CEMAGREF-IIMI International Workshop on
The Application of Mathematical Modelling for the Improvement of Irrigation Canal Operation
October 26-30 1992, Montpellier, FRANCE

The Bival Canal Control System Application to the Sahel Canal Operated by the Office du Niger (Mali)

J. P. Sauvagère

Abstract

PRINCIPLE

The BIVAL system is a level regulating system of the downstream control type. This allows an approximately constant volume of water to be maintained in the controlled canal reach, regardless of the canal flow conditions.

The volume of water in the reach is associated with a theoretical point located more or less in the middle of the reach and around which oscillate the various stream lines corresponding to different flow conditions.

The level of the theoretical point (representative of the volume) is calculated using a simple linear expression between the upstream and downstream levels in the reach :

$$H = \alpha Hu/s = (1 - \alpha)\ Hd/s$$

where : H = theoretical level
Hu/s = elevation of upstream water surface
Hd/s = elevation of downstream water surface
α = weighting coefficient

The level is controlled by slaving the water intake gates to the elevation of the water surface calculated at the theoretical point.

In practice, the control parameters (set level, decrement, gate opening increment, weighting coefficient and time step) are adjusted by means of a computer simulation model.

APPLICATION TO THE OFFICE DU NIGER (MALI)

This system was applied in 1983 to the Sahel Canal and Fala de Molodo serving the extensive irrigation scheme of the Office du Niger in Mali.

The existing canal, includes a 24 km reach which connects up directly with a 56 km long old distributary of the river Niger, the Fala de Molodo.

The maximum flow rate of this water supply system currently stands at 100 m3/s for a total length of 80 km.

The original regulating system was based on a highly empirical upstream control system (very rough planning of the downstream water requirements, no flow control structure, etc...)

This control system was not at all efficient and surplus flows entering the feeder canal at the head of the irrigation network were mainly lost through evaporation and infiltration downstream of the scheme.

In addition, level fluctuations downstream of the reach were such that the water surface level was often insufficient to supply the necessary irrigation water to distributory channels.

The BIVAL system, as installed on site, integrates perfectly within the African context as it does not require any sort of sophisticated equipment likely to break down or become misadjusted.

The control parameters were adjusted on a computer simulation model using the CARIMA software developed by SOGREAH.

From a practical standpoint, the upstream and downstream levels are read once a day on staff gauges by watermen who transfer the information over the telephone or radio to an operator. Using a simple calculator, the operator then determines the gate operating manoeuvres of the control structure by calculating the theoretical level and comparing it to the set level.

Once installed, this control system enabled large volumes of water to be saved. The following table gives the difference in water consumption before (1982) and after (1983) system installation.

Month	**Mean daily flow rate saved between 1982 and 1983 (m3/s)**	**Volume saved (%)**
June	32	35
July	11	20
August	18	31
September	17	16

In addition, the water level variation range downstream of the reach was considerably reduced with the result thate there were no more breakdowns in water supply to the irrigation areas.

1 Introduction

Regulation of the canals of large irrigation networks in the less-developed countries of Africa is made difficult by local conditions (absence of electrical energy, extreme climatic conditions, poor maintenance of infrastructure, etc). It is thus often necessary to adopt the most simple and reliable regulation systems.

The upstream control and downstream control regulation modes are the most widespread, for they do not call on sophisticated techniques.

In an upstream control system, each regulator maintains a constant upstream level. This system is reliable, and economical in terms of initial investment. It requires no energy, since the regulators can be either static weirs or gates slaved to floats. On the other hand, for the system to be efficient, the water requirements must be forecast with a high degree of precision, which is generally impractical to obtain. No water can be stored along the canal, which means that any variation in withdrawal discharges compared to the forecast will result in water losses.

With downstream control, each regulator maintains a constant downstream level. This system is more costly than the previous one; it requires a greater freeboard, hence higher embankments, and automatic gates slaved to floats (AVIO or AVIS type manufactured by Alsthom Fluides). The system operates on demand, and water losses are theoretically zero.

This paper describes an intermediate regulation system, the BIVAL system, developed by SOGREAH. This system has been successfully applied on the Sahel Canal, serving the rice-growing irrigation area of the Office du Niger in Mali.

2 Technical description of the BIVAL system

The BIVAL system is a level regulating system of the downstream control type. This allows an approximately constant volume of water to be maintained in the controlled canal reach, regardless of the canal flow conditions.

The volume of water in the reach is associated with a theoretical point located more or less in the middle of the reach and around which oscillate the various stream lines corresponding to different flow conditions.

The level is controlled by slaving the water intake gates, at the upstream end of the reach, to the elevation of the water surface calculated at the theoretical point.

The level of the theoretical point (representative of the volume) is calculated using a simple linear expression between the upstream and downstream levels in the reach:

$$H = A\,Ha + (1 - A)\,Hb$$

where:
Hr = theoretical level
Ha = elevation of upstream water surface
Hb = elevation of downstream water surface
A = weighting coefficient

The movement of the gates is defined according to the value of the following expression:

$A\ Ha + (1 - A)\ Hb/Hc$

where: Hc = set level

In the case where $A = 1$, downstream control conditions obtain, with a single detected level. The reference level is the same as the upstream level of the reach for the maximum discharge.

This system can remain stable for any value of A between 0.5 and 1.

Let us suppose that the reach has a uniform rectangular section and that Hr is equal to the average between the two values Ha and Hb for a steady flow corresponding to the maximum discharge Qmax.

Under these conditions, a constant volume is maintained for any continuous discharge between 0 and Qmax and for all intermediate discharges. The maximum level corresponds to the level at Qmax in the upstream part of the reach, and to the level at zero discharge in the downstream part. Consequently, the crest of the canal embankments is inclined in the upstream part and horizontal in the downstream part. The bank elevation is thus lower than in the case where $A = 1$ (downstream control only). This clearly demonstrates the saving that can be achieved on construction costs by using the BIVAL regulation system, by comparison with a downstream control system.

In practice the reaches are neither rectangular nor of constant cross-section. Moreover, the control facilities (gates and level detectors) have their own operating characteristics.

A certain number of devices and adjustments are therefore to be envisaged, in order to ensure satisfactory operation of the overall system.

The gates, electrified or manually operated, are generally operated periodically, in incremental steps, which means that the time interval Δt between successive manœuvres has to be defined, as well as the opening step Δx. These two variables define the gate opening and closing speed.

No manœuvre is ordered if:

$A\ Ha + (1 - A)\ Hb = Hc$

In practice, this condition of equality is never obtained exactly, and to avoid unnecessary manœuvres, a range of insensitivity or decrement ($2\ \Delta h$) must be introduced around the set level Hc, so that the gate is then operated according to the following instructions:

— Opening by Δx if

$$A\ Ha + (1 - A)\ Hb < Hc - Dh$$

— Closing by Δx if

$$A\ Ha + (1 - A)\ Hb > Hc - Dh$$

— No action if

$$Hc - Dh < A\ Ha + (1 - A)\ Hb < Hc - Dh$$

The value of Dh must be sufficient to make the gate insensitive to errors in measurement of Ha and Hb, and to avoid auto-excitation. In other words the disturbance caused by the man uvre must be less than 2Dh.

3 Application to the Sahel Canal operated by the Office du Niger (Mali)

The Office du Niger is a large rice-growing development scheme covering about 55 000 hectares, situated in the Republic of Mali, irrigated by gravity with water drawn from the river Niger at the Markala diversion weir. Built between 1932 and 1960, the hydraulic infrastructure of this scheme is in a poor state of repair, and a substantial rehabilitation programme is in progress, with the financial support of various institutions (World Bank, FAC, CCCE, EDF, KFW, Netherlands Government, etc).

Designed many years ago, the entire hydraulic regulation system is based on the principle of upstream control, whereas the network is not equipped with sufficiently reliable discharge control structures.

Moreover, the considerable length of the main canals, combined with the difficulty of forecasting water demand of a multitude of users, makes this regulation mode ill-suited to the efficient operation of the main irrigation supply network. As a consequence, there are substantial water losses related to the poor management of the main network, added to those caused by a series of other factors, including poor paddy field maintenance, where the bunds are often no longer capable of retaining the irrigation water applied.

Excess water presents some serious drawbacks: it saturates the already inadequate drainage network, and makes it difficult if not impossible to drain the paddy fields, thus increasing the risk of submersion of certain villages.

Moreover, it is imperative to save water, following the constantly declining evaluation of available water resources in the Niger in the last few years, also to allow water to be made available to supply projected extensions. This need is all the greater during the river's low flow periods.

In the context of the overall rehabilitation programme of the Office du Niger, SOGREAH was appointed to carry out first the feasibility study and then detailed design studies of the works to rehabilitate the hydraulic network supplying the northern part of the scheme, these services being subsequently followed up by technical assistance with a view to improving management of the existing network.

In the context of these services, SOGREAH:

- studied rehabilitation of the regulation structures and complementary earthworks on the main canal (Sahel Canal and Fala de Molodo), with a view to improving water management and reducing water losses. The BIVAL system was proposed because it is better adapted, and a preliminary design was drawn up on this basis;

- installed the BIVAL system on this same canal before implementation of the proposed rehabilitation works, under a technical assistance contract.

4 Description of Sahel Canal and Fala de Molodo

The Sahel Canal and the Fala de Molodo together form the main supply canal to the northern part of the scheme. This supply line is made up of a first section of canal 26 km long (the Sahel Canal), which connects on the level with a former distributary of the Niger (the Fala de Molodo), which is embanked on both sides, and in places more than one kilometre wide. The total length of the first reach, between the regulator at point A and that at point B is 80 km.

The second reach, 56 km long, is formed by a further length of the Fala de Molodo, also embanked on both sides.

The Sahel Canal is unlined. Its maximum discharge in its present configuration peaks at 100 m/s. The Fala de Molodo includes substantial areas of still water that are partially covered by water lilies. Other areas, particularly along the banks, are completely invaded by thick aquatic vegetation: mainly typha, representing a serious obstruction to flow.

The time of response of the first reach, in other words the time it takes for a wave to propagate from the upstream to the downstream end of the reach, is of the order of one week.

The canal has two regulators:

- The Point A regulator is a structure with five bays equipped with motor-driven flap gates. There is also a navigation lock adjoining the structure.

- The Point B regulator is 80 km downstream, close to the town of Niono. It has three bays equipped with manually operated flap gates. A special device (double gates) enables control both of the base flow through the each bay and of the height of surface flow over the gates.

The lateral offtakes in this reach are all situated immediately above Point B.

5 Detailed rehabilitation design study for the 2 canals

The design study initially involved studying a regulation mode better suited to local conditions than the upstream control system, with a view to subsequent implementation of the rehabilitation works required on the embankments and control structures.

Four alternative systems were studied, each adapted as effectively as possible to local requirements, which may be summarised as follows:

- the need to avoid the constraint of calculating the the water demand, which experience has proven to be impossible to obtain with sufficient precision; this narrowed the choice down to regulation systems working "on demand";

- the need to limit the cost of embankments and rehabilitation of the regulation structures;

- adaptability to the difficult climatic conditions, to the limited or non-existent sources of electricity, and to a relatively low level of technical capability for maintenance, thus excluding the use of systems based on electronics and data processing.

The four variants tested are shown in the table on the following page, and are based on a combination of the downstream control system and the BIVAL system, with or without an additional intermediate regulator.

The chosen variant is the fourth (BIVAL system over the entire reach), which is the least costly, and which allows manual operation, at least in a first phase.

This variant was tested on a mathematical model (SOGREAH's CARIMA programme), in order to evaluate the different parameters of regulation of the system, and the maximum and minimum water surface elevations.

The table on the following page sets out the results of the main simulations made for a future operating state corresponding to a peak discharge of 150 m3/s, taking into account future extensions.

To date the rehabilitation works have still not been undertaken, but the BIVAL system has been installed on the canal in its present state.

6 Installation of the BIVAL system on the existing canal

Operation of the Sahel Canal on the upstream control basis presented serious drawbacks, resulting in very substantial water losses.

In practice, it is impossible to make a sufficiently precise prior evaluation of water requirements, at the scale of the overall scheme, for several reasons:

- the very large number of users, which would require reliable organisation of collection of data on the state of the crops of each farm, an unrealistic objective in the present context,

- users showing little concern to respect an irrigation programme, whether freely chosen or imposed,

- cropping conditions closely related to weather conditions; generally speaking, users prefer to wait until the rains come before ploughing or sowing; under these conditions an irrigation programme has little chance of being respected.

In practice, before installation of the BIVAL system, the water officer in charge opens the gates at the head works by an amount corresponding to the demand of the previous year, and adapts this value empirically to the variations noted downstream of the reach. However, considering the substantial response time of the reach (about 1 week) and the complexity of the system, these corrections result in uncontrolled fluctuations in downstream level, which can lead to interruptions in water supply to the paddy fields.

Under these conditions, the officer naturally tends to increase the discharge diverted into the system, so as to reduce the risk of dissatisfaction of users. This approach results in excessive water consumption and substantial losses.

It should be noted however that the maximum possible discharge is limited by the almost complete absence of safety margin on the embankments, due to inadequate maintenance, and that the water officer's tendency to increase the discharge significantly increases the risk of breaches developing in the canal banks. Breaches occur virtually every year.

To clarify the picture, the following water surface elevations should theoretically be respected at the downstream end of the reach:

- the level below which the water supply to certain rice fields will be interrupted: 296.80,
- the maximum level above which there is a substantial risk of breaches occurring in the banks: 297.00
- the level not to be exceeded under any circumstances: 297.10.

It thus appears that the possible rise and fall of water level in the canal is only 20 cm, at the end of a canal 80 km long.

Clearly, with the upstream control operating conditions, as set out above, these levels can hardly be respected. This can be seen on the graph of water level variations from June to November 1982, where the level is shown ot drop below 296.80 on seven occasions.

The BIVAL system was installed in May 1983, on the basis of the mathematical model simulations.

A few practical difficulties appeared.

On one hand, there were difficulties of a technical nature: the model showed clearly that the downstream level could, in certain extreme conditions of refusal (during heavy rainfall, for example), reach 297.30. The system thus had to be adapted accordingly, and warning systems established, to deal with such circumstances. Moroever, the reliability of transmission was not perfect.

On the other hand, there were difficulties of a human nature: the water distribution officer showed extreme reluctance, no doubt because he feared that the system would fail, with the resulting consequences in terms of behaviour of users in his regard. Furthermore, he was not particularly enthusiastic at the prospect of changing habits established over many years, nor was he willing to accept the proof that the system he was using was insufficiently productive.

In order to meet the difficulties of a technical nature, adaptations had to be made to the calculated variables, in order to reduce the excessively high downstream level.

The water demand fluctuates overall and regularly between 20 and 100 m/s over the year, and there are no sudden variations, except when irrigation is interrupted following heavy rains. It is therefore possible, as a function of the mean discharge over a given period of the year, to modulate the set level at the theoretical mid-reach point.

At the same time, instructions are given for opening the Point B regulator in case of the 297.00 level being exceeded, the regulator in this case working as a safety structure.

The variables calculated by means of the model are as follows:

Frequency of measurements: 24 hours

Weighting on upstream side: 0.826

Weighting on downstream side: 0.174

Gate opening increment: 10 cm

Insensitivity: ± 5 cm

Decrement: 0.045 x Q/75 (Q: discharge in m/s)

Set level: 297.30

The set level was modulated between 297.05 for low flows and 297.30 for the maximum discharge.

In practical terms, the measurements are made once a day, at about 8 am, by two operators, who immediately transmit the data to Markala:

- the upstream level is read at Point A by an operator who transmits it to Markala (8 km), using a vehicle (car or motorcycle),
- the downstream level is read at Point B by another operator who transmits it to Niono using a vehicle, then to Markala by radio-telephone.

At Markala a technician makes the calculations using a four-function calculator and an appropriate form. He then transmits to Point A the decision regarding gate opening manœuvres.

Installation of the system resulted in an immediate reduction in the discharges introduced into the network, hence a significant reduction in water losses, as is shown by the following table, which compares the mean monthly discharges flowing in the canal before (1982) and after the works (1983).

Moreover, security of water supply to the paddy fields was significantly increased, as rell as security of the canal itself: no breach was observed in the four years following installation, whereas previously breaches occurred practically every year.

The accompanying graph shows that the water level upstream of Point B constantly remained within the permitted limits, whereas during the same period in 1982, the level on seven occasions dropped below 296.80, level below which the water supply to the rice fields is interrupted.

With the experience of operation, the BIVAL system has proven to be perfectly suited to local conditions, simple to use and reliable. Without requiring any investment on the infrastructure, it has brought a significant improvement to operation of the Sahel Canal.

Water savings made on the Sahel Canal through application of the BIVAL system

Month	Mean monthly discharge 1982 (m3/s)	Mean monthly discharge 1983 (m3/s)	Mean monthly discharge saved (m3/s)	Monthly volume saved (%)
June	90.7	58.5	32.2	35.5
July	53.6	41.0	12.6	23.5
August	59.6	39.5	20.1	33.7
September	108.1	91.0	17.1	15.8

Installation of the BIVAL system: May 1983

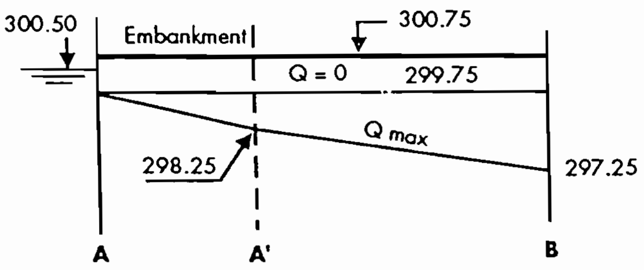
SUMMARY TABLE OF SIMULATIONS

FUTURE STATE : 150 m^3/s AT HEAD

	A	B	C	D	E	F	G	H	I
Frequency of checks	6H	6H	12H	24H	24H	24H	12H	24H	24H
Weighting A	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7
Weighting B	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Y cons lst reach	298.20	298.30	298.30	298.30	298.30	298.00	298.00	298.00	298.00
Y cons 2nd reach	294.55	294.55	294.55	294.55	294.55	294.55	294.55	294.55	294.55
Manœuvre A	$\Delta Q = 10$	$\Delta Q = 10$	$\Delta Q = 10$	$\Delta Q = 20$	$\Delta Q = 10$	$\Delta Q = 10$	$\Delta Q = 10$	$\Delta Q = 10$	$\Delta Q = 10\sqrt{H}/1.5$
Manœuvre B	$\Delta Q = 4$	$\Delta Q = 4$	$\Delta Q = 4$	$\Delta Q = 8$	$\Delta Q = 8$	$\Delta Q = 4$	$\Delta Q = 4$	$\Delta Q = 4$	$\Delta Q = 4\sqrt{H}/2.75$
Hydrographs	1	1	1	1	2	2	3 (surge)	3 (surge)	3 (surge)
Insensitivity (em)	± 5	± 5	± 5	± 5	± 5	± 5	± 5	± 5	5
Gate opening interval (cm)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Max level d/s A	299.60	299.60	299.65	299.65	299.65	299.60	299.60	299.60	299.60
Min level d/s A	298.30	298.40	298.40	298.30	298.40	298.15	298.05	298.10	298.10
Max level u/s B	298.20	298.25	298.25	298.20	298.25	298.00	297.90	297.90	297.95
Min level u/s B	297.05	297.25	297.20	297.25	297.25	297.10	297.00	296.90	296.95
Max level d/s B	295.10	295.10	295.10	295.10	295.10	295.10	295.25	295.75	295.65
Min level d/s B	294.55	294.50	294.50	294.50	294.55	294.50	294.50	294.55	294.55
Max level u/s C	294.55	294.55	294.55	294.55	294.55	294.55	294.65	295.75	295.65
Min level u/s C	294.15	294.15	294.15	294.15	294.15	294.15	294.00	293.45	293.50
Observations	Frequency of controls too high		Effective operation	Manœuvres too sudden	Effective operation		Absorbs the "surge" volume	Need for emergency measures in case of massive refusal	Constant gate opening increments

FACTORS OF CHOICE AMONG ALTERNATIVE SOLUTIONS

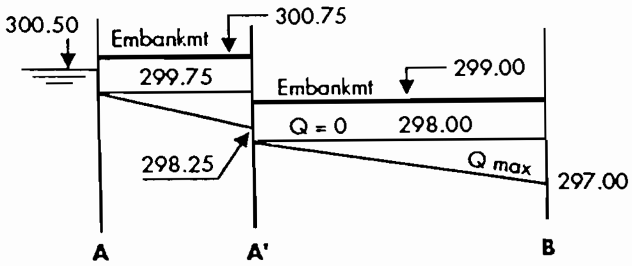
1



Downstream control only — 1 reach

- ● Solution too costly (earthworks, maintenance, structures at point B to be modified)
- ○ Simplest manual regulation

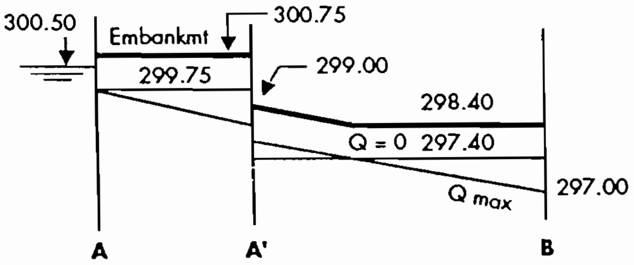
2



Downstream control only — 2 reaches

- ● Solution too costly (earthworks, structures at point B to be raised, new structure at A')
- ● Unrealistic manual regulation (insufficient storage between A and A')

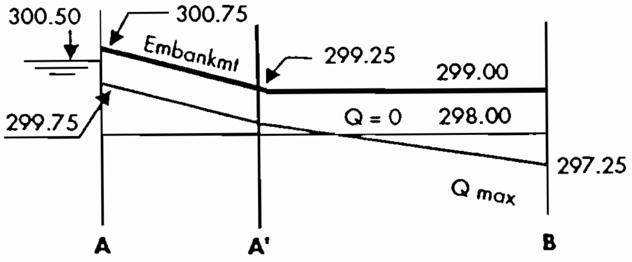
3



Downstream control with BIVAL 2 reaches

- ● Solution more costly than **4** (new structure at A')
- ○ On the other hand, B does nottneed to be raised as much as in solution **4**
- ● Unrealistic manual regulation (insufficient storage between A and A')

4



BIVAL system with single reach

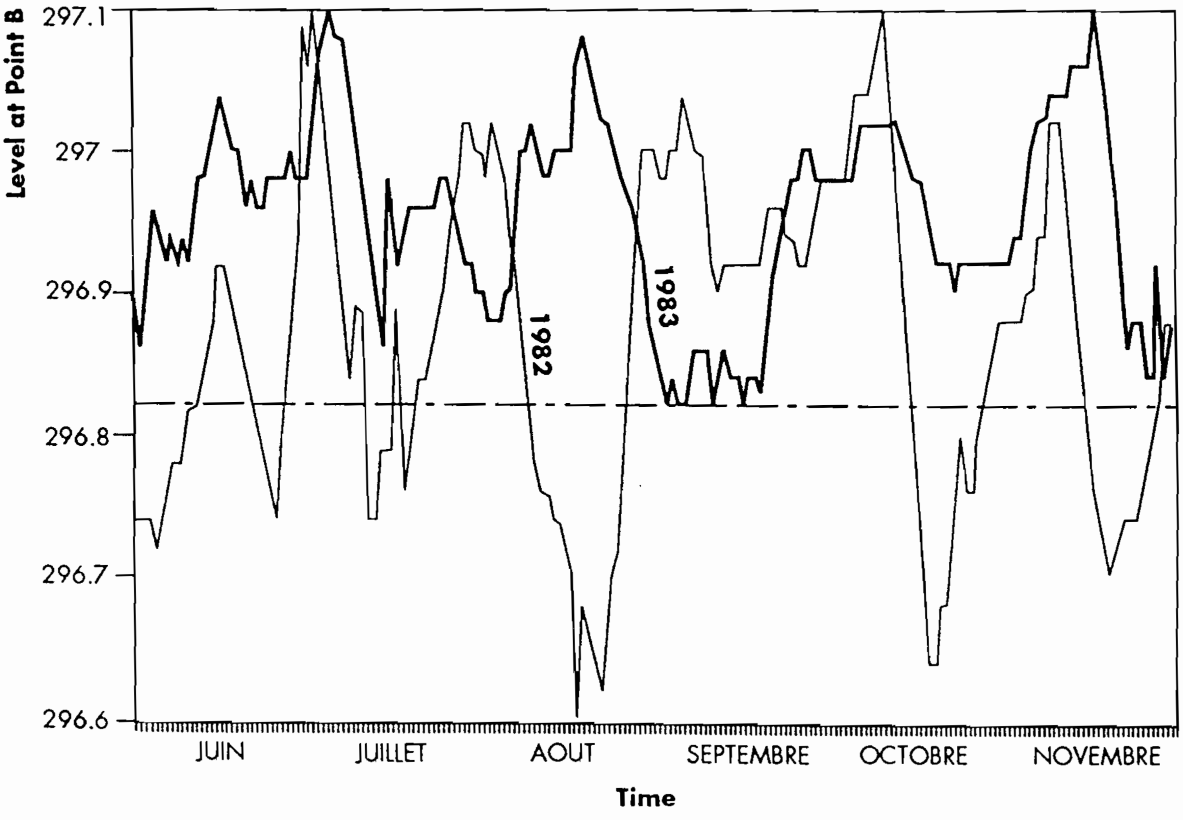
- ○ Least costly solution
- ● Structures at B to be raised
- ○ Manual regulation possible (telephone or radio)

The various set instructions studied correspond to this alternative solution, which is thus recommended

N.B. The elevations taken into account are those given in Report R24 of January 1980.

VARIATIONS IN UPSTREAM WATER LEVEL

at the point B regulator



BIVAL SYSTEM