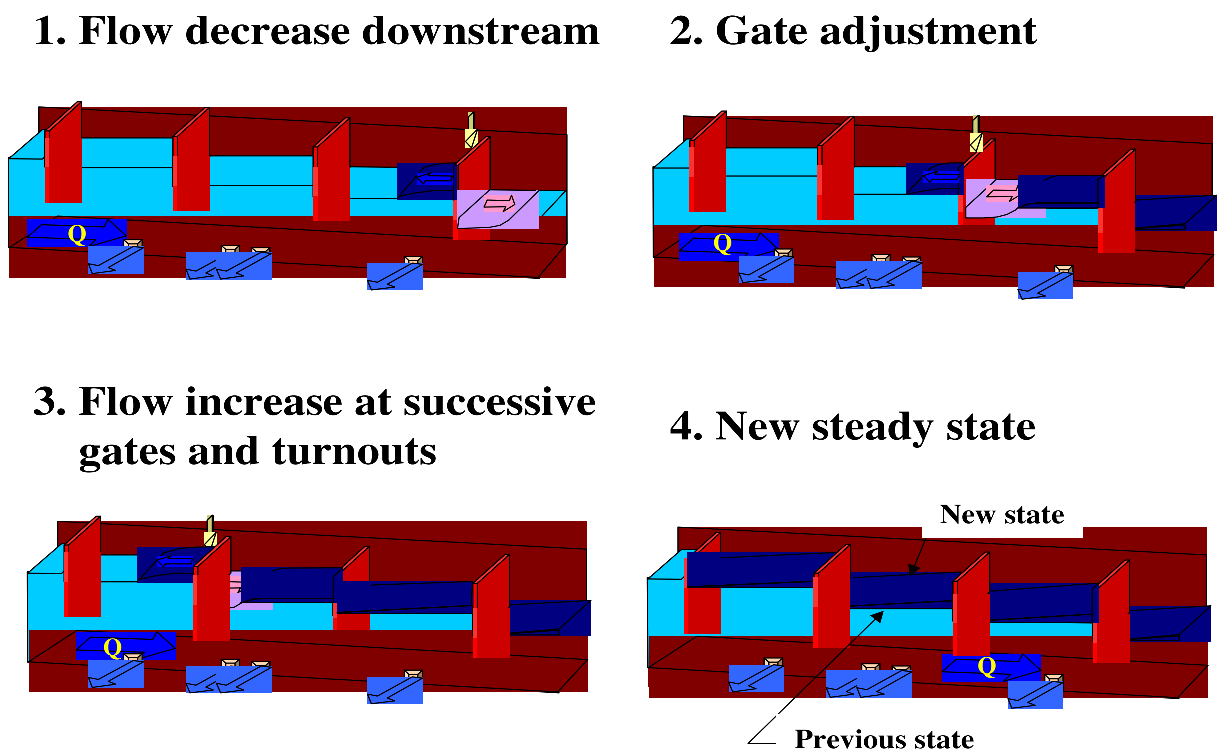

Figure 5. Downstream control dynamic.

Variations of downstream control

BIVAL control and ELFLO (see previous paper from P. Ankum) control are variations of DS for which the location of the sensor varies. For BIVAL the sensor is located at the middle of the reach and for ELFLO at the downstream part. The advantage is that limited or no horizontal embankments are needed.

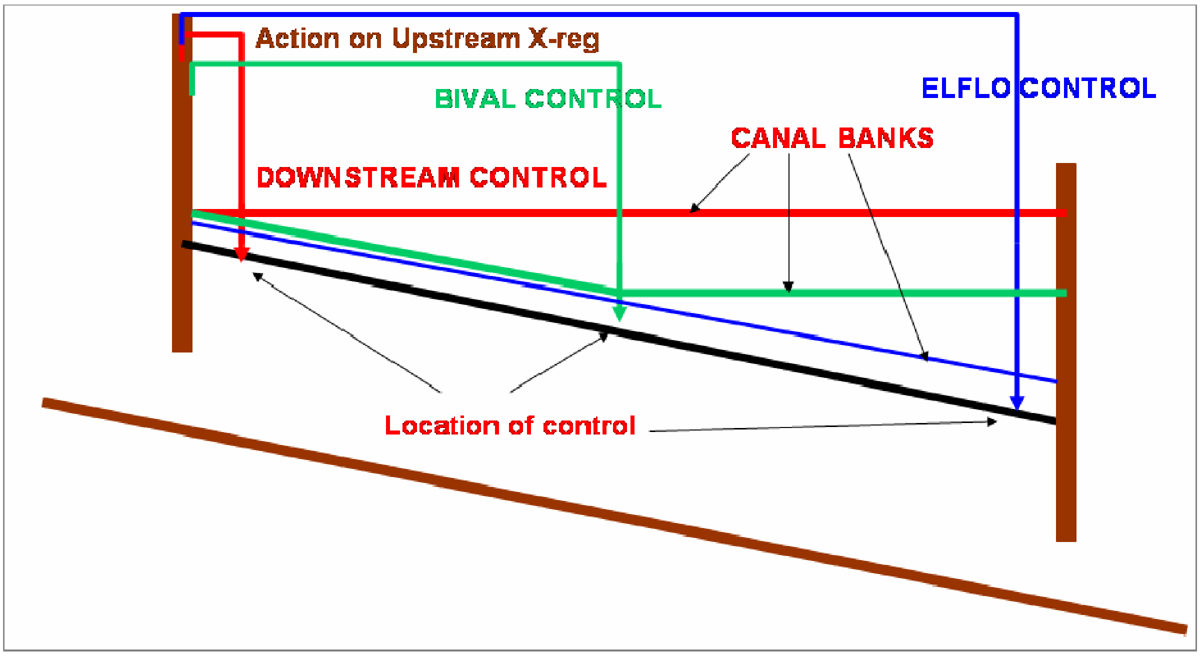

Figure 6. Downstream control variations.

Type of Operation

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

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

Partition of this criterion is finally made considering three classes:

- manually operated gated systems,
- fixed systems and
- automatic/semi-automatic systems.

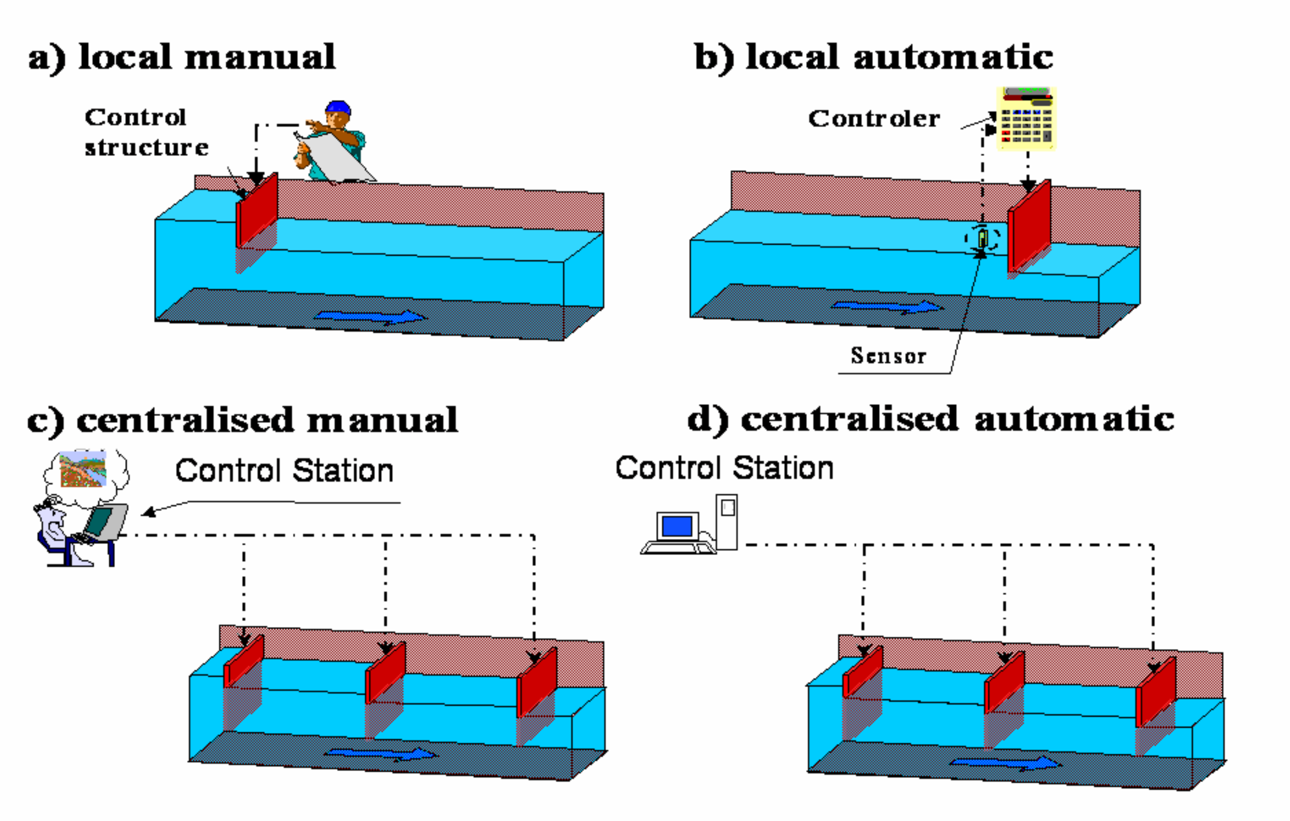

Figure 7. Type of canal operation.

Manually operated Gated Systems

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

Fixed systems

These systems known as 'structured systems', have been largely developed in India, Pakistan and Nepal (Shanan, 1992). Water delivery is organized around pulses of constant discharge with a varied frequency. Distribution is proportional and structures are fixed permanently at the construction stage (no movable parts). Although the non-adjustable section of structured systems is limited to minor canals with the main/branch canals remaining fully operated the savings in resources for manipulation of structures can be important as shown by Shanan (1992).

Automatic/semi-automatic systems

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

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

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Plate 1. An automatic upstream control gate (Tadla Morroco)

Important properties of irrigation structures

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

Adjustment

The properties, freedom of adjustment and precision of control can be analyzed through the classification of structures as proposed by Horst (1983):

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

- For fixed structures, freedom of adjustment is nil, since output is directly imposed by on-going discharge (input), and precision is meaningless.

- For open/closed structures, freedom, and precision are not relevant.

- For stepwise adjustment, freedom and precision are limited by the number of discrete steps in the adjustment between zero and full capacity.

Plate 2. A stepwise regulator (UP India)

- For gradually adjustable structures, the degree of freedom is usually high in that it is generally possible to choose any setting between zero and the maximum value. However, in practice the actual setting will be imposed by the *Input* value. Precision will depend on the increment of the mechanical adjustment.

- For hydraulically automatic structures flow conditions are the governing factors. In general these structures cannot be adjusted in normal use and therefore the degree of freedom is zero. However the operational objective is to maintain constant output and precision is determined by the range of variation of output resulting from variations of input.

Manipulation and control

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

Sensitivity

The *sensitivity* criterion characterizes the hydraulic stability of the control structures. For example when considering discharge control, overshot structures are three times more sensitive than undershot structures (assuming head losses are equal). The difference is due to the exponent of the head loss variable in the discharge equation, $3/2$ and $1/2$, respectively (see chapter on sensitivity).

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

Physical condition

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

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

Conveyance and storage structures: Reach

Canal reaches are considered here as structures for conveyance and/or storage of water. The criteria of significance for operation of these structures are: Storage; Control; and Bed material.

Storage

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

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

Control

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

Bed material

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

Upstream control operation at full supply depth

In the upstream control mode the objective is to control water depth upstream the regulators within specified variation (tolerance) about target. This target is often set to the Full Supply Depth (FSD), which is the depth for which canal has usually been designed for operation, and which allows offtakes under the influence of the regulator to be fed properly.
Cross-regulators can be fix (Duckbill weir), automatic (AMIL gate) or adjustable consisting of one or more central undershot gates. Some undershot gated regulators, as in Sri Lanka, are equipped with dual side weirs set at FSD. In that case the objective for operation is to keep the water surface at the spill level of the side weirs.

Adjustable regulators can be manually operated or motorized, in the latter case specific rules for operating the gates (reaction to a measured deviation of water depth) must be looked for in order to allow a good control of water depth without generating too many oscillations of the water profile along the canal. In manually operated system, specific rules, though much simplier, must also be found. In Sri Lanka, routine operations to cross-regulator gates can be described as a proportional reaction, i.e. the correction applied by the operator to the gate setting is proportional to the observed deviation of water level from the target, FSD.

In describing an operational procedure we have to distinguish:

- **scheduled changes of flow** rates which require direct adjustment of gate settings to impose the desired discharge after the water surface profile has stabilized following the change in the setting, and
- **routine operation**.

Several alternative operational strategies are possible to implement the FSD mode of operation - Figure 7.

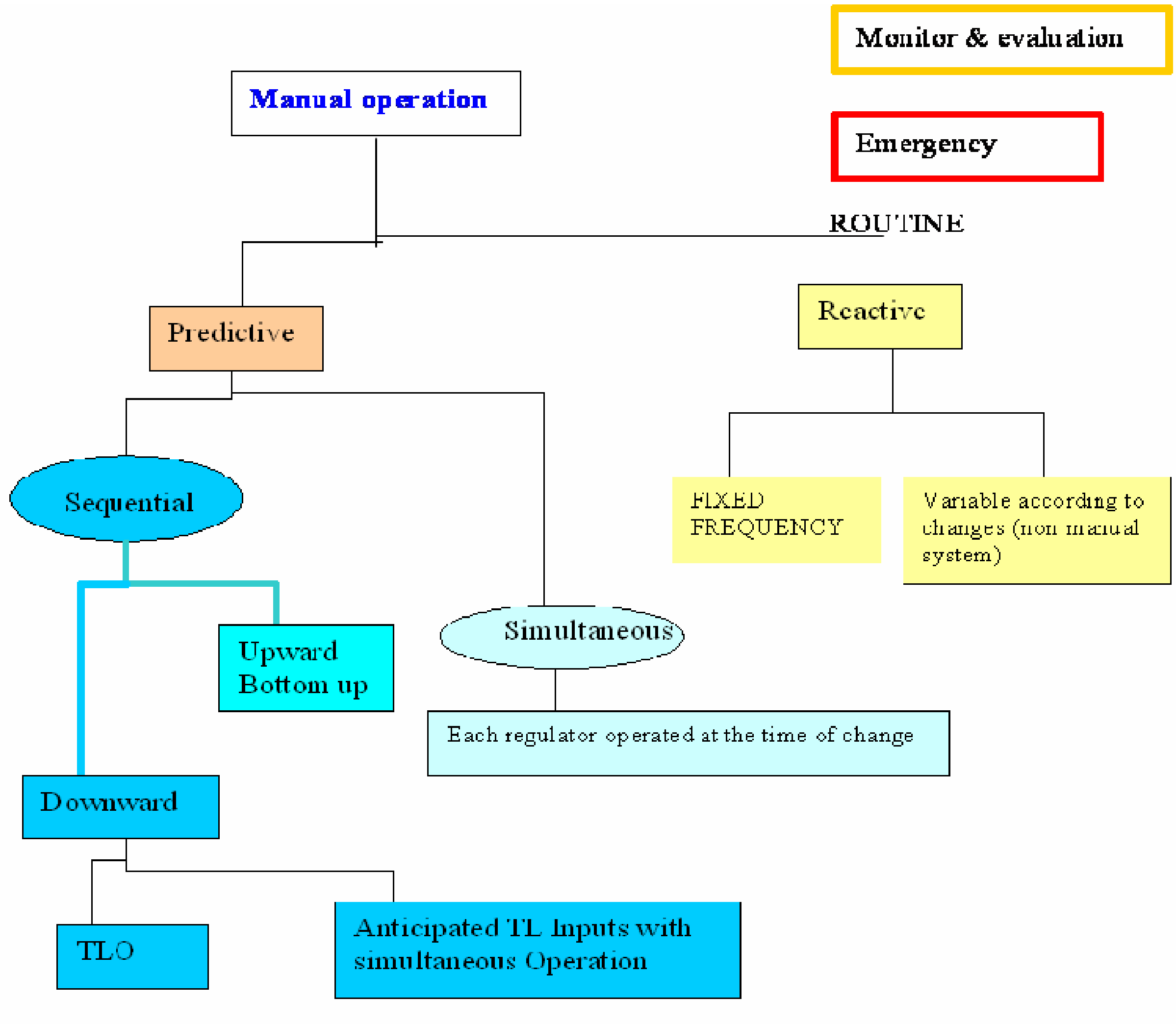

Figure 7. Operational strategies for FSD mode.

Fixed Frequency Operational Procedure

Routine operations are carried out at cross-regulators only and occur at a fixed frequency (FF). For example in Sri Lanka the actual frequency of operation is generally twice per day, one operation taking place between 7 a.m. to 9 a.m. in the morning and the second between 4 p.m. and 6 p.m. in the evening. This pattern corresponds to a nominal 12 hours frequency of operation. Exchanges of operational information between gate operators and the system manager are limited to one exchange per day, usually in the morning.

To implement a scheduled change of delivery, additional operational inputs are required. Cross-regulator gates are adjusted as the wave resulting from change of head intake discharge reaches each cross-regulator. This operational procedure is referred to as Time-lag operation (TLO).

No specific operational procedures are identified for response to unscheduled flow changes, routine operational adjustments at a frequency of 12 hours are considered sufficient response. Normal mode of operation (FSD) does not attempt to actively manage positive flow changes by, for example, storing additional flow volumes either in the canal section or in on-line reservoirs. The management objective is to minimize the impact of flow changes on on-line adequacy and to dissipate peak-flows without structural damage to the canal.

In the context of Sri Lanka potential for improving operational performance have been tested. The first option was to examine the impact of varying frequencies on performance whilst retaining full supply depth (FSD) as the operational objective. Four alternative fixed frequencies were considered and compared 3, 6, 12 (current practice) and 24 hours.

Alternative to fixed frequencies

Alternative procedures for scheduled operations as described in the literature are:

- Time Lag Operation (TLO) - current practice
- Bottom-Up (BU)
- Simultaneous Operation (SO),
- Proportional to Time-Lag (PTL)

The time-lag operation (TLO) requires gate-operators to adjust gate settings as the transient wave front arrives at the cross-regulator in response to upstream operations. Anticipation of the passage of the transient wave is zero.

The Bottom-Up (BU) operation consists in implementing gate adjustments from the tail of the systems. In practice, each gate operator is responsible for operation of several cross-regulators. Therefore each operator starts adjustments at the same time at the most downstream of the regulators in his control. After setting the required gate position the operator moves to the next regulator upstream. In general the delay between operation of successive regulators is about 30 minutes. Finally the main intake regulator is adjusted and the change in the supply propagates through the system. Anticipation of the wave is maximum in Bottom-up (BU) operation.

Simultaneous Operation (SO) requires all structures to be adjusted at the same time. This is possible only if an operator is available at every structure, in practice operators must move from one regulator to the next. Anticipation of the transient wave is intermediate between time-lag and bottom-up operations.

Proportional to Time-lag operations (PTL) are a compromise between (TLO) and (SO). Gates are operated at a specified proportion of time-lag (between 0 and 1). The degree of anticipation is variable. Implementation of PTL requires operators to have a rough estimate of usual time-lag. This can be obtained experimentally by observing the propagation of a flow change along the canal. These estimates can thereafter be used to identify approximate values for PTL at each cross-structure of the canal.

Discharge Control along the main canal

Discharge Control along the main canal (DIC) is a specific procedure for control of the outlet structure of intermediate reservoirs in STO subsystems. Discharge Control seeks to maintain a constant downstream discharge, equal to the initial target value, requiring a gradual closing of the gates until the reservoir water level stabilizes at a new value, after the wave reaches the reservoir. Once water level stabilizes, the outlet structure is operated to issue the new target discharge. This procedure aims to achieve a perfect delivery hydrograph downstream of the reservoir but implies a large frequency of interventions during the transient period. Operational procedures for the reaches upstream of the storage may be fixed frequency or time-lag operation (TLO).

Pseudo downstream control or real discharge control

There are often situations where operation in place looks like downstream control technique but in fact is what we called "pseudo downstream control". This is characterized by operating each cross regulator to maintain a given discharge downstream through a gauge located downstream of the X-reg. This is not real downstream control, BUT **real discharge control** along the main canal, lateral withdrawals are then automatically adjusted by the variation of water level upstream of the regulator, this allows keeping the downstream discharge close to the setting point.

These two situations (real and pseudo downstream control) might be confused on the field because both are dealing with a downstream target. In **the real downstream control** the downstream reach is under the influence of the downstream regulator, flow is submerged[1].

In the **pseudo downstream control** the flow is often non influenced [normal flow occurs] and there is one relationship between height and discharge therefore targeting a specific height means keeping a discharge about target.

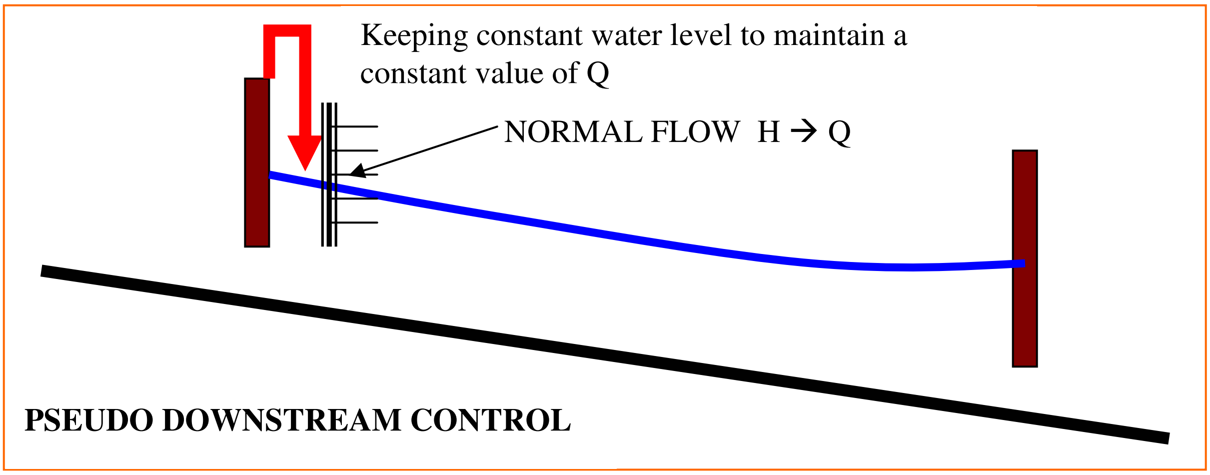

Figure 8. Pseudo downstream control at X-regs

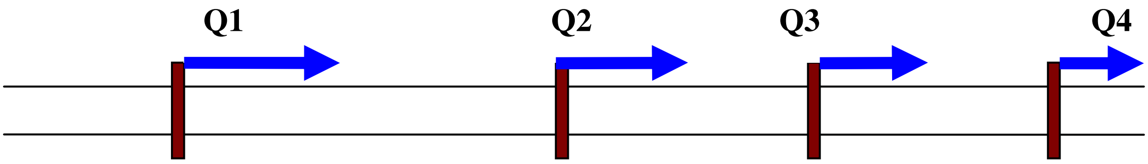

Figure 9. Pseudo downstream control along the canal.

The pseudo DS Control technique is like starting all over again upstream control at each main cross regulator.

Flexibility in operation : flexible Demand & Flexible Inflows

There is abundant literature on the evolution of the numerous canal control concepts and methodologies mostly developed for semi-arid climates, and in contexts where value of water is recognized for highly productive irrigation.

In semi-arid climate contexts, many irrigation systems are characterized by steady water supply and climate conditions, and canal control is primarily considered in terms of changes

[1] There are several options for DS control, the most common that we are referring to here is when the control is exercised on the level immediate downstream of the structure. Others are considering other points within the downstream reach.

in the required delivery pattern. The complexity and the frequency of these changes are influenced by the degree of flexibility allowed in the demand varying between imposed upstream supply and fully on demand supply (Clemmens, 1987).

In tropical areas, variability of both inflows and outflows is a major characteristic of irrigation systems. Studies have recently drawn attention to the importance of supply fluctuations in explaining low performance, of both water management and also agriculture. For instance, in MUDA Scheme, Malaysia (ITIS, 1996), the regulated supply accounts for only 35% (controlled supply from a remote reservoir 29% - recycled drainage water 6%) of the annual total water supply to the area. Other components are direct rainfall 52% and uncontrolled river flows 13 %. In this context fluctuations of inflows are as important as fluctuations in the demand when it comes to operational decisions.

In Sri Lanka studies have shown the importance of inflow fluctuations in irrigation systems (Renault and Goddaliyadda, 1999). The salient features for Sri Lanka systems are those :

- affecting generation of perturbations of flows:
- *Return-flow*: overflows from distributory channels or from fields (paddyfield) which return to the irrigation system (found in about 20% of irrigation systems) varies in time.
- *River Diversion supply*: About 28 % of irrigation systems in Sri Lanka are River Diversion type and are subjected to greater variability of inflows than Reservoir types.
- *Canal branch diversion and canal serial diversion:* A branch subsystem can exert a limited control on the supply rate, whereas a serial diversion has no control, i.e. the flow coming 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. canal without built bank on the uphill side, are common in Sri Lanka due partly to the slightly undulating topography. (92 % of irrigation systems in Sri Lanka are considered partly or entirely of single bank type). Large inflow fluctuations are the results of unregulated run-off entering the canal system during rainfall events.

- with limited (or no) influence on perturbations:
    - *Double-Bank:* This feature uncommon in Sri Lanka when considering systems as a whole (8 %), however most system classified as single-bank type have portions which are double-bank.

- that may ameliorate the impact of inflow variations:
    - *Localized storage:* The presence of intermediate reservoir within the system (42 % of irrigation systems in Sri Lanka) is an opportunity to damp perturbations.
    - *Return-flow*: diverting positive perturbations towards areas with return-flow enables implementation of efficient reactions. This feature is found in about 20% of irrigation systems in Sri Lanka.
    - *Re-Use system:* Positive perturbations can be diverted preferentially towards areas where it is known water can be recycled downstream.

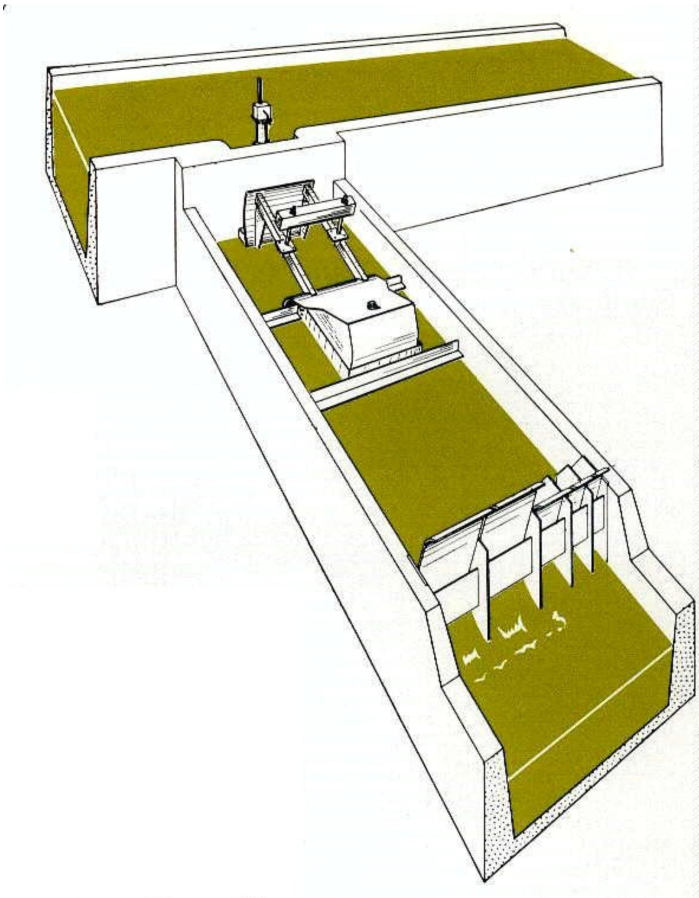

Figure 10. Sketch of downstream control structure AVIO in the lateral to control supply to modules.

Controlled Volume for flexible operation

Controlled volume technique has been originally developed for management of canal storage to enable improved responses to fluctuating demands (Malaterre, 1995), however recent studies in Asia have shown the advantage of using this technique to deal with flexible supplies in particular in systems where there are no recycling facilities. The objective is then to use the available storage in the canal and local reservoirs, to attenuate the variations of inflow.

Dynamic regulation (Rogier et al., 1987) is one example of controlled volume methodology applicable to irrigation canals without intermediate storage reservoirs. The main advantages of using a volume control technique, is the ability to deliver instantaneous discharges greater than the actual transport capacity of the system. This property is of great importance to match peak flows in non-rotational distribution, e.g. on-demand or free access delivery pattern. Volume control techniques are receiving increased attention.

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

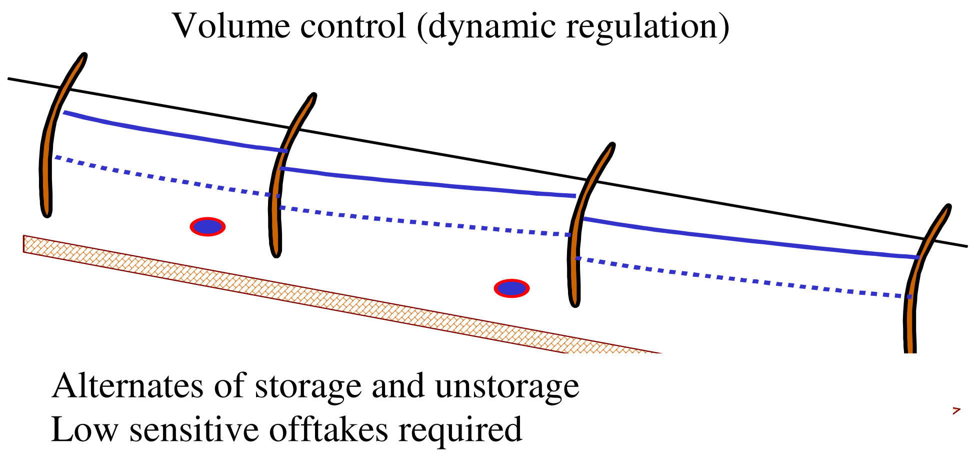

Figure 11. Wedge storage for volume control

Based on the physical characteristics of irrigation systems in Sri Lanka, it is apparent that many are subject to unscheduled variations of inflows. Improved strategies to manage such systems are required to maximize the efficiency of water management and delivery performance.

Use of either canal wedge storage or local reservoir storage are well known forms of controlled volume operations that are widely applied in many irrigation systems:

- *Wedge Storage*: This strategy aims to get benefit from the on-line storage capacity. Wedge storage may be implemented by setting a targeted water level at below the normal full supply level (BFSL) at cross-regulators. Water levels are allowed to fluctuate about this level to full supply depth, which corresponds to the spill level at the cross-regulators as shown in Figure 2. As positive perturbations occur, water levels rise and part of the volume of unscheduled perturbation can be temporarily stored in the canal reaches.

- *Localized Storage*: This strategy uses intermediate reservoirs to store positive perturbations and to compensate for negative perturbations (Burt and Plusquellec,1990).

Two further strategies can be proposed to complement the strategies above, as being applicable to many tropical irrigation systems:

- *Over Supply to Offtakes*: Offtakes to Return-Flow or Re-Use subsystems may be oversupplied during positive perturbations to respectively use the command area to temporarily store water or to make water available downstream within the irrigation scheme with some time delay.

- *Under Supply to Offtakes*: In systems experiencing non-permanent 'water shortage' and having a high probability of unscheduled positive perturbations, some or all offtakes may be deliberately under supplied (level below Full Supply Level or offtake setting below targets) during periods of shortage. Any positive perturbation occurring in the system generates a rise of the water depth in the canal and increases effective delivery to offtakes. This strategy can be tailored to distribute supply fluctuations equitably or to ensure only those sub-systems that are less vulnerable are subject to significant variations.

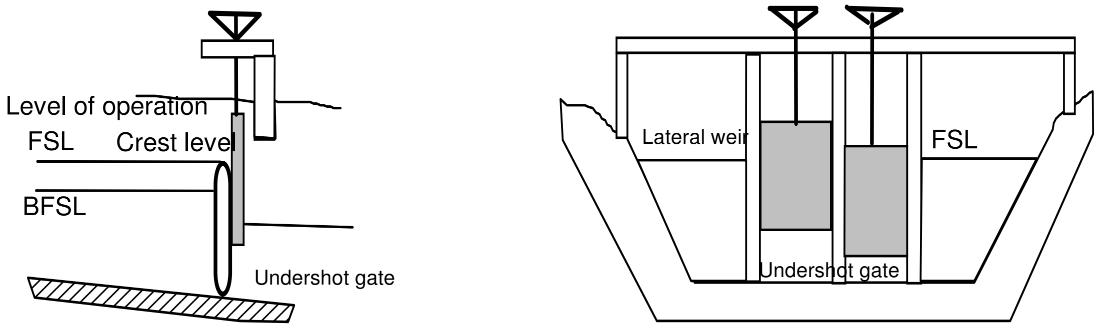

Fig.12. Sketch of a typical cross-regulators in Sri Lanka with undershot gates and lateral weirs.

In practice these latter strategies require offtakes (and regulators) that are relatively more hydraulically sensitive so that surplus flows are diverted to the command areas, as discussed below.

Operational Procedures for Controlled Volume Mode

In manual operation two procedures are possible: 'no-reaction procedure' (for example during night time), or the 'reaction procedure'.

For Over Supply to Offtakes and Under Supply to Offtakes strategies, the objective is to increase the effective use of the perturbations by making additional on-line deliveries. Provided the canal structures are sufficiently sensitive a 'no-reaction procedure' is feasible: water levels are allowed to rise up to the structure spill level (FSL), see Figure 2, and water surplus is diverted from the canal. After water level reaches the spill level, the choice between no-operation and operation is dictated by local physical properties of the canal, the availability of resources for operation and canal safety considerations.

A 'reaction procedure' implies the detection of perturbations and the subsequent implementation of a reaction. Reactions include two types of intervention. One consists of increasing opening of offtakes to further increase deliveries in Over Supply to Offtakes and Under Supply to Offtakes strategies. The second is a Cut-Back (CB) of the main supply to compensate for additional water availability in the system as a result of the storage of the perturbation.

Targets for operations and performance

With controlled volume strategies the operation targets and therefore, performance evaluation, should focus on three aspects: on-line adequacy, i.e. deviation between actual and expected total volume delivered at the offtakes located along the subsystem; efficiency in harvesting perturbations, i.e. volume ratio of water effectively used *vs* perturbation volume; and the safety of the canal. Generally, the later is increased along the main canal with Controlled Volume approach as perturbations are damped or diverted from the canal. However, the capacity along branch canals and distributaries must be compatible with flows likely to be diverted and safety margins must be checked.

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