BIVAL SYSTEM FOR DOWNSTREAM CONTROL

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ABSTRACT

The BIVAL system of canal regulation guarantees that the maximum discharge can be delivered at any time, as for downstream control systems and, moreover, it minimizes the canal dyking works since the banks need not be horizontal along the total length of the reach but only along approximately half. The principle of the BIVAL system (Sogreah's patent) is based on a simple linear equation. It requires simultaneous measurements of levels downstream and upstream in the reach, in order to cause the upstream gate to respond immediately to the downstream demand. In this paper, the BIVAL system is fully described and two examples of application are given.

INTRODUCTION

Nowadays, the growing need for well-developed agriculture requires efficient irrigation systems and management of water. Although the design of irrigation networks follows well-established standards, the appropriate delivery of water to satisfy farmers' needs at the right time is still the topic of research. Many control methods have been developed for new systems or for rehabilitation of old ones. Each method is a compromise between water availability, farmers' needs, costs, existing design if any, safety, training of personnel, etc.

In this paper, the Sogreah's patented BIVAL system of canal regulation, also called "constant downstream volume system", is described and an application is shown in the case of rehabilitation of a canal in Mali (West Africa). Comparisons are drawn with other systems on the basis of the implementation costs and the expected system improvements.

Starting in the early 1960's, Sogreah's people, directed by Dr. A. Preissmann, developed reliable hydraulic simulation programs based on their field experience and mathematical knowledge and also on long-standing use of scale models. Preissmann has introduced numerical schemes for finite differences computation, [4] and [5], which have been succesfully applied in programs in many countries. Other achievements in mathematical modelling have been described by Cunge in [6].

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Sogreah (a non-subsidized French company) has been conducting consulting engineering work in hydraulics for more than 30 years. Its activity, originally focused on irrigation and hydroelectric power, nowadays covers related fields such as human and land resources evaluation, river regulation and flood control, urban water supplies and sewerage systems, multi-purpose dam projects, navigation studies and coastal engineering. Projects are currently carried out all over the world.

TECHNICAL DESCRIPTION OF THE BIVAL SYSTEM

It is useful to place the BIVAL system within the range of choices available. Canal control systems can be classified in three categories according to control principles:

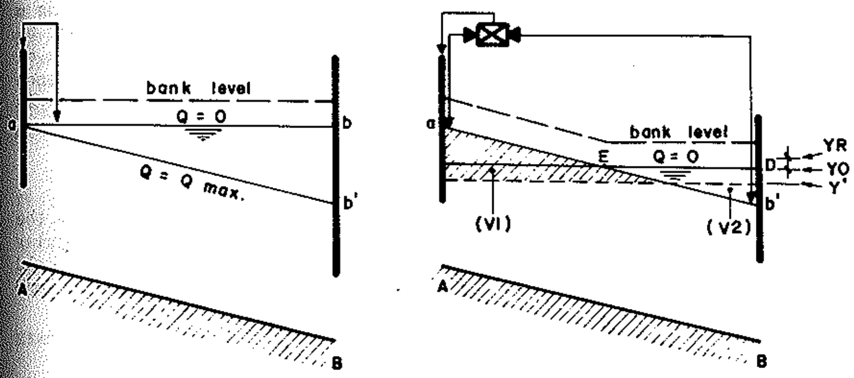
. "Upstream control", in which there is no possibility of water storage in the reach. This type of control requires both accurate forecasting of irrigation demand at the turnouts and a predefined back-routing law in order to determine the water discharge that needs to be delivered upstream. Wastage and shortages of water are inevitable for two reasons: (i) forecasting cannot be 100% accurate, (ii) reliable back-routing is impossible.

. "On-demand control", which guarantees delivery of the exact amount of water needed at the turnouts and hence yields a high irrigation efficiency, but which requires a large storage volume in the reach. This may lead to expensive civil engineering works for dyke construction, especially in the case of very long reaches or steeply sloping land.

. "Mixed control", which still requires forecasting and back-routing algorithms, but where provision can be made for some buffer volumes in the network in order to alleviate discrepancies between the real demand and the head delivery rate. A closed-loop regulation system is necessary for adequate management of these volumes. Generally, such mixed control systems require electronic sensors and transmissions to adjust the gate opening according to a predetermined operating law.

The BIVAL system ([1],[2]) is one type of on-demand control where the necessary storage volume is minimized and set to the optimum value, thus guaranteeing the delivery of the maximum design discharge at any time. This is obtained by a simultaneous measurement of levels at both ends of the reach, the information recorded being used to command the upstream regulator. This system can be described as a "constant downstream volume system" instead of the "constant downstream level system" (downstream of the regulator), currently used for on-demand control (figure 1).

The system works as if the upstream gate controlled the level at an intermediate point E of the reach AB. The ratio of lengths EA and EB represents the weight used to average the information collected at the upstream and downstream ends. Suppose that EA=EB, then the average level between A and B is taken as feedback indicator and gate A will maintain a constant level in the middle of the reach. During operation, when a discharge demand is sensed at the downstream end, a negative wave propagates in the upstream direction. At the same time, the upstream gate controlled by levels at both ends of the reach begins to open and the positive wave propagates downstream. The two waves meet in the middle of the channel, pivoting the water surface twice as quickly as



1a. Constant downstream level   1b. BIVAL: Constant downstream volume

Figure 1   On-demand systems

in the classic constant downstream level system. If the wave celerity varies along the reach, the ratio EA/EB is adjusted consequently. The level Y at point E is expressed as a linear expression of the upstream level of the reach $Y_{u/s}$ and the downstream level $Y_{d/s}$:

$$Y = \alpha\, Y_{u/s} + (1-\alpha)\, Y_{d/s} \qquad (1)$$

where α is the weighting coefficient to be determined.

In practice, α, and hence the position of point E, and the other parameters of the regulation are chosen after a mathematical simulation of the canal reach involving canal cross-sections, bottom level, friction (Manning) coefficients, etc.. The computer program involved is based on integration of the complete Barré de Saint Venant hydraulic equations in order to represent adequately the propagation of the disturbances in the system. Initially, the water line ab′ for the maximum design discharge Q_{max} is computed. Then, gate closures at both ends are simulated. Hence the volume trapped under the ab′ line stabilizes at the horizontal level Y_o. Point E is theoretically at the intersection of the two lines. Several operating cases are simulated with the mathematical model, including exceptional events such as the breakdown of a gate or a transmission fault between downstream and upstream, in order to study the response of the system under critical conditions.

For reasons of stability and flexibility of regulation, a decrement is generally introduced. Indeed, each time a variation in discharge ΔQ_b occurs downstream at B, the expected response ΔQ_a at gate A is not exactly equal to ΔQ_b and the response time of the gate is not exactly zero. In addition, variations in discharge demands may occur anywhere along the reach. It is for this reason that an additional small buffer volume is required in the reach. This is introduced by setting α slightly higher than the theoretical value and by adding a decrement D, i.e. by varying YR, the reference level at E, as a linear function of gate opening such that, when fully opened, for $Q=Q_{max}$, the reference level is YR and for total gate closure (Q=0) the water surface is horizontal at level YR+D. This can be expressed as:

$$YR = Y_o + D\,(Q_{max}-Q)/Q_{max} \qquad (2)$$

During operations, levels are measured at both ends of the reach, the regulated level Y is computed by equation (1) and compared at regular intervals ΔT with YR. If ΔY represents the insensitivity threshold tending to limit the gate operating frequency, the control instructions are as follows:

- . if $Y - YR > \Delta Y$ level is too high: the gates must be closed
- . if $|Y - YR| \leq \Delta Y$ nothing is done
- . if $YR - Y \geq \Delta Y$ level is too low: the gates must be opened.

ΔT, ΔY and D are adjusted during the mathematical model simulations.

ADVANTAGES OF THE SYSTEM

It can be shown that the reach maintains a constant volume for any discharge between 0 and Q_{max} and that for the intermediate discharges, the water surface is always below the ab′ line in the upstream part of the reach and below the horizontal level at Q=0 in the downstream part. Therefore the bank level can be parallel to the ab′ line in the upper part of the reach and horizontal in the lower part, thus minimizing the cost of civil engineering induced by horizontal dyke construction in the case of a constant downstream level system.

However, the horizontal bank level cannot be lower than the one calibrated for the water level YR; indeed, YR is the optimum level to be set for an on-demand type of control if a rapid response time is desired. Suppose that a lower level Y′ is kept in the reach for no-flow conditions (dotted line on fig. 1b), it is clear that if the downstream demand suddenly increased from 0 to Q_{max}, the volume (V2) trapped above the ab′ line would disappear before the volume (V1) below the ab′ line filled in order to ensure the maximum discharge. Hence, it would not be possible to deliver the desired discharge immediately. Conversly, if the bank level were calibrated for the level Y′ and if the downstream gate were suddenly closed to stop the discharge Q_{max}, volume (V2) would not be large enough to store the refused water and the banks would rapidly be overflowed.

The BIVAL system ensures maximum reliability of water delivery since the maximum discharge of the canal can be delivered instantaneously at the turnouts (this is based, of course, on the assumption that there is no limit on the amount of water available upstream of the reach controlled by BIVAL). Also there is no constraint on the time of delivery since there is no need to forecast demand, hence flexibility of delivery at the turnouts placed directly on the reach is fully guaranteed.

The system can be designed to use classic equipment and can be made entirely automatic without being too sophisticated. It also adjusts itself easily to given conditions: during the first years of use of the irrigation systems, low levels can easily be maintained, then progressively, the levels will become higher. Those variations can be made without endangering the stability of the system.

The disadvantages of this system are the same as those of on-demand systems in general, i.e. the cost of automatic gates and the amount of earthworks required which may become prohibitive for canals with a steep bottom slope or for very long reaches. In those later cases, mixed control may be more appropriate.

EXAMPLE : OFFICE DU NIGER (MALI)

Approximately 280 km north-east of Bamako, the capital of Mali, lies an irrigation area covering some 40,000 ha (100,000 acres) managed by the Office du Niger, an administration created in 1919. The area is supplied with water from the River Niger at Markala Dam, completed in 1947, through a feeder system including a 24 km long man-made part, the Sahel canal, and a 100 km long natural part, the Fala de Molodo, a former distributary of the Niger. The Fala de Molodo has an average width of about 1 km and a very gentle slope of about $4x10^{-5}$. This system includes two manually controlled gating structures, one at the upstream end of the Sahel canal (point A), the other at mid-distance along the Fala de Molodo (point B) (Figure 2). Before implementation of the new control system, the gates were manoeuvred according to the "operator's intuition". Due to the long response time of the canal (of the order of one week), this led to the loss of about half of the water. Moreover the lost water choked the drainage system, which could no longer fulfil its principal function. In 1979, Sogreah was commissioned to study a project

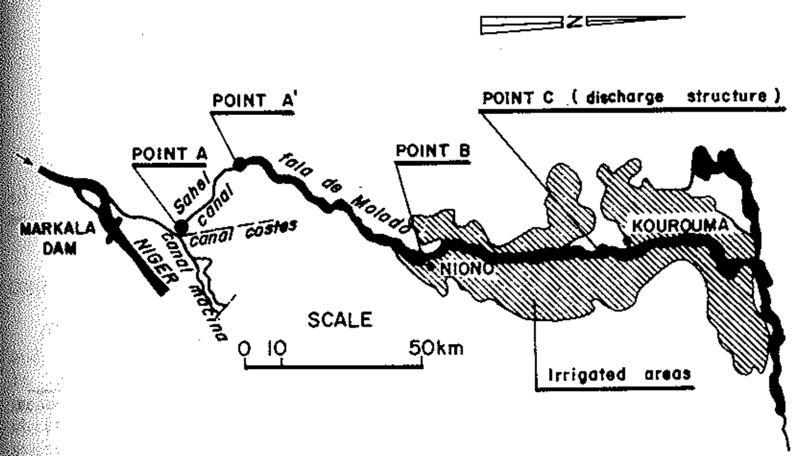
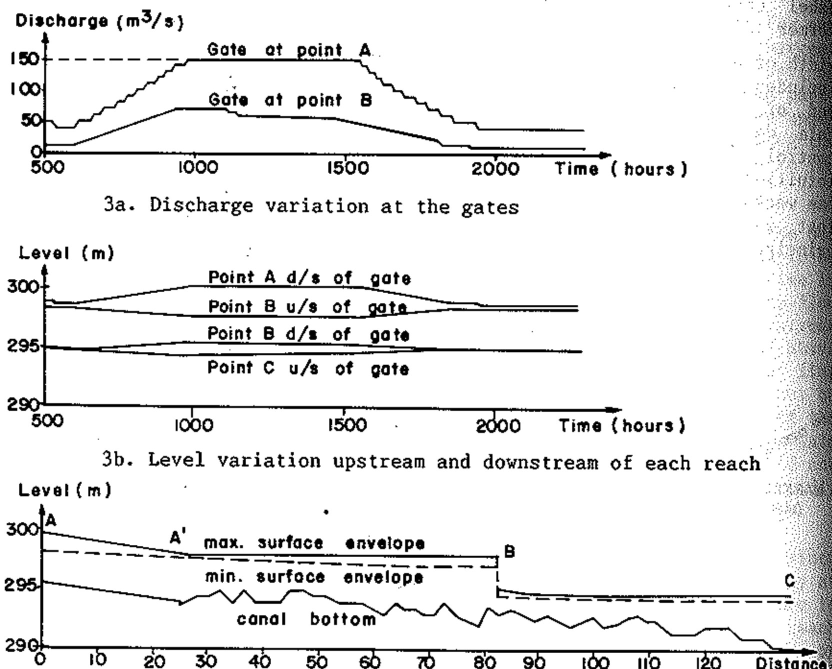


Figure 2 Location map - Sahel Canal, Fala de Molodo

for the rehabilitation of this rice-growing area. The problem lays in finding ways of eliminating these losses by the use of simple unautomated managements orders, without involving costly works. Analysis of the problem showed that the best solution was a BIVAL system [8] because it was the simplest and most flexible.

The study was carried out for present conditions (75 m^3/s) and for future conditions when the system will convey a discharge of 150 m^3/s (head discharge), involving the prior upgrading of the Sahel canal between points A and A'. Different cases of discharge demand variation were simulated on the mathematical model in order to check (i) that the gate operations remain stable in all cases and (ii) that the maximum and minimum water surface envelope curves remain within acceptable limits for navigation and water intake supply and that the earthworks required for embankment upgrading remain limited. As an example, figure 3 shows the results of a calculation:

- Variation of discharge demand and resultant discharge at gates A and B (fig. 3a). No operating instabilities are observed.
- Level variations at the end of each reach (fig. 3b) showing the movement of the water surface curves.
- Minimum and maximum water surface envelope curves obtained during the calculations (fig. 3c).



3a. Discharge variation at the gates

3b. Level variation upstream and downstream of each reach

3c. Longitudinal profile of the reaches

Figure 3 Example of computation - Discharge offtake operations followed by refusal

The regulation parameters were determined as follows:

- The interval ΔT between two consecutive manoeuvres: 24 h. This means that the levels should be observed and gates operated only once a day. This long interval is a consequence of the large dimensions of the feeder system, hence manual operation can be envisaged without any automatic control system,
- The weighting coefficient α is 0.3 for gate A and 0.33 for gate B (for the 150 m^3/s discharge), the insensitivity value ΔY is 5 cm and the decrement D is 4.5 cm. For present conditions (75 m^3/s), only α need to be changed.
- The elementary gate manoeuvres are 10 m^3/s steps for gate A and 4 m^3/s for gate B. These manoeuvres are carried out manually according to calibration curves.

In practice, an observer located at point C transmits by radio or telephone the measured water level (once a day) to an operator located at point B. The operator at point B notes the levels on either side of gate B and determines the manoeuvre to be carried out according to regulation curves drawn during the mathematical study. He also transmits his observations to an operator at point A who will do the same job. In the future, the gates could be motorised and regulation automated.

Pending completion of the topographic survey on the second reach, the system has been implemented on the first reach only (between points A and B). Considerable water savings were made in 1983, the year of implementation, with respect to the previous year:

Table 1

Month	Mean daily discharge saved (m3/s)	Volume of water saved (%)
June	32	35
July	11	20
August	18	31
September	17	16
October	2	2

The level variations immediately upstream of point B did not exceed ±3 cm per 24-hour period, thus providing a certain head stability at the main canal offtakes. Moreover drainage was reduced.

COMPARISON WITH OTHER CONTROL SYSTEMS: RIO YAQUI NETWORK (MEXICO)

On behalf of the Mexican Commission of the National Hydraulic Plan and in cooperation with Mexican engineers, Sogreah carried out a study in order to compare different systems of regulation prior to the rehabilitation of the Rio Yaqui network, located in the state of Sonora, which provides water to a 240,000 ha area of food and cotton crops. This system operates with simple upstream control. Better regulation was sought in order to allow an increase of the irrigated area, and possibly a second annual crop and decrease in the amount of water pumped from the aquifer (about 10% of the total). The aim of the study was to define the most appropriate system of regulation for the two main canals of the network, and also for two lateral canals by way of example. The characteristics of the reaches and the results of the comparison are listed in Table 2:

	LENGTH (km)	Qmax (m3/s)	IRRIGATED AREA (ha)	SOLUTION COST RATIO (the value of 1 is given to the least expensive solution) and SATISFACTION OF REQUIREMENTS (1)					
				Upstream control	Constant downstream level	BIVAL system	Associated levels at each side of the gate	Regulated level in downstream reservoir	Mixed control (PID)
CANAL ALTO									
(a) Tramo Muerto	14	90	0	n.a.	4 ++	2.5 ++	5 ++	1 ++	n.a.
(b) Canal Principal	106	90	87,000	1 +	1.82 +++	1.38 +++	1.59 +++	n.a.	n.a.
CANAL BAJO									
(a) Tramo Rio Yaqui	14	115	20,000	n.a.	n.a.	n.a.	n.a.	1 +	2.12 +++
(b) Canal Principal	100	90	129,000	1 +	1.62 +++	1.40 +++	1.75 +++	n.a.	n.a.
LATERALS									
(a) Lateral K64	14	4	2,700	1 +	4.64 +++	n.a.	n.a.	n.a.	n.a.
(b) Lateral 4	17	28	24,200	1 +	1.37 +++	n.a.	n.a.	n.a.	n.a.

(1) + : low, ++ : good, +++ : very good

Table 2 Comparison of different systems of regulation

For the smaller lateral canal, the comparison showed that the upstream control solution could be kept because of the low discharge delivered, whereas for the second one, due to the larger irrigated area and discharge, the constant downstream level solution was recommended.

The BIVAL system was studied in three cases: the two sections of the Canal Alto and the main section of the Canal Bajo. For the Tramo Muerto of Canal Alto, which has no direct turnout and only conveys water to the Canal Alto, the system was not chosen, because the cheapest solution was also the easiest to implement and the cheapest in terms of maintainance cost for equivalent satisfaction of requirements. For the main sections of Canal Alto and Canal Bajo, the BIVAL system proved to be the cheapest solution which could guarantee a high level of satisfaction of requirements. Moreover, except for the upstream control system, the difficulties of implementation (civil engineering and equipment) were comparable for the other three solutions. The maintainance costs were slightly higher for the BIVAL system and the associated levels solution than for the constant downstream level system. However, with regard to the investment saving, the BIVAL system was recommended for these two sections.

For the Tramo Rio Yaqui, a mixed control system, based on the PID (proportional, integral, derivative) principle was defined on the basis of a mathematical model and was recommended. Indeed, this section has a steep slope and an irregular shape, which requires a more elaborate system including electronic sensors and micro-computer in order to fulfil the regulation requirements.

Based on this regulation study, the total water savings were estimated at about 10 to 20%.

CONCLUSION

When considering the regulation of an irrigation network, a complete analysis is essential to optimize the choice of control system. There is always a compromise between cost and efficiency. The BIVAL system is an economical way of taking advantage of an on-demand system which guarantees the best user' satisfaction and high irrigation efficiency. Implementation of the system is relatively simple and is well adapted to channels of average dimensions. The system can be fully automatized or in some cases, owing to the characteristics of the canal reach to be regulated, it can be manually operated. At any rate, the regulation orders are simulated with a mathematical model of unsteady flow in order to define fully the specific parameters of the reach and to ensure that all the requirements are satisfied.

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