CALIBRATION AND APPLICATION OF A HYDRAULIC MODEL FOR THE OPERATION OF AN IRRIGATION CANAL

A Study in the Chistian Subdivision, Fordwah/Eastern Sadiqia Area,
Punjab, Pakistan

Nicolas Rouillé
Student 2d year ENSEEIHT
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RESUME

Cette étude porte sur le canal principal d'un système d'irrigation, Fordwah Branch, situé dans le Sud-Est du Punjab au Pakistan. La portion de canal étudiée, Chistian Subdivision, est la partie aval de Fordwah Branch. C'est un système complexe de 52 km de long avec 14 canaux secondaires et des prises directes qui irrigue une surface de 232000 hectares. Chistian Subdivision est controllé par 5 ouvrages en travers équipés de vannes.

De précédentes études ont montré que le rendement de ce système est faible (entre 30% et 50%). Cela est dû en majeure partie aux fluctuations des niveaux d'eau dans le canal principal, provoquant des débits irréguliers dans les canaux secondaires. Ces fluctuations ne peuvent pas être expliquées uniquement par le débit irrégulier fourni en tête car leur amplitude croît d'amont en aval. Les opérations de régulation contribuent donc probablemenent à créer des instabilités.

L'objectif de cette étude est d'étudier les possibilités d'utilisation d'un logiciel mathématique (SIC), permettant de simuler des écoulements dans des canaux, afin d'améliorer la gestion de Fordwah Branch.

La première partie de ce rapport concerne la calibration du modèle : détermination des coefficient de Manning, des infiltrations et des coefficients de débit des ouvrages.

Ensuite, plusieurs simulations ont été entreprises afin d'identifier quelques phénomènes de base : temps de retard, influence d'opérations aux régulateurs sur les débits en fin de canal et sur les régulateurs amonts, sensibilité des prises aux variations de tirant d'eau.

Ces simulations ont permis de mettre en évidence les phénomènes suivants:

- les débits dans les canaux exutoires sont trés sensibles aux opérations des vannes de régulateurs.
- un régulateur peut être perturbé par des opérations effectuées en aval dans des conditions particulières (changement de tour d'eau, stockage de l'eau dans un bief en cas de débordement en aval...).
- la sensibilité des prises aux fluctuations dépend du type de prise (vanne ou seuil), de ses dimensions et des conditions d'écoulement (noyée ou dénoyée).

INTRODUCTION.

Pakistan has the largest gravity irrigation system in the world, fed by the Indus river and its tributaries. The total length of the canal system is about 63,000 kilometers and more than one half is located in Punjab (38000 km). The area annually irrigated by the Indus Basin Irrigation System is more than 14 million hectare (Van Essen et al. 1992).

This system was constructed mainly during the British colonization period but with the water treaty signed in 1960 between Pakistan and India which determines the allocation of the water resources between these countries (Ravi, Sutlej and Beas for India; Indus, Jhelum and Chenab for Pakistan), some modifications were made to reorganize the water distribution. Link canals were dug to feed the systems originally receiving water from the rivers allocated to India and two major dams were constructed (Mangla Dam on the river Jhelum and Tarbela Dam on the river Indus) to regulate the water distribution and to assure the water supply throughout the year (Riviere 1993).

The efficiency of the Indus Basin Irrigation System is estimated to be in a range of 30 to 50 percent. These low values are mainly linked with problems of infrastructure, maintenance and management. The demand for water, has increased with the cropping intensities and now far exceeds the originally designed values. The objective of the Punjab Irrigation Department (PID) is to distribute equally the resources rather than to meet the crop water requirements.

The International Irrigation Management Institute (IIMI) started to work in the Fordwah/Eastern Sadiqia area in 1990 to evaluate the performance of the system and to try jointly with PID to increase it. The field of research is the management at the main canal level as it is assumed that the performance can be improved by optimising the regulation of the Fordwah Branch.

1 Presentation of the irrigation system.

Fordwah/Eastern Sadiqia area (name of the two canals offtaking from the Sutlej river at Suleimanki Headworks), is located in southeast Punjab, bounded by the Sutlej River to the northwest, by the border with India in the east and by the Cholistan Desert in the southeast (Kuper and Kijne. 1992). Fordwah canal divides at RD[1] 45 between Fordwah Branch and Macleod Ganj Branch and the tail portion of the Fordwah branch is the Chistian subdivision, from RD 199 to RD 371 (see map in annex 1).

The irrigation system can be divided in three levels :

- the main canal which offtakes from the river at the headworks (dam,reservoir). Some cross structures regulate the water levels along the canal.
- secondary canals called distributaries which distribute the water in the area. The offtakes are mostly located just upstream a cross regulator.
- tertiary canals called watercourses which convey the water to the farms and offtake from the distributaries through outlets.

The Chistian subdivision includes 14 offtaking distributaries, 14 direct outlets and 7 cross regulators (C.R). Some distributaries are perennial which means that they receive water all year long, whereas the nonperennial have a water right only during kharif. The structures are briefly described in Table 1.

The design discharge at C.R 199 is 35 cumecs (m3/s). During kharif (summer season) the water is supplied through the Fordwah canal whereas during rabi (winter season) the water is conveyed through a link canal which offtakes from the Eastern Sadiqia Canal and discharges into the Fordwah Branch at RD 129. The indent (desired amount of water) during rabi is only 12.5 cumecs since there are only 5 perennial secondary canals (Riviere 1993).

---

[1] R.D : reduced distance in thousand feet from the head of the canal.

Table 1. Description of the structures of the Fordwah Branch.

Name of the distributary	location (RD)	type of offtake	number of gates	design capacity cumecs	peren-nial
Daulat	245	gated	2	5.92	NP
Mohar	245	gated	1	1.08	NP
3-L	245	weir		0.65	NP
Phogan	267	weir		0.48	NP
Khemgar	281	gated	1	0.85	NP
4-L	281	weir		0.45	NP
Jagir	297	gated	1	0.71	P
Shahar Farid	316	gated	1	4.13	NP
Masood	316	culvert	1	0.99	P
Soda	334	weir		2.10	NP
5-L	348	weir		0.11	NP
Fordwah dy.	371	gated	2	4.47	P
Mahmood	371	culvert	1	0.23	P
Azim	371	gated	2	6.91	NP

cross regulator	number of gates
C.R 199	6
C.R 245	4
C.R 281	2
C.R 316	2
C.R 353	1

N.B : The cross regulator are refered to by their location in the main canal.

2 Water distribution in the Fordwah Branch.

Water in the Chistian subdivision was meant to be distributed proportionally, which means that it is supplied to each secondary canal with a fixed percentage of the discharge entering the system. The water levels are controlled at some locations with cross regulators and the discharge supplied to the secondary canals is controlled by an offtake (either gated or ungated) which is most of the time located just upstream of a cross regulator. The control is done manually.

In order to manage the water distribution for the whole system including the three subdivisions, a notion of indent was created corresponding to the desired quantity of water. Each subdivision estimates its indents by summing the indents of the distributaries, with an assumption of the direct outlet issues and the seepage losses. At the headworks, the available supplies are compared to the required quantity of water, expressed by the indent. Thus, the water distribution in the whole system can be organized (Riviere 1993).

As there is a shortage of water, a preference order system is ruling the supply of water between the three subdivisions of the Fordwah Canal (Bahawalnagar, Macleod Ganj and Chistian). The subdivision which is in first preference takes water according to its indent, the second tries to meet its requirements with the remaining discharge and the third one takes the rest.

In the Chistian subdivision, a rotation is planned between the four main distributaries : Daulat, Shahar Farid, Fordwah and Azim. Indeed, even in first preference order, the supplied discharge is too low to achieve the indent of all the secondary canals. Moreover, as there is no escape for the overflow, the managers rarely take the risk to run the tail (Fordwah and Azim distributaries) at full supply, in order to avoid breaches or overtopping. The small distributaries are not included in this rotation programme for two main reasons. Their discharge is too low to have an influence on the water balance and most of them have ungated head structures and the flow can only be controlled with bushes or mud. Thus, the small secondary canals are favored as compared to the big ones (Riviere 1993).

The inflow at R.D 199 is irregular and cannot be predicted in a precise way (figure 1). This situation complicates the regulation of the Chistian subdivision and creates some fluctuations which affect the performance of the system. However, the fluctuations are more important at the tail of the subdivision than near the head which means that the operations of regulation also contribute to create an unstable state in the canal.

3 Objective of the study.

The purpose is to study the possibility to use a mathematical model (SIC) as a tool for a better understanding of the behaviour of the Fordwah Branch and the operations at the main canal level.

The first step is to calibrate the model with the field data in order to have a good fit between the results of the computations and what is measured in the field. Then a few hydraulic phenomena will be studied (such as time lag, influence of gate operations, sensitivity of the offtakes) to better understand the hydraulic behaviour of the canal. In a further step, the possibilities of improvement of the management will be studied.

1 PRESENTATION OF SIC.

SIC (Simulation of Irrigation Canal) is a mathematical model which simulates the hydraulic behaviour of an irrigation canal. The model is built around three main programs which generate the topography and carry out the steady flow and the unsteady flow computation. The model was developed by CEMAGREF (Centre du Machinisme Agricole du Genie Rural des Eaux et Forets) in France and was field tested in many countries, amongst others in Pakistan (Habib et al., 1992).

1.1 Presentation of the model.

1.1.1 Topography module.

In this module, the topography of the canal (branches, nodes and reaches) and the geometry of the cross sections have to be defined.

A node is a point of the canal where there is an offtaking canal or a supply of discharge. A reach is a homogeneous portion of the canal between two nodes without any inflow or outflow other than through seepage. In a reach, cross regulators can be defined (gates and weirs). A section which contains a cross structure is a singular section.

A cross section is required upstream and downstream of each node. SIC interpolates sections between two nodes but it is recommended to enter some additional cross sections to have the simulated shape of the canal match reality as close as possible.

1.1.2 Steady flow module.

This unit allows to compute steady flow backwater curves in the canal. The water surface profiles may be used as initial conditions for unsteady flow computation.

The geometry of the cross regulators and the offtakes are defined in this module, and also the seepage losses and the Manning coefficient are determined for each reach.

1.1.3 Unsteady flow.

This unit allows to compute unsteady flow water surface profile and can be used to evaluate the influence of gate operations or modifications to some design parameters. The modifications can be made in terms of discharge (variation of the delivery at the head of the canal) or gate operations at the cross regulators and at the offtakes. The requirements to use SIC are summarized in table 2.

1.2 Theoretical concepts.

1.2.1 Hypotheses.

The classical hypotheses of onedimensional hydraulics in canals are considered to apply:

-The flow direction is sufficiently rectilinear, so that the free surface could be considered to be horizontal in a cross section.

-The transversal velocities are negligible and the pressure distribution is hydrostatic.

-The friction forces are taken into account through the MANNING-STRICKLER coefficients.

Therefore, only onedimensional and subcritical flow is considered.

1.2.2 Differential equation of the water surface profile.

The equation of the water surface profile can be written as follows:

$$\frac{dH}{dx} = -S_f + k.\ \frac{qQ}{gA^2}$$

$$S_f = \frac{n^2 Q^2}{A^2 R^{\frac{4}{3}}}$$

with :
and:

- H = total head
- S_f = friction slope
- k = 0 for lateral inflow, 1 for lateral outflow
- q = discharge per unit length
- Q = volumetric rate of discharge
- g = acceleration of gravity
- A = cross section area of flow
- R = hydraulic radius
- n = Manning's roughness coefficient

As the equation does not have an analytical solution in the general case, it is discretised in order to obtain a numerical solution.

1.2.3 Saint-Venant's equations.

To compute the water surface profile under unsteady flow, Saint-Venant's equation are used; the initial water surface profile is provided by the steady flow module and the hypotheses are the same than in 2.1.

The continuity equation can be written as follows :

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q$$

The dynamic equation can be written as follows :

$$\frac{\partial Q}{\partial t}+\frac{\partial Q^2/A}{\partial x}+g.\,A\frac{\partial z}{\partial x}=-g.\,AS_f+kqV$$

with:

z = water elevation
V = mean velocity

Saint-Venant's equations have no known analytical solution. They are solved numerically by discretising the equations. The discretisation scheme chosen in the SIC model is a four-point semi-implicit scheme known as Preissmann's scheme.

1.2.4 Structures equations.

In the Fordwah Branch, there are two types of structures : weirs and undershot gates, either freeflow or submerged. Masood and Mehmood which are actually gated culverts will be considered as gates for SIC.

The equations used for weirs and undershot gates under freeflow and submerged conditions are given in annex 2. These equations assure the continuity between freeflow, partially submerged flow and totally submerged flow.

Table 1. Data required for the different modules of SIC.

<table>
<tr><th></th><th>REQUIREMENTS</th><th colspan="2">DATA REQUIRED</th></tr>
<tr><td rowspan="2">TOPOGRAPHY</td><td>Lay-out of the canal</td><td colspan="2">List of all the cross regulators, branches and offtaking canals.
Length of the reaches and location of the structures and offtakes.</td></tr>
<tr><td>Canal geometry</td><td colspan="2">Offset/Elevation relation for all the singular sections (U/S and D/S) and if necessary some additional sections.</td></tr>
<tr><td rowspan="8">STEADY FLOW REGIME</td><td rowspan="2">Cross Regulator dimensions</td><td>GATE</td><td>WEIR</td></tr>
<tr><td>crest level
height of gate
width of opening
max opening</td><td>crest level
width</td></tr>
<tr><td>Hydraulic datas for the cross regulators</td><td colspan="2">discharge coefficient (requires water level U/S and D/S, discharge and gate opening)</td></tr>
<tr><td>Off-take description</td><td colspan="2">as for the cross regulators plus downstream condition</td></tr>
<tr><td>Manning coefficient</td><td colspan="2">gate settings and waterline.</td></tr>
<tr><td>Seepage losses</td><td colspan="2">discharge at the beginning and end of a reach.
Length of the reach.</td></tr>
<tr><td>Boundary condition</td><td colspan="2">stage-discharge relation for the tail.</td></tr>
</table>

Note : U/S = upstream
D/S = downstream.

2 CALIBRATION OF THE MODEL.

2.1 Purpose of the calibration.

The purpose of the calibration is to match computation of discharge and water levels with field measurements in order to use the model for other time periods for which no field measurements are available, or to study the marginal impact of different variables on the hydraulic state. Also, alternative scenarios can be run once the model is calibrated.

In this process, discharge coefficients (Cd), seepage losses and Manning coefficients have to be determined.

2.2 Methodology.

The calibration is carried out in steady flow regime. This is an approximation since the state of the Fordwah Branch never remains constant for a long period. But by choosing a period when relatively few changes in gate operations were made this approximation may be valid. The process to determine the different parameters is briefly described below.

The seepage losses are calculated by substracting the outflow of the inflow in the Subdivision, including offtakes and direct outlets. Then this value is adjusted according to the water balance in the different reaches.

The Manning coefficient is calculated by manual iterative method until there is a reasonable agreement between the computed and observed water surface elevation.

The Cd value for the cross regulators is directly calculated by SIC with the calibration module. This module computes the Cd value from the upstream and downstream water levels and the discharge through the gates of the regulator.

For the offtakes, a Cd value and a downstream condition are required. Three different downstream conditions are available : constant downstream water level, downstream weir condition or stage discharge relation. In order to compute the Cd value, a constant downstream water level is required. When this value is computed (by manual iterative method), a better downstream condition can be chosen.

2.3 Field measurements.

Water levels upstream and downstream of each structure were measured daily and discharges were calculated with rating curves.
In order to assess the Cd value of the different structures, some discharge measurements by current metering were made.

A period with few changes in gate operations of the cross regulators was selected. The data entered in SIC are from 25 August 1993 a day when the hydraulic state of the Fordwah Branch was relatively stable.

2.4 Results obtained for the calibration.

2.4.1 Seepage losses.

The average value for the seepage losses, calculated from the discharges of 25/08/94, is 61 l/s/km. The values used for SIC are given in table 3.

Table 3. Seepage losses.

Reach	Seepage losses (l/s/km)
HEAD TO 245	60
245 TO 316	76
316 TO TAIL	96

We can see that the values used for SIC are much higher than the estimated value. This difference can be explained by problems of measurements and computation of discharges at the offtakes with hydraulic formula but also by an underestimation of the discharge through the direct outlets. This second reason is confirmed by the fact that the seepage losses computed with SIC are more important in the tail portion of the canal where most of the direct outlets are located.

2.4.2 Manning coefficient.

The values computed with SIC are given in table 1.

Table 4. Manning coefficient computed with SIC.

Reach	Manning Coefficient
Head to Jagir	0.031
Jagir to Soda	0.032
Soda to tail	0.026

2.4.3 Discharge coefficient for the structures.

The discharge coefficients (Cd) for the cross regulators and the offtakes are given in table 5.1, 5.2 and 5.3. The discharge coefficient of the offtakes in the Fordwah Branch ranges from 0.50 to 0.87 for the gated offtakes (0.60 is considered as a usual value) and from 0.13 to 0.50 for the weirs (0.40 is considered as a usual value).

Table 5.1 Discharge coefficient for the offtakes.

Name of the Offtake	Discharge Coefficient	Name of the Offtake	Discharge Coefficient
DAULAT	0.50	SHAHAR FARID	0.59
MOHAR	0.50	MASOOD	0.60
KHEMGAR	0 87	MEHMUD	0.60
JAGIR	0.55	FORDWAH	0.50

N.B : F.F for freeflow and sub for submerged.

Table 5.2 Sensitivity of the ungated offtakes.

Name of the Offtake	Discharge Coefficient
3-L	0.13
PHOGAN	0.35
4-L	0.40
SODA	0.24
5-L	0.50

Table 5.3 Discharge coefficient for the cross regulators.

Cross Regulator	Discharge coefficient
C.R 199	0.62
C.R 245	0.65
C.R 281	0.77
C.R 316	0.47
C.R 353	0.60
C.R 371	0.60

2.4.4 Accuracy of the calibration.

Discharge at the offtakes.

The model was calibrated for 25/08/93 and the Cd coefficients and downstream boundary conditions were determined in order to have an accuracy of the computed discharge as high as possible (see annex 3). The discharges computed with SIC are very close to the discharges calculated from the field measurements. The percentage of error is less than 5%, except for Fordwah and Jagir where it is slightly higher (9%). For Fordwah, the ratio of submergence is close to 2/3, which is considered as the limit between free flow and submerged flow. The discharge is sensitive to the water level in the main canal and the flow condition can change with a small range of variation of water level or gate opening. For Jagir, the upstream water level is not regulated by a cross structure and was slightly higher than actual. To avoid problems in loop calculation, two offtakes were set in imposed discharge mode, which means that the discharge supplied to the offtake is independant of the water level in the main canal.

The inaccuracy of the measurements, however was not taken into account for the calibration, which means that the percentage of error with the actual conditions might be higher than calculated. Due to difficulties in the calibration process, it was not possible to calibrate the model for different sets of data and take an average value of the parameters.

This is clearly shown by the much higher values of the percentage of error for 26/06/94 (see annex 4) : it ranges from 0.6% to 10.1% for 25/08/93 and from 2.8% to 30% for 26/06/94 (Masood was not taken into account because of problems in loop calculation). However, the accuracy for the main offtakes (Daulat, Shahar Farid, Fordwah and Azim) is acceptable and the total discharge offtaken by the distributaries is relatively close to the actual value (4% of error). It means that the error is distributed among the small distributaries and does not affect too much the main offtakes.

The main reason for the difference between actual and computed discharge is the downstream condition of the offtakes. For most of the offtakes, stage discharge relations established in 93 do not give accurate results for 94 data. Siltation, indeed changes the bed elevation downstream the structure over the year and make it difficult to set up accurate relations valid for more than one year. Thus, downstream weir conditions were used for every offtake. This option gives relatively good results for free flow structures (Daulat, Shahar Farid, Azim) for which the discharge is not affected by the downstream condition but can create some problems for submerged structures where the difference between upstream and downstream water level is only a few centimeters (3-L, 4-L, Masood, 5-L). Indeed, when the water level in the Fordwah Branch is low, the downstream condition cannot be satisfied because of a too high crest elevation of the downstrean weir.

In a study carried out parallel to this one, downstream boundary conditions were defined with a Q-h_2 relation, established with 94 data, which gave better results for the structure calibration for 1994. This is however out of the scope of the present study.

Water surface elevation.

The water surface elevation is difficult to adjust. Fordwah canal has a relatively irregular geometry (both bed elevation and cross sections), being an alluvial channel. In order to describe closely the topology of the Fordwah Branch, a high number of cross section is required particularly at the locations were there are irregularities. Since accurate enough data were not available, it was chosen to simplify the geometry of the canal in order to have a consistent topography and relatively steady flow conditions. The shape of the sections were kept the same, but the bed elevation was calculated by interpolation (figure 2). The results of the computation for 25/08/93 and 26/06/94 are given in annex 3.

Here again, we can see that the accuracy is less for 26/06/94 than for 25/08/93. The main reason is a significant change in the bed elevation at some particular locations due to siltation between 1993 and 1994. The silt deposits mainly downstream of the structure and affects both the discharge and the upstream water level (except C.R 199 and C.R 353, all the cross regulators were submerged).

2.5 Limitations of SIC.

This study enables to point out some limitation of the model:

- difficulties to take into account the geometry of natural canals (irregular longitudinal shape and cross sections).
- necessity of updating the geometry and the calibration for canals where siltation is important.
- inaccuracy of the discharge computation for the offtakes where the difference between upstream and downstream water levels is very small.

3 TIME LAG.

3.1 Definition and use of the time lag.

The time lag is defined here as the time between the release of an extra discharge at the main sluice and the time when half of the wave has reached the selected regulator (Beaume et al., 1993).

This parameter is essential for the management of an irrigation canal because it shows the delay between an operation at the head and its effects at the different regulators. Thus, by computing the time lag, one can assess when the gates have to be operated at the regulators when a change in the head discharge occurs.

3.2 Computation of the time lag.

To evaluate the time lag, a wave was simulated at the head of the canal and the water levels were recorded at the three main Cross Regulators (C.R) : C.R 245, C.R 316, C.R 371 (figure 3.1 and 3.2). The computation was first carried out with no gate operations at the regulators. Then the influence of gate operations was tested. Others variables have also an influence on the time lag : value of the additional discharge at head and sign of the step which is created (positive or negative step).

3.3 Results.

The results of the computation are shown in Table 6.1, 6.2 and 6.3.
One can see that for C.R 245 and C.R 316, the influence of the variables is almost nil. For C.R 245, the reason might be that it is too near from the head ; but for C.R 316, no real explanation can be given.

At C.R 371 however, the influence of this parameters is clear. A wave created by a negative step is propagating faster than one created by a positive step and the higher the value of this step is, the shorter the time lag is. In fact, when an additional discharge is delivered, there is storage at each regulator, which slows the propagation of the wave. In the other hand, when a negative step is created, the water passes through the gates more easily and thus the time lag is reduced.

The influence of the gate operations can be explained in the same way : when the gate opening is reduced, the time lag increases and when the gate are opened it decreases.

Table 6.1 Time lag at the different regulators :
Discharge at the head : 29.29 cumecs
Value of the step : 3 cumecs

CROSS REGULATOR	TIME LAG	
	POSITIVE STEP	NEGATIVE STEP
C.R 245	5H20	5H20
C.R 316	15H	15H
C.R 371	27H	22H

Table 6.2 Time-lag at the different regulators :
Discharge at the head : 20 cumecs
Value of the step : 3 cumecs

CROSS REGULATOR	TIME LAG	
	POSITIVE STEP	NEGATIVE STEP
C.R 245	5H20	5H20
C.R 316	15H	14H40
C.R 371	25H20	23H

Table 6.3 Time lag at the different regulators :
Discharge at the head : 20 cumecs
Value of the step : 1 cumecs

CROSS REGULATOR	TIME LAG	
	POSITIVE STEP	NEGATIVE STEP
C.R 245	5H40	5H40
C.R 316	15H	15H
C.R 371	26H40	25H

4 INFLUENCE OF GATE OPERATIONS.

4.1 Ojective.

The objective is to estimate to what extent an operation at a cross regulator has an impact on the other regulators and offtakes in terms of water levels and discharges. In order to carry out this study, simulations were made with SIC under the following conditions :

i) the opening of the gates of the studied regulator is reduced in order to decrease the discharge through the gates by 10%.

ii) the other regulators are not operated.

iii) all the offtakes are in discharge computation mode, the gates of the offtakes are not operated.

iiii) the simulation lasts until the water levels become constant (30 to 35 hours).

One simulation was made for each regulator, the discharge and water levels upstream and downstream of each structure are recorded and the percentage of variation in the discharge and the difference in water level are calculated.

4.2 Results of the simulations.

4.2.1 Influence on the upstream structures.

When the opening of gates are lowered at a cross regulator, the water level rises upstream of the structure and backwater effects propagate with the hydraulic wave which is created. The objective is to determine upto where these effects can be noticed. One should note that the conditions of the simulation are not realistic since a decrease of 10% in the discharge at a cross regulator can imply a rise of 60 cm upstream of the structure and would create overtopping or breaches in the banks. However, the purpose is not to quantify the back water effects but to estimate the degree of sensitivity of the different structures.

To assess if the operations at a cross regulator have an impact on the regulator upstream, we assume that the operator will take an action when the rise in the upstream level is more than 0.1 feet (3cm). In this case, we can say that the regulator is affected by the downstream conditions. The results are shown in table 7.

Table 7. Influence of operations on upstream regulator.

Operated regulator	Decrease of discharge at the regulator	Rise of U/S water level at the U/S regulator
245	10.6%	0 cm
281	11.2%	4 cm
316	11%	4 cm
353	9.3%	7 cm
371	10.6%	0 cm

Cross regulator 281, 316 and 353 seem to have an influence on the regulator just upstream; cross regulator 245 and 371 (Azim distibutary) have no influence. This can be explained by the fact that C.R 245, 281 and 316 were submerged under the conditions of the simulation and C.R 199 and 353 were free flow.

C.R 353 seems to have a great influence on C.R 316 since the upstream water level at 316 increases by 7 cm when the gate of 353 is closed by 50 cm. The reason is that the water level at 353 is very sensitive to gate operations because 353 is free flow and has a smaller area of opening as compared to the other regulators.

In order to see the real impact of operations on the upstream structures, simulations were made under more realistic conditions: a rise of 10 cm is created upstream of the studied regulator and the water levels are recorded. The results are shown on figure 4.1, 4.2 and 4.3.

It appears that the backwater effects do not reach the regulator upstream in these conditions. The effects can be noticed upto 4 km upstream of the operated regulator in the case of C.R 281 and less for the other regulators.

In usual conditions, gate operations do not influence much the upstream reaches. However, in certain conditions when important changes are made in gate openings, it could effect the upstream regulator. This could be the case when the preference order of the distributaries changes or when a storage is created at a regulator in case of breaches downstream. In these cases, the water level can be risen by more than 10 cm in a short time. It could be interesting to know the impact of these operations in order to optimize them and to reach a stable state as fast as possible.

4.2.2 Influence on the tail.

The variation in discharge for Fordwah and Azim are shown on figure 5. We can see that the tail of the Fordah Branch is very sensitive to gate operations at the different regulators. The variations in discharge are amplified : a variation of 10% in the discharge at a cross regulator creates a variation of more than 10% at the tail. This can partially be explained by the fact that the decrease of discharge created at the regulators represents much more than 10% of the initial discharge in Fordwah or Azim distributaries.

But this cannot explain the difference observed between the different regulators. C.R 245, for example has less influence on the tail than C.R 281 whereas the decrease of discharge created at 245 is more important than the one at 281. This is mainly due to the effects of the upstream offtakes on the hydraulic parameters. When the water level rises upstream of a cross regulator, the water supply to the offtakes increases and the discharge passing through the gates of the regulator decreases. Generally speaking, when a variation in the discharge has to be made at a regulator, the presence of offtakes upstream of the structure attenuates the changes which have to be made in terms of gate opening and reduces the variation of downstream water level. Thus, the offtakes have a perturbation effect on the regulation of the main canal. The control of discharges and water levels is dependent on the offtaking distributaries and cannot be achieved without taking them into account. The geometric parameters of the offtake (width of opening, crest elevation, gated or ungated structure) also have a very important impact on the perturbation which is created at the regulators level and will be studied in the next paragraph.

The example of C.R 245 and 281 is interesting. The presence of an important distributary upstream C.R 245 (Daulat 5 cumecs) which can take considerable extra discharge reduces to a great extent the effects of a 10% variation in discharge on the tailend distributaries. On the other hand, C.R only regulates two small distributaries (Khemgar and 4-L) whose capacity to take an extra discharge is limited. Thus the decrease in the discharge is mainly created by the gate operation and the effects on the downstream structures are larger than in the case of C.R 245.

5 SENSITIVITY OF THE OFFTAKES.

An offtake can be considered as a system with one input (the water level in the main canal) and two outputs (discharge and downstream water level). This system can be described by a certain number of parameters : type of structure (gated or ungated), geometry (crest elevation, width of opening, opening of the gate) and usual flow conditions (free flow or submerged).

The sensitivity of the offtake is the way the structure reacts in terms of discharge to a perturbation in the input . The purpose of this study is to identify the parameters which have an influence on the sensitivity of the offtakes.

5.1 Methodology.

To achieve this purpose, simulations are carried out under the following conditions :

- a simulation is made with the steady state module in order to have the discharges in the offtakes as close as possible to the indents. Upstream water level and discharge are recorded for each structure.
- a rise of 10 cm on the water level of the main canal is created by operating the different crossregulators.
- between the two simulations, no modifications are made on the opening of the gated offtakes.
- the percentage of variation of the discharge between the two simulations is calculated.

As it is difficult to create a uniform rise of 10 cm in the water level of the main canal, the offtakes will be studied separately which means that the cross regulators will be operated in order to create the modification only at the location of the studied offtake, independantly from the rest of the canal. The other structures are put in imposed discharge mode to accelerate the time of computation.

5.2 Results of the simulations.

The results are presented in table 8.1 and 8.2. Fordwah distributary which can be either free flow or submerged has been considered in both cases.

Table 8.1 Sensitivity of the gated offtakes.

Name of the Offtake	Percentage of variation of Q	Name of the Offtake	Percentage of variation of Q
DAULAT	4.5%	SHAHAR FARID	2.6%
MOHAR	10.9%	MEHMUD	30.3%
KHEMGAR	10.8%	FORDWAH (F.F)	5.9%
JAGIR	11.5%	FORDWAH (Sub)	11.9%

N.B : F.F for freeflow and sub for submerged.

Table 8.2 Sensitivity of the ungated offtakes.

Name of the Offtake	Percentage of variation of Q
3-L	20.4%
PHOGAN	18.3%
4-L	19.6%
SODA	17.9%
5-L	51.6%

We can see that generally speaking, the percentage of variation is lower for the gated structures than for the ungated. Except Mehmud which has a percentage of variation of 30%, the other gates are below 12% whereas the weirs have an average variation of 19%.

However, all the gated structures do not seem to react to the perturbation in the same proportion. Daulat, Shahar Farid and Fordwah (when it is free flow) have a variation of approximately 5% whereas the percentage for Mohar, Phogan, Khemgar, Jagir and Fordwah (when it is submerged) is more than 10%. The first structure are free flow whereas the others are submerged which enables to say that in general a submerged offtake is more sensitive than a free flow one. We must however consider the fact that other paramaters than conditions of flow might explain this difference. Indeed Daulat, Shahar Farid and Fordwah have a width of opening much higher than the others. But the role of the condition of flow is confirmed by Fordwah distributary which was considered in both cases.

For the weirs, it is difficult to identify the influence of crest elevation and width of opening. For the crest elevation a criterion has to be chosen since the offtakes are not located at the same location and thus cannot be compared. The way the offtakes have been designed can be helpful. Indeed, for the ungated structures the discharge is controlled by the elevation of the sill. Some weirs are considered as high crested that is to say that they will receive water only if the level in the main canal reaches a certain value. When the level is too low, no water is supplied to these offtakes. Other weirs will receive water even at low discharge in the main canal.

To identify in which category belong a particular weir, the daily measurements have been ploted for kharif 94 (see annex 5). We can see that for some weirs, the discharge frequently drops from an average value to zero and back to this value very sharply. For the other weirs, the curves are less irregular and the number of days when the discharge is nil is less important. The weirs which belong to the first category (3-L, 4-L, 5-L) will be considered as high crested, the others as low crested (Soda, Phogan).

According to the previous results, there seems to be no great difference between the sensitivity of high crested weirs and low crested weirs. Except 5-L whose high sensitivity can be explained by a small width of opening, the percentage of variation in the discharge is close to 20% for all the weirs. However, the high crested weirs will be more sensitive to a decrease in the water level than the high crested weirs and the range of discharge in the main canal for which they receive water is lower than for the low crested weirs.

6 DISCUSSION.

In this section, the results presented in the previous chapters are discussed. Other possibilities of SIC model in general will be evoked particularly in view of the opportunity to use it by the Punjab Irrigation Department.

6.1 Discussion of the results.

Time-lag.

The simulation of a step created in the discharge released at the head of the canal has enabled to compute the time-lag for the different cross regulators of the Fordwah Branch. The influence of the sign of the step, of the value of the extra discharge which is delivered and the original discharge was evident for C.R 371. No difference, however are observed for C.R 245 and C.R 316 where there does not seem to be any influence of these variables. It could be interesting to know if it is linked with the accuracy of the calibration or if the time-lag for these two regulators is actually constant watever the initial situation.

The average distance-time of the hydraulic wave is 2.3 km/h. In a similar study carried out in Sri Lanka (Beaume et al. 1993) an average value of 1.4 km/h was found. The hydraulic wave propagates much faster in the Fordwah Branch than in the Kirindi Oya canal. However, the results have not been validated in the field in the case of the Fordwah Branch. Some field scenarios are required in order to enable a comparison.

Influence of gate operations at the cross regulators.

Some basic results for the influence of gate operations of upstream regulators have been found : great influence of the operations on the tail of the Fordwah Branch and possible influence of gate operations on the upstream regulator. It is now important to assess the actual influence of gate operations in the field.

The influence of downstream structures on upstream regulators is an important thing to know for the operator of the canal because back water effects can create some perturbations in the management and are difficult to assess in the field. Indeed, the supposed range of fluctuations due to the influence of downstream regulators is relatively small (3 to 7 cm) and is difficult to separate from the fluctuations coming from an irregular inflow. However, the study shows that gate operators do react to water level changes greater than 3 cm. The next step of the study would be to assess which proportion of fluctuations are due to the irregular inflow at RD 199 and which proportion is created by the operations at the cross regulators. The possibilities of carrying out a real field scenario could also be studied.

Sensitivity of the offtakes.
The analysis carried out in this study was a comparison between the different offtakes of the Fordwah Branch. Other approaches of the sensitivity of the offtakes are possible (van Essen, van der Feltz. 1992).

Parameters should be studied separately in order to estimate their marginal impact on the way the structures respond to a perturbation. However, this study enables to point out the different factors which explain why a structure is sensitive or not and give a better idea of the hydraulic behaviour of the Fordwah Branch.

As shown previously, the ungated offtakes are more sensitive to changes of water level in the Fordwah Branch than the gated structures. This situation leads to an irregular inflow in the distributary whose head structures are ungated. It would be possible to assess with SIC the improvement made by equiping the weirs with gates on the regularity of the discharge supplied to the distributaries and on the gate operations at the main canal level.

6.2 Possible applications of SIC.

SIC enables to compute discharge and water surface elevations both in steady state and unsteady state. With the first option, it is possible to study some characteristics of the main canal which can be interesting for the managers. Some of the direct applications are given below :

- calculation of the maximum capacity of the canal. This information is very important for the manager because it enables to run the canal at its full supply without taking risks of breaches or overtopping. For this, a very accurate geometry of the canal is required (bed elevation, shape of the cross sections, height of the banks). Given the minimum free board which is required, the maximum discharge at the head of the canal can be computed by successive simulations. Different scenarios can be tested according to the positions of the gates and the discharge required in the distributaries.

- influence of desiltation. The accumulation of silt reduces the capacity of the canal and can affect the flow conditions at the cross regulators and the offtakes. The Fordwah Branch is much affected by siltation as evoked previously and knowing the impact of a desiltation operation could be interesting. One way to proceed is to make an estimation of the actual possibilities of desiltation in the field and to watch with SIC the impact on the maximum capacity of the canal and on the performance of the system.

- influence of canal lining. Canal lining is the operation of covering the cross section of the canal with an artificial layer in order to reduce the roughness coefficient and the seepage losses and to maintain a constant shape of the cross section. The influence of canal lining can be tested with SIC by modifying the shape of the canal and reducing the seepage losses and the Manning coefficient. The improvement can be assessed by comparing the results of the simulations before and after the lining of the canal.

With both steady state and unsteady state modules, the management of the canal in terms of gate operations can be studied and scenarios can be made in order to improve it. By knowing the available discharge at the head and the indents of the different distributaries, SIC enables to compute the gate openings of the different distributaries with the steady state module. It is also possible to determine the opening of the gates of the different cross regulators given a certain upstream water level. Then, operations of gates and cross regulators can be simulated with the unsteady state module. The objective is an optimization of gate operations with a view to limit the perturbations and improve the supplies to the distributaries.

6.2 Opportunity to use SIC for the PID.

To estimate the possible use of SIC for the Irrigation Department, we will first discuss the main obstacles to its application as a tool for the management of the Fordwah Branch and then some suggestions will be made, for possibilities by PID to use this model.

The first obstacle is the lack of accurate field data. The inflow at C.R 199 is irregular and cannot be predicted in a precise way. The measurement devices are not always in a good state and the rating tables used for the computation of the discharges are often outdated. Moreover, the gate settings are not reported to the manager. The amount of data required for the daily use of SIC is large and may well be too large for the field staff of the Irrigation Department.

Moreover, the conditions of the structures and the siltation which changes the cross section shape over the year make it difficult to simulate the actual conditions. Regular topography survey and recalibrations will be required to have updated files.

All the possibilities of using SIC evoked in the previous section could be applied for the Fordwah Branch, once the model is properly calibrated. But the main objective is to use the model to quantify the effects of certain water distribution strategies and to improve the way the operations are made. One example of utilisation of the model is given below to give an idea of the possibilities.

The rotation between the four main distributaries which is presently taking place contributes to create an unstable state in the Fordwah Branch. No fixed strategy seems to be applied, the length of the turns and their frequency are not constant. In order to undertake a real rotation program, SIC would be a useful tool. The different possibilities of alternating the turns and the length and the frequency of the turns can be tested. Then the best scenario can be selected, that is to say, the one for which a steady state is reached the most quickly.

Many other applications of SIC for the Fordwah Branch could be developped. This section only shows the possible use of this model in a close future, despite the problems that have been encountered. However, in order to use SIC as a real tool for the management of the main canal, a lot of work has still to be done.

CONCLUSION.

The decision of using SIC for the Fordwah Branch comes from a real need for more information on the present management of the main canal. The poor performance of the Chistian Subdivision cannot be explained only by its location at the tail end of the Fordwah Canal and an irregular inflow at RD 199. A hydraulic model was required to point out the influence of the state of the physical system and the operations of regulation on the water supply to the distributaries.

SIC enables to model the topography and the geometry of the main canal and to carry out simulations in steady state and unsteady state. SIC was found to provide answers and substantiate the impact of gate operations on the hydraulic state of the canal.

The calibration of SIC for the Fordwah Branch was problematic. It was difficult to take into account the irregular shape of the main canal and to model the downstream boundary condition for some of the offtakes which were totally submerged. The results obtained so far show that a more precise topography survey will be required and emphasis should be put on the downstream boundary condition of the offtakes as it seems to be a key for a good calibration. However, some basic hydraulic phenomena could be studied with the present model.

The first application of SIC for the Fordwah Branch is the computation of the time-lag for the different cross regulators, that is to say the time for a hydraulic wave created at the head to reach the different cross regulators. The different simulations have enabled to point out the influence of some variables on the time-lag : original discharge at the head, sign of the step which is created (increase or decrease of the discharge) and value of the extra discharge that is released. This information is interesting for the managers of the canal in so far as it enables to anticipate the action required by a sudden change in the discharge at the head.

The study has shown that gate operations have an influence on discharge and water levels at other structures. Gate operators are usually not aware of the effects these operations have on structures downstream in the system. The large fluctuations observed in the field were attributed to the irregular inflow at RD 199. Since information on gate settings and water levels transmitted to the system managers is scanty, there is no clear idea by the irrigation agency of the impact of operations on fluctuations in the main canal which lead to a great number of changes in gate openings per day and a highly variable inflow for the distributaries. SIC provides useful insights on the actual influence of gate operations on the hydraulic state of the Fordwah Branch and could enable, in the long term an improvement of the management of the Chistian Subdivision.

Working on SIC can also become a training for the engineers of the irrigation department. Indeed, as it represents the hydraulic conditions in the field, SIC enables a good understanding of the hydraulic phenomena in irrigation canals.

Figure 1 Inflow at RD 245

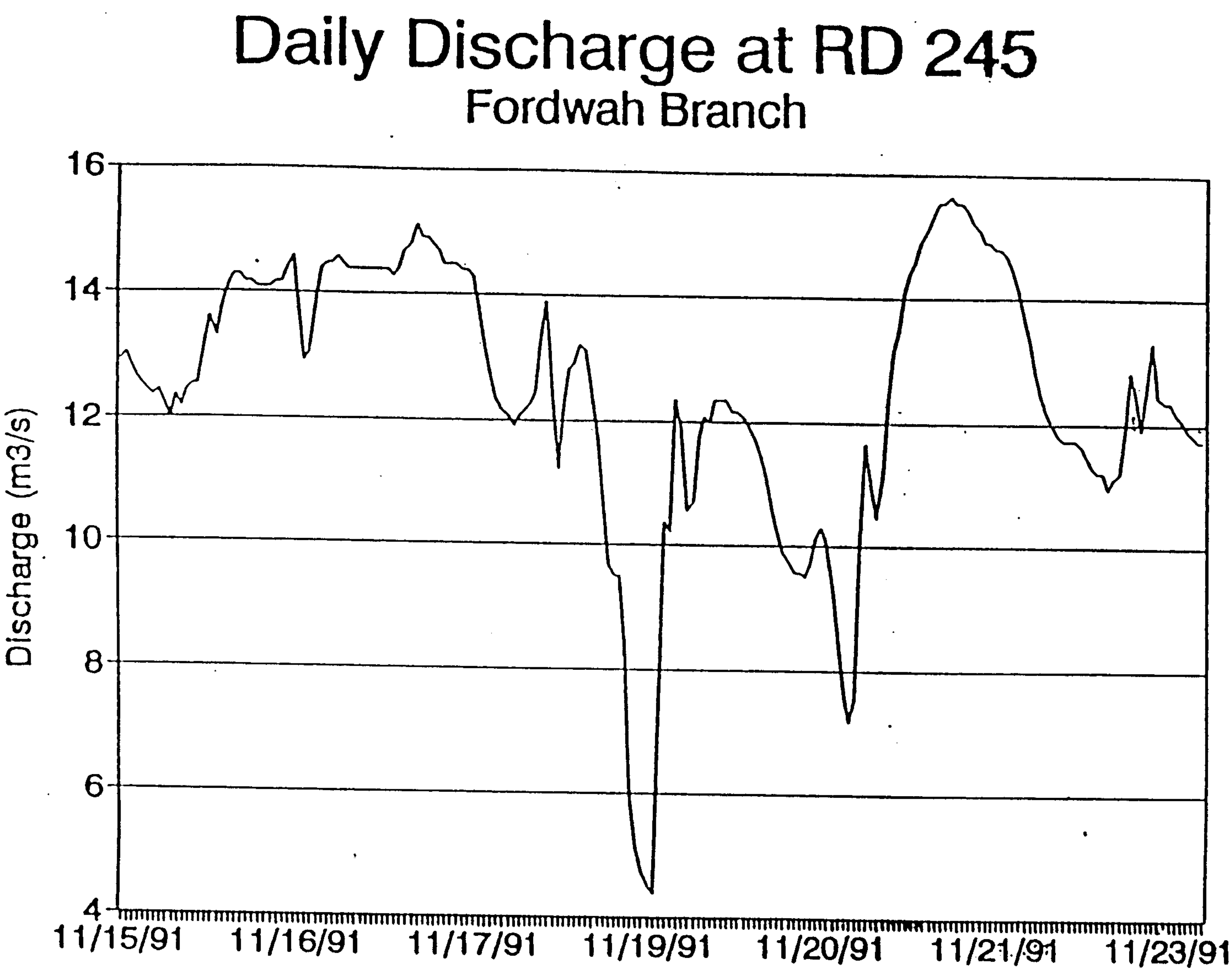


Figure 2 Bed elevation of the Fordwah Branch.

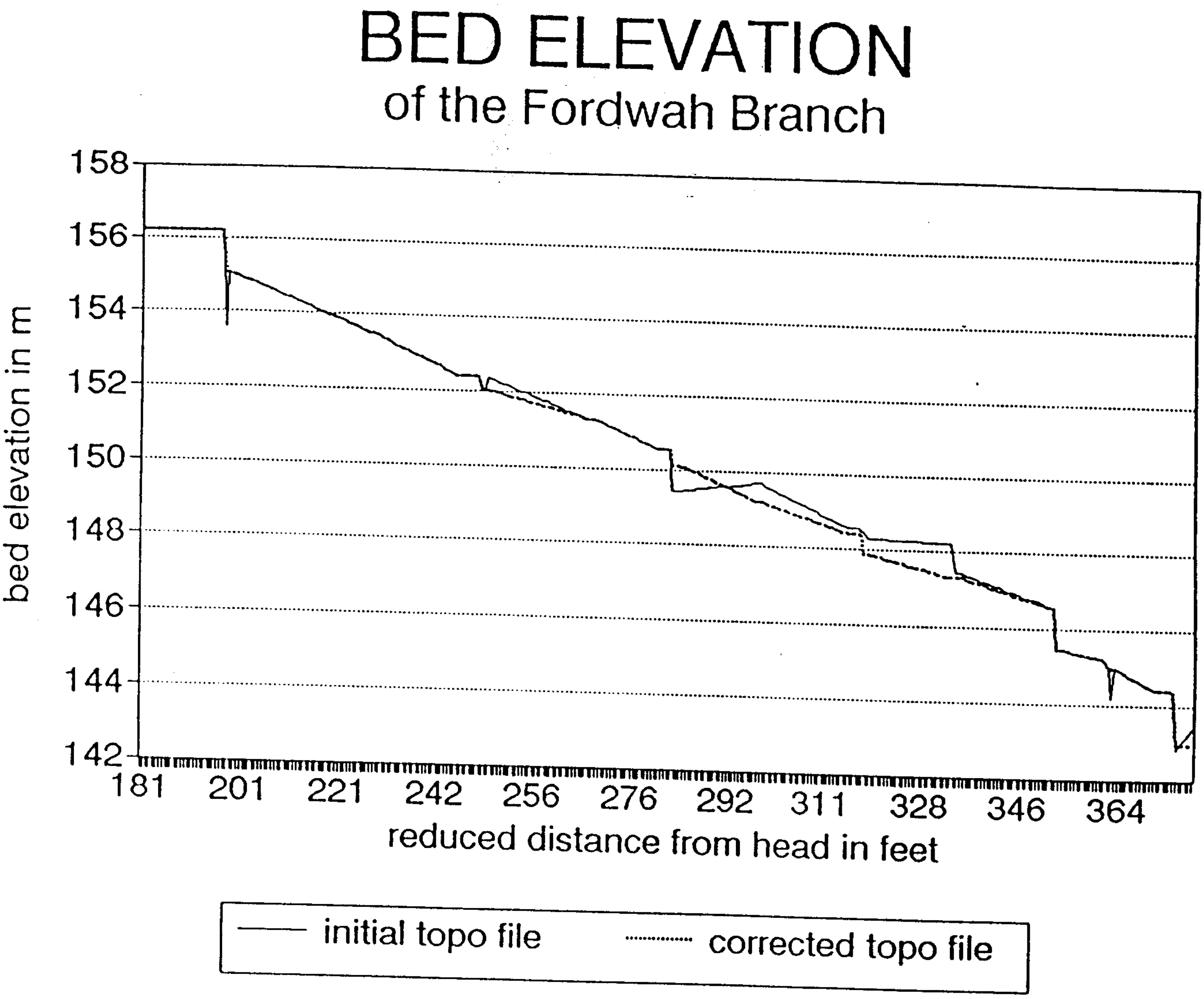
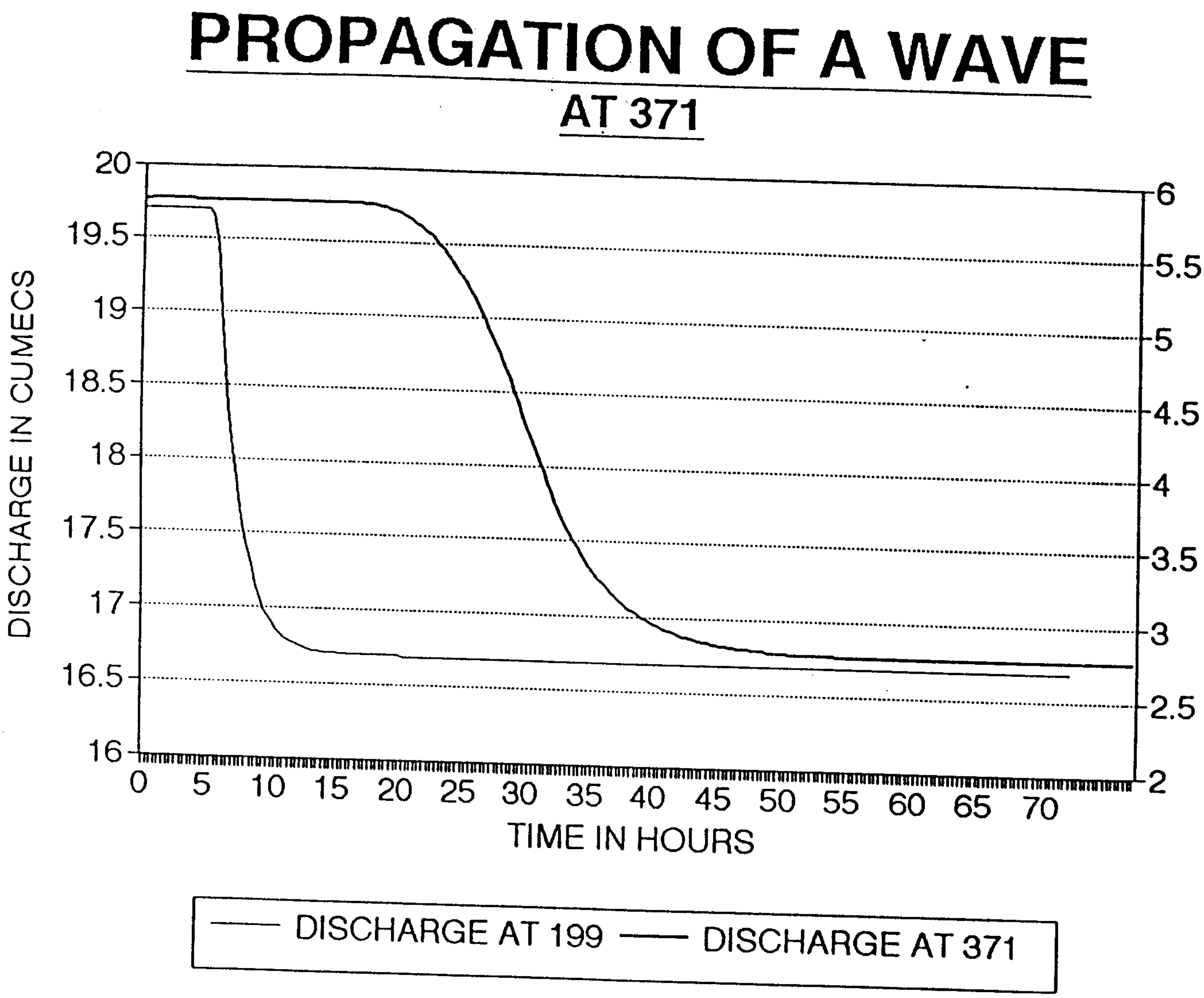


Figure 3.1 Simulation of a hydraulic wave (positive step).



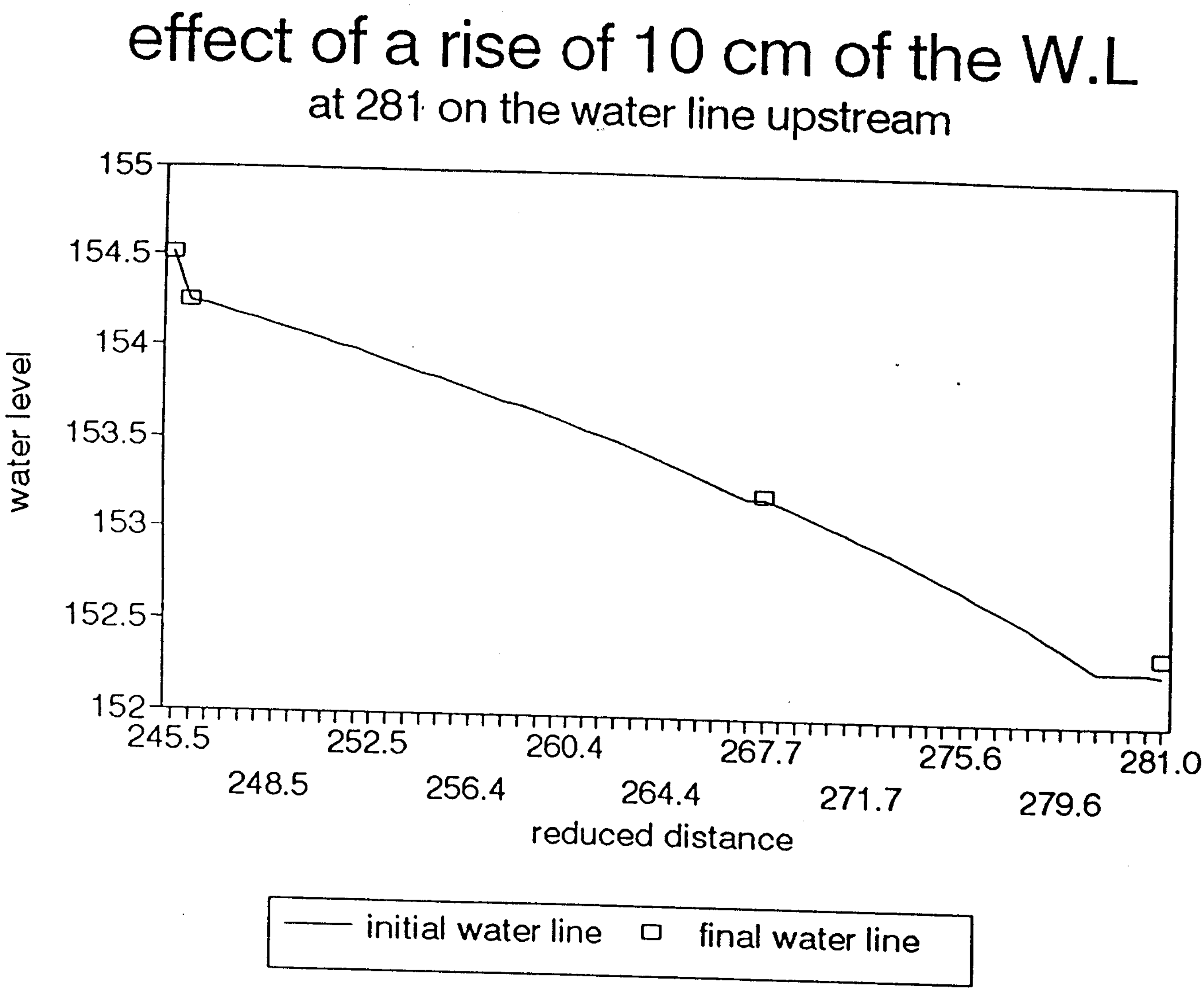
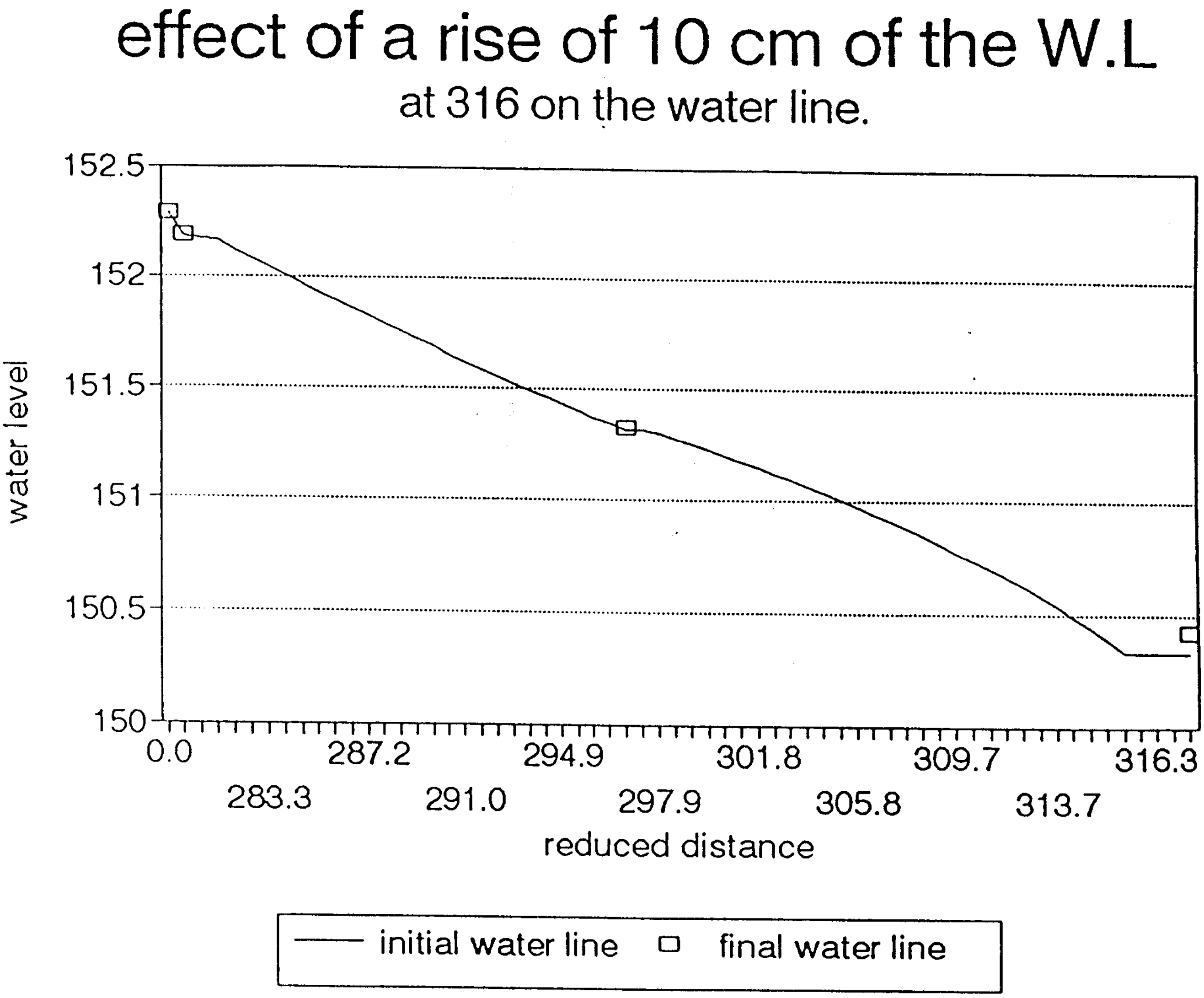

effect of a rise of 10 cm of the W.L
at 281 on the water line upstream
155
154.5
154
153.5
153
152.5
152
water level
245.5
248.5
252.5
256.4
260.4
264.4
267.7
271.7
275.6
279.6
281.0
reduced distance
initial water line
final water line

Figure 4.2 Influence of gate operations on the U/S water level (C.R 316)



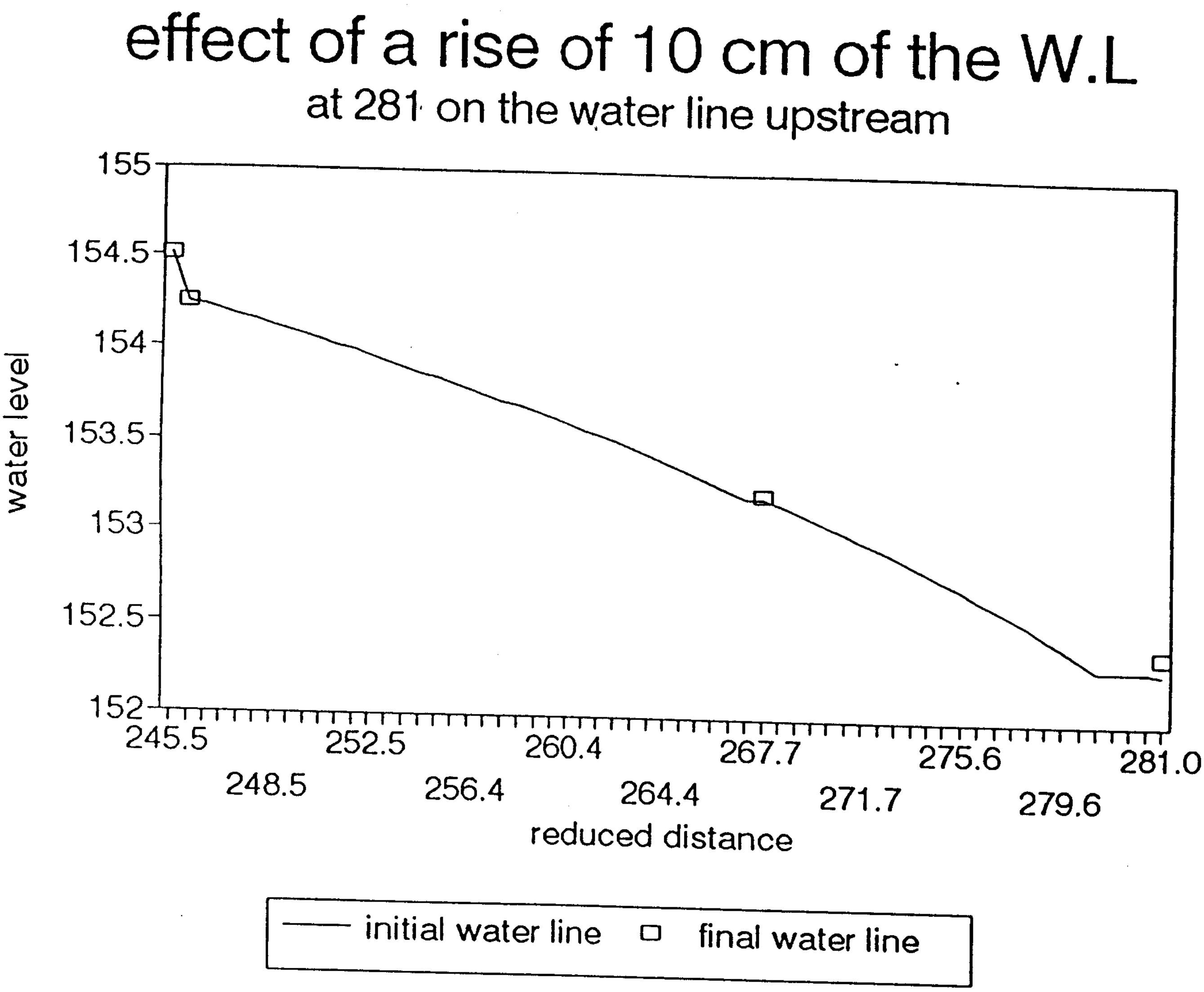

effect of a rise of 10 cm of the W.L
at 281 on the water line upstream
155
154.5
154
153.5
153
152.5
152
water level
245.5
248.5
252.5
256.4
260.4
264.4
267.7
271.7
275.6
279.6
281.0
reduced distance
initial water line
final water line

Figure 4.3 Influence of gate operations on the U/S water level (C.R 353)

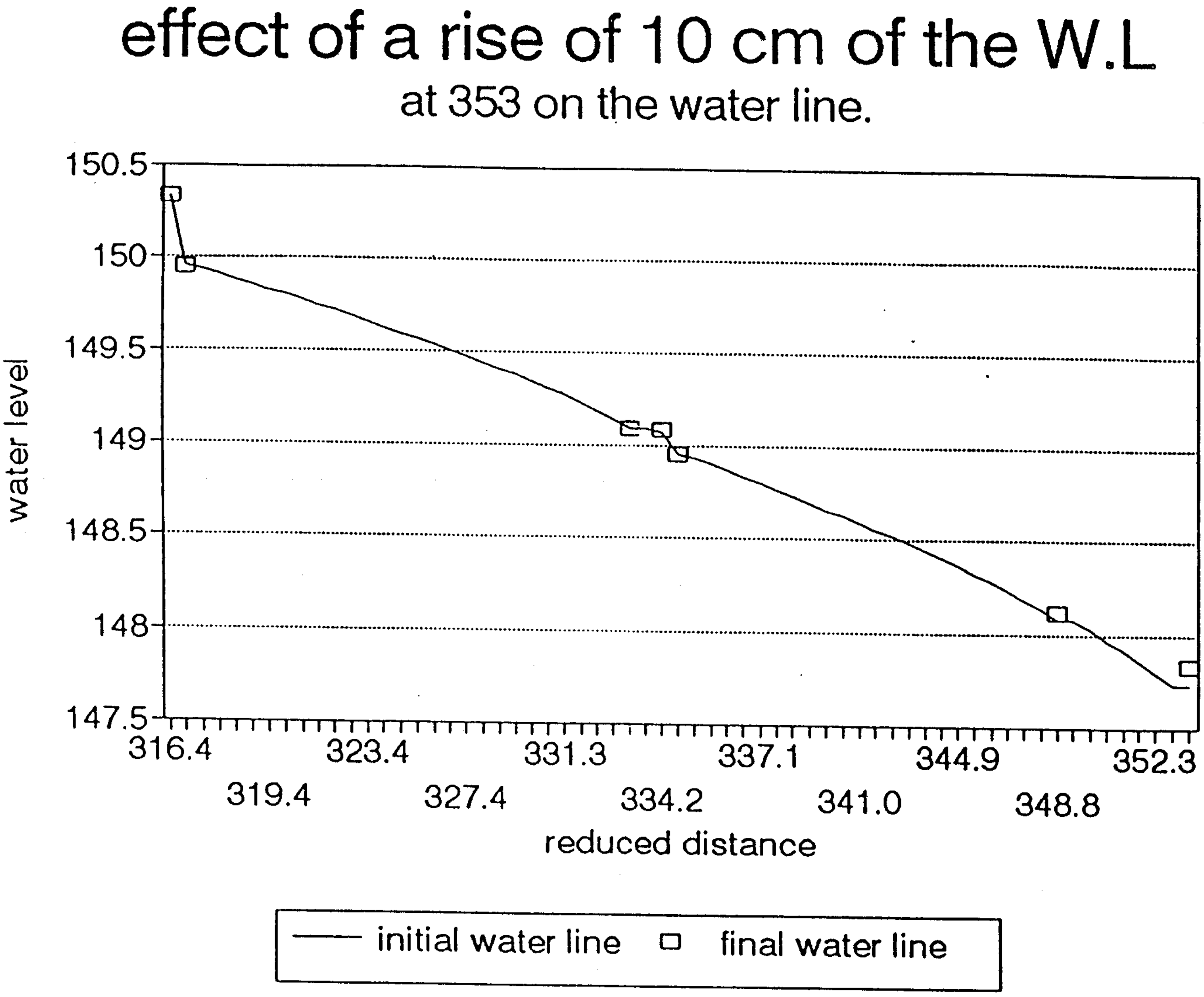
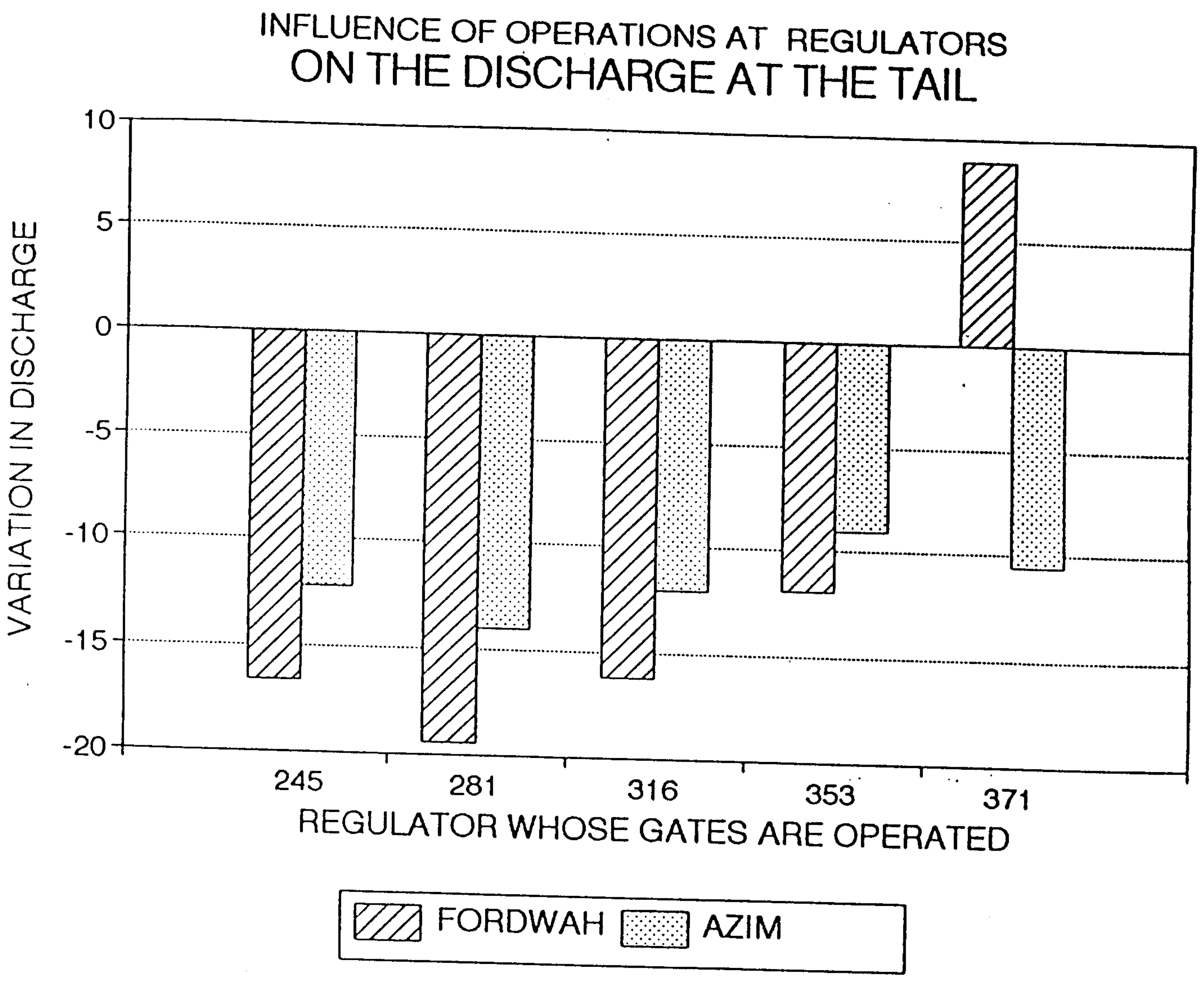
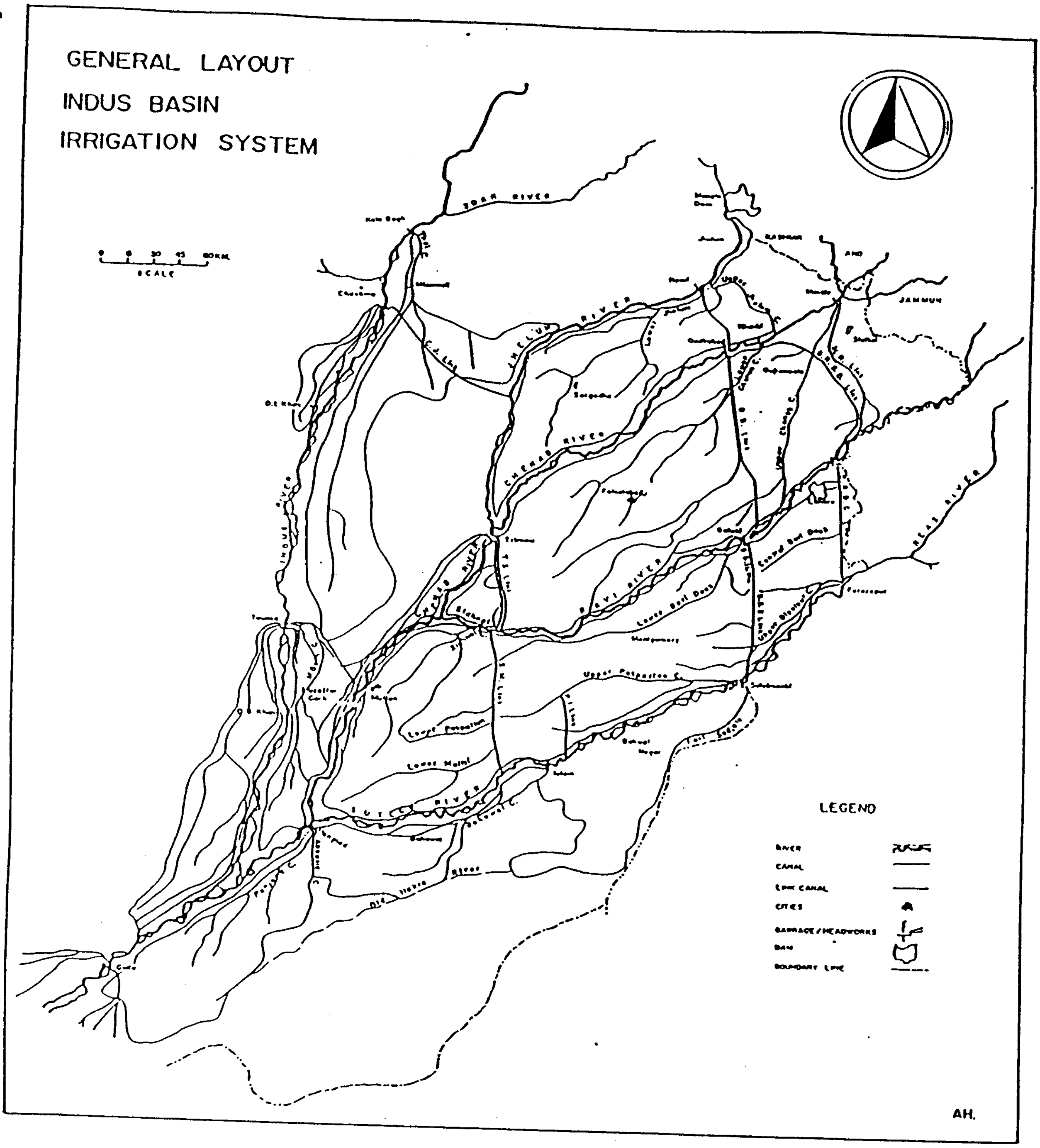


Figure 5 Influence of gate operations on the tail distributaries.



ANNEX I


GENERAL LAYOUT
INDUS BASIN
IRRIGATION SYSTEM
SCALE
SOAN RIVER
JHELUM RIVER
CHENAB RIVER
RAVI RIVER
BEAS RIVER
INDUS RIVER
JAMMU
LEGEND
RIVER
CANAL
LINK CANAL
CITIES
BARRAGE / HEADWORKS
DAM
BOUNDARY LINE
AH.

ANNEX 2 : STRUCTURES EQUATIONS.

WEIR/UNDERSHOT GATES (small sill elevation).

Weir free-flow.

$$Q=\mu_F . L\sqrt{2g}h_1^{3/2}$$

Weir submerged.

$$Q=k_F\mu_F . L\sqrt{2g}h_1^{3/2}$$

with k_F=coefficient of reduction for submerged flow.

The flow reduction coefficient is a function of h2/h1 and of the value α of this ratio at the instant of the free-flow/submerged transition. The submerged conditions are obtained when $\frac{h_2}{h_1} > \alpha$. The law of variation of the kF coefficient has been derived from experimental results.

$$\text{Let } x=\sqrt{1-\frac{h_2}{h_1}}$$

$$\text{If } x>0.2 : k_F=1-(1-\frac{x}{\sqrt{1-\alpha}})^\beta$$

$$\text{If } x\leq 0.2 : k_F=5x(1-(1-\frac{0.2}{\sqrt{1-\alpha}})^\beta)$$

$$\text{With } \beta=-2\alpha+2.6$$

One calculates an equivalent coefficient for free-flow conditions, as before.

Undershot gate.Free-flow

$$Q=L\sqrt{2g}(\mu . h_1^{3/2}-\mu_1(h_1-w)^{3/2})$$

It has been establish experimentally that the undershot gate discharge coefficient increases with h1/W. A law of variation of μ of the following form is adopted :

$$\mu=\mu_0-\frac{0.08}{\frac{h_1}{W}} \quad \textit{with} \quad \mu_0=0.4$$

Hence,

$$\mu_1=\mu_0-\frac{0.08}{\frac{h_1}{W}-1}$$

In order to ensure the continuity with the open-channel free flow conditions for $h1/W=1$, we must have : $\mu_F=\mu_0-0.08$

Hence, $\mu_F=0.32$ *for* $\mu_0=0.4$

Undershot gate-submerged.

Partially submerged.

$$Q=L\sqrt{2g}\,[\,k_F\mu h_1^{3/2}-\mu_1(h_1-w)^{3/2}]$$

kF being the same as for open channel flow.

The following free-flow/submerged transition law has been derived on the basis of experimental results :

$$\alpha=1-0.14\,\frac{h_2}{W}$$
$$0.4\leq\alpha\leq 0.75$$

In order to ensure continuity with the open channel flow conditions, the free-flow/submerged transition under open channel conditions has to be realised for $\alpha=0.75$ instead of 2/3 in the weir/orifice formulation.

Totally submerged.

$$Q=L\sqrt{2g}(k_F\mu h_1^{3/2}-k_{F_1}\mu_1(h_1-w)^{3/2})$$

The k_{F1} equation is the same as the one for k_F where h2 is replaced by h2-W (and h1 by h1-W) for the calculation of the x coefficient (and therefore for the calculation of k_{F1}).

The transition to totally submerged flow occurs for :

$$h_2 > \alpha_1 . h_1 + (1-\alpha_1) . W$$

with :

$$\alpha_1 = 1 - 0.14\,\frac{h_2 - W}{W}$$
$$(\alpha_1 = \alpha(h_2 - W))$$

ANNEX 3 : Results of the calibration for 25/08/93.

Offtakes Name	Discharge		Percentage of accuracy
	SIC	FIELD	
DAULAT 1	1.60	1.59	0.6
DAULAT 2	1.64	1.63	0.6
MOHAR	0.87	0.84	3.4
3-L	0.41	0.39	4.9
PHOGAN	1.11	1.08	2.7
KHEMGAR	1.32	1.36	3.0
4-L	0	0	**
JAGIR	1.21	1.10	9.1
SHAHAR FARID	4.11	4.12	0.3
MASOOD	0	0	**
SODA	1.73	1.81	4.6
5-L	0.33	0.33	***
FORWAH 1	2.63	2.44	7.2
FORDWAH 2	2.47	2.22	10.1
MEHMUD	0.76	0.76	***
AZIM	5.08	5.29	4.1
TOTAL	25.27	24.96	1.2

** : Offtake closed on the 25/08/93.
*** : Offtake in imposed discharge mode.

Cross Regulator	Upstream Water Level	
	SIC	FIELD
C.R 199	157.83	157.91
C.R 245	154.52	154.50
C.R 281	152.28	152.29
C.R 316	150.33	150.37
C.R 353	147.73	147.73
C.R 371	145.83	145.75

ANNEX 4 : **Results of the calibration for 26/06/94.**

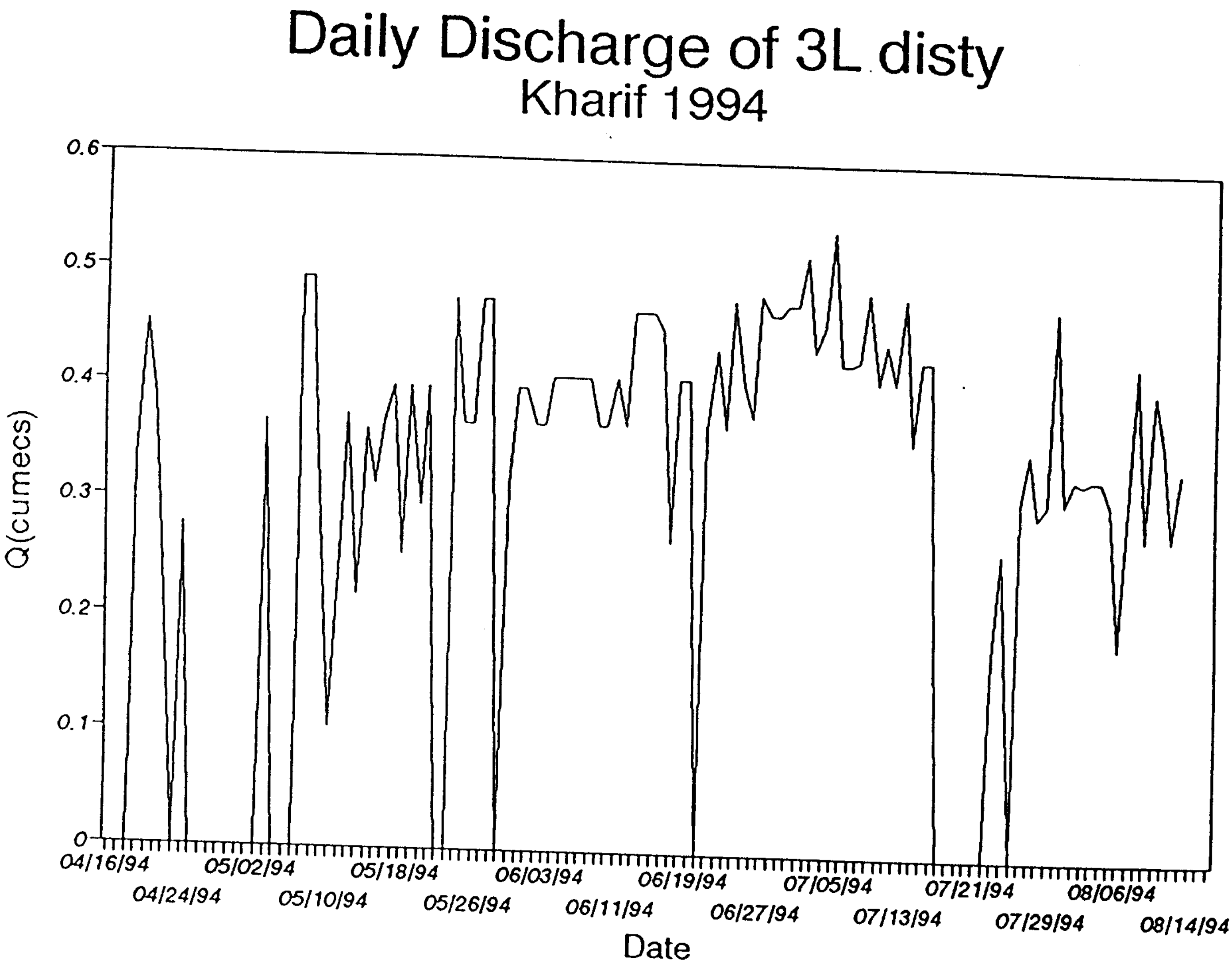
Offtakes Name	Discharge		Percentage of error
	SIC	FIELD	
DAULAT 1	2.42	2.65	9.5
DAULAT 2	2.46	2.71	10.1
MOHAR	0.95	0.89	6.3
3-L	0.51	0.37	27.4
PHOGAN	1.07	0.96	10.3
KHEMGAR	0.98	0.70	28.6
4-L	0.60	0.42	30.0
JAGIR	1.04	0.81	22.1
SHAHAR FARID	4.37	4.25	2.8
MASOOD			*
SODA	1.50	1.68	12.0
5-L	0.33	0.25	24.2
FORWAH 1	3.08	2.58	16.2
FORDWAH 2	3.11	2.58	17.0
MEHMUD	0.76	0.68	10.5
AZIM	1.76	1.84	4.5
TOTAL	25.71	24.68	4.0

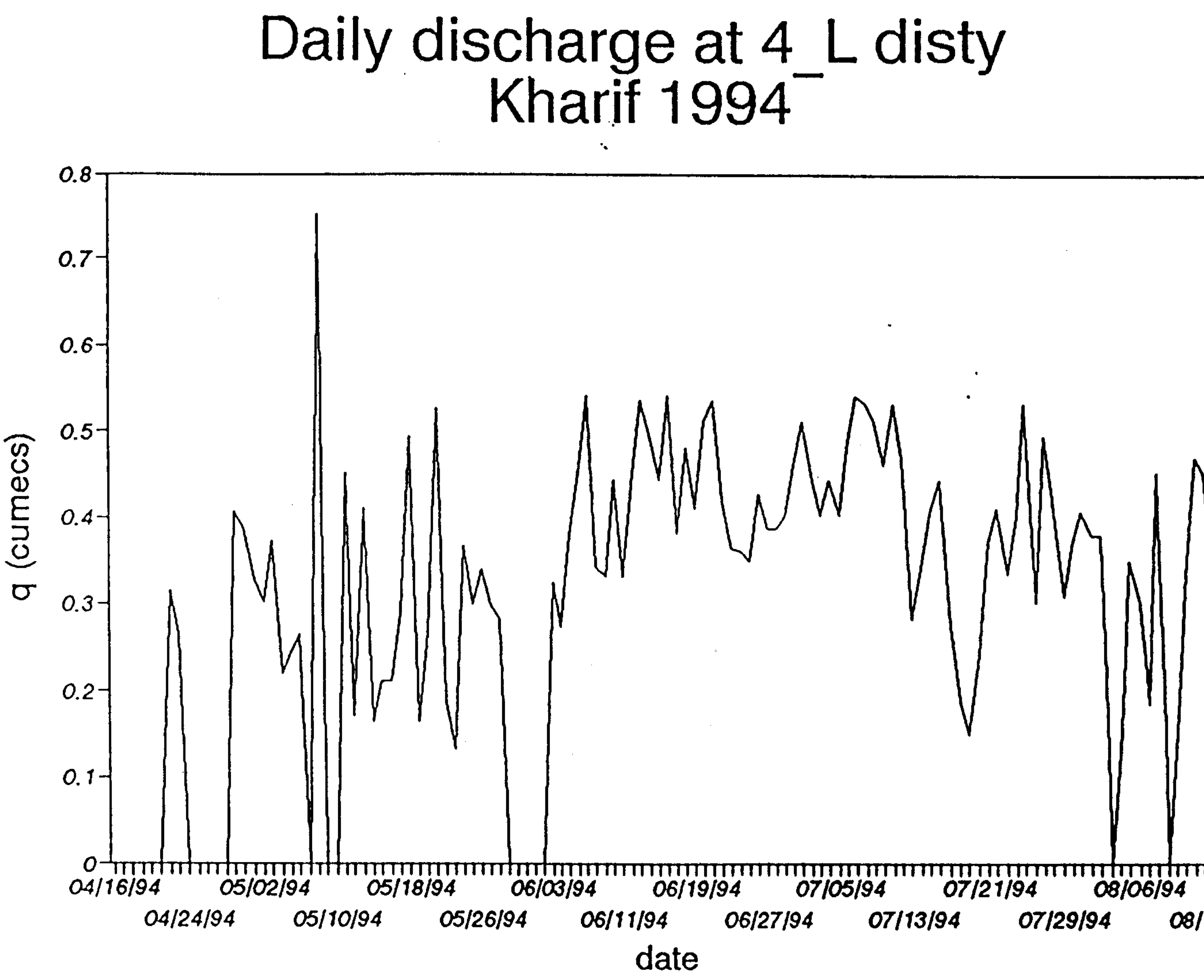
* : problems in loop calculation

Cross Regulator	Upstream Water Level	
	SIC	FIELD
C.R 199	157.91	157.90
C.R 245	154.63	154.55
C.R 281	152.25	152.17
C.R 316	150.36	150.25
C.R 353		**
C.R 371	145.76	145.79

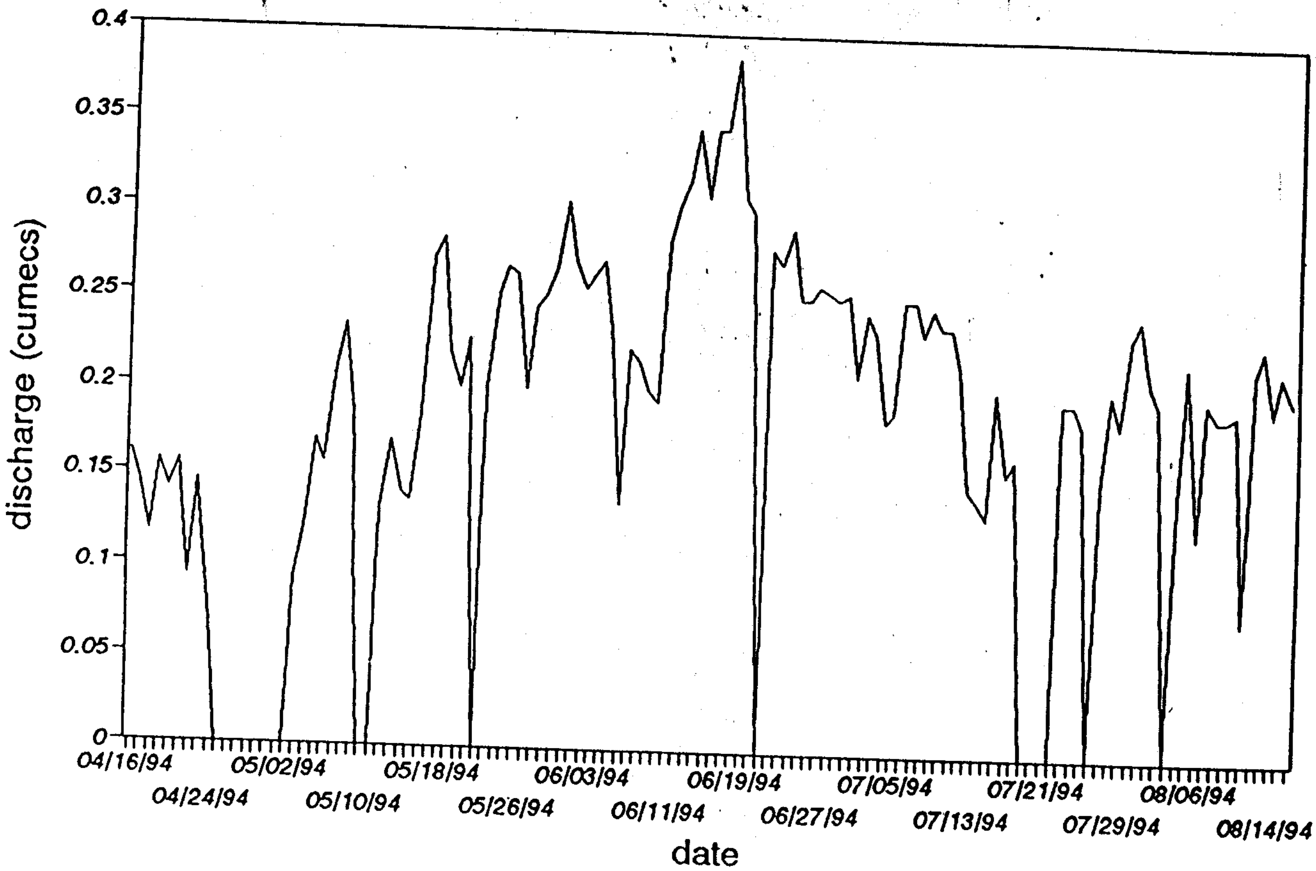
** : data non available.

ANNEX 5 : DAILY MEASUREMENTS KHARIF 1994

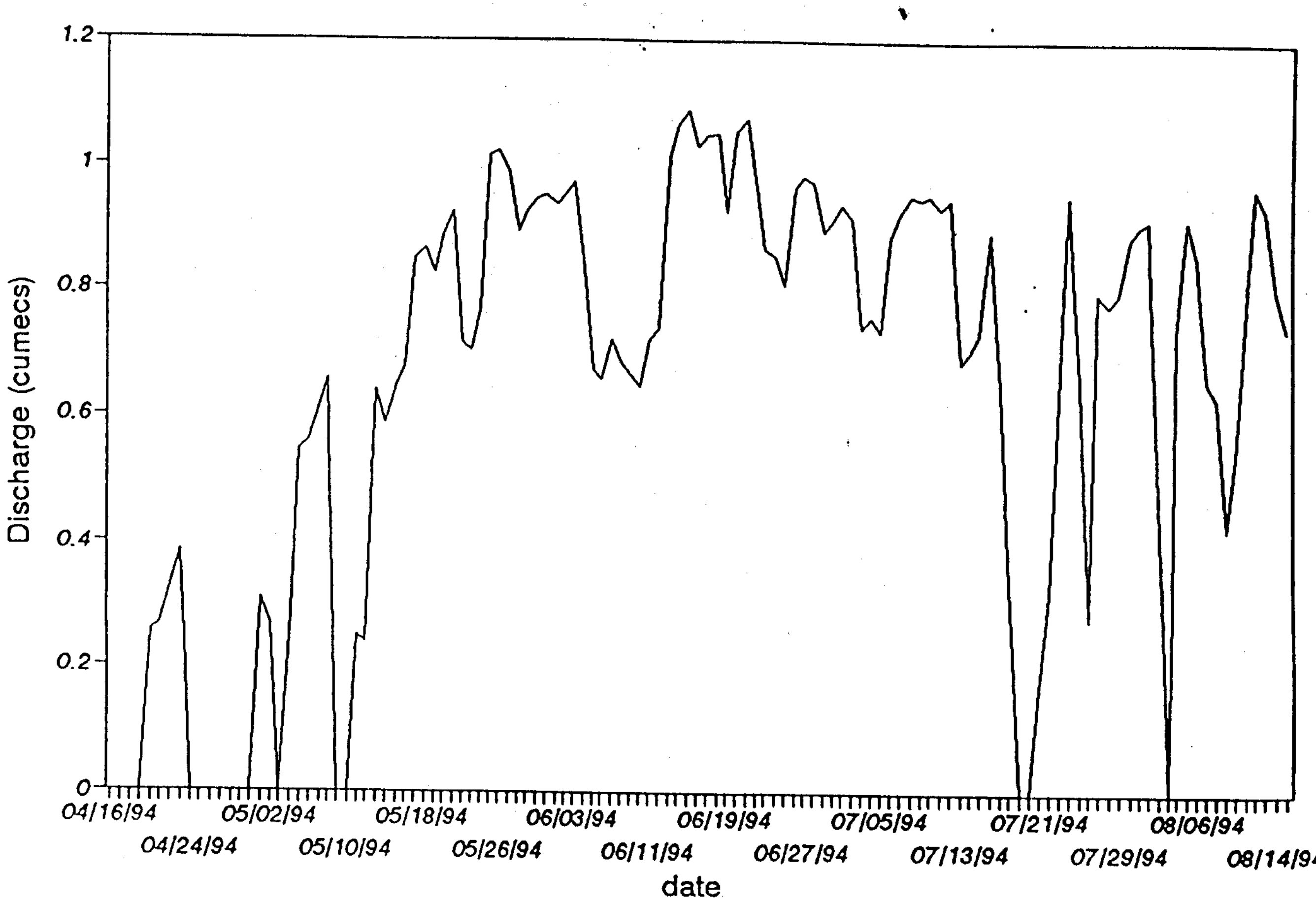


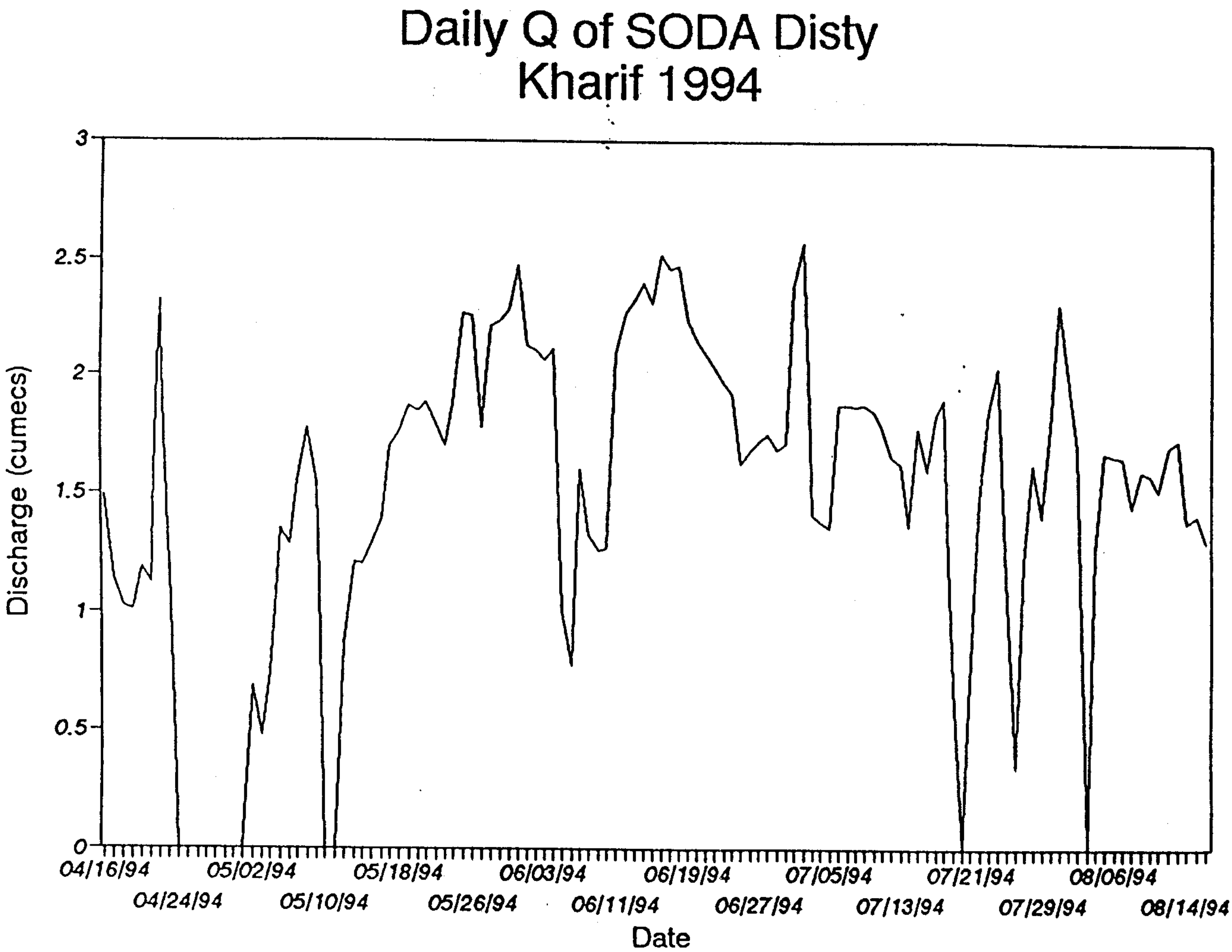

Daily discharge at 4_L disty
Kharif 1994
q (cumecs)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
04/16/94
04/24/94
05/02/94
05/10/94
05/18/94
05/26/94
06/03/94
06/11/94
06/19/94
06/27/94
07/05/94
07/13/94
07/21/94
07/29/94
08/06/94
date

Daily Discharge at head of 5-L Disty Kharif 1994



Daily Discharge of Phogan disty
Kharif 1994




Daily Q of SODA Disty
Kharif 1994
3
2.5
2
1.5
1
0.5
0
Discharge (cumecs)
04/16/94
04/24/94
05/02/94
05/10/94
05/18/94
05/26/94
06/03/94
06/11/94
06/19/94
06/27/94
07/05/94
07/13/94
07/21/94
07/29/94
08/06/94
08/14/94
Date