INTERNATIONAL STANDARD

ISO 18320

First edition
2020-07

Hydrometry — Measurement of liquid flow in open channels — Determination of the stage–discharge relationship

Hydrométrie — Measurage du débit des cours d'eau — Détermination de la relation hauteur–débit

Reference number
ISO 18320:2020(E)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 113, *Hydrometry*, Subcommittee SC 1, *Velocity area methods*.

This first edition of ISO 18320 cancels and replaces ISO 1100-2:2010, which has been technically revised.

The main changes compared to the previous edition are as follows.

— 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.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Hydrometry — Measurement of liquid flow in open channels — Determination of the stage–discharge relationship

1 Scope

This document specifies methods of determining the stage–discharge relationship for gauging stations. It specifies an accuracy for defining the stage–discharge relationship based on a sufficient number of discharge measurements, complete with corresponding stage measurements.

This document considers stable and unstable channels and includes 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 and other complex rating curves are not described in detail.

NOTE 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 documents are referred to in the text in such a way that some or all of their content constitutes requirements 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*

3 Terms, definitions and symbols

3.1 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.2 Symbols

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

Symbol	Definition
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

a 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[16]. Other texts use the hydraulic radius as the characteristic length-scale, with consequently different values of Re for transition and turbulent flow.

Symbol	Definition
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
Pw	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_h	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 (= $4\bar{V}/\nu$)[a]
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

[a] 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[16]. Other texts use the hydraulic radius as the characteristic length-scale, with consequently different values of Re for transition and turbulent flow.

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, that is, those experienced during dry weather, are usually controlled by a section control, whereas high flows, that is, 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 stream or river 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 formulae

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 formulae. In a very general and basic form, these formulae are expressed as shown by Formula (1):

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

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 formula), Chezy, and Darcy-Weisbach formulae, as they apply to the reach of the controlling channel upstream and downstream from a gauge.

The Manning formula is shown by Formula (2):

$$Q=\left(A{r_{\mathrm{h}}}^{0{,}67}\,{S_{\mathrm{f}}}^{0{,}5}\right)/n \qquad (2)$$

where

A	is the cross-sectional area, in square metres;
r_{h}	is the hydraulic radius, in metres;
S_{f}	is the friction slope;
n	is the Manning's channel roughness.

NOTE The Strickler coefficient is just the inverse of Manning's n.

The Chezy formula is shown by Formula (3):

$$Q=CA{r_{\mathrm{h}}}^{0{,}5}{S_{\mathrm{f}}}^{0{,}5} \qquad (3)$$

where C is the Chezy form of roughness.

The Darcy-Weisbach formula is shown by Formula (4):

$$Q=\{8g/f\}^{0{,}5}\,A\,{r_{\mathrm{h}}}^{0{,}5}\,{S_{\mathrm{f}}}^{0{,}5} \qquad (4)$$

where

g	is acceleration due to gravity;
f	is the friction factor, given by the Colebrook-White formula,

which may be used for open channels, see Formula (5):

$$\mathrm{f}^{-0{,}5}=-2\log_{10}\left\{k_{\mathrm{s}}/\left(14\,0{,}8r_{\mathrm{h}}\right)+2{,}51/\left(4\bar{V}\,r_{\mathrm{h}}/v\right)f^{0{,}5}\right\} \qquad (5)$$

where

$\bar{V}$	is the mean stream velocity;
k_{s}	is the Nikuradse roughness size;
ν	is the kinematic viscosity.

The variation of f with relative roughness (= $k_{\mathrm{s}}/4\,r_{\mathrm{h}}$) and Reynolds number is often shown plotted in the form of the so-called "Moody diagram". The roughness of any surface is then characterized by k_{s}, the so-called "Nikuradse equivalent sand roughness size". The Colebrook-White formula 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 formulae are generally applicable for steady or quasi-steady inbank flows. For highly unsteady flow, such as tidal or dam-break flow, formulae, such as the Saint-Venant unsteady-flow formulae, would be necessary. However, these are seldom used in the development of stage–discharge relationships and are not described in this document. 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 adopted in Formulae (2) to (4) is no longer appropriate for characterizing the cross-section of the channel as *Pw* will increase at a higher rate with stage than *A* due to the additional wetted perimeter of the floodplain as the flow goes over bank. This in turn will lead to a dramatic reduction in r_h 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 Formula (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 objective 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 should 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 general rule, this first list shall include a minimum of 15 measurements, all taken during the period of analysis. More measurements will be required for a compound rating curve, i.e. one that is represented by multiple hydraulic controls, if the site experiences an extreme range in stage, is governed by a shifting control due to sedimentation, erosion or seasonal vegetation growth, or if the gauging site is otherwise problematical and the uncertainties in measurement could be high. 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.

Uncertainty analysis (see Clause 7) should be undertaken when developing and analysing the stage–discharge relationship such that it takes due cognisance of the quality of the gauging data and the performance of the rating. If the potential uncertainties are considered to be relatively high, i.e. greater than 10 % to 15 % at the 95 % confidence level, then more frequent gaugings may be required targeting the critical stage range(s) of concern.

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

a) A unique identification name of site, and gauging number.

b) The date of measurement and time of start and time of finish of gauging.

c) 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.

d) The total discharge.

e) An indication of the likely accuracy of measurement, as determined by the person leading the gauging, e.g. whether the channel was heavy with vegetation, whether extensive vortices were evident in the flow pattern, whether the cross section was uniform, whether the flow was 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

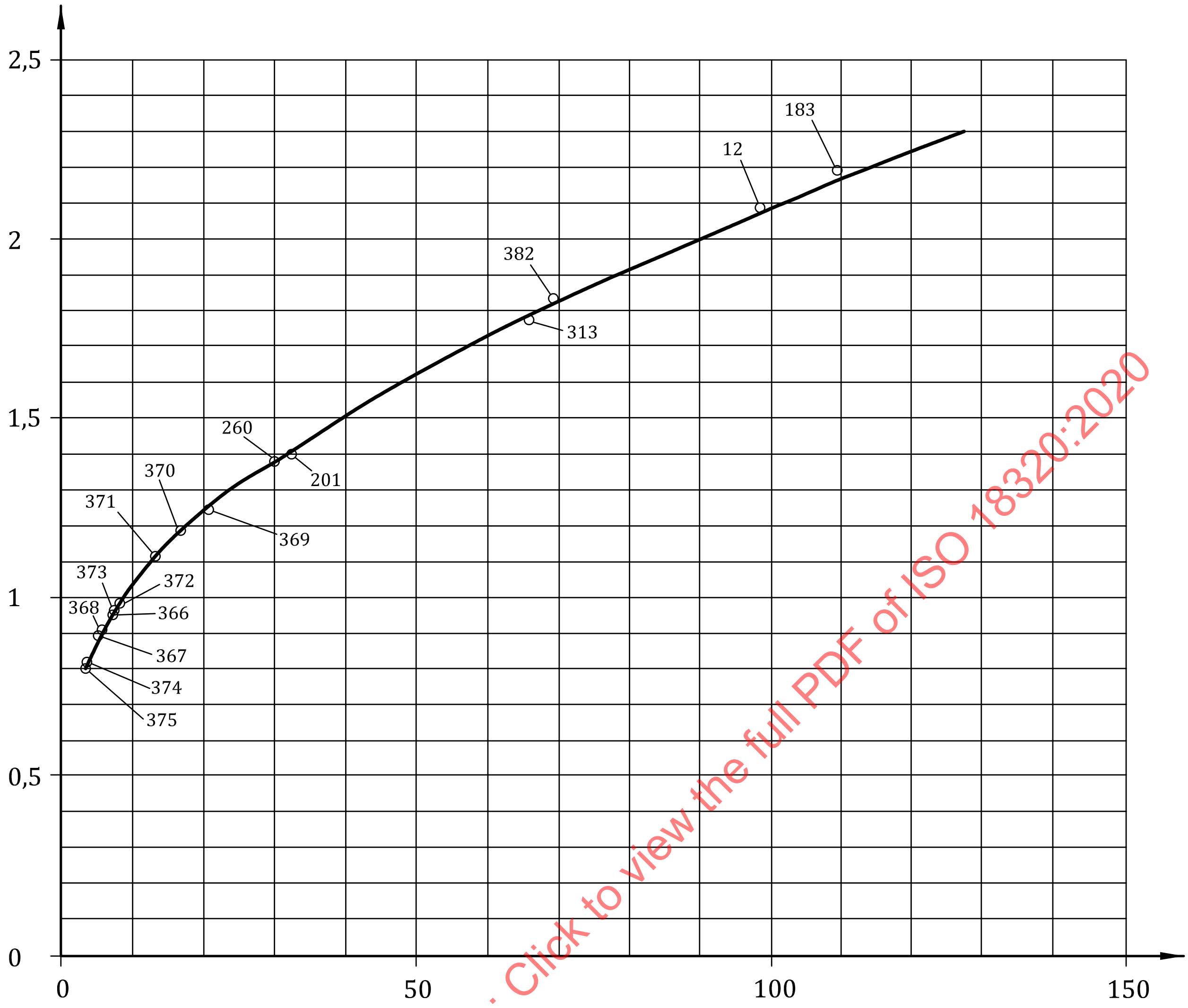
NOTE 1 Discharge measurements made with acoustic Doppler current profilers require additional parameters, including the number of transects and the range of discharges measured during the transects (see ISO/TR 24578).

NOTE 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

Y effective depth, (*h* − *e*), in metres

X discharge, *Q*, in cubic metres per second

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

Figure 1 — Arithmetic plot of stage–discharge relationship

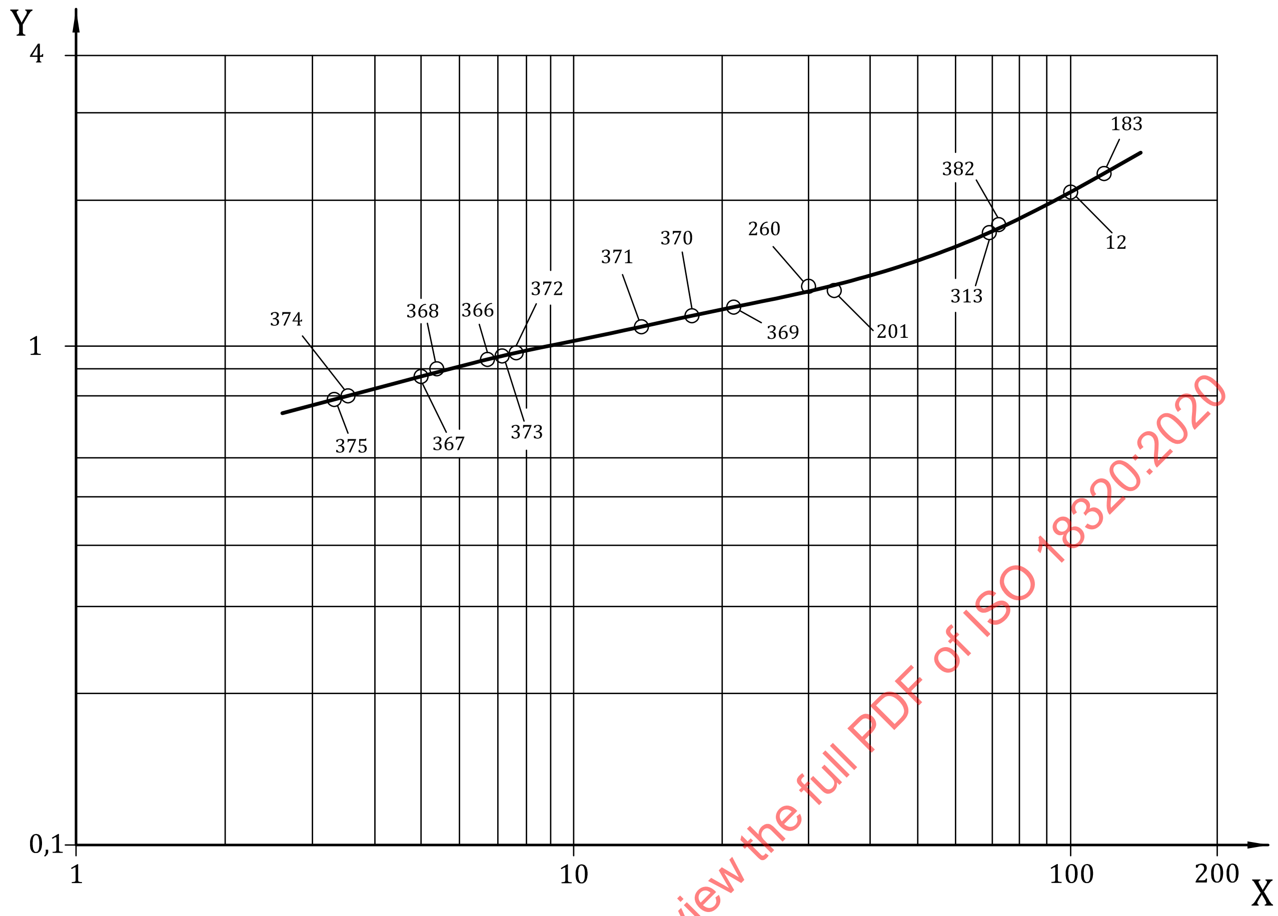
5.2.4 Logarithmic plotting scales

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 of the channel control. Without this determination, one is unable to plot the effective depth versus discharge in log space. For the offset approach, the determination of the proper offset shall 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 line. 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, which is plots effective depth (not gauge height) versus discharge, 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 or another section control downstream from the low-water section control.



Key

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

X discharge, Q, in cubic metres per second

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

Figure 2 — Logarithmic plot of stage–discharge relationship

Rating curves for section controls such as weirs or flumes conform to Formula (1) and, when plotted logarithmically, will have a slope of 1,5 or greater, depending on control shape, velocity of approach and minor variations of the coefficient of discharge. Horizontal crested structures will have a slope of about 1,5, whereas V shaped structures will have slopes of about 2,5. Rating curves for channel controls are governed by one of the standard Formulae (2) to (4) and, when plotted as effective depth versus discharge, the slope is usually between 1,5 and 2. Variations in the slope of the rating curve when channel control exists are the result of changes in roughness and friction slope as depth changes. The effective depth is sometimes not known for channel controls. It can be determined mathematically and statistically during the stage–discharge development process using an iterative process whereby the parameters C, β and e are optimised to give the best fitting relationship taking due account of the physical properties of the channel.

5.2.5 Commercially available software

There are a number of commercially available software packages that can analyse a series of stage and discharge measurements and derive the best stage–discharge relationship (see Annex C). Most packages also give the statistics relating to the standard error and uncertainty of the derived relationship. This also applies to the use of logarithmic stage to flow relationships as covered in 5.2.4

5.2.6 Rating-curve shape

5.2.6.1 General

The details provided in 5.2.2 to 5.2.4 apply to control sections of regular shape (trapezoidal, parabolic, etc.). However, natural channels are rarely regular in section hence the practitioner should be aware of where “step changes” in the stage–discharge relationship are likely to occur. Where a significant change in shape or flow control occurs, there will be a change in the rating-curve slope at that point. These changes are usually defined by short curved segments of the rating curve, referred to as transitions. This information about the plotting characteristics of a rating curve is extremely useful in the calibration and maintenance of the rating curve and in later analysis of shifting control conditions. By knowing the kind of control (section or channel), and the shape of the control, the analyst can define the correct hydraulic shape of the rating curve with greater precision. Additionally, this information allows the analyst to extrapolate accurately a rating curve or, conversely, to know when extrapolation is likely to lead to a large uncertainty.

Examples of a hypothetical rating curves are given in Annex D.

5.2.6.2 Gauge height of zero flow

The actual gauge height of zero flow is the gauge height of the lowest point in the control cross-section for a section control. This is sometimes referred to as the cease-to-flow. For natural channels, this value can sometimes be measured in the field by measuring the depth of flow at the deepest place in the control section and subtracting this depth and the velocity head from the gauge height at the time of measurement.

The effective gauge height of zero flow is a value that, when subtracted from the mean gauge heights of the discharge measurements, will cause the logarithmic rating curve segment for specific to that control to plot as a straight line. Thus, it should be determined for each rating-curve segment. For regularly shaped section controls, this value will be close to the actual gauge height of zero flow. For channel controls there is not a single cross section that controls the stage discharge relation. For these controls, the effective gage height of zero flow is determined by a trial-and-error method of plotting. A value is assumed and adjusted gauge heights are plotted based on this assumed value. If the resulting curve shape is concave upward, then a somewhat larger value for the effective gauge height of zero flow should be used. A somewhat smaller value should be used if the curve plots concave downward. Usually, only a few trials are needed to find a value that results in a straight line for the rating-curve segment.

Formula (6) shows a rating curve that plots as a straight line on logarithmic paper:

$$Q=Q_1\,(h-e)^{\beta} \tag{6}$$

where

$(h-e)$ is the effective depth of water on the control;

h is the gauge height of the water surface;

e is the effective gauge height of zero flow or offset;

β is the slope of the rating curve when plotted on logarithmic paper if discharge is plotted on the abscissa;

Q_1 is a scale factor that is numerically equal to the discharge when the effective depth of flow $(h-e)$ is equal to 1.

5.3 Curve fitting

5.3.1 General

There are a number of software packages (see Annex C) to aid the creation of the stage–discharge relationship given a series of flow measurements at specific stages at the observation site. Such packages contain additional analytical tools that help describe the accuracy and standard errors associated with the rating curve. However, for proponents of hand-based curve fitting, the curve-fitting process for stage–discharge relationships includes the actual drawing, positioning and shaping of the rating curve. Hydraulic-analysis and line-fitting applications can be used to aid in the curve-fitting process but the stage–discharge relationship should represent the best fit of the calibration measurements over the range of measurements and with considerations for the quality or uncertainty of the measurements, as well as the conditions of the hydraulic control.

Nevertheless, for a site with a varying flow control due to, for example, seasonal vegetation growth, every measurement does not need to fit on the same rating curve. A particular gauge location can have a number of ratings that apply to specific control conditions in the channel. The curves produced by the curve fitting process should give stage–discharge relationships that reflect the particular control changes. Further, only measurements made under similar control conditions should be used when developing the rating curve. For example, measurements associated with vegetation on the control should not be included with measurements associated with clear control (no vegetation) conditions when developing a rating curve for clear control conditions.

5.3.2 Hydraulic-formula curves

The shape of stage–discharge relationships can be defined through the use of hydraulic formulae, namely Formulae (1), (2), (3) and (4). Where section control exists, the weir formula, Formula (1), can be used to compute rating-curve points. Coefficients of discharge, C_D, have been defined in other International Standards for certain types of weirs and flumes, so a reasonably accurate rating curve can be computed that will conform to correct hydraulics. For natural section controls, such as a rock outcrop or gravel bar, the coefficient of discharge can be estimated on the basis of calibration measurements. Widths and depths can be determined from a surveyed cross-section of the control section.

Where estimated channel roughness (e.g. Manning’s n) and friction slope are used to compute a rating formula, it shall be recognized that these parameters will vary with stage, and one value cannot be assumed to hold true across the whole range of flow. This aspect is even more important for vegetated and alluvial channels.

A discussion on how channel roughness, hydraulic properties, and the shape of the stage–discharge rating curve vary with stage is given in Annex E.

For segments of the rating curve that are influenced by channel control, the shape of the rating curve can also be defined in a piece-wise manner through the use of Formulae (2) to (4). An average or typical cross-section in the control reach is surveyed to define the channel characteristics of cross-sectional area and hydraulic radius. The Manning roughness, n, the Chezy channel roughness coefficient, C, or the Darcy-Weisbach friction factor, f, is estimated from field observations.

The friction slope can be estimated from channel surveys, maps or calibration measurements. Formulae (2) to (4) can then be used to compute discharge for a few selected gauge heights to define the shape of the rating curve. If uniform flow is assumed, then $S_f = S_o$. This is a simplified procedure which assumes steady, uniform flow.

More complex situations involving non-uniform flow can be analysed with various techniques of backwater curve computation. Computer software is available for such analyses which allow distinction to be made between overall (1-D), zonal (sub-area), depth-averaged (2-D or slice) and local friction factors (3-D). Such analyses allow for how the stage–discharge relation is influenced by both cross-sectional shape and variation in roughness with depth.

For both section and channel control, the rating curve computed by the hydraulic formulae is used only for defining the shape of the rating curve. The correct position of the rating curve is however, defined by stage–discharge measurements and not necessarily by the frictional characteristic of the channel and section. This procedure can also be used to aid in determining when measurements define a new rating-curve position.

Hydraulic models are usually helpful to guide the high-flow extrapolations, but usually not effective in accurately simulating the medium and low-flow ranges accurately.

5.3.3 Mathematical rating curves

The stage–discharge relationship can be defined by mathematical computations, such as regression or maximum-likelihood techniques. Several formulae might be required to define the rating-curve formula, particularly if the channel geometry is complex. Care should be taken when deriving the rating curves for segment transitions. It is important that the rating-curve shape is hydraulically correct.

5.3.4 Software packages to aid the determination of the rating curve

There are a number of software packages available that can be used to determine the form of the rating curve. These are listed in Annex C. It should be noted however, that these are examples of suitable products available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of these products.

5.4 Combination-control stage–discharge relationships

A stage–discharge relationship can be determined by the combination of two or more hydraulic controls in the river. In this circumstance, the rating curve will be composed of several segments, each of which is governed by one of the hydraulic controls. When stage increases, a new control can become the influence on the stage discharge relationship. For instance, a rock riffle section can act as the control at extremely low flows, but at higher flows, a different control either located further downstream from the rock riffle, or channel control can cause submergence of the rock riffle, and hence become the controlling section for medium flows.

In other situations, section controls and channel controls can become embedded. For instance, where a thin-plate weir in situated within a larger broad-crested weir, the thin plate weir will control a segment of the rating curve in addition to the broad-crested weir. For the overbank flow range, the stage–discharge relationship can be computed by either adding the floodplain controls to the main channel control, or by assuming a single compound control that combines the main channel and the floodplain controls.

This effectively creates a multi-phase or composite calibration with different stage–discharge relationships for different ranges of stage. These ranges cross where a distinct change in trend of the scatter of all measurements occurs on a graphical representation. The best way to illustrate the different ranges of the stage–discharge relationship is therefore a graphical plot of the flow measurements. In addition to this, any observational notes taken by the observer at the time of the measurements, can be used to identify the location and type of hydraulic control. This additional information can prove essential in defining a multi-segment stage–discharge relationships.

5.5 Stable stage–discharge relationships

A stable stage–discharge relationship is one that does not vary, or change position, over a period of time. Such a relationship results from stable channel and control conditions, which for natural channels is a relative term. Virtually all natural channels are subject to at least occasional change as a result of scour, deposition or growth of vegetation.

For stable channels and controls, the stage–discharge relationship can usually be defined easily by fitting a curve to the calibration measurements as described in previous subclauses. The example shown in Figure 2 represents a stable stage–discharge relationship as the control is a natural section of rock outcrop that is not subject to change. Shifts of this rating curve can occur, however, because of debris that might accumulate on the control.

5.6 Unstable stage–discharge relationships

Unstable stage–discharge relationships are defined as those that shift and change positions frequently due to variations in the hydraulic control. Channel geometry and friction properties, i.e. the control characteristics, vary continuously over time, and hence, so does the stage–discharge relationship. These changes are likely to occur during floods and during periods when ice or vegetative growth occur. Channel scour and deposition can be a frequent occurrence in some channels due to the nature of the bed and bank materials, thus causing shifts of the rating curve. Likewise, weeds, trees and other vegetation may affect the relationship between stage and discharge during certain times of the year.

It is usually not possible to define all changes of the rating curve with discharge measurements for unstable channels and controls. Shifting-control techniques should be used to estimate the position of the rating curve during periods of time between measurements. These techniques are described in 5.7.

For some gauging stations where unstable channel conditions exist, it is sometimes advisable to install a weir or flume, if practicable and economically justifiable, to establish a stable rating curve. Other, less frequently used, methods of defining an unstable rating curve include the stage-fall method, which uses two stage gauges and the ultrasonic method. These methods are described in ISO 9123 and ISO 6416.

In gauging stations with unstable channel and flow conditions, it will be necessary to do more frequent discharge measurements to reduce the uncertainty of the determination of stage–discharge relationship.

5.7 Shifting controls

Shifting controls occur when channel conditions are unstable. When this condition exists, discharge measurements made at different times but at a specific value of stage, record a different discharge, and hence plot at different positions on the rating graph. Frequent discharge measurements should be made during a period of shifting control to define the stage–discharge relationship, or magnitude of shifts, during that period. However, even with infrequent discharge measurements, the stage–discharge relationship can be estimated with reasonable accuracy if the available discharge measurements are supplemented with knowledge of shifting-control behaviour and a hydrograph of stage.

When discharge measurements indicate a shift of the rating curve, the analyst should decide if the shift is temporary or permanent in nature. If the shift is expected to last for several months or longer, it is advisable to plot a new rating curve. If the shift is a temporary condition that may change relatively soon, the shifting-control condition should be handled by using a temporary shift curve to define discharge during the time of shift and until new information indicates another shift of the rating curve. Experience and knowledge of each control is the best way of knowing whether rating-curve shifts are temporary or permanent.

Shift curves usually have a shape which is similar to that of the original rating curve. That is why it is important to have the original, or base, rating curve shaped correctly as defined by the hydraulics of the stream channel.

Scour or deposition of a natural section control results in a change in the actual and effective gauge height of zero flow. This frequently results in a shift curve that is parallel to the original rating curve when plotted on arithmetic plotting paper. That is, the difference in gauge height between the original rating curve and the shift curve is equal through the stage range controlled by the section control. This same shift curve, if plotted on logarithmic plotting paper, will be concave upward and above the original rating curve for a deposition condition, and concave downward and below the original rating curve for a scour condition.

The use of shift controls to account for this variation is given in Annex F.

For streams that shift continuously, it is usually necessary to define shift curves on the basis of discharge measurements, determinations of the gauge height of zero flow, and hydraulic characteristics of the rating curve, and then continuously adjust the shift curve between itself and another shift curve (or the base rating curve) on the basis of time. The shift curve adjustment can be uniform or proportional with respect to time or, if specific changes can be defined, the shift curve can be changed abruptly to correspond to the control change. For example, a deposit of debris on a section control can quickly wash away during a small rise in water level, thus causing a shift back to the original rating curve or to another position. This can sometimes be detected by examination of the gauge height record, where abrupt changes can signify abrupt changes to the control. Where no obvious reason associated with a hydrologic event can be ascribed to a change in the hydraulic control, it is usually assumed that the change occurred gradual over time, and the shift curve is applied to adjust with time. This is typically the case for shifts caused seasonally by the growth of aquatic vegetation.

Shifting-control procedures are complex and frequently difficult to interpret. Quite often, there is more than one logical explanation or interpretation. Experience with a given stream is important in defining the shift characteristics and in making a logical analysis. Field observations including notes, photographs, and even cross section survey information can help with the interpretation.

5.8 Variable-backwater effects

5.8.1 General

Several conditions can occur in the downstream reaches of a stream to cause apparent changes to the stage–discharge relationship. Subclause 5.7 has detailed shifts of the control. This subclause addresses conditions of variable backwater which can cause submergence, or partial submergence, of a control and result in stage–discharge relationships that require more complex analysis.

Variable backwater can result from downstream influences such as reservoirs or tributary streams, from ice, from vegetation growth or from dynamic conditions known as hysteresis.

5.8.2 Downstream backwater influences

Downstream conditions can occasionally exist such that water levels downstream from a channel-control reach or a section control can rise sufficiently to partially submerge the control. When this happens, the control will no longer be fully effective in defining the stage–discharge relationship.

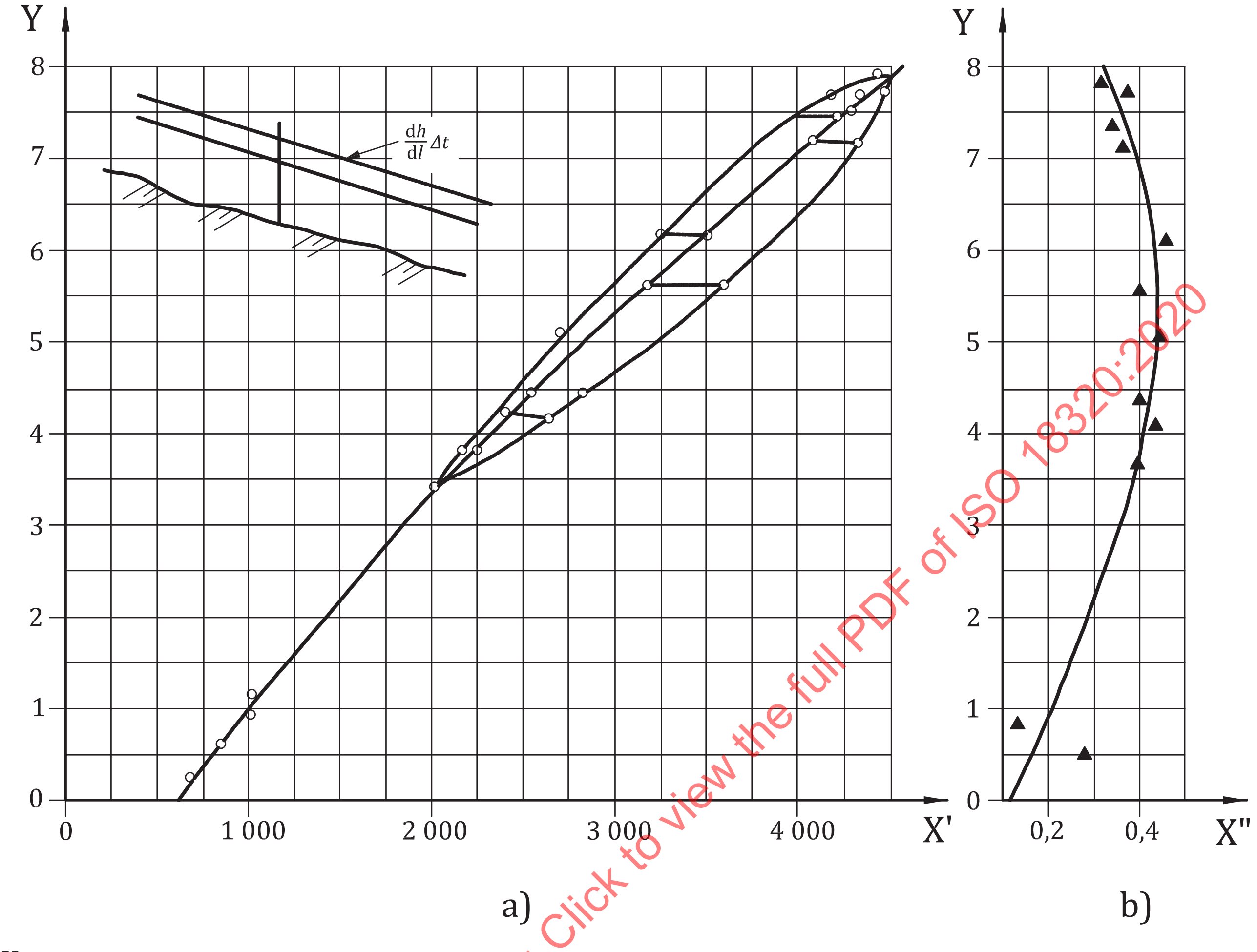
The simplest solution to this is to re-site the gauging station upstream of the variable backwater However, where this is not feasible or economic, adjustments to the gauged record shall be made to account for the downstream effect. In some conditions of downstream backwater, particularly if it is of short duration and occurs very infrequently, it is practical to analyse the discharge record using shifting-control methods. Sometimes, the extent and magnitude of the backwater can be determined by examining a graphical plot of the stage record and estimating the non-backwater stage during the period of backwater.

For variable-backwater conditions that are significant and persist for long periods of time, other measures are required to analyse the discharge record. The most common approach is to use a stage gauge and an auxiliary gauge of index velocity. The index velocity is usually determined by acoustic velocity meters that employ Doppler principles to measure velocity in one vertical or horizontal segment of the channel. An index-velocity rating is developed to predict mean channel velocity from the index velocity gauge, and a stage-area rating is developed to predict area from the stage gauge. Discharge is then computed by multiplying the computed mean velocity and the computed area.

Other approaches include the stage-fall method and the ultrasonic method. These methods are described in ISO 9123 and ISO 6416.

5.8.3 Hysteresis effects or loop rating curves

The stage–discharge relationship for a gauging station gives the value of the normal discharge, i.e. the steady-flow discharge, for a given stage. The discharge for a particular stage can, for some rivers and streams, be greater than the normal discharge during rising stages and less than normal during falling stages because of differences in the water surface slope. This effect is known as hysteresis, or a loop rating curve. It is most pronounced for mildly sloped rivers where dynamic flow conditions are imposed by a passing flood wave. This characteristic is illustrated in Figure 3.



Key

Y gauge height in m

X' discharge in m^3s^{-1}

X" $(S_wV_w)^{-1}$

Figure 3 — Hysteresis effects or loop rating curve

For gauging sites where the hysteresis effect is severe, instantaneous values of the discharge determined from the steady-state rating curve can be significantly different from the true discharge. If this potential error is significant in terms of the use to which the flow information will be used, it might be necessary to use auxiliary equipment to supplement the gauge height record in order to determine discharges accurately. A twin-gauge approach utilizing the stage-fall-discharge relationship can be used (see ISO 9123).

If the hysteresis effect is not severe, but yet of sufficient magnitude to need correction, it might be possible to use a single-gauge record of the stage in conjunction with the rate of change in the stage, to compute the discharge. For certain conditions, it is possible to compute the true discharge, Q, of an unsteady flow from the steady-state discharge, Q_o, using Formula (7):

$$Q = Q_o \left(1 + \frac{1}{S_w V_w} \cdot \frac{dh}{dt} \right)^{0,5} \tag{7}$$

where

S_w is the water surface slope corresponding to steady, non-uniform flow;

V_w is the velocity of the flood wave;

dh/dt is the rate of change of the stage with time.

The slope, S_w, can be determined from observation of gauges during conditions of steady flow. Alternatively, it can be computed approximately from Manning's, Chezy's or the Darcy-Weisbach formula.

The rate of change of the stage, dh/dt, can be obtained from the recorded observations of the stage at the gauge.

The wave velocity, V_w, is given by Formula (8):

$$V_w = \frac{dQ}{dA} = \frac{1}{B} \cdot \frac{dQ}{dh} \tag{8}$$

where

A is the cross-sectional area;

B is the surface width at the cross-section;

$\frac{dQ}{dh}$ can be approximated from the stage–discharge relationship.

Provided the stage–discharge relation is known, then theoretically it is possible to determine the relationship between the product of wave velocity and water slope ($V_w S_w$ versus Q) relationship for the river reach, using dQ/dh, provided the flow area is defined as the total area minus the storage area. This allows the signature $V_w S_w$ versus Q curve of the river to be obtained and estimates made of the arrival time of flood peak discharges to be made.

The above conditions are valid when the rise and fall of the stream is gradual, i.e. when the rate of change in velocity (the acceleration head) can be neglected. Likewise, the velocity should not be high, so that the velocity head can safely be neglected. When a sufficient number of discharge measurements are available, it is possible to calibrate a gauging site with a family of curves by evaluating the term $1/(S_w V_w)$ as a single parameter. This is the basis of the Boyer method.

The Boyer method provides a solution of Formula (7) without the necessity for individual evaluation of V_w and S_w. The method requires numerous discharge measurements made under the conditions of rising and falling stage. Measured discharge, Q, is plotted against stage in the usual manner, and beside each plotted point is noted the value of dh/dt for the measurement. For convenience dh/dt and the algebraic sign of dh/dt is included in the notation — plus for rising stage and minus for falling stage. A trial Q_0 rating curve, representing the steady-flow condition where dh/dt equals zero, is fitted to the plotted discharge measurements, its position being influenced by the values dh/dt noted for the plotted points. Values of Q_0 from the curve corresponding to the stage of each discharge measurement, are used in Formula (7), along with the measured discharge, Q, and observed change in stage, dh/dt, to compute corresponding values of the adjustment factor, $1/S_w V_w$. The computed values of $1/S_w V_w$ are then plotted against stage and a smooth curve is fitted to the plotted points. If the plotted values of $1/S_w V_w$ scatter widely about the curve, the Q_0 curve is modified to produce some new values of $1/S_0 V_w$ that can be better fitted by a smooth curve. The modifications of the curves of Q_0 and $1/S_0 V_w$ should not be so drastic that the modified curves are no longer smooth curves, nor should the modified shape of the Q_0 rating curve violate the principles underlying rating curves, as discussed in previous clauses.

Construction of the two curves completes the rating analysis. Figure 3 b) is an example of such an analysis.

To adjust the value of subsequent discharge measurements for plotting on the Q_o rating curve, the adjustment-factor curve is first entered with the stage of the measurement to obtain the appropriate value of the factor, $1/S_cV_w$. Next, the observed value of dh/dt is used with that factor to compute the term:

$$\left(1+\frac{1}{S_oV_w}\frac{dy}{dx}\right)^{0,5}$$

That term is then divided into the measured discharge, Q, to obtain the required value of Q_c. To determine true discharge Q, based *on* the Q_o rating curve and adjustment-factor curve, during a period when the stage and rate of change of stage are known, the procedure described above is used to obtain the value of the term noted above. That term is then multiplied by Q_o, which is obtained by entering the Q_o rating curve with the known stage. The product is the true discharge, Q.

5.9 Extrapolation of the stage–discharge relationship

Ideally, a stage–discharge relationship should not be applied outside the range of available discharge measurements. However, for many small rivers and streams it is not possible to make a direct measurement of high discharges because of the short duration of the peak discharge or the inaccessibility of the site during flood conditions. Under these circumstances, it will be necessary to make an extrapolation of the rating based on the hydraulic characteristics of the site, including the known section and channel controls. The channel and control should be carefully examined for some distance downstream and upstream of the gauge. Flow obstructions, contractions, expansions, debris, channel shape changes and other conditions should be noted so the shape of the rating curve can be estimated accurately.

Likewise, it is not always possible to measure the lowest discharges, and stage–discharge curves need to be extrapolated downward from the lowest measurement. The lower end of stage–discharge curves are typically controlled by the cross-sectional area and shape of a specific section of the channel. Knowledge of the characteristics of this section and whether it changes with time are critical for extrapolating the lowest end of the curve.

A detailed explanation of manual techniques and a listing of models for extrapolating stage–discharge curves are given in Annex G.

It is recommended that, whenever possible, extrapolations be made using two or more methods. Results can then be compared and the extrapolated part of the rating curve can be defined with added confidence.

6 Methods of testing stage–discharge relationships

It is recommended that a stage–discharge relationship should be checked six or more times per year by making discharge measurements. The number of measurements and the period of time between measurements will vary depending on several factors, including the relative stability of the rating curve, hydrological events such as floods that might affect the rating curve, and other indications that the rating curve might have changed. During certain periods, such as floods or extreme drought, it is desirable to obtain additional measurements to reduce the need for rating-curve extrapolations and to define the effects of backwater or hysteresis if they are present. Also, when a discharge measurement deviates significantly from the rating curve or from previous discharge measurements, a check measurement should be made immediately to confirm or refute the accuracy of the first discharge measurement.

Generally, when a discharge measurement plots within a small percentage of the rating curve, it is assumed that the rating curve still applies, and no correction is made in the form of either a shift or a new rating curve. The percentage by which a measurement may deviate from the rating curve without applying a correction is usually based on the uncertainty of the discharge measurement. See ISO 748 for a description of computing discharge measurement uncertainty. If, for instance, most discharge measurements are made to 5 % uncertainty, then shifting-control techniques will not be employed unless a check measurement plots further than 5 % from the rating curve.

Another approach is to undertake a statistical analysis of the rating curve to define the dispersion (standard deviation) of the measurements around the rating curve. When two or more measurements indicate a deviation of more than two standard deviations from the rating curve, then a shift curve or a new rating curve is defined. Standard deviations are usually defined separately for each segment of a rating curve.

A bias check is also performed in some cases to define periods when the rating curve might have shifted, even though measurements are within the specified uncertainty of discharge measurement or within two standard deviations for the rating curve. For instance, two or more measurements might plot within 5 % of the rating curve, but are all on the same side of the rating curve. Various statistical tests can be used to test for bias.

When testing and checking stage–discharge relationships, it is very important that the analyst understands why the measurements plot as they do. Without this understanding, the analyst might incorrectly apply and interpret certain statistical tests. The analyst should always consider what has been happening to the controlling stream characteristics and make decisions based on hydraulics rather than arbitrarily using statistical results. This may involve using modelling techniques, as described in 5.3.2, noting any changes in the values of calibration coefficients and exploring the reasons for them. In this way the fundamental hydraulics will be preserved and future analysts will be able to understand the complex nature of any particular gauging station, making extension of the relationship to high flows more reliable. Before adopting this approach it is essential that any software has itself been comprehensively tested against benchmark data for a variety of rivers, geometries, substrates and flow conditions, as shown by References [35] and [36].

7 Uncertainty in the stage–discharge relationship

7.1 General

This clause gives the theory and statistical formulae for estimating the uncertainties in the stage–discharge relationship and in the daily mean discharge. Numerical examples of estimating the uncertainty of the stage–discharge relationship and the daily mean discharge, using the procedures in this clause, are given in Annex H.

The uncertainty in a single measurement of discharge shall be evaluated in accordance with ISO 748, the uncertainty calculations in which are based on ISO 5168. The uncertainty in the stage–discharge relationship and in continuous measurements of discharge using a stage–discharge relationship shall be evaluated in accordance with this clause.

7.2 Definition of uncertainty

ISO/TS 25377 sets forth the concepts, terminology and methods used when discussing and computing the uncertainty of hydrometric measurements. The terminology specified by ISO/TS 25377 differs slightly from that used in previous editions of this document. Uncertainty is defined as a parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand. The uncertainty parameter can be a standard deviation or a specified multiple of the standard deviation. The standard uncertainty is defined as “uncertainty expressed as a standard deviation”. Expanded uncertainty is defined as a quantity defining an interval about the result of a measurement that can be expected to encompass a large fraction of the distribution of the values that could reasonably be attributed to the measurand. The expanded uncertainty is computed by multiplying the standard uncertainty by a coverage factor, k, typically in the range 2 to 3. The fraction of the distribution expected to be encompassed by the expanded-uncertainty interval is called the level of confidence. It should be noted that, if the distribution is assumed to be approximately normal (Gaussian), then coverage factors, k, of 1, 2, and 3 correspond to levels of confidence of about 68 %, 95 % and 99,8 %, respectively.

The expanded uncertainty and level of confidence are not to be confused with the statistical quantities "confidence interval" and "confidence level". These quantities are computed using statistical procedures and assumptions that do not always apply to the uncertainty of flow measurement. In particular, the term "confidence level" should not be used, but rather the term "level of confidence".

Previous editions of this document used the term "uncertainty" to refer to expanded relative uncertainty with a coverage factor of 2 and used the terms "standard error" and "standard deviation" to refer to standard uncertainty.

7.3 Statistical analysis of the stage–discharge relationship

7.3.1 General

The uncertainty analysis consists of comparing concurrent measurements of discharge and gauge height ("gaugings") with discharge values read from the stage–discharge relationship at the corresponding gauge heights. The uncertainty will be determined by statistical analysis of the scatter of the measurements around the rating curve. The stage–discharge relationship, being a line of best fit, to a certain extent compensates for random uncertainties in the gaugings. The formula of the relationship can be computed as detailed in 5.3. The standard error of estimate is included in the uncertainty estimation (see 7.3.2).

It is recommended that several current meters be used to establish the stage–discharge relationship to avoid systematic bias in the relationship.

NOTE The uncertainties defined below are very similar in concept to statistical performance measures (standard errors) derived in the statistical theory of regression analysis. Statistical regression theory, however, is based on curve-fitting by the mathematical least-squares method, whereas stage–discharge rating-curve relationships are commonly developed using hydraulic reasoning in addition to mathematical fitting. Thus, the term "uncertainty" is used in preference to the more restrictively defined statistical standard error.

7.3.2 Standard error of estimate

The uncertainty of the rating-curve relationship as a whole is characterized by the standard error of estimate, S (also called "standard error" or "standard deviation of residuals"), which is calculated from the dispersion of the stage–discharge data around the rating curve. The uncertainty of the discharge value computed from the rating curve for any particular value of the stage, $u[Q_c(h)]$, is then calculated. If there are multiple straight-line segments in the stage–discharge relationship, this procedure is repeated for each segment.

The standard error of estimate, S, is calculated from Formula (9):

$$S=\left[\frac{\sum(\ln Q-\ln Q_c)^2}{(N-p)}\right]^{0,5} \tag{9}$$

where

Q is the measured discharge;

Q_c is the corresponding discharge calculated from the rating-curve formula or rating-curve table;

N is the number of gaugings in the rating-curve segment;

p is the number of rating-curve parameters estimated from the N gaugings.

NOTE 1 The value of p depends on how many parameter values are adjusted to make the rating curve fit the gauging data. If all three parameters (Q_1, β, e) are adjusted to fit the N gaugings, then $P = 3$. If the effective gauge height of zero flow, e, is given a priori and another two parameters are adjusted to fit the data, then $P = 2$. If, in addition, the rating-curve slope, β, is determined a priori, from hydraulic considerations for example, and only the intercept Q_1 is estimated, then $P = 1$.

NOTE 2 The quantity $N - p$ is called the number of degrees of freedom. It represents the number of observations that are effective in defining the scatter of observations around the rating-curve relationship, p of the observations having been "used up", in effect, to establish the position of the rating curve.

7.3.3 Standard uncertainty

The standard uncertainty in the calculated value of $\ln Q_c$ at gauge height h, $u[\ln Qc(h)]$, is found from Formula (10):

$$u\left[\ln Q_c(h)\right]=S\left\{\frac{1}{N}+\frac{\left[\ln(h-e)-\overline{\ln(h-e)}\right]^2}{\sum\left[\ln(h-e)-\overline{\ln(h-e)}\right]^2}\right\}^{0,5} \tag{10}$$

An expanded uncertainty, $U[\ln Q_c(h)]$, can be calculated from Formula (11):

$$U\left[\ln Q_c(h)\right]=ku\left[\ln Q_c(h)\right] \tag{11}$$

where k is a coverage factor that provides a specified level of confidence (see NOTE 1). The expanded uncertainty defines an uncertainty interval around the computed value $\ln Q_c(h)$ which is expected to encompass the specified fraction of the distribution of values that could reasonably be attributed to the discharge; this interval can be expressed as Formula (12):

$$\ln Q_c(h)\pm U\left[\ln Q_c(h)\right] \tag{12}$$

The uncertainties and the limits of the uncertainty interval are expressed in natural-logarithmic units. The corresponding uncertainty interval for discharges is found by taking anti-logarithms and mathematically the following approximate relationship can be derived as shown by Formula (13):

$$Q_c(h)e^{\pm U\left[\ln Q_c(h)\right]}\approx Q_c(h)\left\{1+U\left[\ln Q_c(h)\right]\right\} \tag{13}$$

The approximate equality shown in Formula (13), holds when $U[\ln Q_c(h)]$ is small enough so that the linear approximation to the exponential holds (see NOTE 2), i.e. it can be assumed for practical purposes that the uncertainty in the natural logarithm of discharge as derived in Formula (10) is equal to the uncertainty in the discharge.

NOTE 1 For the expanded uncertainty, the coverage factor, k, can be taken as Student's t correction at the desired level of confidence for N p gaugings and can be taken as 2 for a level of confidence of 95 % and 20 or more gaugings. A coverage factor, k, of 1 corresponds to a level of confidence of about 68 %.

NOTE 2 The uncertainty interval limits are symmetrical in logarithmic units but not, in general, in discharge units. If the natural-logarithmic uncertainties, $U[\ln Q_c(h)]$, are small, they are approximately equal to relative uncertainties in discharge units.

The expanded uncertainty, $U[\ln Q_c(h)]$, with coverage factor, k, equal to 2, and the corresponding uncertainty limits on $\ln Qc(h)$ should be calculated for each observation of (h e) related to the corresponding gauging. The limits will therefore take the form of curved lines on each side of the stage–discharge relationship and will exhibit a minimum at the mean value of ln(h e).

NOTE 3 The uncertainty of the calculated value of $\ln Q_c$ refers to the dispersion of the set of reasonably possible positions of the rating curve based on the number of gaugings available and their accuracy. As the gaugings are dispersed around the rating curve, with standard error of estimate S, it is expected that future discharges will be similarly dispersed around the rating curve. This dispersion will therefore be an indication of the accuracy of predictions of future discharges using the rating curve (see 7.4).

If the stage–discharge relationship comprises two or more straight-line segments, S and $U[\ln Q_c(h)]$ should be individually calculated for each segment, and the appropriate number of degrees of freedom, (N p), should be used for each segment. However, it is important that the calculation does not loose site of physical reality and the joining of segments needs to take due account of the physical properties of the channel.

While it is recognized it is often not possible, it is desirable that at least 15 observations be available in each segment in order to achieve a statistically reliable estimate of S and $u[\ln Q_c(h)]$.

7.4 Uncertainty of predicted discharge

The rating curve is used to compute values of discharge corresponding to values of gauge height recorded at a gauging station. The resulting computed discharge is normally considered to be a prediction of the discharge that would be observed if a gauging were made. The magnitude of the difference between the predicted value and the value that would be observed if a gauging were made is important in the practical use and interpretation of the predicted values. The dispersion of the values that could reasonably be attributed to this difference is called the uncertainty of prediction, denoted by $u(Q_p)$ (standard uncertainty) or by $U(Q_p)$ (expanded uncertainty) or by corresponding terms involving logarithms of discharge. The actual values of the predicted discharges, Q_p, are the same as the values, Q_c, computed from the rating curve at the recorded gauge height, but their interpretation is different because they are being compared with the distribution of reasonably possible individual observed discharges rather than with the distribution of reasonably possible positions of the rating curve.

There are three reasons why the predicted discharge might differ from the discharge that would be observed if a gauging were made: change in control conditions (shift in rating curve), measurement error in gauged discharge and error in recorded gauge height. The first two error sources affect the gaugings used to define the rating-curve relationship; their combined magnitude is represented by the standard error of estimate of the rating curve, S. The third error source is not reflected in the gaugings used to define the rating curve because the gauging personnel read auxiliary reference gauges in addition to the recorder to ensure that the correct gauge height is observed. Assuming that the rating curve is virtually linear over the range of reasonably possible values associated with the recorded gauge height, and using the logarithmic form of the rating-curve formula, the standard uncertainty in predicted discharge due to uncertainty in recorded gauge height is given by Formula (14):

$$u\left[\ln Q_p(h)\right] = \beta \cdot u[\ln(h-e)] \tag{14}$$

where $u[\ln(h-e)]$ is the uncertainty in the effective depth.

The standard uncertainty of prediction is computed by combining this uncertainty with the standard error of estimate, S, and the uncertainty in the calculated discharge, $U[\ln Q_c(h)]$, in root-sum-squares (RSSs), as shown by Formula (15):

$$u\left[\ln Q_p(h)\right] = \sqrt{\beta^2 u[\ln(h-e)]^2 + S^2 + u\left[\ln Q_c(h)\right]^2} \tag{15}$$

Expanded prediction uncertainties, prediction uncertainty limits and percentage (relative) prediction uncertainties are computed in the same way as in 7.3.3. In particular, if the standard uncertainties of the natural-logarithmic quantities are small, they are equivalent to relative (percentage) uncertainties of the corresponding stages and discharges.

NOTE 1 At some gauging stations, most likely ones with rock-ledge controls or well-maintained artificial controls, it is possible to show that the standard error of estimate represents only the measurement uncertainty of the gaugings used to establish the rating curve. In such cases, the predictions would not be affected by measurement error, and the standard error of estimate, S^2, can be omitted from the calculation of the prediction uncertainty.

NOTE 2 There are different schools of thought among statisticians and hydrometric practitioners on the most appropriate methods to use for estimating uncertainties, e.g. Bayesian approaches have been researched. While recognizing its limitations the methodology presented here has been widely accepted for many years and provides a consistent approach for comparing the quality of ratings. The basis for applying the methodology described in this clause are currently built into several commercially available hydrometric data management software packages. Research on other approaches is referenced in Reference [30]. This compared 7 methods for estimating rating curves and their uncertainties, including the method described in this document. Alternative methods like HydraSub, GesDyn and BaRatin are already in use by operational hydrometric services in Norway and France to build rating curves and quantify their uncertainties. HydraSub and BaRatin can be freely downloaded and used.

Annex A
(informative)

Types of control

A.1 Section control

A section control is a specific cross-section of a stream channel, located downstream from a water-level gauge that controls the relationship between gauge height and discharge at the gauge. A section control can be a natural feature, such as a rock ledge, a gravel bar, a severe constriction in the channel or an accumulation of debris. A section control can also be a man-made feature, such as a small dam, a weir, a flume or an overflow spillway. Section controls can often be visually identified in the field by observing a riffle, or pronounced drop in the water surface, as the flow passes over the control. Frequently, as gauge height increases because of higher flows, the section control will become submerged to the extent that it no longer controls the relationship between gauge height and discharge. At this point, the riffle is no longer observable, and flow is then regulated either by another section control further downstream or by the hydraulic geometry and roughness of the channel downstream (i.e. channel control).

A.2 Channel control

A channel control consists of a combination of features throughout a reach at, or downstream from, a gauge. These features include channel size, shape, curvature, slope and roughness. The length of channel reach that controls a stage–discharge relationship varies. The stage–discharge relationship for a relatively steep channel could be controlled by a short channel reach, whereas the relationship for a flat channel could be controlled by a much longer channel reach. Additionally, the length of a channel control will vary depending on the magnitude of flow. Precise definition of the length of a channel-control reach is usually neither possible nor necessary.

A.3 Combination controls

At some stages, the stage–discharge relationship can be governed by a combination of section and channel controls. This usually occurs for a short range in stage between section-controlled and channel-controlled segments of the rating curve. This part of the rating curve is commonly referred to as a transition zone of the rating curve and represents the change from section control to channel control. In other instances, a combination control can consist of two section controls, where each has a partial controlling effect. More than two controls acting simultaneously are rare. In any case, combination controls and/or transition zones occur for very limited parts of a stage–discharge relationship and can usually be defined by plotting procedures. Transition zones, in particular, represent changes in the slope or shape of a stage–discharge relationship.

Annex B
(informative)

Complexities of stage–discharge relationships

Stage–discharge relationships for stable controls (such as rock outcrops and man-made structures such as weirs, flumes and small dams) present few problems in their calibration provided a suitable maintenance regime can be achieved. However, complexities can arise when controls are not stable and/or when variable backwater occurs. For example, a major cause of variable control is mobile bed material such as sand or gravel in bars. High flood flows can cause migration of sand and gravel bars and hence impact on the stability of a stage–discharge relationship. For such unstable controls, segments of a stage–discharge relationship can change position occasionally, or even frequently. This is usually a temporary condition which can be accounted for through the use of the shifting-control method.

Variable backwater can affect a stage–discharge relationship both for stable and unstable channels. Sources of backwater can be downstream reservoirs, tributaries, tides, vegetation, ice, dams and other obstructions that influence the flow at the gauging-station control.

A complexity that exists for some streams is hysteresis, which results when the water surface slope changes due to either rapidly rising or rapidly falling water levels in a channel-control reach. Hysteresis is also referred to as loop rating curves and is most pronounced in relatively flat-sloped streams. On rising stages, the water surface slope is significantly steeper than for steady-flow conditions, resulting in greater discharge than indicated by the steady-flow rating curve. The reverse is true for falling stages. See 5.8.3 for details of hysteresis rating curves. Hysteresis can also occur in channels affected by heavy vegetation growth, and this adds a further complexity, as this effect will vary with the rate of vegetative growth over the seasons of the year.

The effect of vegetative growth is in itself a serious problem in this context. Variable seasonal growth and other channel maintenance activities such as weed cutting to improve navigation or flood flow capacity, all create additional complications in deriving a stable stage–discharge relationship for a channel, especially for low flows.

Another complexity exists when rivers are in flood. It is often difficult to define the portion of the stage–discharge relationship above bankfull level. Flow patterns on a flood plain are often complex, especially when flood plain storage is filling on the rising limb of the hydrograph, or emptying on the falling limb. This means that flood flow measurement should ideally be undertaken to coincide with the peak flow, Q_p. Additionally, problems with safe access can mean that, for some floods, not all the flow can be adequately measured. Consequently, the definition of the flood-plain rating-curve section can become very complicated and contain significant errors.

Annex C
(informative)

Software packages available to evaluate the stage–discharge relationship[1)]

C.1 General

There are a number of available software packages to aid the creation of the stage–discharge relationship given a series of flow measurements at specific stages at the observation site. Some packages contain additional analytical tools that help describe the accuracy and standard errors associated with the rating curve. An example of such a package is the UK Environment Agency's CES-AES software (Conveyance and Afflux Estimation System), which is freely available at www.river-conveyance.net. This specifically determines rating curves, but also includes a roughness advisor, a backwater calculator, and an uncertainty and afflux estimator. It is based on a depth-averaged velocity approach, using the Reynolds-Averaged Navier-Stokes (RANS) formulae to give the depth-averaged velocity, $\overline{V}_{\mathrm{d}}$, as a function of lateral distance, y. It is capable of dividing any river cross-section into a user-defined number of vertically sliced elements and solves the governing formula for $\overline{V}_{\mathrm{d}} = f\{y\}$, from which the discharge, Q may be obtained for a given value of depth, h. A description of the Conveyance Estimation System, abstracted from the CES Conveyance Manual (Defra/EA, 2004) is given in C.2. However, more detail can be found in References [32] and [37].

C.2 CES

An example of a public domain software package is the CES. This includes a component termed the "roughness advisor", which provides advice on this surface friction or roughness, and a component termed the "conveyance generator", which determines the channel capacity based on both this roughness and the channel morphology. In addition, the CES includes a third component, the "uncertainty estimator", which provides some indication of the uncertainty associated with the conveyance calculation.

C.3 Components of the CES

These outputs are:

— roughness advisor: roughness values;

— conveyance generator: stage-conveyance relationship;

— uncertainty estimator: upper and lower bands for the stage-conveyance relationship.

The new approach to estimating conveyance is a method whereby the energy "loss" mechanisms, e.g. lateral shear, transverse currents and boundary friction are treated individually. The channel section is divided into a number of elements, through vertical slicing, and the contributions to the total conveyance are determined within each slice. To this end, it is necessary to express the roughness in terms of a unit roughness value, which may vary laterally across the section, and is only dependent on the local boundary friction.

1) These are examples of suitable products available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of these products.

The roughness advisor was developed after an extensive review of available information on different techniques for determining the roughness characteristics in channels. The advisor provides for three roughness types: bed, bank, and floodplain. Within each type, the roughness will result from different components. For the bed and bank types, the three components are bed material, irregularities and vegetation. The components for the floodplain are similar except that ground material is used instead of bed material. Reference [23] provides numerous tables for estimating the component roughness for each roughness type.

The energy “losses” arise through the development of vortex structures on a variety of length scales. Once vorticity is created, its rotational energy cascades down in length scale into increased turbulence intensity until it dissipates as heat through viscosity. The stream wise translational kinetic energy is thus transferred in part to rotational kinetic energy, which no longer contributes to the stream wise channel conveyance capacity. It is possible to identify situations in which the vorticity is increased, e.g. these vortex structures may arise from the following.

— Boundary friction caused by the resistance due to surface roughness.

— Turbulence due to lateral shearing in regions with steep velocity gradients, e.g. adjacent to a flow boundary layer; and at the floodplain main channel interface, where the water is flowing faster in the main channel than on the floodplains.

— Transverse currents developing in regions of steep velocity gradients. These secondary currents vary with relative depth, i.e. they change their orientation as the flow moves from in-bank to out-of-bank flow; and sinuosity, i.e. the secondary flows expand into the bend in a helical-type shape and then gradually dissipate beyond the bend.

— Water moving from the floodplain region into the main channel, which is also subject to expansion losses. The velocity, i.e. both magnitude and direction of the flow, is important here, as high velocity results in a greater shear as the floodplain flow passes over the main channel flow, driving the vorticity structures. In meandering channels, this direction may retard or enhance the main stream rotations. Contraction losses may occur as water passes from the main channel into the floodplain region.

C.4 Calculating conveyance in CES

The approach for calculating conveyance in CES is based on the depth-integrated Reynolds Averaged Navier-Stokes (RANS) formulae for flow in the stream wise direction, as shown by Formula (C.1):

$$gHS_o - \varphi \frac{f}{8} \frac{q^2}{H^2} + \frac{d}{dy}\left(\lambda \left(\frac{f}{8} \right)^{\frac{1}{2}} Hq \frac{d}{dy}\left(\frac{q}{H} \right) \right) - C_{uv} \frac{d}{dy}\left(\frac{q^2}{H} \right) = 0 \tag{C.1}$$

where

λ	is the dimensionless depth averaged eddy viscosity;
g	is the gravitational acceleration;
q	is the unit flow rate;
φ	is the projection onto plane due to the choice of Cartesian coordinate system;
H	is the local depth normal to the channel bed;
S_o	is the reach-averaged bed slope;
y	is the lateral distance across the channel;
β	is the coefficient to account for influence of local bed slope on the bed shear stress;
f	local friction factor dimensionless eddy viscosity;
C_{uv}	is the meandering coefficient.

Formula (C.1) is a nonlinear, elliptic, second order partial differential formula that is approximated using linear finite elements. The cross-sectional area of flow represents the solution domain, which is discretised laterally into a number of elements, and the variable q is replaced with piecewise linear approximations. The solution to the resulting system of discrete formulae is generated through an iterative procedure, designed to converge nearly quadratically.

C.5 Other packages

— AQUARIUS (Aquatic Informatics), see http://aquaticinformatics.com/products/aquarius-time-series/better-rating-curves/

The AQUARIUS Time-Series Rating Development toolbox is a tool for building and maintaining rating curves. It is used to gauge measurements, focus on hydrologic relations, and shift or blend ratings to account for conditions, such as scour, fill, vegetation and ice.

— WISKI (Kisters Pioneering Technologies), see https://www.kisters.net.

SKED, the KISTERS rating curve editor, offers a diverse range of rating curve types and analysis methods. BIBER and SKED fulfil many international standards (e.g. ISO, USGS British and German standards). Complex tasks according to the stage-fall method, discharge hysteresis, USGS stage/date shifts or various backwater methods can be solved with BIBER and SKED.

— Hydstra (Kisters Pioneering Technologies), see https://www.kisters.net.

The graphical rating editor provides:

— Rating Selection;

- Insert New Period(s);
- Zoom In/Zoom Out;
- Fit Table (Power Fit);
- Move Point With Mouse;
- Formulae and Points;
- Logarithmic Interpolation;
- Display Vertical Velocity Curve;
- Displays coefficient of discharge;
- Complies to USGS standard;
- Parabolic Function;
- Exponential Function;
- LOWESS Smoothing Method;
- Selects Gaugings;
- Delete New Points;
- Scale Changes;
- Undo Last Change;
- Insert new point;
- Loads Cross Sections;
- Linear Interpolation;
- Power2/5 Interpolation;
- Uses Manning's formula;
- ISO Standards Tests;
- Hyperbolic Function;
- Regression Fitting Method
- User Configurable.

- Tempest Hydro-Met Analysis System (Sutron), see http://www.sutron.com/product/tempest-hydro-met-analysis-system/

  The Hydro-Met Analysis System stores decoded data in a SQL Time Series Database. The schema is capable of storing several years' worth of decoded data online. A computation module handles derived parameters, such as USGS ratings, table-lookup, interpolation, averaging and user-defined formulae. It provides tools for limit and rate-of-change alarms, import/export, spreadsheet-access, plotting and custom applications.

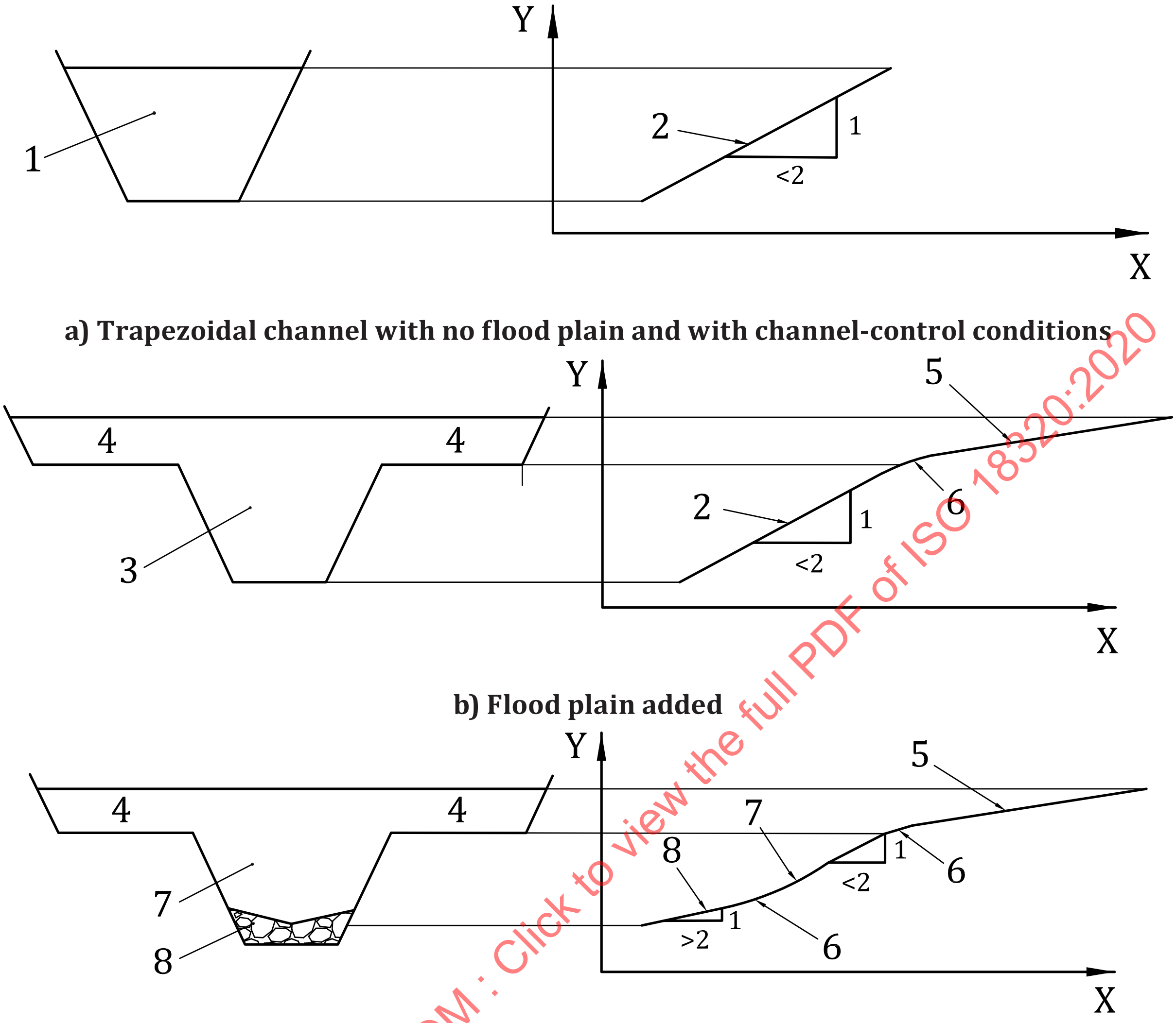
  - HydraSub
  - GesDyn
  - BaRatin

Annex D
(informative)

Examples of a hypothetical rating curve

Figure D.1 provides examples of a hypothetical rating curve showing the logarithmic plotting characteristics for channel and section controls and for cross-section shape changes. Figure D.1 a) shows a trapezoidal channel with no flood plain and with channel-control conditions. The corresponding logarithmic plot of the rating curve, when plotted with an effective gauge height of zero flow, *e* that results in a straight-line rating curve has a slope less than 2. In Figure D.1 b), a flood plain has been added, which is also a channel control. There is a change in the shape of the control cross-section which results in a change in the shape of the rating curve above the bankfull stage. If the upper segment (above the transition curve) is re-plotted to the correct value of effective gauge height of zero flow, it would also have a slope less than 2. In Figure D.1 c), a section control for low flow has been added. This results in a change in rating-curve shape because of the change in control. For the low-water part of the rating curve, the slope will usually be greater than 2.

The examples shown in Figure D.1 are intended to illustrate some of the principles of logarithmic plotting. The analyst should use these principles to the greatest extent possible, but should always be aware that there are probably exceptions and differences that occur at some sites.



a) Trapezoidal channel with no flood plain and with channel-control conditions

b) Flood plain added

c) Section control for low flow added

Key

Y log($h - e$)
X log$Q$
1 channel control (no flood plain, no section control)
2 channel-control rating curve
3 channel control (no section control)
4 flood plain
5 flood-plain rating curve
6 transition curve
7 channel control
8 section control

NOTE The left-hand drawing in each pair shows the channel shape, the right-hand drawing shows the rating-curve shape.

Figure D.1 — Relationship of the channel and control properties to the rating-curve shape

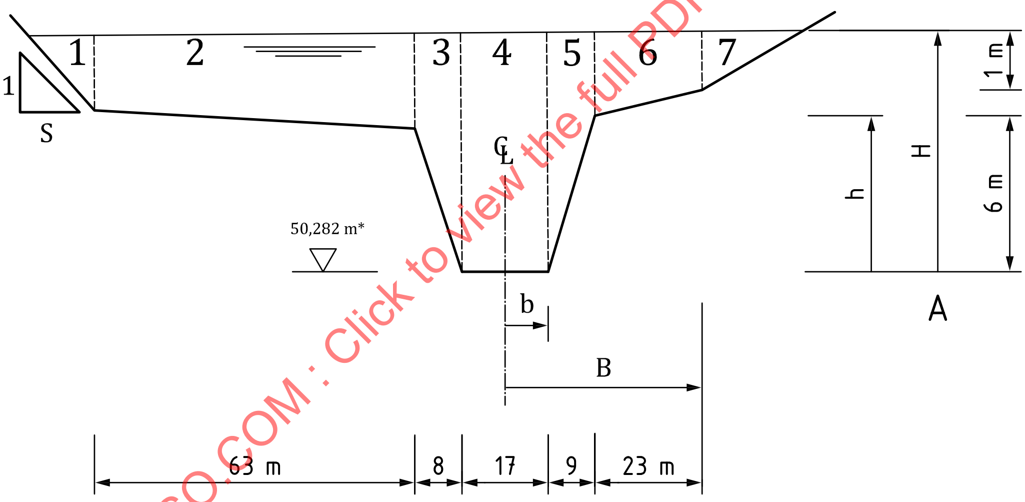
Annex E
(informative)

Example of how hydraulic properties of a river channel properties vary with stage

E.1 General

Examples of how the hydraulic properties of a river channel vary with stage are shown in Figures E.1 to E.5 for the River Severn at Montford Bridge, UK. They were obtained by repeated measurements of discharge and individual point velocities, and illustrate some of the features outlined in 4.3.

Figure E.1 shows the cross section of the channel. Figures E.2 to E.5 show how the wetted perimeter, hydraulic radius, cross section area and Manning, respectively, vary with stage at this site. Figure E.6 shows the stage–discharge relationship for this site using the CES software, together with upper and lower estimates.



Key

S_1 −4,0

S_2 −63,0

S_3 −1,33

S_4 ∞

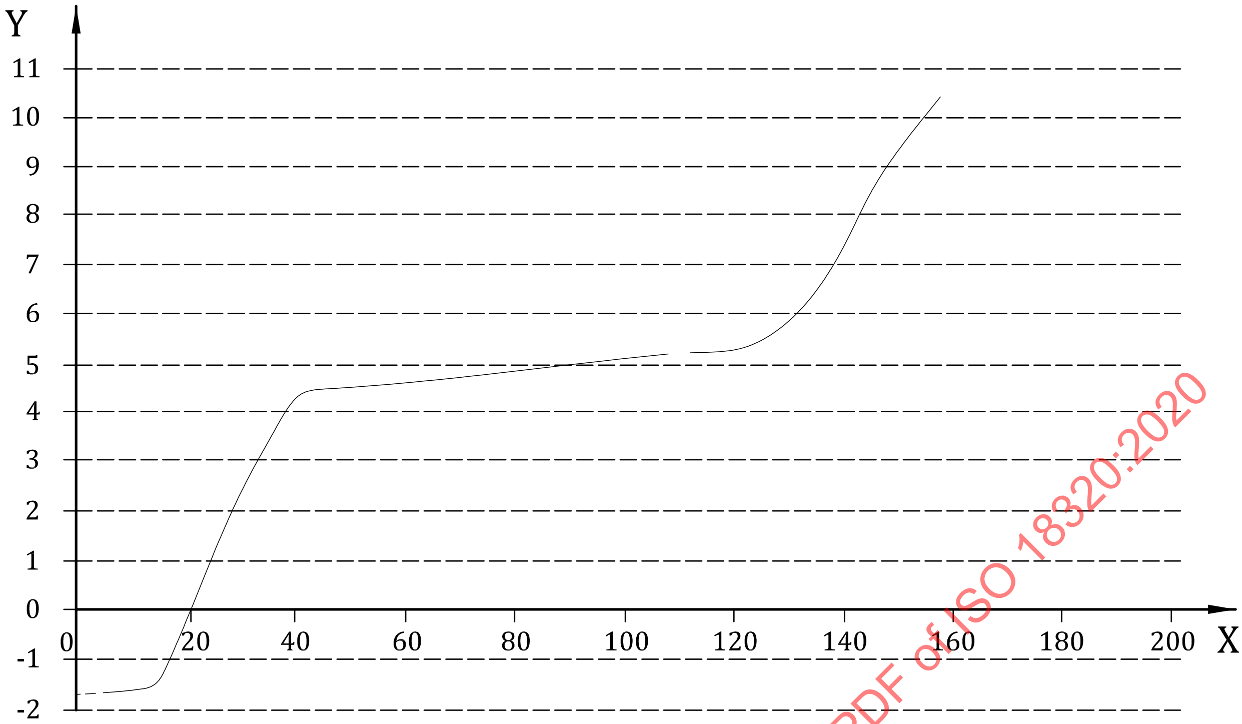
S_5 +1,50

S_6 +23,0

S_7 +7,1

NOTE See Reference [30].

Figure E.1 — Cross-section of River Severn at Montford Bridge

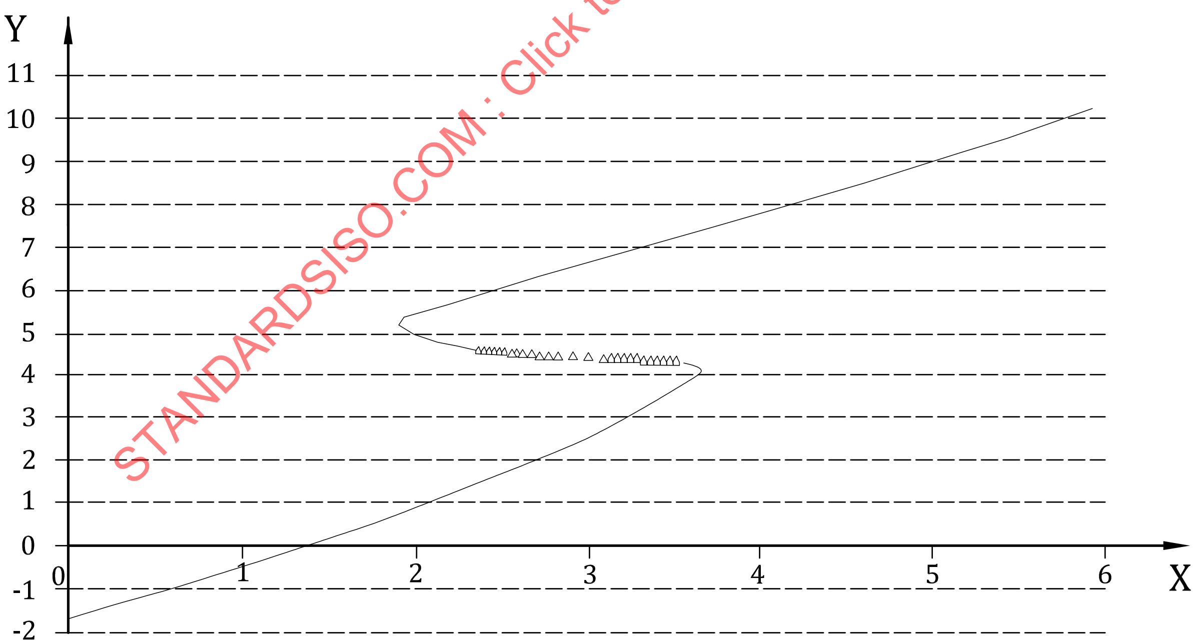


Key

Y stage in metres

X wetted perimeter

Figure E.2 — Variation of wetted perimeter with stage, River Severn at Montford Bridge

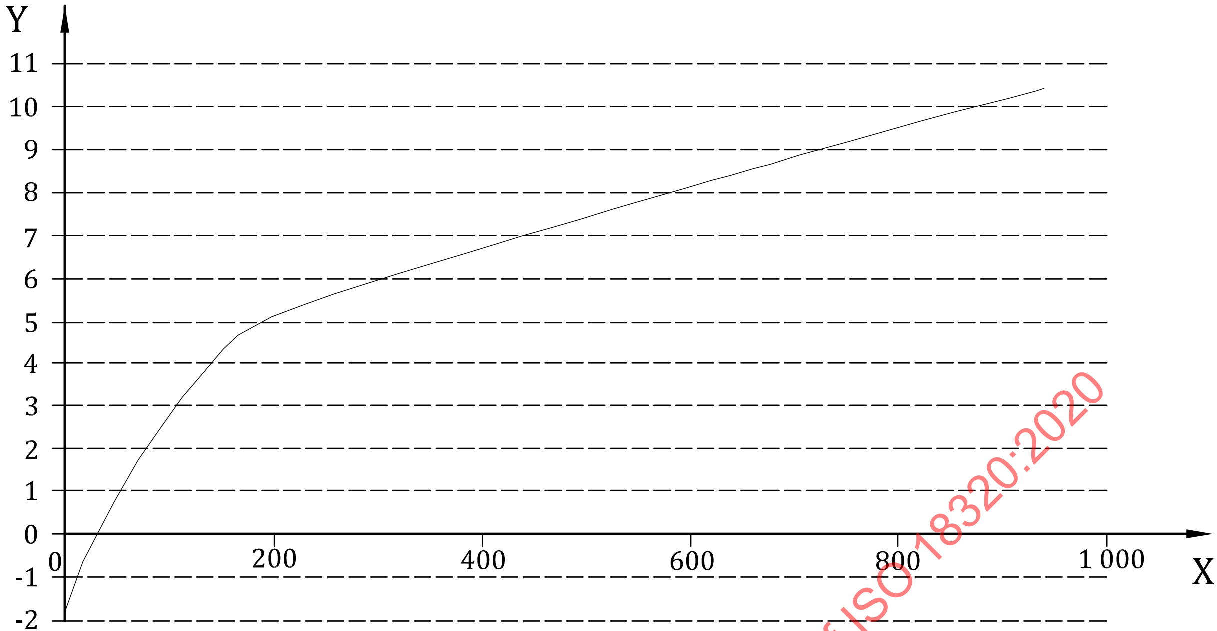


Key

Y stage in metres

X hydraulic radius

Figure E.3 — Variation of hydraulic radius with stage, River Severn at Montford Bridge

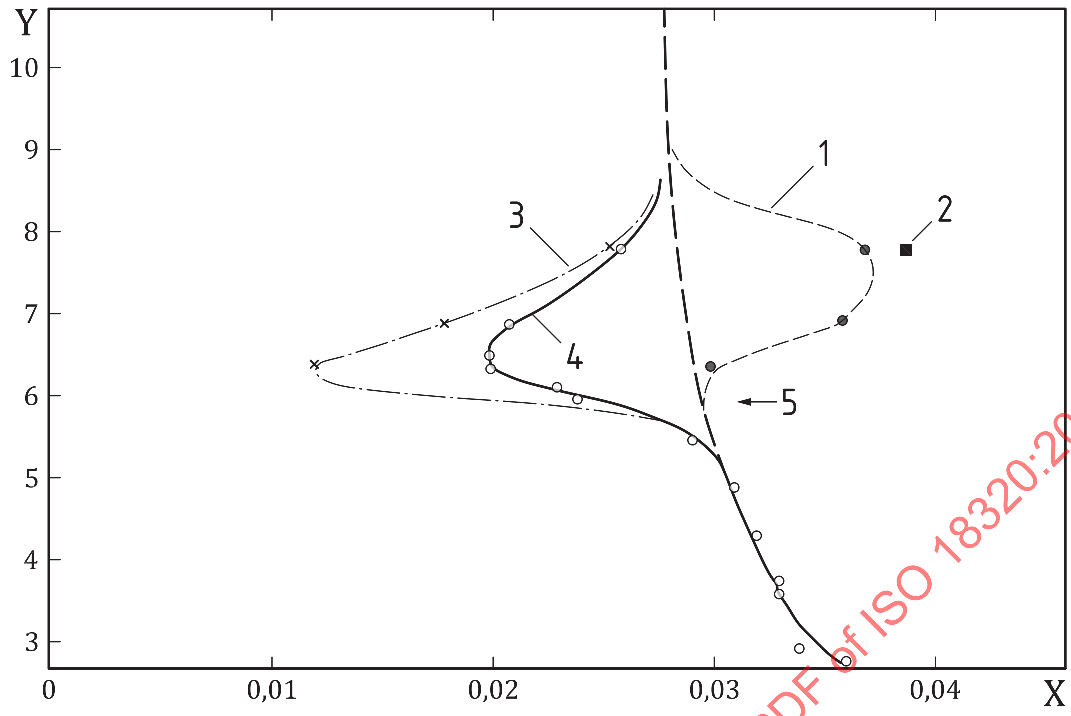


Key

Y stage in metres

X cross section area in m^2

Figure E.4 — Variation of cross section area with stage, River Severn at Montford Bridge



Key

Y stage in metres

X Manning n

1 n_{mc} effective

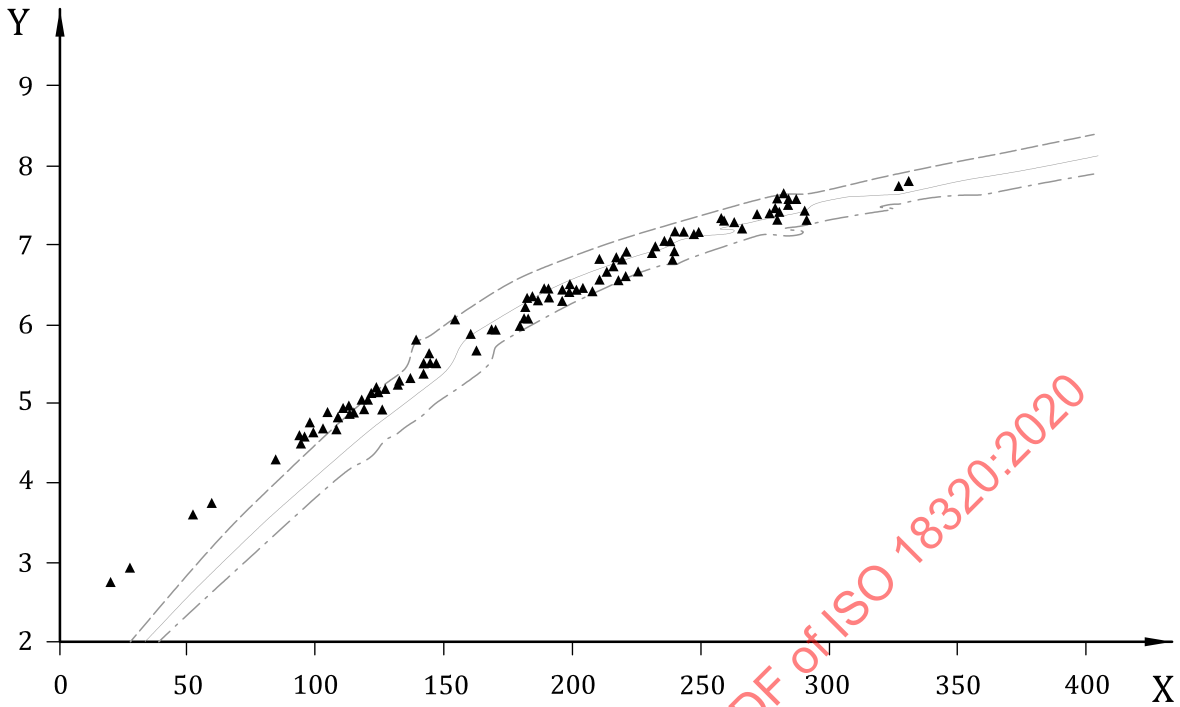
2 n_{fp} actual

3 n_{fp} effective

4 $n_{composite}$

5 bankfull

Figure E.5 — Variation of Manning n with stage, River Severn at Montford Bridge



Key

▲	measured data
———	CES prediction
– – – –	upper scenario
—·—	lower scenario
Y	stage in metres
X	discharge in m^3s^{-1}

NOTE This is graphic is taken directly from Reference [31].

Figure E.6 — Stage–discharge prediction for the River Severn, based on the CES software

The solid line in Figure E.5 shows that if the river is treated as a single channel, then the composite n value, $n_{composite}$, decreases with increasing depth from 0,036 to 0,030 at the bankfull level, as might be expected for most inbank flows. However, with further increase in stage above bankfull, $n_{composite}$ appears to decrease sharply to around 0,020, before increasing again to join the original trend line of the stage v n relationship at n = ~0,029. This apparent reduction in overall resistance coefficient is entirely fictitious and due to the use of Formula (2) with the changes in the hydraulic radius observed in Figure E.3. In fact, the overall resistance of the river actually increases when overbank flow occurs, due to the effects of bankside and floodplain vegetation.

Using measured water surface slope and velocity data, and dividing the channel into three zones, the left-hand floodplain (panels 1 and 2 in Figure E.1), the main channel region (panels 3 to 5) and the right-hand floodplain (panels 6 and 7), then the effective n value for the main channel n_{mc} (effective), based on the main channel area, appears to increase from 0,030 to around 0,038, and the effective n value for the floodplains n_{fp} (effective), based on the inundated floodplain areas, appears to decrease from 0,030 to 0,012. The estimated floodplain roughness, based on type of vegetation in the floodplain, is about 0,040.

The physical explanation for this anomaly is that by dividing the channel into separate zones, typically using vertical lines that form panel boundaries, then using measured U_{mc}, A_{mc} and S_f values, the resulting zonal Q_{mc} takes no account of the retarding effects of the shear layers between the slower moving floodplain flows and the faster moving main channel flow. Consequently, to match the observed Q_{mc} a larger resistance is apparently needed. The reverse is true of the zonal floodplain flow, Q_{fp}, where it appears that an impossibly low resistance value is required to account for the accelerating effects of the main channel flow on the floodplain flow (0,012 compared with the estimated value of approximately 0,040). This highlights just one of the difficulties of dealing with overbank flows. The approach used in the CES software considers this issue from first principles and accounts for this and other effects, being based on extensive experimental data and observations.

Figure E.6 shows the stage–discharge rating curve for the River Severn at Montford Bridge produced by the CES software. Such rating curves as this should ideally take into account all of the effects described in this annex, particularly when dealing with overbank flows. Care should be taken to distinguish between resistance coefficients defined by the section-mean velocity, U_A, the zonal velocity U_z, the depth-mean velocity, U_d, and a local near bed velocity, u, used in the so-called “law of the wall” in any turbulence model. The four friction factors used in 1-D, 2-D and 3-D river models, are generally referred to as “global”, “zonal” and “local”, by Formula (E.1):

$$\tau_o = \left(\frac{f}{8}\right)\rho U_A^2; \quad \tau_z = \left(\frac{f_z}{8}\right)\rho U_z^2; \quad \tau_b = \left(\frac{f_b}{8}\right)\rho U_d^2; \quad \tau_b = \left(\frac{f_t}{8}\right)\rho u^2 \tag{E.1}$$

(global) (zonal/sub-area) (local/depth-averaged) (local/turbulence)

1-D model quasi 1-D model 2-D model 3-D model

It should be noted here that, within the CES, the third option is used, with the boundary shear stress on the bed assumed to be in the same streamwise direction as U_d. The topic of how resistance is represented in numerical models is addressed more fully by Morvan, et al. (2008)[51].

NOTE In Formula (E.1) and discussion in the preceding three paragraphs, the symbols used relate only to this annex.

Annex F
(informative)

Use of shift controls

Table F.1 and Figure F.1 demonstrate the use of shift curves. Measurements 366 to 368 and 372 to 375 from Table 1 in 5.2.2 have been modified to represent a period of deposition or vegetation growth that occurred at least between 21 August and 26 November 1973, and a period of channel scour that occurred at least between 14 July and 11 November 1974. Measurements 366 to 368 reflect a +0,05 shift from the lower end of the base rating curve. Measurements 372 to 375 reflect a – 0,06 shift from the base rating curve. Measurements 369 to 371, which were made between the other two sets of measurements, show that the shift did not occur in the transition zone between the two section-control segments of the rating curve. The measurements define the shift curves. The actual periods of the two shifts would be defined during a hydrographic analysis of the stage and discharge data to determine the most likely time when the deposition or vegetation growth and scour occurred.

Table F.1 — List of discharge measurements modified from Table 1

ID number	Date (yyyy/mm/dd)	Effective depth m	Discharge m^3/s
366	1973/08/21	0,957	7,080
367	1973/10/10	0,890	4,928
368	1973/11/26	0,909	5,296
372	1974/07/10	0,973	7,703
373	1974/08/22	0,970	7,590
374	1974/10/01	0,814	3,483
375	1974/11/11	1,832	3,313

NOTE The effective depths of measurements 366 to 368 were modified to represent deposition in the stream channel and the effective depths of measurements 372 to 375 were modified to represent channel scour.

