OFFTAKES SENSITIVITY IN IRRIGATION CANAL OPERATION

by

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Abstract

This article, is an attempt to develop an analytical framework to address sensitivity of irrigation offtakes. The perturbation of water depth and the deviation of the gate setting, are both considered for analysis. Sensitivity of delivery, takes into account the impacts of the perturbations, on the delivery to the command area of the offtake. Sensitivity of conveyance, assesses the effects on the conveyance discharge of the parent canal. Analytical formulations of six sensitivity indicators, are provided. The concept of head losses equivalent, is introduced to explicitly take into account, the hydraulic behaviour in the dependent canal downstream the offtakes. Hydraulic perturbations are considered either as upstream deviation in the parent canal or downstream perturbation in the dependent canal. It is assumed here that the identification of sensitive locations or parts of the system would help the canal manager to formulate a more simplified monitoring system.

1. INTRODUCTION

Sub-optimal performance of many irrigation systems, could be attributed to inappropriate canal operation strategies. One possible solution to this, could be the development of canal operation strategy on the basis of the sensitiveness of canal structures (gated offtakes & cross-regulators). However, there is a lack of knowledge on methodologies to diagnose irrigation systems and to identify sensitive locations/structures. The objective of this study, is to fill this gap and to enable canal managers to incorporate the sensitiveness of structure into their canal operation procedure.

'Sensitivity', is defined as the ability of responding to external stimuli or impressions (Collins). From a conceptual point of view, sensitivity expresses the flexibility between output and input variations. Applied to irrigation offtakes, it characterizes the way delivery machines respond when they are operated or stimulated by an external cause. Offtakes sensitivity discussed here, focuses on the instantaneous effect of perturbations or stimuli on discharge. Hence, unsteady flow is not considered here.

Sensitivity analysis for irrigation canals, aims to answer the following questions:

- What is the propensity of the system to be affected by perturbations?
- How to develop more simplified operational procedures?
- Where, should managers concentrate efforts, in ensuring that no unpredictable deviation, affects the water balance?

The ability to identify the locations of the sensitive points or sensitive parts of the system, is of specific importance for the managers. For these points, precise operation and regular checking, are recommended to minimize possible deviations. Two major set of rules can be drawn from sensitivity analysis. The first one, is a set of **modulated rules and guidelines for canal operation** to achieve a uniform performance level whatever the distribution of the sensitivity is. The second one, is a set of practical rules for the implementation of **a selective information system**. The first one, may imply the need to give more attention to reaches where sensitivity is high, in order to maintain deliveries within an acceptable range of variation. The second set., may help to monitor the irrigation system with only a limited number of points. These points should be selected on the basis of their sensitivity.

In a broad sense, irrigation systems can be considered as a factory, composed of numerous machines. Irrigation machines consist of offtakes, regulators, canal reaches and storage facilities. A machine is meant to transform an input variable into an output variable.

We address, here, the offtake sensitivity of delivery machines, in two senses: sensitivity to hydraulic perturbation and sensitivity to setting perturbation. The impacts of perturbations, are analyzed with regard to Delivery, for the command area of the offtake, and Conveyance for the parent canal.

2. GENERALITIES ON SENSITIVITY OF IRRIGATION CANAL

2.1 Defining INPUTS

Delivery machines INPUTS, are either hydraulic variables or setting variables. Water depth in the parent canal, is, commonly, the primary input for the offtake discharge. Irrigation systems are both downstream and upstream influenced. Thus a physical variable, can be alternately taken as an input or an output, depending on the effect and the direction we are looking at.

Pertinent variables for offtake sensitivity analysis, are: offtaking discharge (q) and on-going discharge in the parent canal (Q), discharge deviations through the offtake (dq) and in the parent canal (dQ), water level change (dH_1) in the parent canal upstream the offtake, water level change (dH_2) in the dependent canal, the flow section area through the delivery structure (A), the setting value (w) of the structure. Relative deviation or absolute deviation of both input and output, are considered here.

2.2 Conveyance and delivery oriented sensitivities

A increase in the offtake discharge, has two consequences: more water is made available for the users of the command area (**delivery**) and less water is left in the parent canal (**conveyance**). These two effects are linked. High sensitive offtake, diverting a small flow, is unlikely to make an impact on the parent discharge. Inversely, a medium sensitive offtake, diverting a big flow, may have more impact on the on-going discharge.

2.3 Types of input perturbations

The 'offtake system' is the set composed of the upstream parent canal section, the offtake structure and the dependent canal section downstream the offtake. Three situations are faced:

- **Downward Effect:** Upstream water depth perturbation in the parent canal, making an impact on the offtake discharge;
- **Upward Effect**: Downstream flow perturbation in the dependent canal, making an impact on the diverted discharge from the parent canal;
- **Setting Effect:** Perturbation of the setting of the offtake, making an impact on the discharge in the dependent canal and in the parent canal.

3. BACKGROUND BEHIND OFFTAKE SENSITIVITY

Work on sensitivity so far published, focuses on the downward effect only. Sensitivity and sensitiveness for irrigation outlets (offtake), were thoroughly analyzed by Mahbub and Gulati (1951) and later used in India.

Sensitivity of an offtake is defined, as the fractional change of discharge (q) caused by the rate of change in water level (dH_1) in the parent canal. This expression, refers to normal depth (D) (Mahbub and Gulati, 1951) or to actual depth H_1, (Shanan et al, 1986) as follows:

$$S = \frac{dq}{q} \Big/ \frac{dH_1}{D} \qquad S = \frac{dq}{q} \Big/ \frac{dH_1}{H_1} \qquad (1)$$

One advantage in assessing relative input fluctuations as in Eq.(1), is when comparing sensitivity within a whole irrigation system, with a large variability in canal size. However, in practice, canal managers may prefer to use the absolute water level deviation more than the relative value. **Sensitiveness** is defined as the fractional increase or decrease of offtake discharge per 0.1 foot rise (or fall) in the parent canal (Mahbub and Gulati, 1951):

$$S = \frac{dq/q}{dH_{US}} \qquad \text{(with dHus = 0.1foot)} \qquad (2)$$

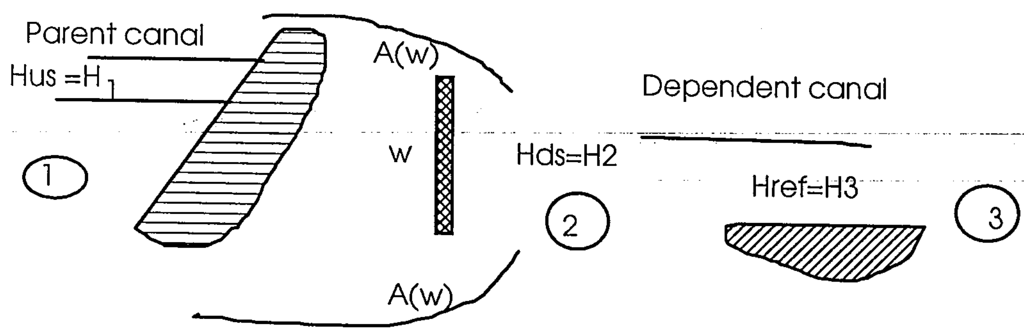
One major advantage in using the sensitiveness indicator, Eq.(2), instead of sensitivity, is its effectiveness in comparing offtakes, belonging to a homogenous canal. For example, we may look at the variation of offtake sensitivity along the main canal for a given range of variation in water level, say plus or minus 0.1 foot. In this study, the term sensitivity is used when relative variation of input is considered, and the term sensitiveness, when absolute input variable is considered.

4. DOWNWARD OFFTAKE SENSITIVITY TO HYDRAULIC PERTURBATION

Hydraulic perturbations, here, are expressed as water depth changes in the parent canal. Discharge through the offtake, is the combination of two hydraulic stages, as shown in Fig.1:

- Stage 1 = Through the offtake: from the parent canal (1) to downstream the offtake (2).
- Stage 2 = Entrance conditions in the dependent canal: from downstream the offtake (2) to one point downstream (3) in the dependent canal.

Figure 1. Schematic representation of an offtake



Generic equations of discharge, are related to the physical features of these two stages, and can be written as follows:

$$q_{1-2} = a\,A(w)\left(H_1 - H_2\right)^{\alpha} \qquad \text{stage 1} \qquad (3)$$

$$q_{2-3} = b\left(H_2 - H_3\right)^{\beta} \qquad \text{stage 2} \qquad (4)$$

$A(w)$ = Flow section through the offtake expressed as a function of the setting w;
a, b = Discharge coefficients;
H_1 = H_{US}, water level in the parent canal upstream the offtake;
H_2 = H_{DS}, water level in the dependent canal downstream the offtake;
H_3 = H_{Ref} , a fixed downstream level taken in the dependent canal.

H_3 is taken as a constant reference level (canal bed or weir-crest level if any) within the dependent canal to account for the downstream law. It is assumed that $dH_3 = 0$.

Under free flow conditions at the offtake, Eq.(4) is irrelevant and the problem reduces to one equation, i.e., Eq. (3). Then, H_2 is taken either as the crest level of the weir in case of overshot or as the orifice axis in case of undershot.

Expressions of sensitivity indicators can be derived from Eqs(3) and (4), by introducing the concept of head losses equivalent (H_E).

Head losses equivalent, H_E, of a particular offtake, are equal to the head losses of the same kind of offtake (undershot or overshot), having the same sensitiveness value, but with free-flow downstream conditions. Expression of H_E writes:

$$H_E = \left(H_1 - H_2\right)\left[1 + \frac{\alpha}{\beta}\frac{\left(H_2 - H_3\right)}{\left(H_1 - H_2\right)}\right] \qquad (5)$$

The second term of the right member can be called as coefficient of head losses equivalent (C_{HE}), although it is depth dependent. This coefficient, greater or equal to 1, writes:

$$C_{HE} = \left[1 + \frac{\alpha}{\beta}\frac{\left(H_2 - H_3\right)}{\left(H_1 - H_2\right)}\right] \qquad C_{HE} \geq 1 \qquad (6)$$

An important point to keep in mind, is that Head losses equivalent are always equal or greater than the available head.

4.1 Offtake sensitivity of delivery

The offtake sensitivity indicator of delivery, S_1, writes:

$$\boxed{S_1 = \frac{\alpha}{H_E}} \qquad (7)$$

4.2 Offtake sensitivity of conveyance

Offtake sensitivity of Conveyance, is defined as the ratio of the relative variation of on-going discharge in the parent canal to the change of water height in the parent canal, as a result of a deviation (dq) in the offtake discharge.

$$S_2 = \frac{dQ/Q}{dH_1} \qquad (8)$$

Assuming dQ = dq, we establish the sensitiveness of conveyance as:

$$\boxed{S_2 = \frac{q}{Q}\frac{\alpha}{H_E}} \qquad (9)$$

5. OFFTAKE SENSITIVITY TO SETTING

Deviation in the setting of an offtake, can be expressed as an absolute or relative variation of the flow area (A) through the structure or of the setting of the structure (w) (crest level or gate opening variables). The relationship between flow area variable (A) and setting (w), can be derived for any geometric feature of the offtake (Skogerboe, 1996).

5.1 Sensitivity to flow area

Sensitivity related to the effective flow area, is defined as the fraction of relative change in the offtake discharge and relative change in the flow area, as follows:

$$S_3 = \frac{dq/q}{dA/A} \qquad (10)$$

and equal to the inverse of the coefficient of head losses equivalent:

$$\boxed{S_3 = \frac{1}{C_{HE}}} \qquad \text{Sensitivity to flow area (A)} \qquad (11)$$

5.2 Sensitivity to setting

The deviation between targeted and actual offtake discharge, can be the result of change in the setting or lack of precision in initial implementation. The **sensitivity to setting,** writes:

$$S_4 = \frac{dq/q}{dw} \qquad (12)$$

In practice, this indicator is more practical than the sensitivity indicator, as managers can easily specified the range in the setting, say 1 cm at spindle height. Expression of S_4 is given in Appendix.

6. UPWARD OFFTAKE SENSITIVITY

Perturbation in the dependent canal, can affect the discharge in the parent canal, if the flow downstream the offtake, is submerged. This situation is also considered. See Appendix.

7. ASSESSMENT OF DISCHARGE EQUATIONS IN PARAMETERS

Theoretically, parameters in discharge Eqs. (3) and (4), can be easily derived from the physical features of the offtake (undershot/overshot), using basic hydraulic knowledge. In practice, the flow regimes through the offtake, can sometimes be fluctuating and not easy to specify (sub/supercritical).

a. Hydraulic formula for the exponent 'α' in equation (3):

The exponent 'α' can usually be identified from the given hydraulic pattern through the offtake. Usually, it can be set to 1/2 for undershot conditions and 3/2 for overshot conditions.

b. Hydraulic formula for the exponent 'β' in equation (4):

Assessment of the hydraulic behaviour downstream the offtake, can be a little more difficult on site. It is due to deterioration of the equipment or even to unclear flowing conditions (sub/super critical). In clearly identifiable cases, the parameter β will be set to 1/2 for undershot conditions (C.H.O. offtake type for example), to 3/2 for overshot conditions (weir), and to 5/3 if normal depth conditions prevail. If downstream conditions are under the influence of a backwater curve, then it seems better to measure β on the site.

c. On site assessment of the exponent 'β' in equation (4):

Field measurements, can circumvent the difficulty in identifying the downstream flow regime. By a slightly modifying the setting structure (dw), we generate a variation of discharge, dq. Assuming H_1 stays constant (FSD), the measurements of the variation of H_2, leads to identify the value of the exponent β.

8. ILLUSTRATIONS FOR DOWNWARD SENSITIVITY

To illustrate how the previous analytical approach, can be useful in bringing new insights into canal operation, we applied it to two irrigation canals in Sri Lanka. Canal A, is the upper part of the Left Bank Main Canal of Mahaweli System-B. It is a lined canal 44 km long, designed for a full supply of 65 m3/s, equipped with 12 cross-control machines and 24 offtakes. Canal A distributes 22 m3/s to branched and tertiary canals. Canal B, is the Right Bank Main Canal of Kirindi Oya Irrigation and Settlement Project. It is an earthen canal 27 km long. Its full discharge is 11 m3/s. It has 19 cross-regulators and 43 offtakes.

Variations of offtake sensitiveness of delivery and of conveyance and sensitiveness to setting, are displayed in Figures 2 and 3. Table 1 below, gives some statistical information on the two sets of offtakes.

Canal A appears to be much more sensitive than Canal B. The sensitiveness of delivery, is almost three times greater in A than in B (1.31/0.47). This is also valid for sensitivity of conveyance (0.61/0.18). The only aspect in which Canal B appears to be a little more sensitive, is the sensitivity to flow area (0.67/0.94).

Both canals present a high variability for conveyance indicator. This is somewhat expected as it integrates the variability of delivered discharges. Variability of delivery and flow area indicators, are low for Canal B, whereas Canal A appears to be highly variable in that respect.

Table1. **Statistical information on sensitivity indicators for canal A and B.**

Indicator	Variable	Canal A	Canal B
Sensitiveness of Delivery S_1	Mean	1.31	0.47
	Coefficient of variation	0.6	0.22
Sensitiveness of Conveyance S_2	Mean	0.61	0.18
	Coefficient of variation	0.85	1.20
Sensitivity to Flow Area S_3	Mean	0.67	0.94
	Coefficient of variation	0.27	0.05

Most offtakes of Canal B have low sensitivities to perturbations. Only three offtakes might be considered a little different (D4T1, BC2 & D1T6) in that they have indicators above 0.6.

Two offtakes of Canal A, have highly sensitivity to perturbations as S1 is greater than 3.0 (D3/104 and D5/508). 12 offtakes are sensitive as they have values of S1 or S2, between 1.0 and 2.0.

Offtake LBL1 of Canal A, illustrates the advantage of looking at several indicators. Its sensitiveness of delivery, is moderately high (1.05), but the indicator for conveyance reaches a peak of (2.1). This is related to the fact that, LBL1 discharge represents a high proportion (0.23) of the ongoing flow in the parent canal. Practically, it means that a deviation of 0.1 meter in water level at that location, corresponds to a deviation of 20 % in the on-going discharge. Hence, this delivery point, has to be monitored carefully. A similar statement applies to LBL3 as well.

Operation of Canal A, requires much more attention than that of Canal B. For a given level of control on deliveries in both systems, managers of Canal A must be two to three times more effective in controlling water depth. Allowed fluctuations of water depth (ΔH) are 2 to 3 times less for Canal A than for B.

Sensitivity analysis, can help to allocate efforts in operating irrigation system, based on the spatial distribution of sensitiveness. For example in Canal A, it seems worthy to consider three domains. The first one covers offtake down to D3/507, and is fairly sensitive. The second one, from LBL1 to D7/104, is highly sensitive. The last one is sensitive. Adjusting the allocation of efforts for operation on the basis of these three levels of sensitiveness is seen as means to improve the cost effectiveness of operation.

9. SUMMARY AND PERSPECTIVES

This study, is designed to provide managers, with a set of analytical tools to assess physical properties of delivery machines along gravity irrigation systems. The attempt is part of a larger research program on the behaviour assessment of irrigation canals, undertaken by IIMI. Subsequent works, will focus on control machines, (regulators), on reaches (offtakes+regulator) and finally on sub-systems or on irrigation system as a whole.

We mainly built on the previous works made for delivery analysis, and enlarge on the approach to conveyance and setting perturbations. The analytical development, identifies the concept of head losses equivalent as the key point in computing the sensitivity. Head losses equivalent, accounts for the two stages of flow through the offtake when downstream flow is submerged. Practical considerations for the estimation or measurement of the parameters entering different formulae, are given in the paper.

One of the uses of sensitivity analysis, is to compare different systems, or parts of the same system. Cases taken from Sri Lanka, illustrate these aspects. Sensitivity analysis can help to better mobilize resources for canal operation. Putting more efforts where the system is more sensitive, seems more effective than spreading them uniformly. This last aspect will be further investigate.

Figure 2. Offtake sensitiveness indicators for Mahaweli System B (Sri Lanka)

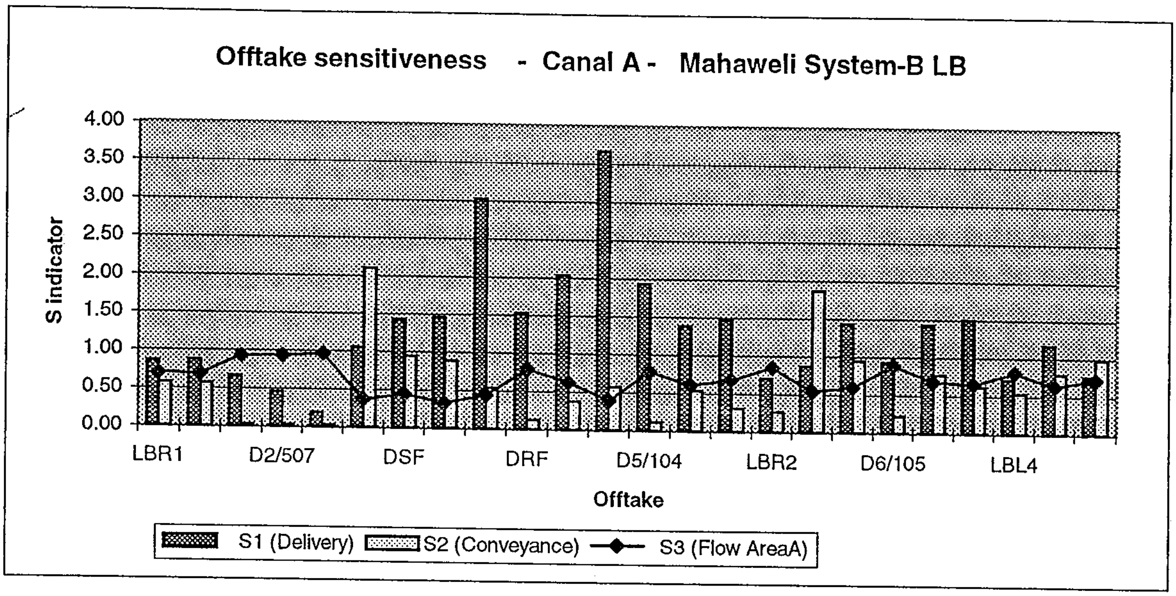
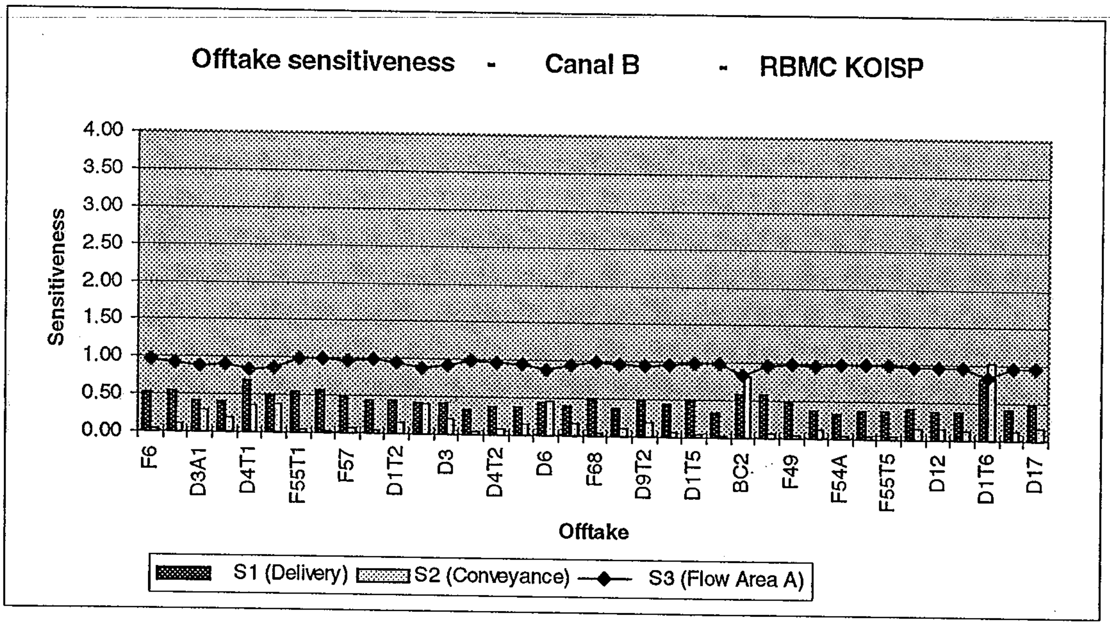


Figure 3. Offtake sensitiveness indicators for KOISP RBMC (Sri Lanka)



10. ACKNOWLEDGMENT

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Appendix

Offtake sensitivity indicators and related expressions (after Renault and Hemakumara, submitted).

Notation	Function	Definition	Equation
S_1	Sensitiveness of Delivery	$S_1 = \frac{dq/q}{dH_1}$	$S_1 = \frac{\alpha}{H_E}$
S_2	Sensitiveness of Conveyance	$S_2 = \frac{dq/Q}{dH_1}$	$S_2 = \frac{q}{Q}\frac{\alpha}{H_E}$
S_3	Sensitivity to Flow Area	$S_3 = \frac{dq/q}{dA/A}$	$S_3 = \frac{1}{C_{HE}}$
S_4	Sensitiveness to Setting	$S_4 = \frac{dq/q}{dw}$	$S_4 = \frac{1}{C_{HE}}\frac{dA/A}{dw}$ $S_4 = \frac{1}{C_{HE}}\frac{L(w)}{A}$
S_5	Upward Sensitiveness for Conveyance	$S_5 = \frac{dQ/Q}{dH_2}$	$S_5 = \frac{q}{Q}\frac{\alpha}{H_1 - H_2}$
S_6	Sensitivity of Delivery	$S_6 = \frac{dq/q}{dH_1/H_1}$	$S_6 = \frac{\alpha H_1}{H_E}$
H_E	Head Losses Equivalent		$H_E = (H_1 - H_2)\left[1 + \frac{\alpha}{\beta}\frac{(H_2 - H_3)}{(H_1 - H_2)}\right]$
CH_E	Coefficient of Head Losses Equivalent		$C_{HE} = \left[1 + \frac{\alpha}{\beta}\frac{(H_2 - H_3)}{(H_1 - H_2)}\right]$

Notation The following symbols are used in this paper:

a	=	Discharge coefficient
A	=	Flow area through the offtake
$A(w)$	=	Flow area as a function of the setting (w)
b	=	Discharge coefficient
C_{HE}	=	Coefficient of head losses equivalent
dA	=	Variation of the flow area through the offtake
dH	=	Variation of water height
dH_1	=	Variation of water height in the parent canal
dH_2	=	Variation of water height downstream the offtake
dH_{US}	=	Variation of water height upstream the offtake
dq	=	Variation of discharge through an offtake
dQ	=	Variation of discharge in the parent canal
dw	=	Variation of offtake setting
D	=	Normal depth
F	=	Flexibility
H	=	Water height
H_1	=	Water elevation in the parent canal
H_2	=	Water elevation downstream the offtake
H_3	=	Elevation of the reference point downstream the offtake
H_E	=	Head losses equivalent
H_{US}	=	Water elevation upstream the offtake
$L(w)$	=	Length of the wetted perimeter of the flow in contact with the mobile part of the structure
q	=	Discharge through the offtake
q_{1-2}	=	Discharge value between the present canal (1) and downstream the offtake (2)
q_{2-3}	=	Discharge value between downstream the offtake (2) and the dependent canal (3)
Q	=	Discharge in the parent canal
S	=	Sensitivity or sensitiveness indicator
S_1 to S_6	=	Specific sensitivity indicators
u	=	Exponent
w	=	Setting variable of the offtake (opening or height)
α	=	Exponent in q_{1-2}
β	=	Exponent in q_{2-3}