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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

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Foreword

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

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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 (= $4\bar{V}/v$)[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):

$$Q = C_D B H^{\beta} \quad (1)$$

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):

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

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):

$$Q = C A r_{\mathrm{h}}{}^{0{,}5} S_{\mathrm{f}}{}^{0{,}5} \tag{3}$$

where C is the Chezy form of roughness.

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

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

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):

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

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 m^2	Mean velocity m/s	Average gauge height m	Effective depth m	Discharge m^3/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

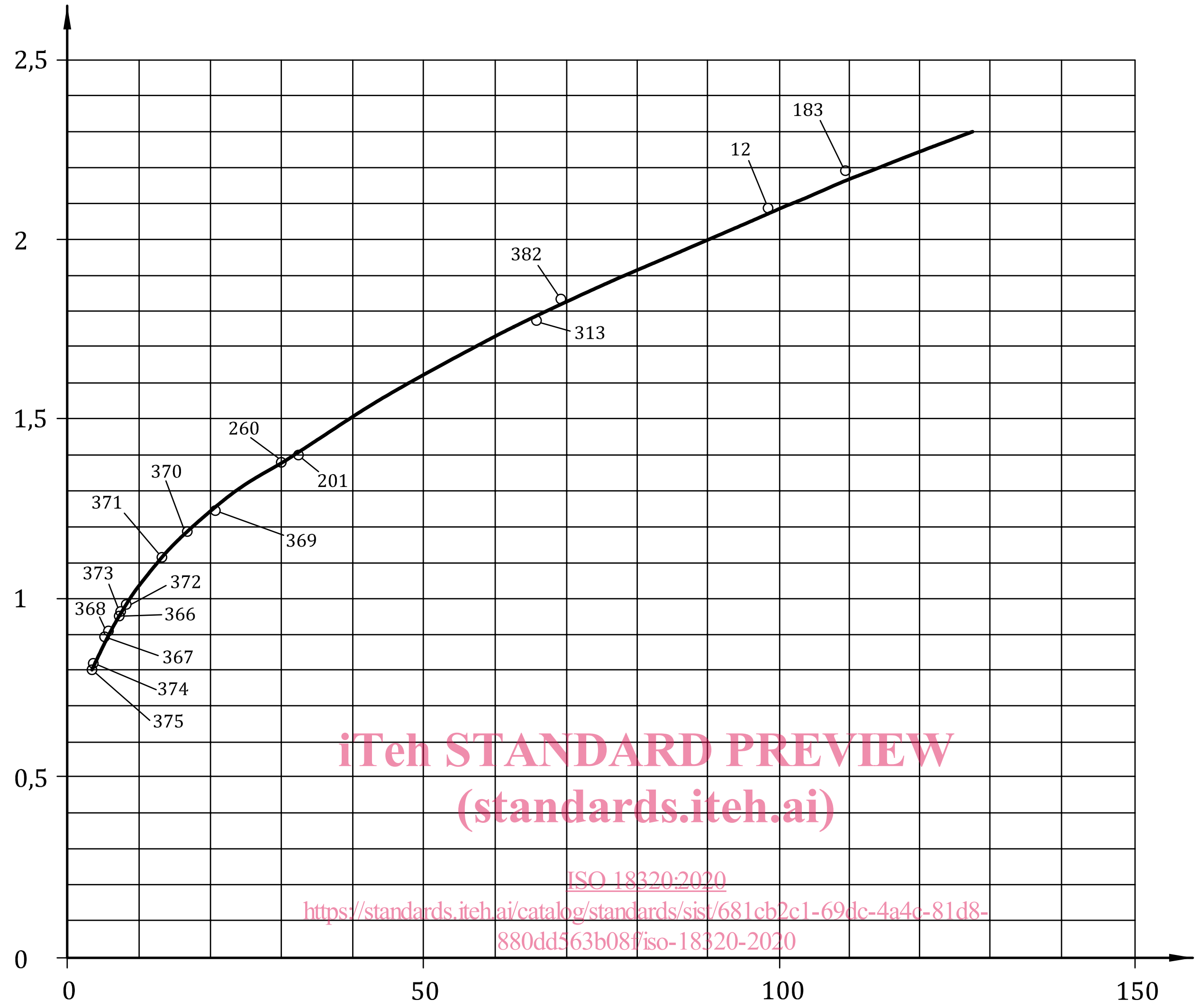
NOTE 1 Discharge measurements made with acoustic Doppler current profilers require additional parameters, including the number of transects and the range of discharges measured during the transects (see ISO/TR 24578).

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.