Flow-measuring structures

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The use of flow-measuring structures is one of the various methods for the continuous measurement of discharges in open channels. In this paper, the distinct functions of water-control structures are described. The flow-measuring structures are classified according to international rules. The fields of application are dealt with and the definitions of weir flow are given. Much attention is paid to the aspects of how to select the most suitable flow-measuring structure. The accuracy in the evaluation of the discharge has been related to the different error sources. A review of international standards on flow-measuring structures concludes the paper.

Keywords: flow gauging structures; weirs; flumes; gates

Introduction

Flow-measuring structures are defined as hydraulic structures installed in open channels or in closed conduits with a free water level where in most cases the discharge can be derived from the measured upstream water level. Figure 1 shows a flow-measuring structure. In fact, such a structure is an artificial reduction of the cross-sectional area in the channel or pipe, which causes an increase in the upstream water level, thus creating a drop in water level over the structure. Provided the reduction is strong enough, we have a unique relation between the discharge and the upstream water level. By measuring this water level continuously, we can also obtain a continuous record of discharges as a function of time.

The relation between discharge and upstream water level depends primarily on the shape and dimensions of the structure, and only slightly on the geometry of the upstream channel or pipe. The relation can be set up from a theoretical approach, which is to be supported by a calibration, mostly carried out by a hydraulic model study.

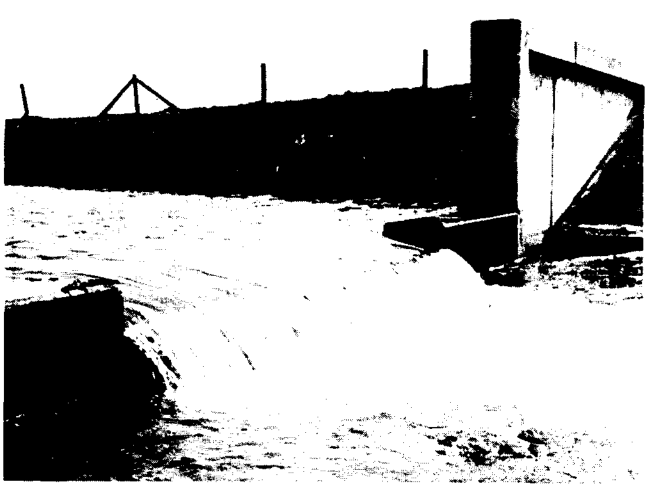

Figure 1 A flow-measuring structure

During the past centuries, numerous types of flow-measuring structures have been designed whose characteristics meet modern demands of water-resources development, particularly in irrigation schemes and hydrological studies.

The most effective way to obtain a good understanding of the use of flow-measuring structures is to consult a handbook on these structures. Such a handbook[1,2] not only gives a rather complete review of existing structures, but it also provides the necessary basic principles and practical outlines of how to select the most appropriate structure for specific demands and how to plan the hydraulic design of a flow-measuring structure.

This paper deals with flow-measuring structures in open channels like weirs, flumes and gates. In addition, some of these structures are used in closed conduits with a free water level, for instance in sewers. Other methods are outlined elsewhere in this issue and in various handbooks[3–6], and selection of appropriate methods is decribed in ISO standards[7].

Function of structures

In all water-conservation systems, natural flow through canals can be controlled by human intervention. The responsible authority and, in some cases, the individual farmer have tools to control the water level and the amount of flow, to answer supply and demand of water.

The hydraulic structures necessary to control level and flow are weirs, gates and flumes. The following functions can be identified:

(a) *Upstream water-level control and discharge of excess flow.* Examples are check structures and

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cross-regulators in irrigation canals, and drop structures in steep natural streams and canals.

(b) *Flow measurement.* When the application is limited to flow measurement only, the structure does not have adjustable parts: the crest or sill has a fixed elevation. In general, flow-measurement structures are used in:

- ☐ natural streams,
- ☐ irrigation and drainage canals,
- ☐ water-purification plants and industries,
- ☐ hydraulic laboratories.

As long as the downstream water level does not affect the flow, the discharge depends exclusively on the upstream water level (Figure 2). Modern flow-measurement stations are equipped with microprocessors, which convert the measured heads directly into digital records of discharges. If desired, discharges can be totalized to flow volumes over a certain time interval, for instance per hour or per day.

(c) *Flow regulation and measurement.* These structures are basically designed to regulate and to measure the flow for an almost constant or sometimes a varying upstream water level. Examples of large structures are headworks on rivers and irrigation canals. Farm turnouts can be considered as small hydraulic structures. Figure 3 shows an overflow structure with a movable crest, a so-called Hobrad weir (*ho*rizontal, *br*oadcrested, *ad*justable).

(d) *Flow division and measurement.* In irrigation canals, the main flow has to be distributed sometimes proportionally into two or more branches. An example to illustrate this is the division boxes in irrigation canals. These boxes are not adjustable (open or closed). In other structures, the percentage distribution ratio can be adjusted by movable parts.

(e) *Removal of excess flow.* Part of the incoming flow both in reservoirs and in irrigation canals will not be used. This surplus water has to be drained off. Examples here are overflow structures and radial gates in diversion dams.

A clear insight into the structure's function is essential as it provides many relevant answers to questions that may arise when an appropriate type must be chosen. However, the field conditions as well as other specific demands play an important role in this process, and for this reason

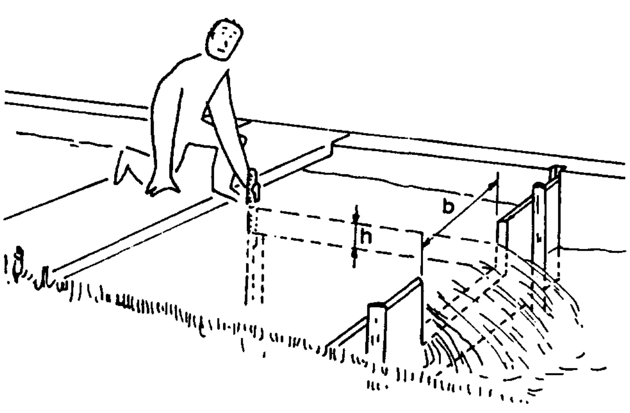

Figure 2 Measurement of the upstream water level

Figure 3 The Hobrad weir

no simple schedule can be made up that relates the required function directly to a particular structure.

A summary of the above-mentioned functions is presented in Table 1.

Classification of flow-measuring structures

Discharge-measuring structures are classified according to the shape of the crest in the flow direction. They can further be subdivided according to the different cross-sections:

Broad-crested weirs

The length of the crest should be sufficient to allow straight and parallel streamlines at least along a short distance above the crest. The crest height with respect to the bottom of the approach channel must comply with a certain minimum value. The best-known structures are the following weirs:

- ☐ the round-nose horizontal broad-crested weir,
- ☐ the rectangular broad-crested weir,
- ☐ the Romijn measuring and regulating weir,
- ☐ the trapezoidal profile weir,
- ☐ the Fayoum standard weir,
- ☐ the V-shaped broad-crested weir.

Sharp-crested weirs

The length of the crest is 1 to 2 mm (Figure 4). For this reason they are also called thin-plate weirs. The nappe is completely free from the weir body after passing the weir, and the streamlines above the crest are strongly curved. In the air-filled area below the underside of the outflowing jet, atmospheric pressure should prevail. Among the most-used thin-plate weirs are:

- ☐ the horizontal sharp-crested weir (Rehbock),
- ☐ the rectangular sharp-crested weir (with side contraction),
- ☐ the V-shaped sharp-crested weir (Thomson),
- ☐ the trapezoidal shaped weir (Cipoletti),

Table 1 Summary of the function of measuring/regulating structures

Function	Structure name	Adjustable parts	Applied in
Upstream water-level control and discharge of excess flow	Check structures	Sometimes	Irrigation canals
	Cross-regulators	Sometimes	
	Drop structures	No	Natural streams
	Stoplogs	Yes	All types of watercourses
	Flap gates	Yes	
Flow measurement	Many weirs and flumes	No	All types of watercourses
Flow regulation and measurement	Headworks	Yes	Irrigation canals
	Offtakes, turnouts	Yes	
Flow division and measurement	Division structures	Yes	Irrigation canals
	Division boxes	Yes	
Removal of excess flow	Spillways	Sometimes	Reservoirs
	Escapes, wasteways	Sometimes	Irrigation canals

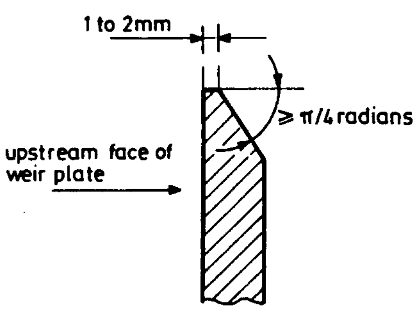

Figure 4 Detail of a sharp crest

- ☐ the circular sharp-crested weir,
- ☐ the proportional weir (Sutro weir).

Short-crested weirs

We call weirs short-crested when their characteristics in some way look like those of broad-crested and sharp-crested weirs. The streamlines above the crest are curved. Well-known examples are:

- ☐ weir sill with rectangular control section,
- ☐ V-notch weir sill,
- ☐ the triangular profile weir (Crump weir),
- ☐ the flat V-weir,
- ☐ Butcher's movable standing-wave weir,
- ☐ WES-standard spillways,
- ☐ cylindrical crested weir,
- ☐ the streamlined triangular profile weirs,
- ☐ flap gates.

End depth methods

Where the bottom of the canal drops suddenly, a free overfall is created. The water level is measured exactly above the drop (end depth or brink depth). The discharge is a function of both the end depth and the shape of the cross-section. There we can identify:

- ☐ rectangular channels with a free overfall,
- ☐ non-rectangular channels with a free overfall.

Flumes

Critical depth flumes and broad-crested weirs have some resemblance to each other. Flumes are less restricted in crest height and the downstream section is gradually divergent to regain energy. Distinction is made between long-throated flumes and short-throated flumes. Long-throated flumes are similar to broad-crested weirs (parallel streamlines). Short-throated flumes behave like short-crested weirs (curved streamlines). The following long-throated flumes are mentioned:

- ☐ rectangular flumes (venturi flumes),
- ☐ trapezoidal flumes,
- ☐ U-shaped flumes.

All other flumes are called short-throated flumes:

- ☐ throatless flume with rounded transition,
- ☐ throatless flume with broken plane transition (cut-throat flumes),
- ☐ Khafagi venturi (Figure 5),

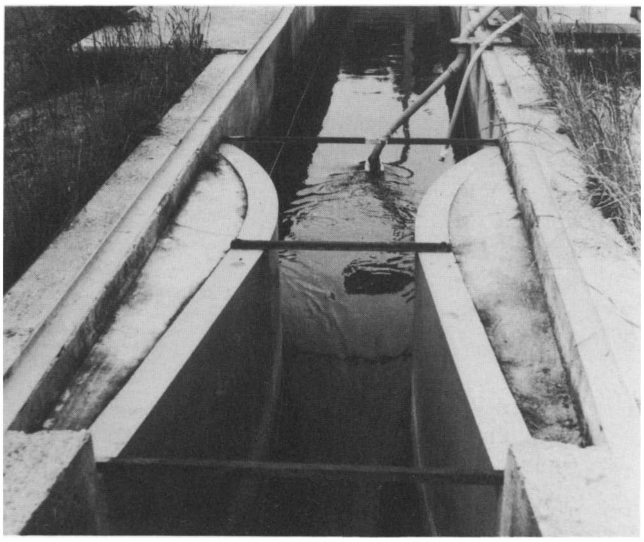

Figure 5 A Khafagi venturi

- □ Parshall flumes (22 different widths),
- □ Saniiri flumes,
- □ H flumes,
- □ San Dimas flume (and modified San Dimas flume),
- □ Palmer Bowlus flumes (for use in conduits).

Orifices and gates

Each opening in a plate or a wall, the top of which is placed at a sufficient distance below the upstream water level, is an orifice. Water flows through the opening, which is called orifice flow, underflow or undershot flow. Flow may be either free or submerged. Distinction is made between sharp-edged orifices in thin plates and a variety of gates:

- □ sharp-edged orifices (rectangular, circular and other shapes),
- □ constant-head orifice,
- □ radial gate (tainter gate),
- □ Crump-de Gruyter adjustable gate,
- □ vertical gates (sluice gate),
- □ Neyrpic modules,
- □ various valves,
- □ culverts (measurement of peak flows).

The majority of the above-mentioned flow-measuring structures are constructed between vertical side walls, thus creating two-dimensional flow. Other structures show three-dimensional flow.

For detailed information on all the different flow-measuring structures, reference is made to the relevant handbooks[1,2] and other literature, as mentioned in the references[8–16].

Fields of application

Flow-measuring structures are applied in several fields:

Irrigation and drainage projects (agriculture)

Flow is regulated, measured and distributed. All types of weirs, flumes and gates are applied in irrigation schemes. Table 2 gives a review of the irrigation structures and their functions. The reader may observe that the majority of the irrigation structures have the combined function of flow regulation and flow measurement.

Sanitary engineering and industry

In most water-purification plants the effluent flow is measured, often in combination with water-quality measurements. In some cases the effluent is discharged and measured in closed conduits. In other situations the purified water leaves the plant through open channels provided with a weir or a flume. Traditionally the selection of flow-measurement structures here is rather limited and not very logical. The following types are applied:

- □ sharp-crested weirs, such as the rectangular, the Cipoletti and the V-notch,
- □ long-throated and short-throated flumes, such as the conventional venturi flume, the Khafagi venturi and the Parshall flume.

Where water flows through circular canals with a free water level (no pressure conduits), several types of flumes may be applied such as Venturi and Palmer Bowlus flumes. The same structures are used to measure waste water discharge in industrial plants.

Hydrological studies

Both in hydrological studies and for water management in urban and rural areas, many types and different sizes of flow-measurement structures are being used. Flow measurement as a component of the water balance in a hydrological cycle may take place in very small creeks and brooks as well as in large rivers. The variety of types depends mainly on the following conditions:

- □ the expected discharge range $\gamma = Q_{max}/Q_{min}$
- □ presence of sediment transport,
- □ available fall,
- □ flow measurement or measurement and regulation (function).

All the different types of weirs, flumes and gates are applied in hydrological networks. Sometimes compound weirs are designed. These structures normally consist

Table 2 Functions of irrigation structures (X = main function, 0 = additional function)

Structures	Function: Level control	Flow regulation	Flow measurement	Flow removal
Headworks	X	X	X	
Cross-regulators and check structures $Q = Q_{FS}$ (FS = fully supply)	X		0	
Cross-regulators and check structures $0 < Q < Q_{FS}$	X	X	X	
Tail and emergency structures	X		0	0
Structures in secondary and tertiary canals	X	X	X	
Small farm intakes	X		X	
Division structures	X	X	X	
Drop structures	X		0	

Figure 6 A Thomson weir

of a number of overflow structures with different crest levels and separated by piers.

Laboratory measurements

The main features of laboratory weirs are:

- □ the required high accuracy $X_Q \leq 1\%$,
- □ sufficient available fall to operate under free-flow conditions,
- □ relatively low discharges $Q_{max} < 100$ to 200 l s^{-1}.

The most appropriate structures are found in the family of sharp-crested weirs:

- □ horizontal weirs (Rehbock) and rectangular weirs with side contraction,
- □ V-shaped weirs, for $\alpha = 90°$ also called Thomson weir (Figure 6),
- □ circular shaped weirs.

The reason for the high accuracy of sharp-crested weirs is the well-defined flow pattern and the thorough calibration in several hydraulic laboratories.

Definition of weir flow

Flow-measuring structures, fixed weirs (Figure 7), adjustable weirs, undershot gates and flumes, control both water discharge and water level. Each discharge-measuring structure aims at a local narrowing of the cross-section, in which the major part of the total energy head H_1 is converted into kinetic energy used to obtain critical flow, whereas a minor part is lost due to friction at the structure, and by eddies upstream and downstream of the structure.

For all discharge-measuring structures, a head–discharge relation can be derived. The head is defined as the difference between water level and crest level, where the water level needs to be measured at a sufficient distance upstream of the weir to avoid the influence of the surface drawdown. Once the relation between the upstream head h_1 and the discharge Q has been determined with a certain accuracy, the structure is called a discharge-measuring structure.

When it is also considered necessary to regulate the flow or the water level, the crest level must then be made movable, thus creating a measuring and regulating structure. Frequently occurring structures are vertical sliding structures—like the Hobrad weir—and structures turning around a low-situated or a high-situated horizontal axis. Flow of water over a weir or flume is called *overflow*, whereas flow of water through a submerged opening is called orifice flow or *underflow*.

In view of the tail water level, distinction should be made between free flow and submerged flow. Discharge under *free-flow* conditions supposes a unique relation between the upstream head and the discharge, not depending on the downstream water level. Free flow turns into *submerged flow* as soon as the downstream water level affects the unique relation between the upstream water level and the discharge.

The submergence ratio is expressed as

$$S = 100H_2/H_1 \approx 100h_2/h_1$$

The transition between free flow and submerged flow is called the modular limit S_1. Free flow occurs for $S < S_1$ and flow becomes submerged for $S > S_1$.

The head–discharge equation for horizontal overflow structures—under free-flow conditions—reads

$$Q = (2/3)^{3/2}\, g^{1/2}\, C_D\, C_V\, h_1^{\,1.50} \qquad (1)$$

where

- Q = discharge ($m^3\ s^{-1}$)
- g = gravitational acceleration, $g = 9.81$ m s^{-2}
- C_D = characteristic discharge coefficient (–)
- C_V = coefficient for the approach velocity (–)
- h_1 = upstream head over the weir (m).

The general equation reads

$$Q = C\, h_1^u$$

where u varies from 0.5 to 2.5 depending on the type and shape of the structure.

The relevant equations for other flow-measuring structures are given in handbooks[1,2] and other references.

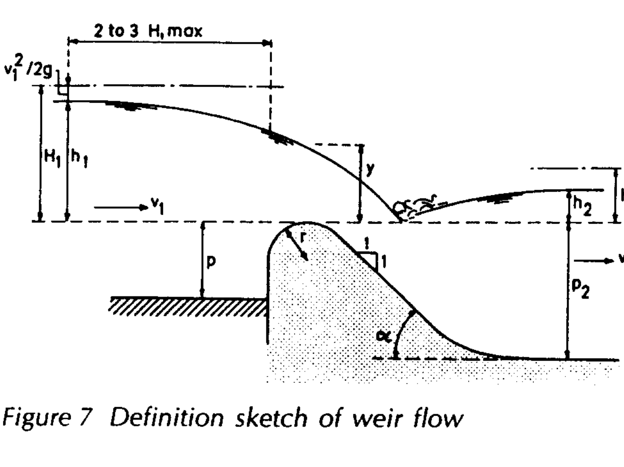

Figure 7 Definition sketch of weir flow

Selection of the most suitable flow-measuring structure

The selection of a structure (Figure 8) and the design of its dimensions determine to a high degree the quality of the discharge measurements. The designer will make a choice on the basis of the characteristics of the structures, the field or boundary conditions, and the human requirements (demands) imposed by the water management.

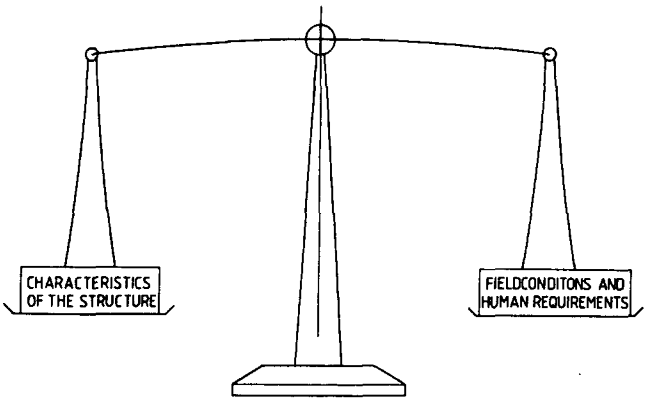

Figure 8 Selection of the type of flow-measuring structure

Characteristics

The characteristics of the numerous different structures are expressed in a number of properties:

Loss of head required by the measuring device

Structures with a high discharge capacity are characterized by a high discharge coefficient. For example, the short-crested weir with cylindrical crest $C_D = 1.48$ needs considerably less head than the broad-crested rectangular profile weir $C_D = 0.85$. However, the necessary head of loss decreases with higher modular limit, consecutively for sharp-crested weirs (a low value) and flumes (a high value).

Measuring range

The shape and the width of the crest determine the minimum discharge, assuming a minimum head $h_1 = 0.05$ m. The measuring range is defined as $\gamma = Q_{max}/Q_{min}$. Structures with a triangular cross-section allow larger ranges than structures with a rectangular cross-section.

Ability to transport solid materials

The passage of sediment across the bottom of the approach channel will be facilitated by a low crest height and a streamlined inflow (flumes). Gates and overflow structures with low sills (or even without a sill) are the most favourable structures with respect to sediment transport capability. Transport of floating materials needs a streamlined structure, including the crest shape: sharp-crested devices will for this reason not be considered as discharge-measuring structures in water in which there is floating debris.

Sensitivity

The overall error in flow measurements with structures depends strongly on the sensitivity expressed as

$$S = u\,\Delta h/h \qquad (2)$$

where

$\Delta h/h_1$ = relative change in upstream water level

u = power in the equation $Q = C\,h_1^u$

Gates are by far the least sensitive to water level changes, whereas overflow structures are three to five times more sensitive.

Accuracy

The accuracy of the structure depends on the number and the reliability of the calibrations and whether the measurements can be reproduced within a limited percentage. Sharp-crested weirs are famous for their high accuracy.

Possibilities to regulate discharges or water levels

Some structures have been developed both as a measuring and a regulating structure, either by movability in vertical slots or by turning around an axis. Other structures are exclusively designed with a fixed crest (flumes).

Field conditions

The selection of the location of the measuring station and the type of structure will be influenced by the field or boundary conditions. The most relevant information will be given by the following:

The available head

The installation of a structure causes a loss of head, which must be created by raising the upstream water level or by lowering the downstream water level. Both actions have their limitations.

The ranges of discharges and water levels

In the case of designing a structure in a natural stream, the designer should be informed about the range of discharges and water levels and about the frequency of occurrence.

Transport of solid material

Natural streams as well as artificial and recently designed canals may transport sediment or floating debris. Both are seasonally dependent and will mostly occur during a limited period, but in a high degree.

Human requirements

From the water-management point of view, the following demands have to be considered:

Requirements covering the function of the structure

In many cases we want to regulate the water supply and to control the upstream or the downstream water level.

Required minimum water level

To maintain a minimum water level, for example during drought periods, the crest level of overflow structures shall either lie at a certain height (apex height) above the canal bottom or be adjustable (movable weir), which also can be done using gates.

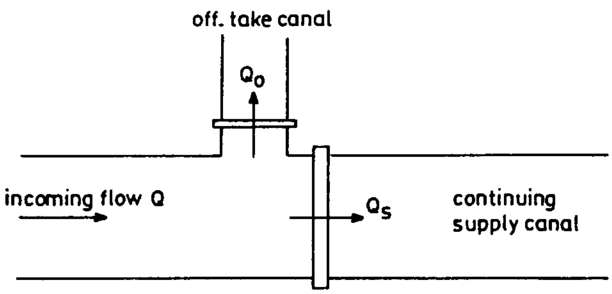

Figure 9 Example of a bifurcation

Flexibility

Figure 9 shows how the incoming flow Q from a supply canal is bifurcated over the offtake canal Q_o and the continuing supply canal Q_s. The discharges Q_o and Q_s are measured with hydraulic structures.

If for any reason the upstream water level should change (as a consequence of a change in the incoming flow Q), the discharges Q_o and Q_s will change also. Will they change by the same percentage (proportionally)? To answer this question, the term flexibility F is used:

$$F = \text{(rate of change of } Q_o) / \text{(rate of change of } Q_s) = (dQ_o/Q_o) / (dQ_s/Q_s) \quad (3)$$

with the general rating for a structure $Q = Ch_1^u$. The flexibility can be rewritten as

$$F = u_o h_s / u_s h_o \quad (4)$$

where

u_o = u-power of the structure in the offtake canal
u_s = u-power of the structure in the continuing supply canal
h_o = upstream head over the structure in the offtake canal
h_s = upstream head over the structure in the continuing supply canal

Now we present three possibilities with respect to the flexibility of the bifurcated offtake (we assume free flow at both structures):

(a) $F = 1$. This holds when both structures are of the same type $u_o = u_s$ and when they have the same crest level or sill level. Distribution is proportional and not dependent on upstream changes.
(b) $F < 1$. This happens when, for instance, the offtake structure is an undershot gate, $u_o = 0.5$, and the continuing canal has a horizontal overflow structure, $u_s = 1.5$. Then $F = 0.5h_s/1.5h_o$ and provided $h_s < 3h_o$, then $F < 1$. With this design the variation in the offtake is less than in the continuing canal, which is an advantage for tail-end users of irrigation water in the offtake canal.
(c) $F > 1$. Now we assume the offtake structure is a horizontal overflow structure, $u_o = 1.5$, and the continuing canal has an undershot gate, $u_s = 0.5$. Then $F = 1.5h_s/0.5h_o$ and provided $h_o < 3h_s$, then $F > 1$. This may occur when the offtake structure acts as a spillway, to prevent the supply canal from overload.

For any bifurcation, the flexibility of the offtake can be calculated from the u-values (type of structure) and the h-values (water level related to sill level).

Accuracy

Field structures will measure discharges generally with an error $X_Q \approx 5\%$. The accuracy in the evaluation of discharges is dealt with in the next section.

Non-technical demands

- ☐ The availability of construction materials.
- ☐ Familiarity with a certain type of structure.
- ☐ Importance of standardization. It is generally recommended that the number of different types of structures in an area be restricted. When new types are introduced, technicians and farmers need to be familiarized. Standardization also leads to a reduction in costs.
- ☐ At many places structures are exposed to alterations by unauthorized people. Such alterations can be avoided by building the structures sturdily and by locking movable parts.

The most suitable structure can only be selected after performing an in-depth study into the integration of all field-boundary conditions and human requirements.

Accuracy of discharge measurements

Errors occurring in indirect discharge measurements have different natures. The most significant contributions are as follows:

(a) The sensitivity of the structure: change of discharge per unit change of head. The sensitivity is proportional to the u-power in $Q = Ch_1^u$, consequently on the shape of the cross-section.
(b) The way in which the head h_1 is measured and the method of registration of both the water level and the crest level.
(c) Errors in the calibration affecting the reliability of the characteristic discharge coefficient C.
(d) Errors in the dimensions of the structure (B and α).

The magnitude of the error in the determination of the discharge is derived from the head–discharge relation

$$Q = CBh_1^u$$

Figure 10 Free flow over a large flow-measuring structure

Table 3 Flow-measuring structures, standardized by ISO/TC 113

Type of structure	Structure name	ISO Standard
Broad-crested weirs	Round-nose horizontal broad-crested weirs	ISO 4374-1990
	Rectangular broad-crested weirs	ISO 3846-1989
	Trapezoidal profile weirs	ISO 4362-1990
	V-shaped broad-crested weirs	ISO 8333-1985
Sharp-crested weirs	Thin plate weirs	ISO 1438/I-1980
Short-crested weirs	Triangular profile weirs	ISO 4360-1984
	Flat V-weirs	ISO 4377-1990
	Streamlined triangular profile weirs	DIS 9827
End depth methods	Rectangular channels with a free overfall	ISO 3847-1977
	Non-rectangular channels with a free overfall	ISO 4371-1984
Flumes	Rectangular, trapezoidal and U-shaped flumes	ISO 4359-1983
	Parshall and Saniiri flumes	DIS 9826
Gates		No standards yet
All types	Guidelines for the selection of flow gauging structures	ISO 8368-1985

namely

$$X_Q = \sqrt{[X_C^2 + X_B^2 + (uX_h)^2]} \quad (5)$$

where the following values hold:

orifice	$u = 0.5$
Sutro weir	$u = 1.0$
rectangular cross-section	$u = 1.5$
parabolic cross-section	$u = 2.0$
V-shaped cross-section	$u = 2.5$

and where

X_Q = error in discharge (%)
X_C = error in C, generally $2\% < X_C < 5\%$
X_B = error in width, can be corrected (%)
X_h = error in head measurement $X_h = 100(\delta_h/h_1)$ (%)
δ_h = absolute error in head measurement, normally $0.002 \text{ m} < \delta_h < 0.005 \text{ m}$.

Standardization of flow-measuring structures

The International Organization for Standardization (ISO) has, through its Technical Committee TC 113, issued a number of standards on flow-measuring structures. Table 3 gives a summary of the ISO standards, which have been drafted by experts in many countries all over the world.

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