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Hydrometry — Determination of liquid flow in open channels

Hydrométrie - Mesurage du débit des liquides dan les canaux décourts

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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ISO 18320 was prepared by Technical Committee ISO/113, Hydrometry, Subcommittee SC 1, Velocity Area Methods.

This edition cancels and replaces precious editions. Most of the clauses have been updated and technically revised. Major revisions have been made to Clause 5, including a new figure of a stage-discharge relationship and shift curves., Clause 7 has been revised to be consistent with new standards on uncertainty.

Hydrometry — Measurement of liquid flow in open channels

1 Scope

ISO 18320 specifies methods of determining the stage-discharge relationship for a gauging station. A sufficient number of discharge measurements, complete with corresponding stage measurements, are required to define a stage-discharge relationship to the accuracy required by this Standard.

Stable and unstable channels are considered, including brief descriptions of the effects on the stage-discharge relationship of the transition from inbank to overbank flows, shifting controls, variable backwater and hysteresis. Methods of determining discharge for twin-gauge stations, ultrasonic velocity-measurement stations, electromagnetic velocity-measurement stations and other complex rating curves are not described in detail. These types of rating curves are described separately in other International Standards, Technical Specifications and Technical Reports, which are listed in the Bibliography.

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 748, *Hydrometry — Measurement of liquid flow in open channels using current-meters or floats*

ISO 772, *Hydrometry — Vocabulary and symbols*

ISO 5168, *Measurement of fluid flow — Procedures for the evaluation of uncertainties*

ISO 9123, *Measurement of liquid flow in open channels — Stage-fall-discharge relationships*

ISO 15769, Hydrometry—Guidelines for application of acoustic velocity meters using Doppler and echo correlation methods

ISO/TR 24578, Hydrometry—Acoustic Doppler Profiler—Method and application for the measurement of flow in open channels

ISO 4373 Hydrometry - water level measuring devices

3 Symbols

For the purposes of this document, the symbols given in ISO 772 and the following apply:

A wet cross-sectional area

B cross-sectional width

β power-law exponent (slope on logarithmic plot) of the rating curve

C_D coefficient of discharge

C Chezy's channel roughness coefficient

e effective gauge height of zero flow

f Darcy-Weisbach friction factor

g acceleration due to gravity

h gauge height of the water surface

$(h - e)$ effective depth, this is basically the difference between the cease to flow level and the gauge reading. For example, for a horizontal control with a gauge zero at the same level as the crest of the control, e will be effectively zero

H total head (hydraulic head)

k height of roughening above smooth surface

k_s Nikuradse equivalent sand roughness size

n Manning's channel roughness coefficient

N number of stage-discharge measurements (gaugings) used to define the rating curve

p number of rating-curve parameters (Q_1, β, e) estimated from the N gaugings

P wetted perimeter

Q total discharge

Q_o steady-state discharge

Q_1 power-law scale factor of rating curve, equal to discharge when effective depth of flow $(h - e)$ is equal to 1

R hydraulic radius, equal to the effective cross-sectional area divided by the wetted perimeter, A/P_w (only strictly suitable for inbank flows)

Re Reynolds number ($= 4\bar{V} / \nu$)

Note -. some reference texts use a characteristic dimension of four times the hydraulic radius, because it gives the same value of Re for the onset of turbulence as in pipe flow,[15] . Other texts use the hydraulic radius as the characteristic length-scale, with consequently different values of Re for transition and turbulent flow.

S standard error of estimate

S_f friction slope

S_0 bed slope

S_w water surface slope corresponding to steady discharge

t time

u standard uncertainty

$\bar{v}$ stream mean velocity (= Q/A)

U expanded uncertainty

V_w velocity of a flood wave

ν kinematic viscosity

4 Principle of the stage-discharge relationship

4.1 General

The relationship at a gauging station between stage and discharge is commonly referred to as the stage-discharge relationship, rating curve or rating. A stage-discharge relationship is developed to enable the future production of a time series of discharge based on continuous stage measurements at the gauging station. It is generally much easier to continuously measure stage than it is to measure discharge. Hence, once a stable stage–discharge relationship has been established at a gauging station, the creation of a record of discharge is greatly simplified.

4.2 Controls

The stage-discharge relationship for open-channel flow at a gauging station is governed by channel conditions at and downstream from the gauge, referred to as a control. Two types of control can exist, depending on channel and flow conditions. Low flows ie those experienced during dry weather, are usually controlled by a section control, whereas high flows ie those experienced after stormy and wet weather, are usually controlled by a channel control. Medium flows can be controlled by either type of control. At some stages, a combination of section and channel control might occur. These are general rules, and exceptions can and do occur. Knowledge of the channel features that control the stage-discharge relationship is important. The development of stage-discharge curves where more than one control is effective, where control features change and where the number of measurements is limited requires judgement in interpolating between measurements and in extrapolating beyond the highest or lowest measurements. This is particularly true where the controls are not stable and tend to shift from time to time, resulting in changes in the positioning of segments of the stage-discharge relationship.

High flows may cause a channel to overflow its banks and inundate any adjoining floodplains. Under these circumstances, some of the discharge will be contained in the main river channel and some takes place over the floodplains. A distinction should therefore be made between when the discharge is wholly inbank or when flow has exceeded the bankfull capacity. The stage-discharge relationship will be affected by the transition from inbank to overbank flow arising from the changing hydraulic conditions. The description of the types of control is given in Annex A

4.3 Governing hydraulic equations

Stage-discharge relationships can be defined according to the type of control that exists. Section controls, either natural or man-made, are governed by some form of the weir or flume equations. In a very general and basic form, these equations are expressed as:

$$Q = C_D B H^{\beta} \tag{1}$$

where

Q is the discharge, in cubic metres per second;

C_D is a coefficient of discharge and includes several factors;

B is the cross-sectional width perpendicular to the direction of flow, in metres;

H is the hydraulic head, in metres;

β is a power-law exponent, dependent on the cross-sectional shape of the control section.

Stage-discharge relationships for channel controls with uniform flow are typically governed by the Manning, (in Europe this is sometimes known as Manning- Strickler equation), Chezy, and Darcy-Weisbach equation as they apply to the reach of the controlling channel upstream and downstream from a gauge.

The Manning equation is:

$$Q = (AR^{0.67}\ S_f^{0.5})\ /\ n \qquad (2)$$

where

A is the cross-sectional area, in square metres;

R is the hydraulic radius, in metres;

S_f is the friction slope;

n is the Manning's channel roughness.

Note that the Strickler coefficient is just the inverse of Manning's n.

The Chezy equation is:

$$Q = CAR^{0.5}S_f^{0.5} \qquad (3)$$

where C is the Chezy form of roughness.

The Darcy-Weisbach equation is:

$$Q = \left(\frac{8g}{f}\right)^{0.5} AR^{0.5} S_f^{0.5} \qquad (4)$$

where g is acceleration due to gravity, and f is the friction factor, given by the Colebrook- White equation, which may be used for open channels:

$$\frac{1}{\sqrt{f}} = -2.0 \log_{10}\left[\frac{k_s}{14.8R} + \frac{2.51}{\left(4\overline{V}R/\nu\right)\sqrt{f}}\right] \qquad (5)$$

where $\overline{V}$ is the mean stream velocity, k_s = Nikuradse roughness size and ν = kinematic viscosity.

The variation of f with relative roughness (= $k_s/4R$) and Reynolds number, ($R_e = 4\bar{V}/\nu$) is often shown plotted in the form of the so-called 'Moody diagram' (f versus Re and $k_s/4R$). The roughness of any surface is then characterised by k_s, the so-called Nikuradse equivalent sand roughness size. The Colebrook-White equation is physically well founded, since it tends towards two theoretically limiting cases, one for hydraulically smooth surfaces and another for hydraulically rough surfaces; and the shape of the channel is captured through use of appropriate coefficients.

The above equations are generally applicable for steady or quasi-steady inbank flows. For highly unsteady flow, such as tidal or dam-break flow, equations such as the Saint-Venant unsteady-flow equations would be necessary. However, these are seldom used in the development of stage-discharge relationships and are not described in this standard. Overbank flows typically require special attention due to the strong interaction between the flows in different regions of the channel, giving rise to significant lateral momentum transfer effects. For overbank flows, the hydraulic radius ($R = A/P$) adopted in the equations (2) to (4) is no longer appropriate for characterising the cross-section of the channel as P will increase at a higher rate with stage than A due to the additional wetted perimeter of the floodplain as the flow goes overbank. This in turn will lead to a dramatic reduction in R at the bankfull stage and a consequent apparent decrease in the resistance coefficient for the whole section, even though the actual hydraulic roughness increases. Under these circumstances, the individual resistance coefficients for the main channel and floodplains also need re-defining, as explained further in Annex E and Equation (6).

A full description of the complexities of stage–discharge relationships is given in Annex B.

5 Stage-discharge calibration of a gauging station

5.1 General

The primary object of a stage-discharge gauging station is to provide a record of the discharge of the open channel or river at which the water level gauge is sited. This is achieved by measuring the stage and converting this stage to discharge by means of a stage-discharge relationship which correlates discharge and water level. In some instances, other parameters, such as index velocity, water surface fall between two gauges or rate-of-change in stage, can also be used in rating-curve calibrations as given in ISO 15769 and ISO 9123. Stage-discharge relationships are usually calibrated by measuring discharge and the corresponding gauge height. Theoretical computations can also be used to aid in the shaping and positioning of the rating curve. Stage-discharge relationships from previous time periods should also be considered as an aid in the shaping of the rating curve.

5.2 Preparation of a stage-discharge relationship

5.2.1 General

The relationship between stage and discharge is defined by plotting measurements of discharge with corresponding observations of stage, taking into account whether the discharge is steady, increasing or decreasing, and also noting the rate of change in stage. This can be done either manually by plotting on paper or automatically using computerized plotting techniques (see Annex C). The plotting scale used can be an arithmetic scale or a logarithmic scale. Each has certain advantages and disadvantages, as explained in 5.2.3 and 5.2.4. Most national hydrological services plot the stage as ordinate (Y axis) and the discharge as abscissa (X axis). However, when using the stage-discharge relationship to derive discharge from a measured value of stage, the stage is treated as the independent variable.

For gauging sites where there is significant flow in the floodplain, through multiple channels or via submerged structures, the determination of the composite stage discharge relationship is prone to difficulty. Poor or unsafe access can mean that flood flows cannot be adequately measured. In addition to this, flow across a floodplain can be complex, and is impacted by changes in storage as a flood builds up or ebbs. The extent of these complexities can mean that theoretical considerations have to be used in conjunction with the limited measurements when determining the stage-discharge relationship.

5.2.2 List of discharge measurements

The first step prior to plotting a stage-discharge relationship is the preparation of a list of discharge measurements that will be used for the plot. The measurements should be checked to ensure that the recorded stages are related to a common datum and that the discharge calculations are accurate. As a minimum, this list should include 15 measurements, all taken during the period of analysis. More measurements would be required for a compound rating curve, i.e. one that is represented by multiple hydraulic controls, or if the site experiences an extreme range in stage. For a general purpose gauging station, these measurements should be well distributed over the range of gauge heights experienced. Alternatively, where a specific flow range is to be observed, the measurements should cover that range. For example, at low flows for a site that is intended to inform a low flow management system, or at high flows where flood flows are to be monitored and managed. The list of measurements should include low and high measurements across the desired flow range, particularly if extrapolation of the rating curve is to be done.

For each discharge measurement in the list, the following items are required (see Table 1):

1. a unique identification name of site, and gauging number;
2. the date of measurement and time of start and time of finish of gauging;
3. The name of the person undertaking or leading the gauging, as well as the type of instruments used to measure the discharge, the average gauge height, based on a minimum of the readings at the start and end of the complete gauging.
4. the total discharge;
5. an indication of the likely accuracy of measurement, as determined by the person leading the gauging e.g. was the channel heavy with weed, were extensive vortices evident in the flow pattern, was the cross section uniform, was the flow steady. Documentary evidence of the channel and flow conditions at the time of each gauging can also be compiled using photographic or video recordings.

Table 1 — List of discharge measurements made by a hydrometric practitioner using current meters and depth soundings

ID number	Date (yy/mm/dd)	Made by	Width m	Area m²	Mean velocity m/s	Average gauge height m	Effective depth m	Discharge m³/s	Method	Number of verticals	Gauge height change m/h	Rated
12	78/04/08	MEF	36,27	77,94	1,272	2,682	2,080	99,12	0,2/0,8	22	−0,082	GOOD
183	85/02/06	GTC	33,53	78,41	1,405	2,786	2,186	110,2	0,6/0,2/0,8	22	−0,047	GOOD
201	87/02/04	AJB	28,96	21,92	1,511	2,002	1,402	33,13	0,6/0,2/0,8	21	−0,013	POOR
260	93/03/13	GMP	26,52	21,46	1,400	1,981	1,381	30,02	0,6	22	−0,020	GOOD
313	96/08/24	HFR	30,18	42,08	1,602	2,374	1,774	67,40	0,6/0,2/0,8	22	+0,006	GOOD
366	03/08/21	MAF	28,96	14,86	0,476	1,557	0,957	7,080	0,6	21	0	GOOD
367	03/10/10	MAF	28,96	13,66	0,361	1,490	0,890	4,928	0,6	21	0	GOOD
368	03/11/26	MAF	29,26	14,21	0,373	1,509	0,909	5,296	0,6	18	0	GOOD
369	04/02/19	MAF	29,87	16,26	1,291	1,838	1,238	20,99	0,6	21	0	GOOD
370	04/04/09	MAF	29,26	21,27	0,805	1,780	1,180	17,13	0,6/0,2/0,8	21	0	GOOD
371	04/05/29	MAF	29,57	19,69	0,688	1,710	1,110	13,54	0,6	21	0	GOOD
372	04/07/10	MAF	28,96	16,81	0,458	1,573	0,973	7,703	0,6	21	0	GOOD
373	04/08/22	MAF	29,26	15,79	0,481	1,570	0,970	7,590	0,6	21	0	GOOD
374	08/10/01	MAF	29,26	13,19	0,264	1,414	0,814	3,483	0,6	21	0	GOOD
375	09/11/11	MAJ	28,96	11,71	0,283	1,396	0,796	3,313	0,6	21	0	GOOD
382	10/10/01	MAF	30,48	43,76	1,598	2,432	1,832	69,95	0,2/0,8	21	+0,017	GOOD

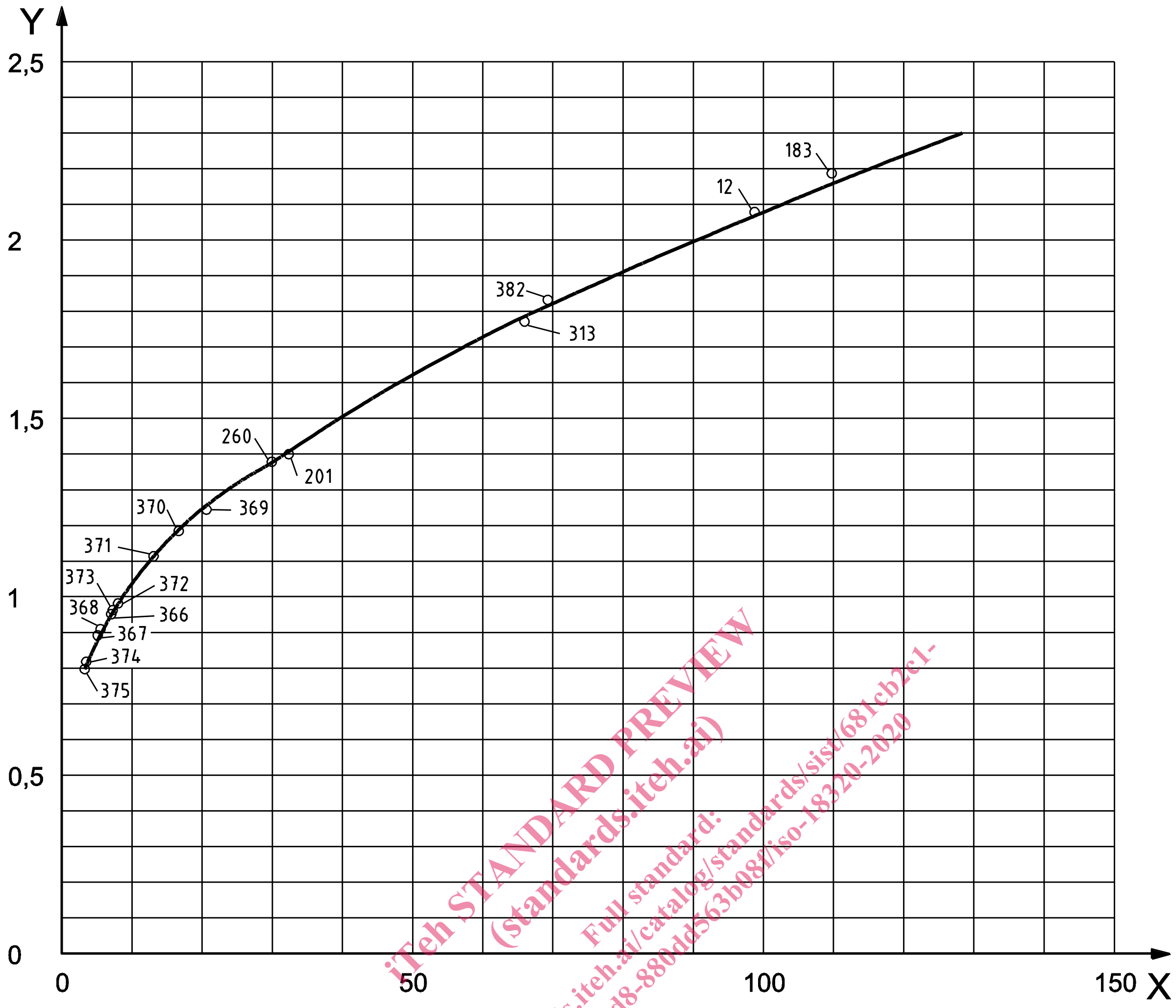
NOTES 1. Discharge measurements made with acoustic Doppler current profilers require additional parameters, including the number of transects and the range of discharges measured during the transects (see ISO/TS 24578).

2. In terms of uncertainty of the stage discharge relationship, a relationship is regarded as 'poor if its uncertainty is >15%. A 'good' relationship has uncertainty of +/- 5%

5.2.3 Arithmetic plotting scales

The simplest type of plot uses an arithmetically divided plotting scale, as shown in Figure 1. Scale subdivisions should be chosen to cover the complete range of gauge height and discharge expected to occur at the gauging site. Scales should be subdivided in uniform increments that are easy to read and interpolate. The choice of scale should also produce a rating curve that is not unduly steep or flat. If the range in gauge height or discharge is large, it may be necessary to plot the rating curve in two or more segments to provide scales that are easily read with the necessary precision. This procedure can result in separate curves for low water, medium water and high water.

Where a hand derived relationship is required, graph paper with arithmetic scales is convenient to use and easy to read. Such scales are ideal for displaying a rating curve and have an advantage over logarithmic scales in that zero values of gauge height and/or discharge can be plotted. However, for analytical purposes, arithmetic scales have practically no advantage. A stage-discharge relationship on arithmetic scales is usually a curved line, concave downward, which is difficult to shape correctly if only a few discharge measurements are available. Logarithmic scales, on the other hand, have a number of analytical advantages as described in 5.2.4. Generally, a stage-discharge relationship is first drawn on logarithmic plotting paper for shaping and analytical purposes and then later transferred to arithmetic plotting paper if a display plot is needed.



Key

X discharge, Q, in cubic metres per second

Y effective depth, $(h - e)$, in metres

NOTE The numbers indicated against the plotted observations are the ID numbers given in Table 1.

Figure 1 — Arithmetic plot of stage-discharge relationship

5.2.4 Logarithmic plotting scales

Most stage-discharge relationships, or segments thereof, can be analysed graphically through the use of logarithmic plotting. There are two methods that can be used to fully utilize this procedure; by plotting effective

depth of flow, also known as hydraulic head, versus discharge, or by applying scale offsets to the gauge height axis and plotting gauge height versus discharge. Effective depth of flow on the control, or hydraulic head, for a section control is computed by subtracting the gauge height of zero discharge (also known as cease to flow gauge height) from the gauge height associated with the measured discharge. In theory, a straight line relation in log space can be achieved by plotting the effective depth versus discharge. Similarly, the gauge height of zero discharge for a section control, can be used as a scale offset for the gauge height axis in log space to also achieve a straight line segment. The offset approach allows for plotting of actual gauge height versus discharge which provides some simplification to the process as real data does not need to be transformed.

The approaches discussed above are simple to apply for section type controls. Channel type controls present a more complicated situation. When a reach is under channel control there is not a single cross section of the channel that is controlling the height of the water at the gauge, rather the reach characteristics, including geometry, slope, and roughness, where the gauge is located controls the height of water. Because of this, it is not feasible to measure and determine the gauge height of zero discharge (cease to flow) of the channel control. Without this determination, one is unable to plot the effective depth (hydraulic head) versus discharge in log space. For the offset approach, the determination of the proper offset must be made through a trial-and-error approach. The trial-and-error approach is applied by iteratively adjusting the offset on the gauge height axis and visually examining the plot of actual gage height versus discharge for measurements under the channel control for a straight line relation. For gauges that experience multiple hydraulic controls, such as section and channel, multiple offsets are required to obtain straight line segments for each control.

Regardless of the approach taken, a rating-curve segment for a given control will then tend to plot as a straight. The slope of the straight line should conform to the type of control section, thereby providing valuable information for correctly shaping the rating-curve segment. Additionally, this feature allows the analyst to calibrate the stage-discharge relationship with fewer discharge measurements. The slope of a rating curve is the ratio of the horizontal distance to the vertical distance. This method of measuring the slope is used since the dependent variable (discharge) is always plotted as the abscissa.

Figure 2 is a logarithmic plot of an actual rating curve, using the measurements shown in Table 1. This rating curve is for a stream where section control exists throughout the range of flow, including the high-flow measurements. The effective gauge height of zero flow, *e*, for this stream is 0,6 m, which is subtracted from the gauge height of the measurements to define the effective depth of flow at the control. The slope of the rating curve below 1,4 m is about 4,3, which is greater than 2 and conforms to a section control. Above 1,5 m, the slope is 2,8, which also conforms to a section control. The change in slope of the rating curve above about 1,5 m is caused by a change in the shape of the control cross-section.