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Hydrometry — Open channel flow measurement using triangular profile weirs

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British Standards

National foreword

This British Standard is the UK implementation of ISO 4360:2008. It supersedes BS 3680-4B:1986 which is withdrawn.

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Hydrometry — Open channel flow measurement using triangular profile weirs

Hydrométrie — Mesure de débit des liquides dans les canaux découverts au moyen de déversoirs à profil triangulaire

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Contents

Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 4360 was prepared by Technical Committee ISO/TC 113, *Hydrometry*, Subcommittee SC 2, *Flow measurement structures*.

This third edition cancels and replaces the second edition (ISO 4360:1984), of which it constitutes a technical revision.

Hydrometry — Open channel flow measurement using triangular profile weirs

1 Scope

This International Standard specifies methods for the measurement of the flow of water in open channels under steady flow conditions using triangular profile weirs. The flow conditions considered are steady flows which are uniquely dependent on the upstream head and drowned flows which depend on downstream as well as upstream levels.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 772, *Hydrometric determinations — Vocabulary and symbols*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 772 apply.

4 Symbols

A	m^2	area of approach channel
B	m	width of approach channel
b	m	breadth of weir crest perpendicular to flow direction
C		discharge coefficient
C_d		coefficient of discharge
C_v		coefficient of velocity
$C_v f$		combined coefficient of velocity
E	m	elevation of ultrasonic air range sensor above hydraulic datum
f		drowned flow reduction factor
g	m^2/s	acceleration due to gravity
H	m	total head relative to crest level
h	m	gauged head relative to crest level (upstream head is inferred if no subscript is used)
N		number of measurements in a set
p	m	height of weir (difference between mean bed level and crest level)
Q	m^3/s	volumetric rate of flow
$u^*(\ )$		percentage uncertainty in parameter
$\bar{v}$	m/s	mean velocity
U	%	expanded percentage uncertainty

Subscripts:

1	upstream
2	downstream
c	combined
p	measured crest tapping head above crest level

5 Principle

The discharge over a triangular profile weir is a function of the upstream head on the weir (for free flow), upstream and downstream head (for drowned flow), experimentally determined coefficients, the geometrical properties of the weir and approach channel and the dynamic properties of the water.

6 Installation

6.1 General

The required conditions regarding selection of site, installation conditions, the measuring structure, the approach channel, the downstream channel, maintenance, measurement of head, and stilling or float wells which are generally necessary for flow measurement are given in the following sub-clauses.

6.2 Selection of site

A preliminary survey shall be made of the physical and hydraulic features of the proposed site, to check that it conforms (or can be made to conform) to the requirements necessary for accurate measurement by a weir.

Particular attention should be paid to the following features in selecting the site:

a) availability of an adequate length of channel of regular cross-section;

b) the existing velocity distribution;

c) the avoidance of a steep channel, if possible;

d) the effects of any increased upstream water level due to the measuring structure;

e) conditions downstream including such influences as tides, confluences with other streams, sluice gates, mill dams and other controlling features which might cause submerged flow;

f) the impermeability of the ground on which the structure is to be founded, and the necessity for piling, grouting or other means of controlling seepage;

g) the necessity for flood banks to confine the maximum discharge to the channel;

h) the stability of the banks, and the necessity for trimming and/or revetment in natural channels;

i) the clearance of rocks or boulders from the bed of the approach channel;

j) the effect of wind; wind can have a considerable effect on the flow in a river or over a weir, especially when these are wide and the head is small and when the prevailing wind is in a transverse direction.

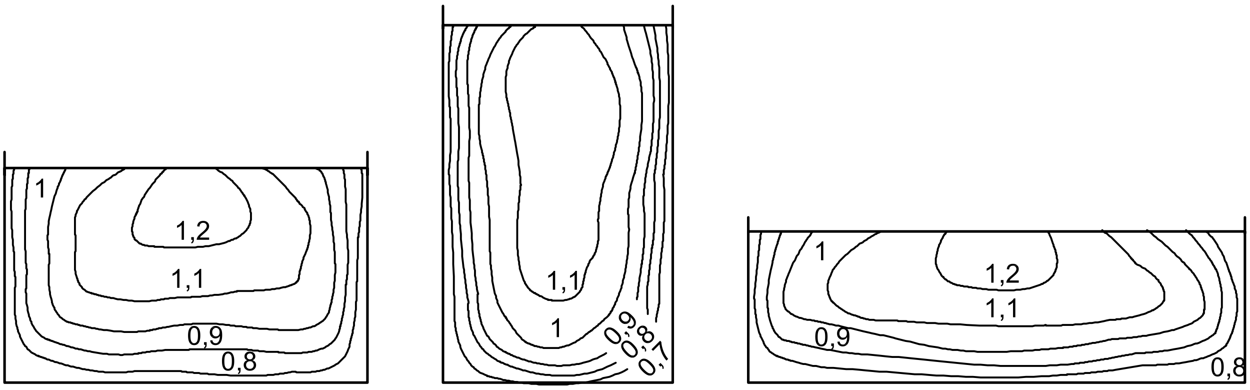
If the site does not possess the characteristics necessary for satisfactory measurement, the site shall be rejected unless suitable improvements are practicable.

If an inspection of the stream shows that the existing velocity distribution is regular, then it may be assumed that the velocity distribution will remain satisfactory after the construction of a weir.

If the existing velocity distribution is irregular and no other site for a gauge is feasible, due consideration shall be given to checking the distribution after the installation of the weir and to improving it if necessary.

Several methods are available for obtaining a more precise indication of irregular velocity distribution: velocity rods, floats or concentrations of dye can be used in small channels, the latter being useful in checking conditions at the bottom of the channel. A complete and quantitative assessment of velocity distribution may be made by means of a current-meter or other point velocity measurements. Information about the use of current-meters is given in ISO 748 [1]. Further information on measuring river velocities using acoustic Doppler profilers can be found in ISO/TS 24154 [5].

Figure 1 gives examples of satisfactory velocity distributions.



NOTE The contours refer to values of local flow velocity relative to the mean cross-sectional velocity.

Figure 1 — Examples of satisfactory velocity distributions

6.3 Installation conditions

6.3.1 General

The complete measuring installation consists of an approach channel, a measuring structure and a downstream channel. The conditions of each of these three components affect the overall accuracy of the measurements.

Installation requirements include features such as the surface finish of the weir, the cross-sectional shape of the channel, the channel roughness and the influence of control devices upstream or downstream of the gauging structure.

The distribution and direction of velocity have an important influence on the performance of the weir, these factors being determined by the features mentioned above.

Once an installation has been installed, the user shall prevent any change which could affect the discharge characteristics.

6.3.2 Measuring structure

The structure shall be rigid and watertight and capable of withstanding flood flow conditions without distortion or fracture. It shall be at right angles to the direction of flow and shall conform to the dimensions given in the relevant clauses.

The weir comprises an upstream slope of 1 (vertical) to 2 (horizontal) and a downstream slope of 1 (vertical) to 5 (horizontal). The intersection of these two surfaces forms a straight line crest, horizontal and at right angles to the direction of flow in the approach channel. Particular attention shall be given to the crest itself, which shall possess a well-defined corner of durable construction. The crest may be made of pre-formed sections, carefully aligned and jointed, or may have a non-corrodible metal insert, as an alternative to *in situ* construction throughout.

The dimensions of the weir and its abutments shall conform to the requirements indicated in Figure 2. Weir blocks may be truncated but not so as to reduce their dimensions in plan to less than $h_{\max}$ for the 1:2 slope and 2 $h_{\max}$ for the 1:5 slope.

Figure 2 shows the general arrangement of the triangular profile weir.

6.3.3 Approach channel

On all installations, the flow in the approach channel shall be smooth, free from disturbance and shall have a velocity distribution as satisfactory as possible over the cross-sectional area. This can usually be verified by inspection or measurement. In the case of natural streams or rivers, this can only be attained by having a long straight approach channel free from projections into the flow. Figure 1 gives examples of satisfactory velocity distributions.

The following general requirements shall be complied with.

a) As the altered flow conditions due to the construction of the weir might cause a build-up of shoals of debris upstream of the structure, which in time might affect the flow conditions, the likely consequential changes in the water level shall be taken into account in the design of gauging stations.

b) In an artificial channel, the cross-section shall be uniform and the channel shall be straight for a length equal to at least 5 times its water-surface width.

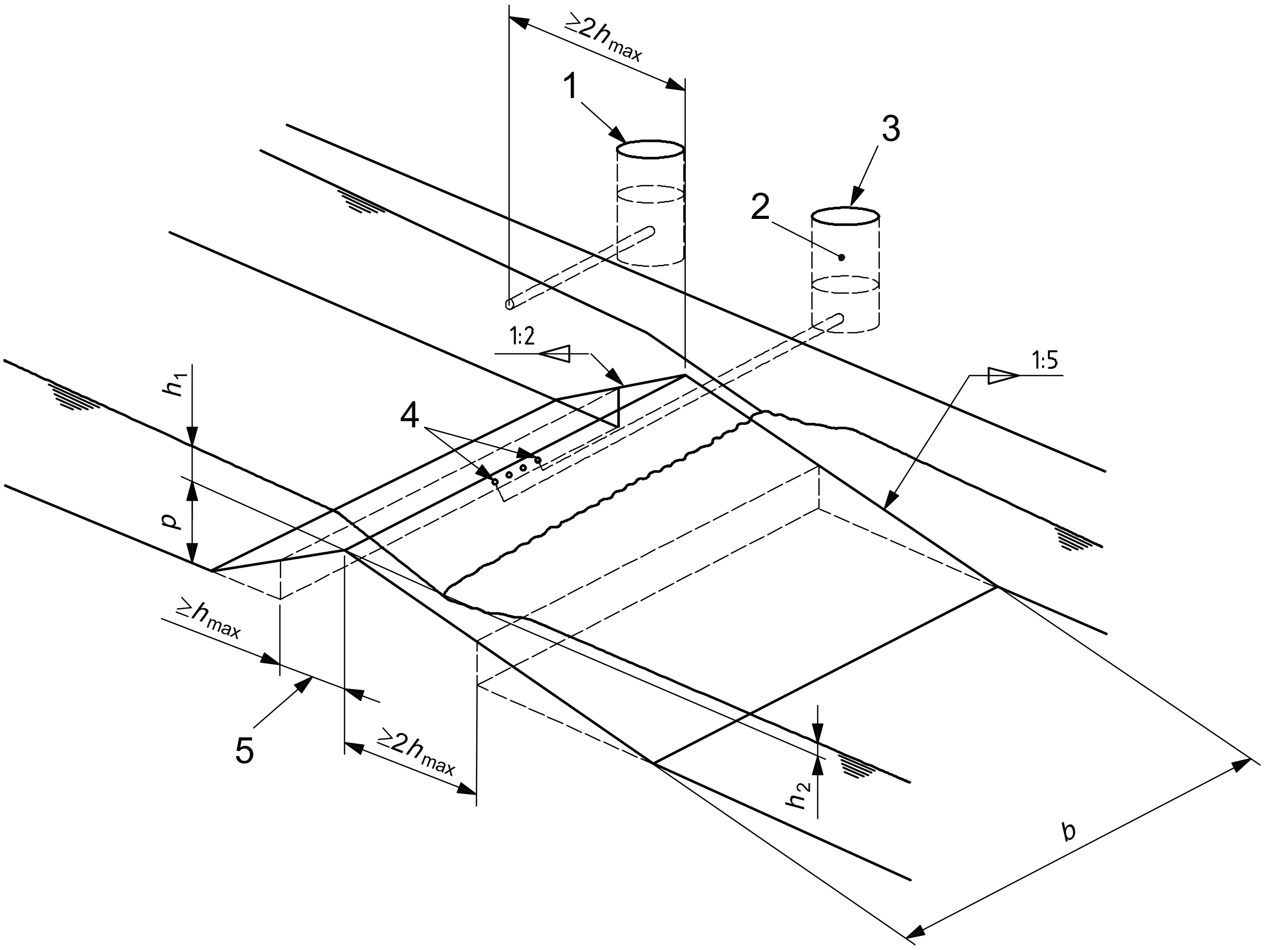
c) In a natural stream or river, the cross-section shall be reasonably uniform and the channel shall be straight for a sufficient length to ensure a regular velocity distribution.

d) If the entry to the approach channel is through a bend, or if the flow is discharged into the channel through a conduit or a channel of smaller cross-section, or at an angle, then a longer length of straight approach channel may be required to achieve a regular velocity distribution.

e) Baffles shall not be installed closer to the points of measurement than a distance 10 times the maximum head to be measured.

f) Under certain conditions, a standing wave may occur upstream of the gauging device, e.g. if the approach channel is steep. Provided that this wave is at a distance of not less than 30 times the maximum head upstream, flow measurement is feasible, subject to confirmation that a regular velocity distribution exists at the gauging station and that the Froude number in this section is no more than 0,6. Ideally, high Froude numbers should be avoided for accurate flow measurement.

   If a standing wave occurs within this distance, the approach conditions and/or the gauging device shall be modified.



Key

1 upstream head measurement
2 crest tapping head measurement
3 gauge wells
4 crest tappings
5 limit of truncated sections

Figure 2 — General arrangements of the triangular profile weir

6.3.4 Downstream channel

The channel downstream from the structure is usually of no importance as such if the weir has been designed so that the flow is modular (i.e. unaffected by tailwater level) under all operating conditions. A downstream gauge shall be provided to measure tailwater levels to determine if and when drowned flow occurs.

In the event of the possibility of scouring downstream, which phenomenon may also lead to the instability of the structure, particular measures to prevent this happening may be necessary.

A crest tapping and separate stilling well shall be fitted if the weir is designed to operate in a drowned condition or if there is a possibility that the weir may drown in the future.

The latter circumstance may arise if the altered flow conditions due to the construction of the weir have the effect of building up shoals of debris immediately downstream of the structure or if river works are carried out downstream at a later date.

7 Maintenance

Maintenance of the measuring structure and the approach channel is important to secure accurate continuous measurements.

The approach channel shall be kept free of silt, vegetation and obstructions which might have deleterious effects on flow conditions specified for the standard installation. The float well and the entry from the approach channel shall also be kept clean and free from deposits. The downstream channel shall be kept free of obstructions which might cause the weir to drown.

The weir structure shall be kept clean and free from clinging debris and care shall be taken in the process of cleaning to avoid damage to the weir crest.

Head-measurement piezometers, connecting conduits and stilling wells shall be cleaned and checked for leakage. The hook or point gauge, manometer, float or other instrument used to measure head shall be checked periodically to ensure accuracy.

If a flow straightener is used in the approach channel, perforated plates shall be kept clean so that the percentage open area remains greater than 40 %.

8 Measurement of head(s)

8.1 General

Where spot measurements are required, the heads can be measured by vertical gauges, hooks, points, wires or tape gauges. Where continuous records are required, recording gauges shall be used.

NOTE As the size of the weir and head reduces, small discrepancies in construction and in the zero setting and reading of the head measuring device become of greater relative importance.

8.2 Location of head measurement(s)

8.2.1 Modular (free) flow

Flow is modular when it is independent of variations in tailwater level. This requirement is met when the tailwater total head is equal to or less than 75 % of the upstream total head.

Piezometers or point-gauge stations for the measurement of head on the weir shall be located at a sufficient distance upstream from the weir to avoid the region of surface drawdown. On the other hand, they shall be close enough to the weir to ensure that the energy loss between the section of measurement and the control section on the weir shall be negligible. In this International Standard, it is recommended that the head-measurement section shall be located at a distance equal to twice the maximum head ($2h_{\text{max}}$) upstream of the crest.

8.2.2 Drowned flow

A significant error in the calculated discharge will develop if the tailwater total head above crest level exceeds 75 %, unless a crest tapping is provided and two independent head measurements are made.

The optimum position for the crest tapping is at the centre of the weir crest. The tapping may be off-centre on weirs wider than 2,0 m provided that the distance from the centreline of the crest tapping to the nearest side wall or pier is greater than 1,0 m.

8.3 Gauge wells

It is usual to measure the upstream head in a gauge well to reduce the effects of water surface irregularities.

NOTE 1 Devices for the measurement of head are described in ISO 4373 [2].

Periodic checks on the measurement of the head in the approach channel shall be made.

Where the weir is designed to operate under drowned flow, a second measurement of head is required. For accurate flow measurement, the head shall be measured within the separation pocket immediately downstream of the crest. Alternatively, but with less precision, the head may be measured in the channel downstream of the structure.

Gauge wells shall be vertical and of sufficient height and depth to cover the full range of water levels. In field installations, they shall have a minimum height of 0,6 m above the maximum water levels expected. Gauge wells shall be connected to the appropriate head measurement positions by means of pipes.

Both the well and the connecting pipe shall be watertight. Where the well is provided for the accommodation of the float of a level recorder, it shall be of adequate size and depth.

The pipe shall have its invert not less than 0,10 m below the lowest level to be gauged.

Pipe connections to the upstream and downstream head measurement positions shall terminate either flush with, or at right angles to, the boundary of the approach and downstream channels. The channel boundary shall be plain and smooth (equivalent to carefully finished concrete) within a distance 10 times the diameter of the pipes from the centre line of the connection. The pipes may be oblique to the wall only if they are fitted with a removable cap or plate, set flush with the wall, through which a number of holes are drilled. The edges of these holes shall not be rounded or burred. Perforated cover plates are not recommended where weed or silt are likely to be present.

The static head at the separation pocket behind the crest of the weir shall be transmitted to its gauge well as follows.

a) An array of tapping holes shall be set into a plate covering a cavity in the crest of the weir block.

b) The underside of the plate shall be supported on a manifold into which the static head is communicated via an array of feed tubes.

NOTE 2 No firm rule can be laid down for determining the size of the connecting pipe to the upstream well, because this is dependent on a particular installation, e.g. whether the site is exposed and thus subject to waves, and whether a larger diameter well is required to house the floats of recorders.

c) A horizontal conduit shall lead from the cavity through the weir block beneath the crest and terminating at the gauge well.

d) A flexible transmission tube shall communicate static head within the manifold to the gauge well.

e) A watertight seal around the transmission tube shall prevent static head within the cavity from influencing the static head transmitted from within the manifold.

NOTE 3 This may be at a different pressure because of leakage around the perimeter of the cover plate.

These arrangements minimize the occurrence of silting within the communication path between the separation pocket and the gauge well and allow effective purging of the pipework by the occasional backflushing of the system. For this purpose, a volume of water shall periodically be introduced to the gauge well.

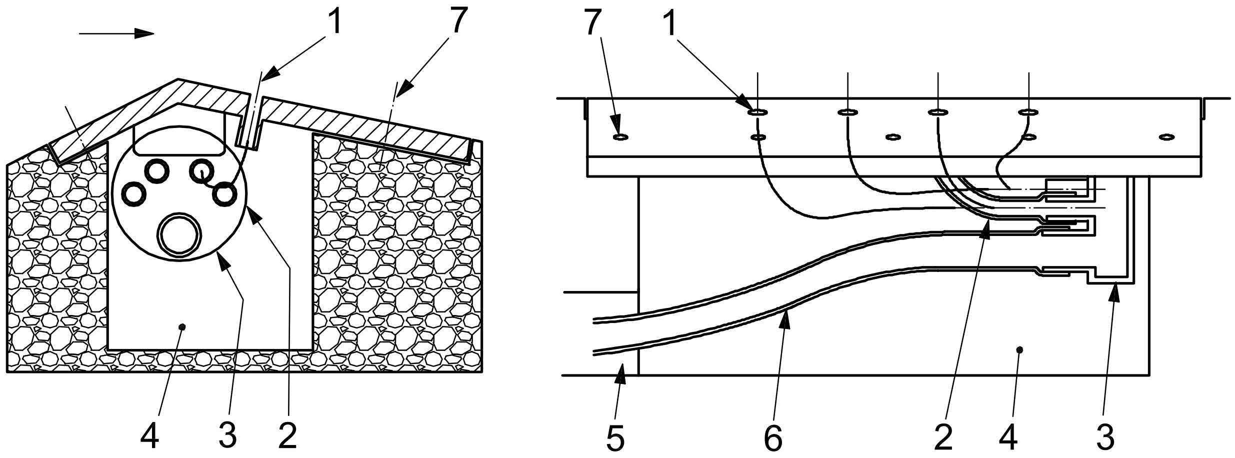
Figure 3 shows the general arrangement for the crest tapping installation.

The crest tapping shall consist of five to ten holes of 10 mm diameter drilled in the weir block with centres 75 mm apart, 20 mm down from the weir crest on the 1:5 slope. The edges of the holes shall not be rounded or burred. The number of holes shall be sufficient to ensure that the water level in the stilling well follows variations in crest separation pocket pressure without significant delay.

Adequate additional depth shall be provided in wells to avoid the danger of floats (if used) grounding either on the bottom or on any accumulation of silt or debris.

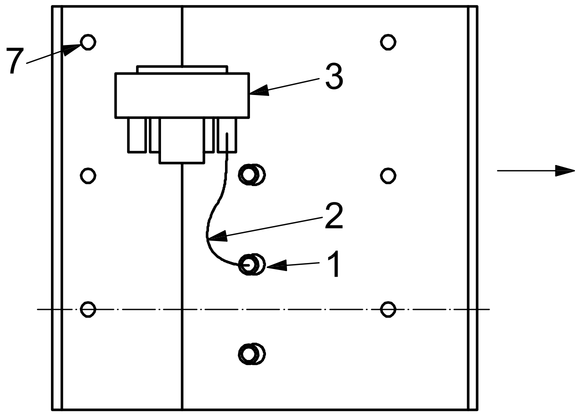
The gauge well arrangement may include an intermediate chamber of similar size and proportions to the approach channel, to enable silt and other debris to settle out where it may be readily seen and removed.

The diameter of the connecting pipe or width of slot to the upstream well shall be sufficient to permit the water level in the well to follow the rise and fall of head without appreciable delay. Care should be taken however not to oversize the pipe, in order to ensure ease of maintenance and to damp out any oscillations due to short period waves.



a) **Side view (in direction of flow)**

b) **Side view (normal to flow)**



c) **View of tappings from underneath the weir**

Key

1 crest tappings

2 feed tubes communicating crest head to the manifold (some shown as single lines only)

3 manifold [section in view b)]

4 cavity in the crest of the weir block

5 conduit leading to a gauge well

6 transmission tube (other end sealed within the conduit but communicating head in the manifold to the gauge well)

7 holes for screw-mounting the crest plate onto the weir block

Figure 3 — General arrangement for the crest tapping installation

8.4 Zero setting

Accurate initial setting of the zeros of the head measuring devices with reference to the level of the crest, and subsequent regular checking of these settings, is essential.

An accurate means of checking the zero at frequent intervals shall be provided. Benchmarks, in the form of horizontal metal plates, shall be set up on the top of the vertical side walls and in the gauge wells. These shall be accurately levelled to ensure their elevation relative to crest level is known.

NOTE Instrument zeros can be checked relative to these benchmarks without the necessity of resurveying the crest each time. Any settlement of the structure may, however, affect the relationships between crest and benchmark levels and it is advisable to make occasional checks on these relationships.

A zero check based on the water level (either when the flow ceases or just begins) is susceptible to serious errors due to surface tension effects and shall not be used.

The crest elevation shall be measured with respect to benchmarks at regular intervals across the breadth of the weir with not less than ten measurements in total. The mean of these crest elevation measurements shall be used to define the gauge zero.

9 Discharge characteristics

9.1 Equations of discharge

9.1.1 Modular (free) flow

In terms of total head, the basic discharge equation for a triangular profile weir operating under modular flow conditions is:

$$Q = C_\mathrm{d} \sqrt{g}\, b\, H^{\frac{3}{2}} \tag{1}$$

The total head, H, is given by the expression:

$$H = h + \frac{\overline{v}^2}{2g} \tag{2}$$

The total head equation is solved by iteration. An initial assumption is made that $H = h$ and an initial value of Q is computed. The velocity of approach, v, is then computed from values of Q and A, the cross-sectional area of the approach channel. Equation (2) then provides a refined value of H. This process is repeated until successive values of H are within the bounds of accuracy required.

Alternatively, the discharge modular flow equation may be expressed in terms of gauged head by introducing a coefficient of velocity dependent upon the weir and flow geometries:

$$Q = C_\mathrm{d} C_v \sqrt{g}\, b\, h^{\frac{3}{2}} \tag{3}$$

where C_v is the coefficient allowing for the effect of approach velocity $(H/h)^{3/2}$ (non-dimensional).

9.1.2 Drowned flow

In terms of total head, the basic discharge equation for a triangular profile weir operating under drowned flow conditions is:

$$Q = C_d f \sqrt{g}\ b\ H^{\frac{3}{2}} \tag{4}$$

where f is the drowned flow reduction factor (non-dimensional).

Alternatively, the drowned flow discharge equation may be expressed in terms of gauged head by introducing a coefficient of velocity dependent upon the weir and flow geometries:

$$Q = C_d C_v f \sqrt{g}\ b\ h^{\frac{3}{2}} \tag{5}$$

9.2 Coefficients

9.2.1 Coefficient of discharge, C_d

The value of the coefficient of discharge, C_d, is 0,633 (non-dimensional).

C_d is almost independent of h, except at very low heads when fluid properties influence the coefficient. C_d is given by the following equation:

$$C_d = 0{,}633\left(1 - \frac{0{,}000\ 3}{h}\right)^{\frac{3}{2}} \tag{6}$$

where h is in metres. For practical purposes, C_d can be set equal to 0,633 for $h \geqslant 0{,}1$ m.

9.2.2 Coefficient of velocity, C_v

The coefficient of velocity, C_v, for the modular flow equation is obtained from Figure 4 where A is the area of the approach channel.

9.2.3 Combined coefficient of velocity, $C_v f$

The combined coefficient $C_v\ f$ for the drowned flow equation is obtained from Figure 5 where h_p is the measured crest tapping head above crest level. Under modular flow conditions, the value of h_p/h is constant at 0,20 and the value of f is 1,00. Hence, under these conditions, values of $C_v f$ read from Figure 5 coincide with values of C_v from Figure 4.

9.3 Limitations

The following general limitations are recommended:

$h \geqslant 0{,}03$ m (for a crest section of smooth metal or equivalent);

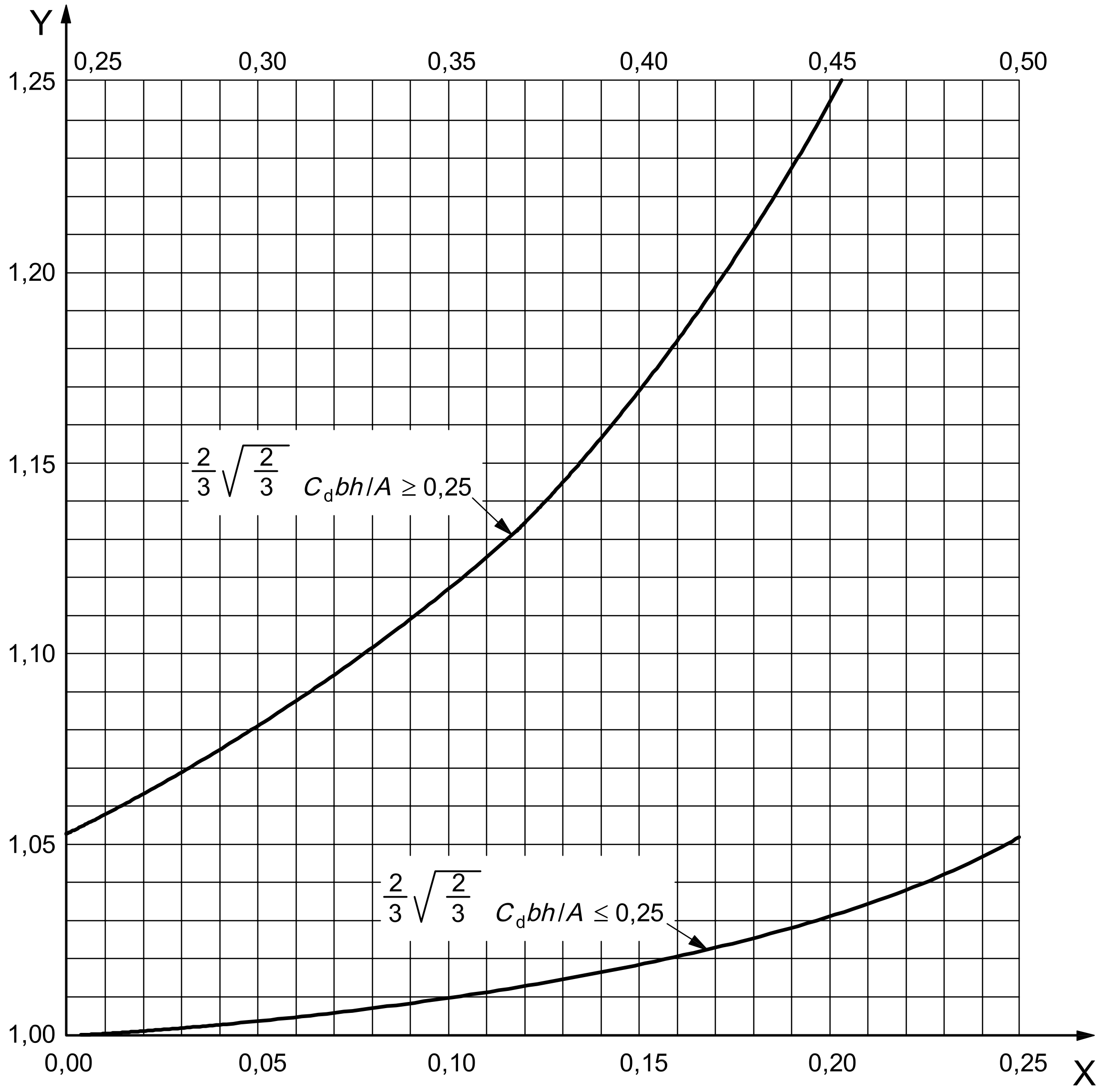
$h \geqslant 0{,}06$ m (for a crest section of fine concrete or equivalent);

$p \geqslant 0{,}06$ m;

$b \geqslant 0{,}1$ m;

$h/p \leqslant 4{,}5$;

$b/h \leqslant 2{,}0$.

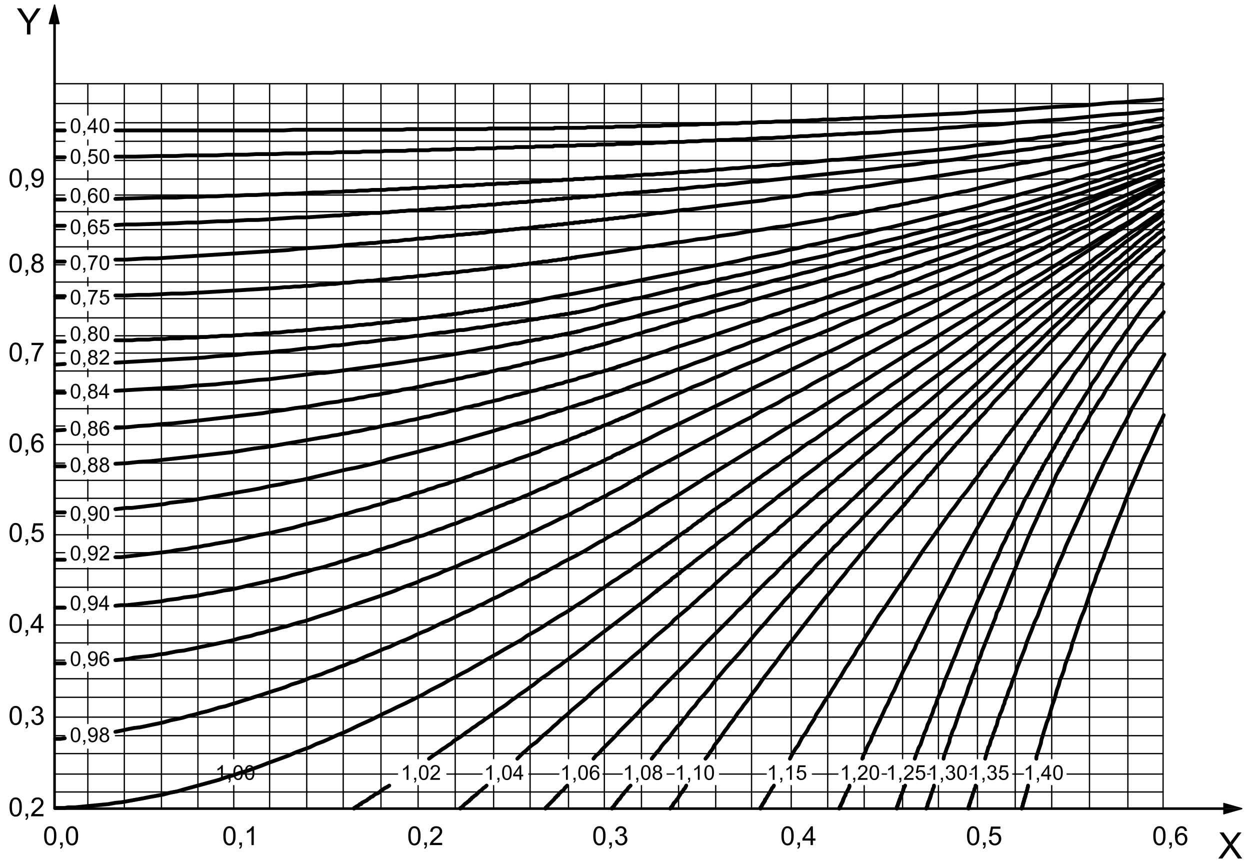


Key

X $\frac{2}{3}\sqrt{\frac{2}{3}}C_d\frac{bh}{A}$

Y C_v

Figure 4 — Coefficient of velocity, C_v, in terms of $C_d\frac{bh}{A}$



Key

X $C_{\mathrm{d}} \frac{bh}{A}$

Y $\frac{h_{\mathrm{p}}}{p}$

Figure 5 — Combined coefficient of velocity, $C_v f$, in terms of $\frac{h_{\mathrm{p}}}{p}$ and $C_{\mathrm{d}} \frac{bh}{A}$

10 Uncertainties of flow measurement

10.1 General

10.1.1 This clause provides information for the user of this International Standard to state the uncertainty of a measurement of discharge.

NOTE In accordance with former practice in hydrometry the expression for uncertainty is continued to be expressed at the 95 % confidence limit for the discharge coefficient and the determined flow rate.

The *Guide to the expression of uncertainty in measurement* (referred to hereafter as the GUM) [4] and ISO/TS 25377 (referred to hereafter as the HUG)[6] operate using *standard uncertainties* (i.e. at the 68 % confidence limit). However, the HUG requires final resultant uncertainty of measurement to be expressed at the 95 % confidence limit. Some components of uncertainty are expressed at the 95 % limit, i.e. $u_{95}(C_{\mathrm{d}})$ while others are standard uncertainties, i.e. those derived from Type A and Type B methods (see A.5 and A.6). Before these can be combined, those at the 95 % limit must be converted to the 68 % confidence limit by dividing them by the coverage factor, k. Having so combined these components to determine the standard uncertainty, this result is now multiplied by the coverage factor ($k = 2$) to express uncertainty at the 95 % confidence limit.

10.1.2 Annex A is an introduction to measurement uncertainty. It provides supporting information based on the GUM and the HUG.

10.1.3 A measurement result comprises:

i) an estimate of the measured value, with

ii) a statement of the uncertainty of the measurement.

10.1.4 A statement of the uncertainty of a flow measurement in a channel has four separate components of uncertainty:

i) uncertainty of the measurement of head in the channel

ii) uncertainty of the dimensions of the structure

iii) uncertainty of the discharge coefficient stated in this International Standard from laboratory calibration of the flow structure being considered

iv) uncertainty of channel velocity distribution related to the velocity coefficient, C_v.

This Clause does not accommodate component iv). It is assumed that the channel hydraulics are substantially equivalent to those existing in the calibration facility at the time of derivation of component iii) as defined in 6.3.2.

10.1.5 The estimation of measurement uncertainty associated with items i) and ii) of 10.1.3 is provided in Annex B.

Values taken from Annex B are used in the example in Clause 11. These values are for illustrative purposes only, they should not be interpreted as norms of performance for the types of equipment listed. In practice, uncertainty estimates should be taken from test certificates for the equipment, preferably obtained from a laboratory with accreditation to ISO/IEC 17025 [7].

10.2 Combining measurement uncertainties

See Clause A.7.

The proportion in which each flow equation parameter contributes to flow measurement uncertainty, $U(Q)$, is derived by analytical solution using partial differentials of the discharge equation.

The general equation of discharge for modular and for drowned flow is Equation (5):

$$Q = C_\mathrm{d} C_v \ f \sqrt{g} \ b \ h^{\frac{3}{2}}$$

where f = 1 for modular flow conditions.

The effect on the value Q due to small dispersions of and is ΔC_d, ΔC_v, (or $\Delta C_v f$), Δb and Δh_1 is:

$$\Delta Q = \frac{\partial Q}{\partial C}\Delta C + \frac{\delta Q}{\partial b}\Delta b + \frac{\partial Q}{\partial h_1}\Delta h_1 \tag{7}$$

Note that the quantities ΔC_v, or $\Delta C_v \, f$ are assumed to be determined without error from Figure 4 and from Figure 5 respectively. The partial derivatives are the sensitivity coefficients of Clause A.7 that relate to the discharge equation. ΔQ is the resultant dispersion of Q. Evaluating the partial differentials and using Equation (3), the relationship can be written:

$$\frac{\Delta Q}{Q} = \frac{\Delta C}{C} + \frac{\Delta b}{b} + 1{,}5\frac{\Delta h_1}{h_1} \tag{8}$$

Thus the relative sensitivity coefficients are:

$$\frac{\delta Q}{\delta C} = 1$$

$$\frac{\delta Q}{\delta b} = 1$$

$$\frac{\delta Q}{\delta h_1} = 1{,}5$$

The values $\frac{\Delta Q}{Q}$, $\frac{\Delta b}{b}$, $\frac{\Delta C}{C}$ and $\frac{\Delta h_1}{h_1}$ are referred to as dimensionless standard uncertainties and are given the notation $u^*(Q)$, $u^*(C)$, $u^*(b)$ and $u^*(h)$. Since the uncertainties of b, C and h_1 are independent of each other, probability requires summation in quadrature rather than a simple summation.

$$u^*(Q) \cong \sqrt{u^*(C)^2 + u^*(b)^2 + \left[1{,}5u^*(h_1)\right]^2} \tag{9}$$

10.3 Uncertainty of discharge coefficient $u(C_\mathrm{d})$ for the triangular profile weir

The discharge coefficient C_d has been determined from a series of hydraulics tests using a high-resolution calibration facility.

For well-constructed triangular profile weirs which are installed in a channel in which the approach conditions comply with those given in 6.3.3, the relative standard uncertainty of the coefficient of discharge C_d is:

$$u^*(C) = (5C_v - 4{,}5)\,\% \tag{10}$$

10.4 Uncertainty budget

In reports, an uncertainty budget table may be presented (or referenced) to provide the following information for each source of uncertainty:

a) the method of evaluation (from Annex A);

b) the determined value of relative standard uncertainty $u^*(C)$, $u^*(b)$ and $u^*(h)$ including datum uncertainly of $u^*(h)$;

c) the relative sensitivity coefficients.

The values for each source are then applied according to Equation (9) to give the combined standard uncertainty, $U^*(Q)$. A coverage factor $k = 2$ is then applied to define the uncertainty at the 95 % level of confidence.

It is customary to present these steps in tabular form with one row for each source and a column for each of the items a) to c) above.

The table may include, where appropriate, the critical thinking behind the subjective allocation of uncertainty to the quantities b and h. This section of the table may be replicated for a range of values of h_1 to determine a relationship between $U^*(Q)$ and h_1.

11 Example

11.1 General

In presenting examples, the equations given in Clause 10 define the relationship between the parameters which determine flow rate.

Uncertainty of the discharge coefficient is a fundamental uncertainty and is defined by Equation (10). To determine the overall uncertainty of flow measurement, practical estimations must be made of the head measurement uncertainty and the uncertainty of the measurement of physical dimensions.

Annex A provides a consistent framework for evaluating these uncertainties for the commonly used measurement techniques.

One such technique is selected in 11.3 for the example that follows.

11.2 Characteristics — Gauging structure

The example relates to modular flow conditions, therefore:

$f = 1$

The crest height p above the bed of the approach channel is 0,060 m with no measurable variation along the crest. The width of the weir crest varies from a minimum value of 0,149 m to a maximum at 0,151 m. The approach channel is assumed to be of the same width as the mean width of the weir (0,150 m).

11.3 Characteristics — Gauged head instrumentation

In this example, an air range ultrasonic sensor is used to determine the head.

- i) The sensor is fixed at an elevation of 0,340 m above the hydraulic datum (the mean level of the weir crest). The datum procedure determines that the elevation is between 0,340 5 m and 0,349 6 m. Referring to Annex B, the relative datum uncertainty, assuming a triangular probability distribution is:

  $u(E) = 0{,}000\,4$ m.

- ii) The sonic range from the sensor to the water surface is the primary measurement of the sensors. The range value is 0,140 m.

The resultant head measurement is therefore $h = 0{,}200$ m.

From Table C.1 in the HUG:2007, the uncertainty of head measurement stated as a percent of range is 1 %. This is 1 % at the 95 % confidence limit and equates to 0,5 % as a standard uncertainty.

This equates to 0,007 m.

The combined head measurement uncertainty is therefore:

$$u(h) = \sqrt{\left(0{,}000\,4^2 + 0{,}007^2\right)}\ \text{m}$$

$$u(h) = 0{,}000\,8\ \text{m}$$

or expressed as a percentage of $h = 0{,}200$ m

$$u^*(h) = 0{,}403\ \%$$

If the crest is liable to accumulate algal or other growth, the uncertainty value of head measurement shall be increased accordingly.

11.4 Discharge coefficient

The value of the discharge coefficient for head values over 0,100 m, refer to 9.2.1, is $C_\mathrm{d} = 0{,}633$.

11.5 Discharge calculation

The flow rate is calculated from Equation (3):

$$Q = C_\mathrm{d} C_v \sqrt{g}\ b\ h^{\frac{3}{2}}$$

with a value of C_v derived by iteration or with reference to Figure 4 and with:

$$C_\mathrm{d} \frac{bh}{A} = C_\mathrm{d} \frac{h}{h+p} = 0{,}487$$

From which C_v = 1,329

Applying these values to Equation (3):

$$Q = 0{,}633 \times 1{,}329 \times \sqrt{g} \times 0{,}150 \times (0{,}2)^{\frac{3}{2}}$$

$$Q = 0{,}035\ 3\ \mathrm{m}^3/\mathrm{s}$$

11.6 Uncertainty statement

11.6.1 From Equation (10), the value for uncertainty of the discharge coefficient is:

$$u_{95}^*(C_\mathrm{d}) = (10 \times 1{,}329) - 9 = 4{,}29\ \%$$

with a coverage factor at k = 2

$$u_{95}^*(C_\mathrm{d}) = 2{,}145\ \%$$

11.6.2 From Equation (A.4), the value of uncertainty of the width of the weir may be written:

$$u(b) = \frac{1}{\sqrt{6}} \cdot \left(\frac{\text{Maximum width} - \text{Minimum width}}{2} \right)$$

$$u(b) = \frac{1}{\sqrt{6}} \cdot \left(\frac{0{,}151 - 0{,}149}{2} \right)$$

$$u(b) = 0{,}000\ 41\ \mathrm{m}$$

or

$$u^*(b) = \frac{0{,}000\ 41}{0{,}150}$$

$$u^*(b) = 0{,}27\ \%$$

11.6.3 The combined uncertainty value is determined from Equation (9):

$$u_{\mathrm{c}}^{*}(Q)=\sqrt{u^{*}(C_{\mathrm{d}})^{2}+u^{*}(b)^{2}+\left[1{,}5u^{*}(h)\right]^{2}}$$

$$u_{\mathrm{c}}^{*}(Q)=\sqrt{2{,}145^{2}+0{,}27^{2}+(1{,}5\times 0{,}403)^{2}}$$

$$u_{\mathrm{c}}^{*}(Q)=2{,}24\ \%$$

or using a coverage factor $k = 2$

$U_{\mathrm{c}}^{*}(Q)=4{,}49\ \%$ at the 95 % level of confidence.

11.6.4 The statement of discharge is therefore:

— the flow rate is 0,035 3 m^3/s,

— with an uncertainty of 4,48 % at the 95 % level of confidence with a coverage factor of $k = 2$.

11.6.5 An uncertainty budget for the example is given in Table 1.

Table 1 — Uncertainty budget for the example

	Type/Evaluation	u, u^* Value	Sensitivity coefficients	Comment
$u^*(C_\mathrm{d})$	B/ Normal	2,145 %	1,0	From laboratory tests
$u^*(b)$	B/ Triangular	0,27 %	1,0	Using A.6.2
$u(E)$	B/ Triangular	0,000 4 m		From Table B.1
$u(h)$	B/ Manufact	0,5 % of range		From Table B.1
$u^*(h)$	Combined	0,403 %	1,5	From 11.3
$u_\mathrm{c}^*(Q)$	Combined	2,24 %	—	Using Equation (9)

Annex A
(informative)

Introduction to measurement uncertainty

A.1 General

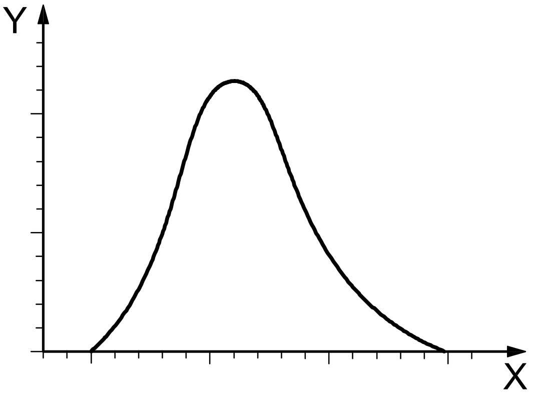
Results of measurements or analysis cannot be exact. The discrepancy between the true value, which is unknowable, and the measured value is the measurement error. The concept of uncertainty is a way of expressing this lack of knowledge. For example, if water is controlled to flow at a constant rate, then a flow meter will exhibit a spread of measurements about a mean value. If attention is not given to the uncertain nature of data, incorrect decisions can be made which have financial or judicial consequences. A realistic statement of uncertainty enhances the information, making it more useful.

The uncertainty of a measurement represents a dispersion of values that could be attributed to it. Statistical methods provide objective values based on the application of theory.

Standard uncertainty is defined as:

> *Standard uncertainty equates to a dispersion of measurements expressed as a standard deviation.*

From this definition, uncertainty can be readily calculated for a set of set of measurements.



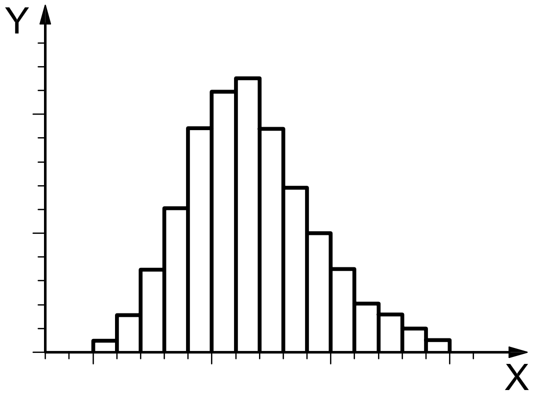
a)

Key

X flow value

Y probability

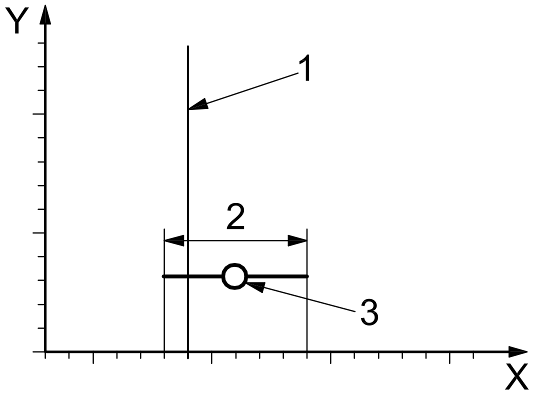
Figure A.1 — Pictorial representation of some uncertainty parameters



b)

Key

X	flow value
Y	number of samples



c)

Key

1	limit
2	standard deviation
3	mean value
X	flow value
Y	number of samples

Figure A.1 (*continued*)

Figure A.1 a) shows the probability that a measurement of flow under steady conditions takes a particular value due to the uncertainties of various components of the measurement process, in the form of a probability density function.

Figure A.1 b) shows sampled flow measurements, in the form of a histogram.

Figure A.1 c) shows standard deviation of the sampled measurements compared with a limiting value. The mean value is shown to exceed the limiting value but is within the band of uncertainty (expressed as the standard deviation about the mean value).

A.2 Confidence limits and coverage factors

For a normal probability distribution, analysis shows that 68 % of a large set of measurements lie within one standard deviation of the mean value. Thus, standard uncertainty is said to have a 68 % level of confidence.

However, for some measurement results, it is customary to express the uncertainty at a level of confidence which will cover a larger portion of the measurements: for example at a 95 % level of confidence (see Figure A.4). This is done by applying a factor, the coverage factor k, to the computed value of standard uncertainty.

For a normal probability distribution, 95,45 % (effectively 95 %) of the measurements are covered for a value of $k = 2$. Thus, uncertainty at the 95 % level of confidence is twice the standard uncertainty value.

In practice, measurement variances rarely follow closely the normal probability distribution. They may be better represented by triangular, rectangular or bimodal probability distributions and only sometimes approximate to the normal distribution.

So a probability distribution must be selected to model the observed variances. To express the uncertainty of such models at the 95 % confidence limit requires a coverage factor that represents 95 % of the observations. However, the same coverage factor, $k = 2$, is used for all models. This simplifies the procedure while ensuring consistency of application within tolerable limits.

A.3 Random and systematic error

The terms “random” and “systematic” have been applied in hydrometric standards to distinguish between

i) random error that represent an inherent dispersion of values under steady conditions, and

ii) systematic errors that are associated with inherent limitations of the means of determining the measured quantity.

A difficulty with the concept of systematic error is that systematic error cannot be determined without pre-knowledge of true values. If its existence is known or suspected, then steps must be taken to minimize such error either by recalibration of equipment or by reversing its effect in the calculation procedure. At which point, systematic error contributes to uncertainty in the same way as random components of uncertainty.

For this reason, the GUM does not distinguish between the treatment of random and systematic uncertainties. Generally, when determining a single discharge, random errors dominate and there is no need to separate random and systematic errors. However, where (say) totalized volume is established over a long time base the systematic errors, even when reduced, can remain dominant in the estimation of uncertainty.

A.4 Measurement standards

The GUM and the HUG provide rules for the application of the principles of measurement uncertainty: in particular on the identification of components of error, the quantification of their corresponding uncertainties and how these are combined using methods derived from statistical theory into an overall result for the measurement process.

The components of uncertainty are characterized by estimates of standard deviations. There are two methods of estimation.

a) **Type-A estimation** (by statistical analysis of repeated measurements from which an equivalent standard deviation is derived)

   This process may be automated in real-time for depth or for velocity measurement.

b) **Type-B estimation** (by ascribing a probability distribution to the measurement process)

This is applicable to

1) human judgement of a manual measurement (distance or weight),

2) manual readings taken from instrumentation (manufacturer's statement), or

3) calibration data (from manufacturer).

A.5 Evaluation of Type-A uncertainty

Defined in A.1, the term "standard uncertainty" equates to a dispersion of measurements expressed as a standard deviation. Thus, any single measurement of a set of n measurements has by definition an uncertainty:

$$u(x) = t_e \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2} \tag{A.1}$$

where $\overline{x}$, the "best estimate", is the mean value:

$$\overline{x} = \frac{1}{n}\left(x_1 + x_2 + \ldots\ldots x_n\right) \tag{A.2}$$

and t_e is a factor derived from statistical theory to account for the increased uncertainty when small numbers of measurements are available; refer to Table A.1.

If, instead of a single measurement from the set, the uncertainty is to apply to the mean of all n values, then:

$$u(\overline{x}) = \frac{t_e}{\sqrt{n}} \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2} \tag{A.3}$$

For continuous measurement, Type-A evaluations may be derived as a continuous variable from the primary measurement, i.e. from water level or water velocity.

By taking average values over large numbers, n, of measurements, the uncertainty of the mean value $u(\overline{x})$ is reduced by a factor of $\frac{1}{\sqrt{n}}$ compared to the uncertainty $u(x)$ of an individual measurement. For this reason, monitoring equipment should specify measurement performance in terms including both $u(\overline{x})$ and $u(x)$ to show the extent to which averaging is applied.

Table A.1 — t_e factors at 90 %, 95 % and 99 % confidence levels

	Confidence level %		
Degrees of freedom	**90**	**95**	**99**
1	6,31	12,71	63,66
2	2,92	4,30	9,92
3	2,35	3,18	5,84
4	2,13	2,78	4,60
5	2,02	2,57	4,03
10	1,81	2,23	3,17
15	1,75	2,13	2,95
20	1,72	2,09	2,85
25	1,71	2,06	2,79
30	1,70	2,04	2,75
40	1,68	2,02	2,70
60	1,67	2,00	2,66
100	1,66	1,98	2,63
infinite	1,64	1,96	2,58

A.6 Evaluation of Type-B uncertainty

A.6.1 General

When there is no access to a continuous stream of measured data or if a large set of measurements is not available, then the Type-B method of estimation is used to:

i) assign a probability distribution to the measurement process to represent the probability of the true value being represented by any single measured value;

ii) define upper and lowers bounds of the measurement; and then

iii) determine a standard uncertainty from a standard deviation implied by the assigned probability distribution.

The Type-B methods allow estimates of upper and lower bounding values to be used to derive the equivalent standard deviation.

Four probability distributions are described in the GUM and in A.6.2 to A.6.5.

A.6.2 Triangular distribution

The triangular distribution is represented in Figure A.2.

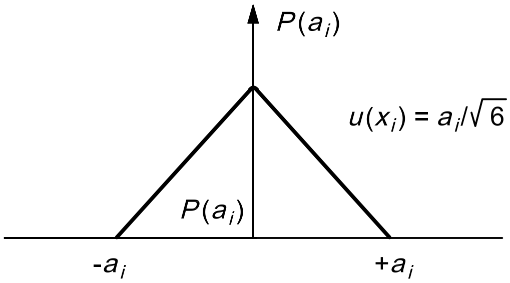


Figure A.2 — Triangular distribution

$$u(x_{\text{mean}}) = \frac{1}{\sqrt{6}}\left(\frac{x_{\text{max}} - x_{\text{min}}}{2}\right) \tag{A.4}$$

This usually applies to manual measurements where the mean value is most likely to be closer to the true value than others between the discernible upper and lower limits of the measurement.

A.6.3 Rectangular distribution

The rectangular distribution is represented in Figure A.3.

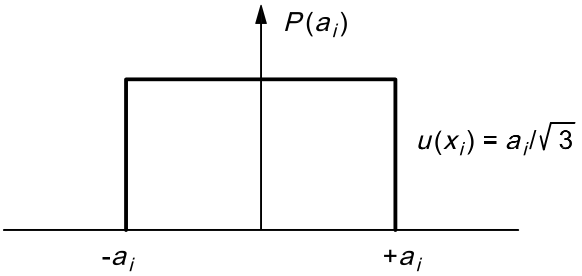


Figure A.3 — Rectangular distribution

$$u(x_{\text{mean}}) = \frac{1}{\sqrt{3}}\left(\frac{x_{\text{max}} - x_{\text{min}}}{2}\right) \tag{A.5}$$

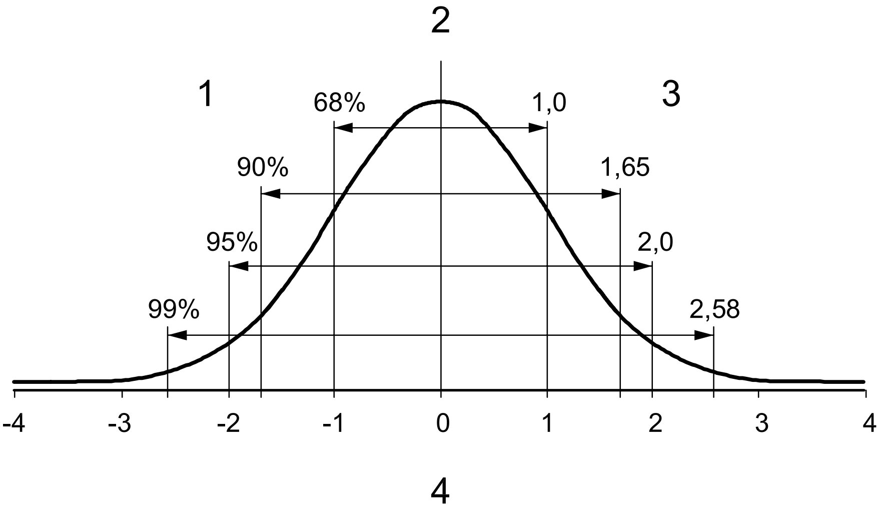
This probability distribution is usually applied to the resolution limit of the measurement instrumentation (i.e. the displayed resolution or the resolution of internal analogue/digital converters).

However, this is not the only source of uncertainty of measurement equipment. There may be uncertainty arising from the measurement algorithm used and/or from the calibration process.

If the equipment measures relative values, then there will also be uncertainty in the determination of its datum.

A.6.4 Normal probability distribution

The normal probability distribution is represented in Figure A.4.



Key

1 percent of readings in bandwidth
2 probability
3 coverage factor
4 standard deviations

Figure A.4 — Normal probability distribution

$$u\left(x_{\text{mean}}\right)=\frac{u\left(\text{specified}\right)}{k} \tag{A.6}$$

where k is the coverage factor applying to the specified uncertainty value.

These are uncertainty statements based on ‘off-line’ statistical analysis, usually as part of a calibration process where they have been derived using a Type-A process. When expressed as standard uncertainty, the uncertainty value is to be used directly with an equivalent coverage factor of k = 1.

A.6.5 Bimodal probability distribution

The bimodal probability distribution is represented in Figure A.5.

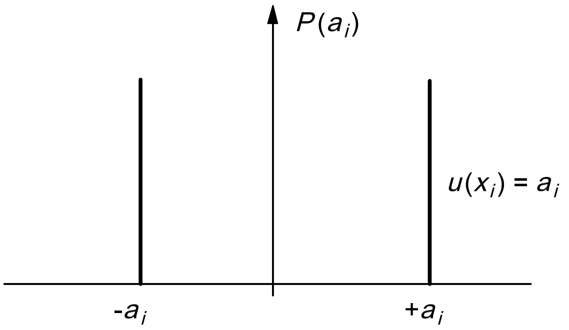


Figure A.5 — Bimodal probability distribution

$$u\left(x_{\text{mean}}\right)=\frac{\left(x_{\text{max}}-x_{\text{min}}\right)}{2} \tag{A.7}$$

Measurement equipment with hystersis can only exhibit values at the upper and lowers bounds of the measurement.

An example of this is the float mechanism where friction and surface tension combine to cause the float to move in finite steps.

A.7 Combined uncertainty value, u_c

For most measurement systems, a measurement result is derived from several variables. For example, flow measurement, Q, in a rectangular channel can be expressed as a function of independent variables:

$$Q = b \times h \times \bar{V} \tag{A.8}$$

where

b is the channel width;

h is the depth of water in the channel;

$\bar{V}$ is the mean velocity.

These three components are measured independently and combined to determine a value for Q.

Just as b, h, and $\bar{V}$ are combined to determine the value Q, so each component of uncertainty must be combined to determine a value for $u_c(Q)$. This is done by evaluating the sensitivity of Q to small change, Δ, in b, h or V. Thus:

$$\Delta Q = \frac{\partial Q}{\partial b}\Delta b + \frac{\partial Q}{\partial h}\Delta h + \frac{\partial Q}{\partial \bar{V}}\Delta \bar{V} \tag{A.9}$$

where the partial differentials, $\frac{\partial Q}{\partial b}$, $\frac{\partial Q}{\partial h}$ and $\frac{\partial Q}{\partial \bar{V}}$, are sensitivity coefficients. For the equation $Q = b \times h \times \bar{V}$, this is equal to:

$$\frac{\Delta Q}{Q} = \frac{\Delta b}{b} + \frac{\Delta h}{h} + \frac{\Delta \bar{V}}{\bar{V}} \tag{A.10}$$

In uncertainty analysis, the values, $\frac{\Delta Q}{Q}$, $\frac{\Delta b}{b}$, $\frac{\Delta \bar{V}}{\bar{V}}$ and $\frac{\Delta h}{h}$ correspond to dimensionless standard uncertainties. They are given the notation $u_c{*}(Q)$, $u{*}(b)$, $u{*}(V)$ and $u{*}(h)$.

Since the uncertainties of b, V and h are independent of each other, probability considerations require summation in quadrature.

$$u_c^*(Q) \cong \sqrt{u^*(\bar{V})^2 + u^*(b)^2 + u^*(h)^2} \tag{A.11}$$

Annex B
(informative)

Sample measurement performance for use in hydrometric worked examples

Table B.1 — Sample measurement performance for use in hydrometric worked examples

Measurement technologies		Comment	Symbol			Installed equipment to have corresponding values certified by the manufacturer									
				Uncertainty options		Nominal range of measurement					Corresponding standard uncertainty (68 % confidence limit)				
Velocity (continuous)				A	B	Minimum	25 %	50 %	75 %	Maximum	Minimum	25 %	50 %	75 %	Maximum
Point velocity	Propeller	Calibration certificate	$u(V)$	YES	Normal	0,005 m/s	1,250 m/s	2,500 m/s	3,750 m/s	5,000 m/s	0,000 5 m/s	0,010 m/s	0,022 m/s	0,030 m/s	0,040 m/s
	Electromagnetic	Calibration certificate	$u(V)$	YES	Normal	0,005 m/s	0,750 m/s	1,500 /s	2,250 m/s	3,000 m/s	0,000 5 m/s	0,010 m/s	0,018 m/s	0,025 m/s	0,025 m/s
Path velocity	Time of flight sonar	Sonic velocity path angle	$u(V)$	YES	Rectangular	0,030 m/s	0,250 m/s	0,500 m/s	0,750 m/s	1,000 m/s	0,003 m/s	0,005 m/s	0,007 m/s	0,007 m/s	0,010 m/s
	Gated Doppler sonar	Particle dependent - low velocity resolution	$u(V)$	YES	Rectangular	0,030 m/s	0,250 m/s	0,500 m/s	0,750 m/s	1,000 m/s	0,003 m/s	0,005 m/s	0,007 m/s	0,007 m/s	0,010 m/s
	Sonar correlation	Particle dependent	$u(V)$	YES	Rectangular	0,030 m/s	0,250 m/s	0,500 m/s	0,750 m/s	1,000 m/s	0,003 m/s	0,005 m/s	0,007 m/s	0,007 m/s	0,010 m/s
Section velocity	EM	To be calibrated *in situ*	$u(V)$	—	Rectangular	0,030 m/s	0,250 m/s	0,500 m/s	0,750 m/s	1,000 m/s	0,003 m/s	0,005 m/s	0,007 m/s	0,007 m/s	0,010 m/s
Water level (continuous)															
Relative datum (to be applied to all methods)		Manual process	$u(E)$	—	Triangular	Not applicable	0,500 m	1,000 m	1,500 m	2,000 m	0,001 m	0,001 m	0,001 5 m	0,001 5 m	0,001 5 m
In-contact methods	Encoder/float system	Requires regular maintenance	$u(h_1)$	—	Bimodal	Extension 0,200 m	Extension 1,250 m	Extension 2,500 m	Extension 3,750 m	Extension 5,000 m	0,001 5 m	0,002 0 m	0,002 0 m	0,002 5 m	0,002 5 m
	Pressure transducer	Datum value drift	$u(h_1)$	—	Rectangular	0,010 m	0,500 m	1,000 m	1,500 m	2,000 m	0,002 m	0,002 m	0,002 5 m	0,002 5 m	0,003 0 m
	Sonar	Surface wave effects	$u(h_1)$	YES	Rectangular	0,050 m	0,500 m	1,000 m	1,500 m	2,000 m	0,001 m	0,001 m	0,001 5 m	0,001 5 m	0,001 5 m
Non-contact methods	Pulse echo ultrasound	Surface wave effects Air temperature compensation	$u(R)$	YES	Rectangular	Range 0,300 m	Range 1,250 m	Range 2,500 m	Range 3,750 m	Range 5,000 m	0,002 m	0,004 m	0,010 m	0,025 m	0,060 m
	Pulse echo opto/radar	Surface wave effects	$u(R)$	—	Rectangular	Range 0,300 m	Range 1,250 m	Range 2,500 m	Range 3,750 m	Range 5,000 m	0,002 m	0,004 m	0,010 m	0,025 m	0,060 m
Cross-section profile (distance measurement)															
	Natural channels	Sonar or dip gauging / GPRS or tracking	$u(B)$	—	Rectangular	0,500 m	5,000 m	10,000 m	15,000 m	20,000 m	0,002 m	0,020 m	0,060 m	0,100 m	0,200 m
	Man-made channels	Manual measurement	$u(B)$	—	Triangular	Not applicable	0,500 m	1,000 m	1,500 m	2,000 m	0,001 m	0,001 m	0,001 5 m	0,001 5 m	0,001 5 m

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1) ISO/IEC Guide 98-3 will be published as a reissue of the GUM:1995.

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