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Hydrometry — Slope-area method

Hydrometrie — Methode de la pente de la ligne d'eau

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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*.

This third edition cancels and replaces the second edition (ISO 1070:1992), which has been technically revised. It also incorporates the amendment ISO 1070:1992/Amd.1:1997. The main changes compared to the previous edition are as follows:

— the document has been reorganized to first present two-section computations followed by multiple reach computations;

— a third governing formula has been added;

— three annexes have been added.

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.

Introduction

The slope–area method is an indirect method of determining discharge in open channels when direct measurement of the flow is not possible because of the timing of the flow or because the site is too hazardous for direct measurement techniques. The method is usually used to document the discharge of a flood and to extend the stage–discharge rating of a stream flow gauging station above direct measurements of discharge. The method can also be used at locations where bridge, cableway or boat measurements are not possible. Water discharge is computed using flow resistance formulae based on channel characteristics, water-surface profiles, and a roughness or friction coefficient.

Hydrometry — Slope-area method

1 Scope

This document specifies a method of determining discharge in open channels from observations of the surface slope and cross-sectional area of the channel.

It is applicable to use under special conditions when direct measurement of discharge by typically more accurate methods, such as the velocity-area method, is not possible. Generally, the method can be used to determine discharge

a) for a peak flow that left high-water marks along the stream banks,

b) for a peak flow that left marks on a series of water-level gauges or where peak stages were recorded by that series of gauges, and

c) for flow observed at the time of determining gauge heights from a series of gauges.

The method is commonly used to undertake the extension of stage–discharge relationships above the highest gauged flows.

It does not apply to determining discharges in tidal reaches.

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 772, *Hydrometry — Vocabulary and symbols*

ISO 4373, *Hydrometry — Water level measuring devices*

3 Terms and definitions

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

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/

4 Principle of the method of measurement

A measuring reach is chosen for which the mean area of the stream or river cross section is determined, and the surface slope of the flowing water in that reach is measured. The mean velocity is then established using known empirical formulae that relate the velocity to the hydraulic radius. The surface slope is corrected to account for the kinetic energy of the flowing water and the characteristics of the bed and bed material. The discharge is computed as the product of the mean velocity and the mean area of the stream cross section.

Hydraulic assumptions of the method limit its suitability for use in very large channels with very flat surface slopes, steep mountainous channels where free fall over riffles and boulders occurs, or channels having significant curvature. Such conditions require experienced judgement to determine whether the method is applicable.

The most common governing formulae for flow resistance are the Manning and Chezy formulae. The Manning formula is shown by Formula (1):

$$Q = \frac{AR_h^{\frac{2}{3}}}{n} S^{\frac{1}{2}} \tag{1}$$

where

Q is the discharge, in cubic metres per second;

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

R_h is the hydraulic radius, in metres;

S is the friction slope;

n is the channel roughness, in seconds per metres to the one-third power.

The Chezy formula is shown by Formula (2):

$$Q = CAR_h^{\frac{1}{2}} S^{\frac{1}{2}} \tag{2}$$

where C is the Chezy form of roughness, in metres to the one-half power per second.

NOTE Manning n and Chezy C values of roughness for various open channel conditions are given in Annex A. The Strickler coefficient, K_s, is the reciprocal of n and it is used in some countries (see Annex B).

Another flow resistance formula is the Darcy-Weisbach (Colebrook-White) formula, which is a theoretically based formula commonly used in the analysis of pressure pipe systems. It applies equally well to any fluid flow rate and is general enough to be applied to open-channel flows. Although it has not been widely used (because the solution to the formula is difficult), it is gaining more acceptance because it successfully models the variability of effective channel roughness with respect to channel material, geometry and velocity. The Darcy-Weisbach (Colebrook-White) formula is shown by Formula (3):

$$Q = \left(\frac{8g}{f}\right)^{\frac{1}{2}} AR_h^{\frac{1}{2}} S^{\frac{1}{2}} \tag{3}$$

where

f is the Darcy-Weisbach friction factor;

g is the acceleration due to gravity, in metres per second squared.

The Darcy-Weisbach friction factor, f, can be determined using the Colebrook-White formula for fully developed turbulent flow, as shown by Formula (4):

$$\frac{1}{\sqrt{f}} = -\log_{10}\left(\frac{k}{14{,}83\,R_h} + \frac{2{,}52}{R_e\sqrt{f}}\right) \tag{4}$$

where

k is roughness height, in metres;

R_e is the Reynolds number.

Since the Darcy-Weisbach friction factor is on each side of the formula, an iterative computation algorithm is required to solve for f.

The three formulae and associated friction coefficients are employed best in streams or rivers with a uniform or slightly constricting reach in which the cross-sectional profile and bed material are consistent throughout the reach. The use of this method in non-uniform reaches, composite cross sections (a main channel and one or more overflow sections), and/or changes in channel geometry and roughness factors will introduce additional uncertainty in the computations.

5 Selection and demarcation of site

5.1 Initial survey of site

It is recommended that approximate measurements of widths, depths and surface slopes be made in a preliminary survey to decide whether the site is suitable and conforms (to the extent possible) with the conditions specified in 5.2 and 5.3. Interviews with witnesses, if any, should be done to get information about the flood timing, flow paths, high water levels, and possible bed changes during the event, and to ascertain the availability of photographs or videos of the flood event.

5.2 Selection of site

Ideally, the river reach should be straight, and should contain no large curvatures or meanders. There should not be any abrupt change in the bed slope in the measuring reach, as can occur in steep, rocky channels. The cross section should be as uniform as possible or slightly constricting throughout the reach and free from obstructions. Preferably, vegetation should be minimal and distributed uniformly throughout the reach. Ideal reach conditions are rare, so a reach with the best combination of desirable characteristics should be chosen.

Good high-water mark definition is essential to the slope–area method. The presence and quality of high-water marks are therefore key factors in selecting the measurement site.

The bed material should be similar in nature throughout the reach.

Wherever possible, the length of the reach should be such that the difference between the water levels at the upstream and downstream ends of the reach is at least 0,25 m.

Flow in the reach should be free from significant tributary inflows (or distributary outflows), and from disturbances in the high-water profile caused by any tributaries or distributaries.

The flow in the channel should be contained within defined boundaries. If possible, reaches in which over-bank flow conditions exist should not be selected. Where this is unavoidable, however, a reach in which there are no very shallow flows over the floodplain should be sought. This will require additional computations for determining the discharge.

The site should not be subject to change in the flow regime from subcritical to supercritical or from supercritical to subcritical.

While a uniform reach is ideal, a converging reach should be selected in preference to an expanding reach. The energy losses induced by large expansions over the entire reach cannot be properly accounted for, thus reaches with large or rapid expansions should not be selected (see 9.3.3).

5.3 Demarcation of site

If the site is used for periodic slope–area measurements or continuous measurement of high flows, permanent cross sections normal to the direction of flow shall be chosen and markers (clearly visible and identifiable) shall be placed on both banks.

The site should be monitored to identify and assess any physical changes to the cross sections or reach that occur over time.

6 Measurement of slope

6.1 High-water marks

The slope–area method is most often used to document a flood or very high flow event. The friction slope defined in the flow resistance formulae is approximated by surveying high-water marks on both banks within the measuring reach to determine the change in water surface elevation, determining the velocity heads at each section, and evaluating the loss due to contraction or expansion. The high-water marks should extend upstream of the most upstream cross section and downstream of the most downstream cross section. The high-water marks may consist of drift on banks, wash lines, seed lines on trees, mud lines, and drift in bushes or trees. Each high-water mark should be rated as excellent, good, fair or poor, which will help with interpreting the high-water profile and slope. Mud lines and seed lines on tree trunks or structures typically are excellent high-water marks. Drift and wash lines are usually good, fair or poor depending on the tendency of the stream bank vegetation to bounce back from the forces exerted on it by the flowing water. Care should be exercised in using high-water marks on trees and other obstacles in high-velocity areas because they may be more representative of the total energy than the water level, which will reduce the accuracy of the computed discharge.

The high-water marks should be surveyed as soon as possible after the flood. If this is not practical, the marks should be preserved with paint, nails, flagging or labels until the survey can be done.

6.2 Crest-stage gauges

If the site is to be used for periodic measurement of high flows, a series of crest-stage gauges installed on each side of the reach can be used to determine the high-water profile and slope. There should be at least one crest-stage gauge at the left and right bank of each cross section; cross-section locations should reflect known hydraulic changes in the measurement reach (observed slope breaks in the high-water profile, for example). The crest-stage gauges should conform to ISO 4373.

6.3 Pressure transmitters

If the site is to be used for periodic measurement of high flow or continuous measurement of flood hydrographs, a series of recording gauges installed on each side of the reach can be used to determine the high-water profile and slope; as noted in 6.2, cross-section locations should reflect any known hydraulic changes in the measurement reach. The recording devices can be individual water-level recording gauges, or a series of pressure transmitters connected to a single data logger or recorder.

6.4 Reference gauge

The water levels determined by surveying high-water marks or from crest-stage or recording gauges should be referenced to national or local datum by precise levelling to the nearest benchmark. If the site is maintained as a stage–discharge gauging station, the water levels should be surveyed to the reference gauge whether it is a vertical staff gauge or inclined gauge. The reference gauge shall conform to ISO 4373 and be securely fixed to an immovable, rigid support in the stream or river.

7 Determination of slope

The high-water profile or surface slope is usually determined from a plot of high-water marks from both river banks. The average of the intersections of the lines of best fit of the high-water marks on both banks with the cross sections represent the water levels at each cross section. Each high-water mark will be defined by its position and quality rating on a graphical plot of water level versus distance, as measured along the stream thalweg or centre line of conveyance through the reach.

Alternatively, the water levels can be the difference in the average of the left and right bank crest-stage gauge measurements at the upstream and downstream cross sections of the measuring reach.

A large number of high mark levels, even if apparently redundant and not located in the considered cross sections, will help to identify and discount inconsistent flood marks and confirm uniformity of the flow regime along the reach.

8 Cross sections of a stream

8.1 Number and location of cross sections

A minimum of three cross sections in the selected measuring reach generally is desirable; five or more cross sections can provide insight into and reduce the uncertainty of the computed discharge. Cross sections shall be clearly marked on the banks by means of masonry pillars or easily identifiable markers. The cross sections shall be numbered so that the cross section furthest upstream is identified as section 1, the adjacent cross section downstream is identified as section 2, and so on.

Cross-section locations should be determined based on plotted high-water profiles (see Clause 7), with cross sections located at any major slope breaks in the high-water profiles. This approach ensures conveyance varies uniformly between cross sections, which is an assumption of the slope–area method. In addition to this criterion, cross-section spacing should be consistent with the length of the measurement reach and number of cross sections used. Each cross section should be oriented perpendicular to the direction of flow[4].

8.2 Measurement of cross-sectional profiles

The profile of each of the cross sections selected shall be measured at the same time at which the gauge observations are made, or as close as possible to this time. It is often impossible to measure (by sounding) the cross section during flood and therefore an error may be introduced in the flow determination owing to an unobserved and temporary change in a cross section. If the section is stable, however, it will be sufficient to measure the cross sections before and after a flood.

9 Computation of discharge

9.1 General

Discharge calculations are presented for three types of stream reaches. The first case is for reaches with uniform cross-section geometry and roughness. In this case, the water surface slope (S_w) is virtually equivalent to the friction slope (S) because the velocity head throughout the reach is constant. The more complex cases are reaches that have converging or slightly diverging cross-sectional areas, and reaches that have composite cross sections consisting of a main channel section and one or two floodplain sections.

9.2 Uniform cross sections

9.2.1 General

The discharge of a stream for which the cross sections are uniform (both for geometry and roughness) is the product of the mean cross-sectional area and the mean velocity of flow in the reach, as shown by Formula (5):

$$Q = \bar{v}_{1-m} \bar{A} \tag{5}$$

where $\bar{v}_{1-m}$ is the mean velocity in the reach between section 1 and section m.

9.2.2 Determination of the mean cross-sectional area and mean wetted perimeter of the reach

In natural streams, it is very difficult to find a reach that has a uniform cross section throughout its length. However, if the reach is uniform with only small differences in the cross-sectional areas A_1, A_2, ..., A_m, the mean cross-sectional area of the reach may be taken as shown by Formula (6):

$$\bar{A} = \frac{A_1 + 2A_2 + ... + 2A_{m-1} + A_m}{2(m-1)} \tag{6}$$

where m is the number of cross sections chosen.

The corresponding wetted perimeters shall then be determined and the mean wetted perimeter, $\bar{P}$ may then be calculated as shown by Formula (7):

$$\bar{P} = \frac{P_1 + 2P_2 + ... + 2P_{m-1} + P_m}{2(m-1)} \tag{7}$$

9.2.3 Determination of hydraulic radius

The hydraulic radius, R, at any section is the ratio of the area of flow A to the wetted perimeter P, as shown by Formula (8):

$$R_h = \frac{A}{P} \tag{8}$$

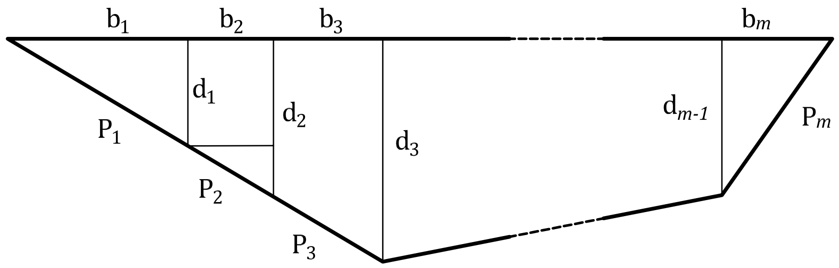
The area of flow, i.e. the area of the cross section, and the wetted perimeter are computed as follows (also see Figure 1).

If the depths of flow of a channel, measured at different points along a cross section by sounding, are d_1, d_2, d_3, ..., d_{m-1} and $d_0 = d_m = 0$ (see Figure 1), the area of the cross section may be computed as shown by Formula (9):

$$A = \frac{1}{2} \sum_{i=1}^{m} b_i (d_{i-1} + d_i) \tag{9}$$

and the wetted perimeter may be computed as shown by Formula (10):

$$P = \sum_{i=1}^{m} \sqrt{b_i^2 + (d_i - d_{i-1})^2} \tag{10}$$



Key

$b_1, b_2, \ldots b_m$ distances between depth measuring points

$d_1, d_2, d_3, \ldots d_{m-1}$ depths

$P_1, P_2, P_3, \ldots P_m$ values of wetted perimeter

Figure 1 — Cross section of a channel

9.2.4 Determination of the mean velocity in the reach

9.2.4.1 Using Manning's formula

The mean velocity between two or more cross sections (where $A_1 \neq A_2. \ldots, A_m$) when the flow is not significantly different from uniform flow is given by Formula (11):

$$\bar{v}_{1-m} = \frac{\bar{R}_h^{\frac{2}{3}} S_w^{\frac{1}{2}}}{\bar{n}} \qquad (11)$$

where

$\bar{v}_{1-m}$ is the mean velocity in the reach $1 - m$;

$\bar{R}_h$ is $\frac{\bar{A}}{\bar{P}}$;

$\bar{n}$ is the arithmetic mean of the m values of Manning's coefficient of rugosity for the cross sections in the reach;

S_w is the water surface slope for the reach and approximately equal to S (the friction slope) for steady, uniform flow.

9.2.4.2 Using Chezy's formula

The mean velocity between two cross sections for the same conditions as described in 9.2.4.1 is shown by Formula (12):

$$\bar{v}_{1-m} = \bar{C}(\bar{R}_h S_w)^{\frac{1}{2}} \qquad (12)$$

where $\bar{C}$ is the arithmetic mean of the m values of Chezy's discharge coefficient for the cross sections in the reach.

9.2.4.3 Manning and Chezy coefficients

Where a reasonable value of Manning's coefficient of rugosity or Chezy's discharge coefficient can be extrapolated from direct discharge measurements taken in the measuring reach, the values obtained can be used provided there have been no subsequent changes in the channel characteristics. Reasonable values also can be estimated from surface flow velocities observed on videos, if available.

In the absence of measured data, the values given in Table A.1 for Manning's coefficient of rugosity and Chezy's coefficient can be used for channels with relatively coarse bed material and not characterized by bed formations, and those given in Table A.2 can be used for channels with other than coarse bed material and for channels having vegetation, clay, and rocky banks. Annex C provides an alternative method for estimating Manning's coefficient of rugosity.

9.2.4.4 Using the Darcy-Weisbach (Colebrook-White) formula

The mean velocity between two cross sections for the same conditions as described in 9.2.4.1 is shown by Formula (13):

$$\bar{v}_{1-m} = \sqrt{\frac{8g\bar{R}_\mathrm{h}S_\mathrm{w}}{f}} \tag{13}$$

where the Darcy-Weisbach friction factor, f, is determined through iterative solutions of Formula (4).

9.3 Non-uniform cross sections (2-cross-section formulation)

9.3.1 General

The discharge of a stream in a reach shall be calculated from Formula (14):

$$Q = \bar{K}S^{\frac{1}{2}} \tag{14}$$

where $\bar{K}$ is the mean conveyance. Formula (14) extrapolates the Manning formula, see Formula (1), by assuming the formula is valid by allowing S to include not only the energy losses due to friction, but also those from contraction/expansion.

9.3.2 Computation of conveyance

When the channel reach is a single channel and it varies uniformly between sections, say sections 1 and 2 (it can be either converging or slightly expanding) the conveyance K_1 and K_2 of the upstream and downstream cross sections, respectively, should be calculated. The mean conveyance for the reach will then be given by the geometric mean of K_1 and K_2 thus, as shown by Formulae (15), (16) and (17):

$$\bar{K} = (K_1 \times K_2)^{\frac{1}{2}} \tag{15}$$

where K_1 is the conveyance of the upstream cross section,

$$K_1 = \frac{1}{n_1} A_1 R_{\mathrm{h}1}^{\frac{2}{3}} \tag{16}$$

where K_2 is the conveyance of the downstream cross section,

$$K_2 = \frac{1}{n_2} A_2 R_{\mathrm{h}2}^{\frac{2}{3}} \tag{17}$$

where

n_1 and n_2 are Manning's coefficient of rugosity at section 1 and section 2, respectively, see Formula (1);

A_1 and A_2 are the cross-sectional areas at section 1 and section 2, respectively, see Formula (9);

R_{h1} and R_{h2} are the hydraulic radii at section 1 and section 2, respectively, see Formula (8).

9.3.3 Evaluation of the friction slope

The friction slope S of a reach between cross sections may be defined as shown by Formula (18):

$$S = \frac{(z_1 - z_2) + \left(\frac{\alpha_1 v_1^2}{2g} - \frac{\alpha_2 v_2^2}{2g} \right)(1 - C_e)}{L} \quad (18)$$

where

$z_1 - z_2$ is the measured fall;

α_1 and α_2 are the velocity head coefficients;

C_e is the energy loss coefficient;

v_1 and v_2 are the mean velocities at section 1 and section 2, respectively, and are given as the ratio of Q/A at the two sections;

L is the length of the reach between cross sections 1 and 2.

Terms in Formula (18) are depicted in Figure 2. The numerator of Formula (18) is defined as h_T, the total energy loss due to boundary friction and contraction/expansion in the reach.

Owing to the non-uniform distribution of velocities over a channel section, the velocity head of an open channel flow is generally greater than the expression $v^2/2g$. When the energy principle is used in the computation, the true velocity head will be expressed as $\alpha v^2/2g$ where the value of α may be greater than 1 and calculated from Formula (19):

$$\alpha = \frac{\sum \left(\frac{K_i^3}{A_i^2} \right)}{\frac{K^3}{A^2}} \quad (19)$$

where

K is the conveyance of the cross section;

K_i is the conveyance of subsection i, where i = 1 to n;

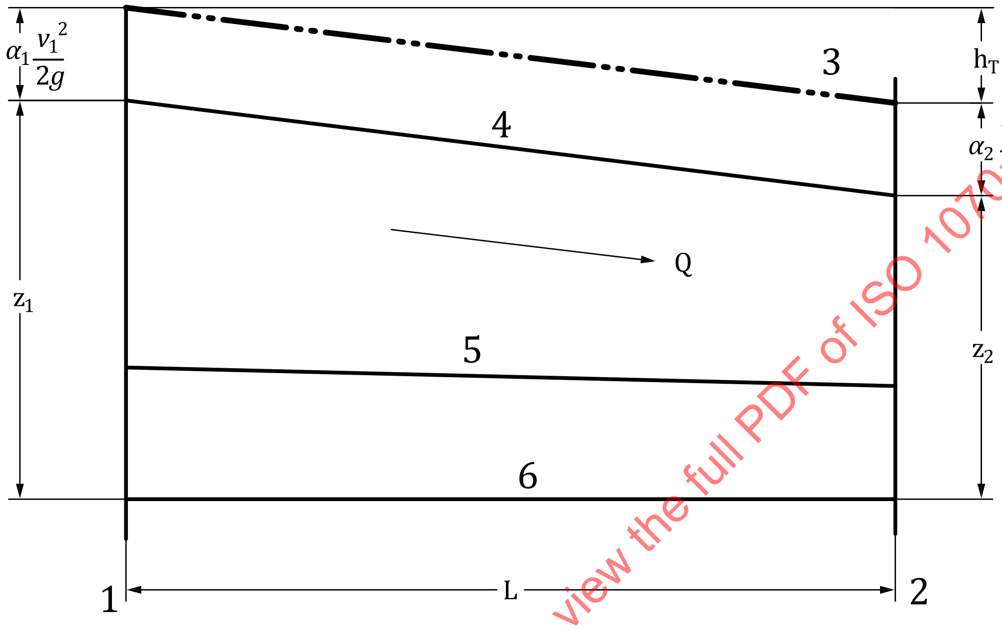
A is the area of the cross section;

A_i is the area of subsection i.

The velocity head coefficient may also be obtained by the empirical Formula (20):

$$\alpha = 1 + 0{,}88\left(0{,}34 + \frac{1 + \frac{\sqrt{g}}{C}}{2{,}3 + \frac{0{,}3C}{\sqrt{g}}}\right)^2 \tag{20}$$

where C is the Chezy coefficient.



Key

1 cross section 1

2 cross section 2

3 energy gradient

4 water surface slope

5 streambed slope

6 datum

Figure 2 — Longitudinal section of a converging reach longitudinal section of a converging reach

The energy head loss due to convergence or expansion of the channel in the measuring reach is assumed to be equal to the difference in the velocity heads at the two sections considered multiplied by a coefficient $(1 - C_e)$. The value of C_e is taken to be zero for uniform and converging reaches and 0,5 for expanding reaches. The true energy loss in expanding reaches is unknown. Lacking better understanding, the energy loss coefficient for expanding reaches is assumed to be 0,5. Therefore, large or rapidly expanding reaches should not be selected for slope–area measurements.

For a converging reach, the friction slope should be calculated as shown by Formula (21):

$$S=\frac{(z_1-z_2)+\left(\frac{\alpha_1 v_1^2}{2g}-\frac{\alpha_2 v_2^2}{2g}\right)}{L} \tag{21}$$

and for expanding reaches, the friction slope includes the expansion losses and is given by Formula (22):

$$S=\frac{(z_1-z_2)+0{,}5\left(\frac{\alpha_1 v_1^2}{2g}-\frac{\alpha_2 v_2^2}{2g}\right)}{L} \tag{22}$$

The friction slope S between two adjacent cross sections can be determined by successive approximation. First, assume a value for the discharge Q. A reasonable assumption can be made using the water-surface slope in place of the friction slope in Formula (14). Then, calculate v_1 and v_2 as Q/A_1 and Q/A_2, respectively. Calculate all other values in Formula (21) from cross-sectional properties and water-surface elevations at sections 1 and 2. Calculate the friction slope S using Formula (21). Calculate the discharge Q using the calculated value of S and the geometric mean conveyance K. If this calculated value of Q agrees with the assumed value of Q, with reasonable limits, then the calculated values of S and Q are correct. If the calculated and assumed values of Q do not agree, the process should be iterated starting with a new assumed value of Q.

9.4 Composite cross sections

Rivers with a floodplain generally have composite sections that reflect an abrupt break in cross-section shape between the main channel and the floodplain, as illustrated in Figure 3, where a and c are floodplain sub-sections and b is the main channel sub-section. Computing a discharge for a river or stream with a composite cross section stretches the application of the three governing formulae for flow resistance (see Clause 4). The conveyance component of the formulae is based on the area, wetted perimeter and roughness factor. If the cross section is not subdivided properly or subdivided when it shouldn't be, the wetted perimeter of the subsections will be too small or too large resulting in a too large or too small hydraulic radius. This would then require a fictitious value for the roughness factor for the formulae to yield an accurate discharge. Knight, Shiono and Pirt[17] and Davidian[9] provide examples of inappropriate subdivision and application of roughness factors.

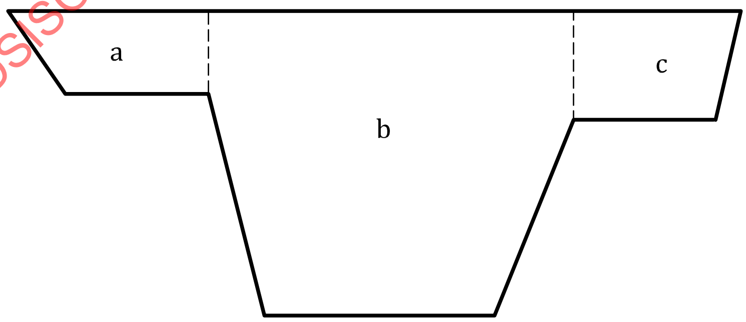


Figure 3 — Composite cross section of a main channel and floodplain

When subdivision is done correctly, a discharge is computed based on Formula (14) and the combined conveyance of each subsection, as shown by Formula (23):

$$K = K_a + K_b + K_c \tag{23}$$

where for the Manning formula, see Formula (1):

$$K_a = \frac{1}{n_a} A_a R_{ha}^{\frac{2}{3}}$$

$$K_b = \frac{1}{n_b} A_b R_{hb}^{\frac{2}{3}}$$

$$K_c = \frac{1}{n_c} A_c R_{hc}^{\frac{2}{3}}$$

where

A_a, A_b and A_c are the areas of the three subsections of the composite section, see Formula (9);

R_{ha}, R_{hb} and R_{hc} are the hydraulic radii for the three subsections of the composite section, see Formula (8);

n_a, n_b and n_c are Manning's coefficient of rugosity for the three subsections of the composite section, see Formula (1).

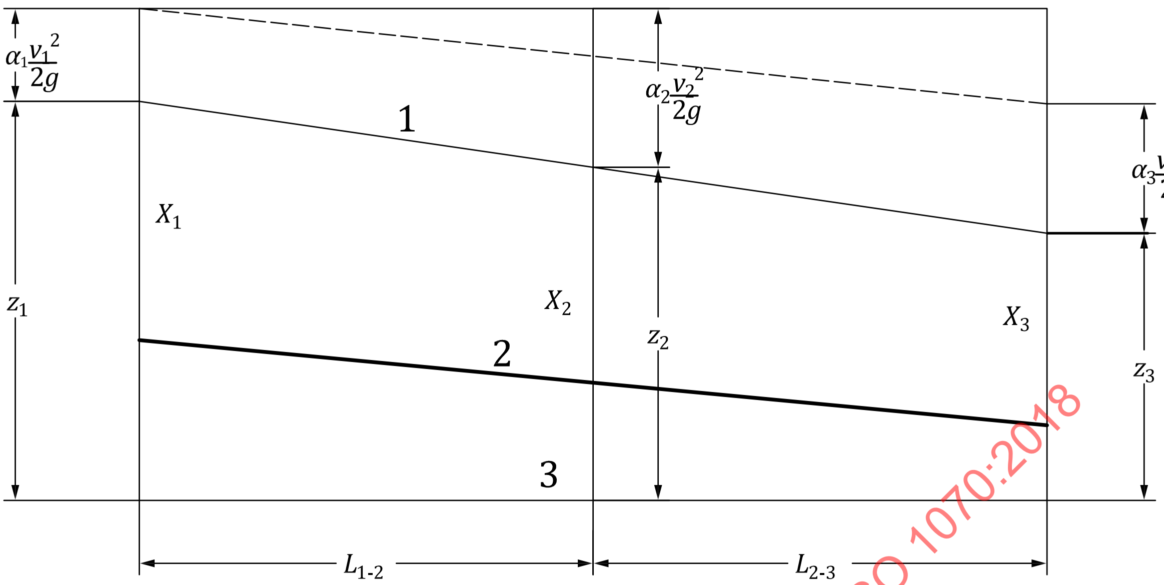
If the shape of the composite cross section varies between sections 1 and 2, then the conveyance factors for both composite cross sections 1 and 2 should be evaluated separately and the mean conveyance of the reach should then be calculated following the procedure given in 9.3.2.

It should be noted that, due to the momentum transfer across the vertical between the main channel and the floodplain, there can be an overestimation or under estimation of the discharge. The conveyance estimation system (CES) (see 10.3 and Annex D) offers a more comprehensive approach for addressing roughness boundary and momentum transfer issues of composite cross sections.

9.5 Computation of discharge using three or more cross sections

For reaches with three or more cross sections, the discharge should be computed for each pair of adjacent sections. These computed discharges will most likely be different and an average should be taken such that the energy balance is satisfied throughout the reach. This usually is a trial-and-error procedure; however, formulae are available for these computations to avoid the trial-and-error method. Formula (24) is used for a reach with three cross sections (see Figure 4):

$$Q = K_3 (z_1 - z_3)^{\frac{1}{2}} \left\{ \frac{K_3}{K_2} \left(\frac{K_3}{K_1} L_{1-2} + L_{2-3} \right) + \frac{K_3^2}{2gA_3^2} \left[-\alpha_1 \left(\frac{A_3}{A_1} \right)^2 (1 - C_{e1-2}) + \alpha_2 \left(\frac{A_3}{A_2} \right)^2 (C_{e2-3} - C_{e1-2}) - \alpha_3 (1 - C_{e2-3}) \right] \right\}^{-\frac{1}{2}} \tag{24}$$



Key

1	water surface
2	bed
3	datum
X_1, X_2, X_3	cross sections 1, 2, and 3
z_1, z_2, z_3	water elevation above datum
L_{1-2} and L_{2-3}	length of reach between cross sections 1 and 2 cross sections 2 and 3, respectively

Figure 4 — Longitudinal section of a reach with three cross sections

9.6 State of flow

After the final discharge has been determined, the value of the Froude number F_r should be computed for each cross section to evaluate the state of flow, as shown by Formula (25):

$$F_r = \frac{\bar{v}}{\sqrt{g\bar{d}}} \tag{25}$$

where

$\bar{v}$ is the mean velocity;

g is the acceleration due to gravity;

$\bar{d}$ is the mean depth of the cross section, which is the ratio of the area of the cross section and the water surface width.

Although the slope–area method can be used for both subcritical ($F_r < 1$) and supercritical ($F_r > 1$) flow, if the state of flow changes in the channel reach from subcritical to supercritical or vice versa, there is cause for further examination of the data.

10 Alternative methods to estimate conveyance

10.1 General

The methods described in Clause 9 use the single channel method for computing conveyance and discharge for reaches with uniform cross sections and those with non-uniform or composite sections. The single channel method produces good estimates of discharge for reaches with uniform cross sections; however, the uncertainty of the computed discharge increases as the conveyance varies with non-uniform channel geometry, bed material and river bank vegetation.

10.2 Divided channel method

The divided channel method of computing discharge uses the same governing formulae as the single channel method; however, the stream reach is divided into multiple channels to better account for variation in channel roughness due to irregular geometry, differences in bed material and variation in stream bank vegetation. The stream reach typically is subdivided by vertical lines (see Figure 3), and the conveyance and discharge are calculated for each channel as in 9.3. The discharges of the individual channels are then summed as the total discharge of the stream or river.

10.3 Conveyance estimation system

The CES is a public-domain software system for estimating conveyance for various channel types and flow conditions that was developed for the Environmental Agency in the United Kingdom. A key component of the CES is the increased knowledge in recent years on river resistance from a diverse set of sources, covering different types of vegetation and surface material (bed, bank and floodplain) for the fluvial system. The CES includes enhanced roughness knowledge, improved conveyance estimation and the quantification of uncertainty. The components of CES and how conveyance is calculated in CES are described in Annex D.

11 Uncertainty in flow measurement

11.1 Definition of uncertainty

ISO/TS 25377 sets forth the concepts, terminology and methods to be used in discussing and computing the uncertainty of hydrometric measurements. 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 measurement. 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 measurement. 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.

11.2 Sources of uncertainty for a uniform reach

11.2.1 General considerations

From Formula (5):

$$Q = \bar{v}\bar{A}$$

where $\bar{v}$ and $\bar{A}$ are the mean velocity and the mean area, respectively. Using Manning's formula, as shown by Formulae (26) and (27):

$$\bar{v} = \frac{\bar{R}_h^{\frac{2}{3}} S_w^{\frac{1}{2}}}{\bar{n}} \tag{26}$$

where $\bar{R}_h = \frac{\bar{A}}{\bar{P}}$

then

$$Q = \frac{\bar{R}_h^{\frac{2}{3}} S_w^{\frac{1}{2}} \bar{A}}{\bar{n}} = \frac{\bar{A}^{\frac{5}{3}} S_w^{\frac{1}{2}}}{\bar{P}^{\frac{2}{3}} \bar{n}} \tag{27}$$

Thus, the overall relative uncertainty of the discharge computed using the Manning formula for a stream with uniform cross sections will be the combined uncertainty of the area (u_A), slope (u_{S_w}), wetted perimeter (u_P) and the coefficient of rugosity (u_n). The same uncertainty components will apply for the Chezy and the Darcy-Weisbach (Colebrook-White) formulae.

11.2.2 Uncertainty of the mean cross-sectional area

The uncertainty in the mean cross-sectional area $u_{\bar{A}}$ of a reach is composed of the following three separate components:

a) uncertainties due to errors in measurement;

b) uncertainties due to differences between assumed and actual shapes of the subsections and to the number of subsections selected;

c) uncertainties due to intrinsic differences in cross-sectional area throughout the reach.

Of these uncertainties, it is likely that component c) will be the greatest by far. Where only a limited number of cross sections have been measured, the uncertainty of component c) will need to be assessed subjectively and should take into account any specialized knowledge of the reach.

11.2.3 Uncertainty in the calculation of the mean wetted perimeter

The uncertainty in the mean wetted perimeter $u_{\bar{P}}$ is also divided into the three components:

a) uncertainties due to errors in measurement;

b) uncertainties due to differences between assumed and actual shapes of the bed;

c) uncertainties due to intrinsic differences in wetted perimeter throughout the reach,

Again, component c) likely is the largest source of uncertainty. As noted in 11.2.2, subjective assessment will need to take into account any known facts concerning the reach, including a suitable allowance for the uncertainties of components a) and b).

Since both the cross-sectional area and the wetted perimeter are determined from the same measurements of width and depth, their values will not be independent; the uncertainty in the discharge therefore should be decreased to take this relationship into account. However, in view of the difficulty of quantifying the uncertainty and of assessing the dependent effect of the changes in cross-sectional areas and wetted perimeters through the reach, it is suggested that this adjustment (decrease in uncertainty) be omitted from the calculation.

11.2.4 Uncertainties in determination of the friction slope

The uncertainty in the determination of the friction slope will depend on

a) uncertainties in the gauge or high-water mark readings,

b) uncertainties due to corrections for non-uniform slope, and

c) uncertainties due to estimating the friction slope based on the observed slope.

Component a) probably is the most significant source of uncertainty, especially where the slope is determined from high-water marks. The assessment of the uncertainty of component a) can be facilitated by taking several consecutive readings of the gauges in question over a period of steady-state flow and comparing the differences in the slopes obtained. The assessment should also include an allowance for the uncertainties of components b) and c).

11.2.5 Uncertainty due to the choice of the rugosity coefficient

The uncertainty in the rugosity coefficient used will include both of the following components:

a) uncertainties due to mischaracterizing channel shape, bed material size, and type and extent of vegetation;

b) errors of judgement in the selection of *n*, *c* or *f*, depending on which governing formula is used.

Assessment of the magnitude of these uncertainties is particularly difficult and is again largely subjective. However, as experience with the method is gained, this difficulty is likely to reduce. It should be noted that once a value has been selected, any uncertainty introduced will be systematic rather than random; this systematic uncertainty will result either in an over-estimate or an under-estimate of the mean. Nevertheless, magnitude and sign of these uncertainties relative to the mean ultimately are unknown, and it is only possible to assess the range subjectively. In view of this subjectivity, the uncertainty due to this source should be taken as half of the estimated range and treated as random.

11.2.6 Overall uncertainty in the measurement of discharge

The combined relative uncertainty of discharge computed by the Manning formula is expressed as shown by Formula (28):

$$U = \left(\frac{25}{9} u_A^2 + \frac{1}{4} u_{S_\mathrm{w}}^2 + \frac{4}{9} u_P^2 + u_\mathrm{n}^2 \right)^{\frac{1}{2}} \qquad (28)$$

As noted in 11.2.2, the parameters used to calculate area and wetted perimeter are the same and the uncertainty of area and wetted perimeter are not independent of each other. Therefore, the combined relative uncertainty should be less than the value calculated by Formula (28).

Annex A
(informative)

Approximate value of coefficients *n* and *C* for open channels

Tables A.1 and A.2 indicate the coefficients *n* and *C*, which may be used subject to the following observations.

a) The values given for the coefficients in Tables A.1 and A.2 are not comprehensive and should be used only as a guide; appreciable error will be introduced when R_h is small and the size of the bed material is large.

b) Chezy's and Manning's coefficients are inter-related for the bed conditions mentioned in Tables A.1 and A.2. Using the Darcy-Weisbach friction factor, the bed conditions may be defined more explicitly, but it is an iterative process using the Colebrook-White formula.

c) It is advantageous to determine the range of roughness for natural channels by measurement, to photograph the channels and to record their corresponding verified coefficients; this documentation will serve as guidance in the selection of coefficients for a reach under survey. Appropriate values of the coefficients may thus be selected by visual comparison. Barnes[5] and Hicks and Mason[14] provide photographs of channels and their computed *n* values for streams and rivers in the United States and New Zealand, respectively.

Table A.1 — Coefficients for channels with relatively coarse bed material and not characterized by bed formations (adapted from Chow[6])

Type of bed material	Size of bed material mm	Manning's coefficient *n*	Chezy's coefficient *C* for the following values of R_h R_h = 1 m	 R_h = 2,5 m	 R_h = 5 m	 R_h = 10 m
Gravel	4 to 8	0,019 to 0,020	53 to 50	61 to 58	69 to 65	77 to 73
	8 to 20	0,020 to 0,022	50 to 45	58 to 53	65 to 59	73 to 67
	20 to 60	0,022 to 0,027	45 to 37	53 to 43	59 to 48	67 to 54
Pebbles and shingle	60 to 110	0,027 to 0,030	37 to 33	43 to 39	48 to 44	54 to 49
	110 to 250	0,030 to 0,035	33 to 29	39 to 33	44 to 37	49 to 42

Table A.2 — Coefficients for channels other than those with coarse bed material

Type of bed material	Manning's coefficient *n*	Chezy's coefficient *C* for the following values of R_h R_h = 1 m	 R_h = 2,5 m	 R_h = 5 m	 R_h = 10 m
A. Excavated or dredged					
a) Earth, straight and uniform					
1) Clean, recently completed	0,016 to 0,020	63 to 50	72 to 58	81 to 65	91 to 73
2) Clean, after weathering	0,018 to 0,025	55 to 40	64 to 46	72 to 52	81 to 59
3) With short grass, few weeds	0,022 to 0,033	45 to 30	53 to 35	59 to 40	67 to 44
b) Rock cuts					

Table A.2 *(continued)*

Type of bed material	Manning's coefficient n	Chezy's coefficient C for the following values of R_h			
		R_h = 1 m	R_h = 2,5 m	R_h = 5 m	R_h = 10 m
1) Smooth and uniform	0,025 to 0,040	40 to 29	46 to 29	52 to 33	59 to 37
2) Jagged and irregular	0,035 to 0,050	29 to 20	33 to 23	37 to 26	42 to 29
B. Natural stream					
B.1 Minor stream (top width at flood stage less than 30 m)					
a) Streams on plains Clean, straight, full stage, no rifts or deep pools.	0,025 to 0,033	40 to 30	46 to 35	52 to 40	59 to 44
b) Clean, winding stream with some pools and shoals	0,033 to 0,045				
c) Clean, winding, with some pools and shoals, and more rocks	0,045 to 0,060				
B.2 Floodplains					
a) Pasture, no brush					
1) Short grass	0,025 to 0,035	40 to 29	46 to 33	52 to 37	59 to 42
2) High grass	0,030 to 0,050	33 to 20	39 to 23	44 to 26	49 to 29
b) Cultivated areas					
1) No crop	0,020 to 0,040	50 to 25	58 to 29	65 to 33	73 to 37
2) Mature row crops	0,025 to 0,045	40 to 22	46 to 26	52 to 29	59 to 33
3) Mature field crops	0,030 to 0,050	33 to 20	39 to 23	44 to 26	49 to 29
c) Brush					
1) Scattered brush, heavy weeds	0,035 to 0,070	29 to 14	33 to 17	37 to 19	42 to 21
2) Light brush and trees (without foliage)	0,035 to 0,060	29 to 17	33 to 19	37 to 22	42 to 24
3) Light brush and trees (with foliage)	0,040 to 0,080	25 to 12	29 to 14	33 to 16	37 to 18
4) Medium to dense brush (without foliage)	0,045 to 0,110	22 to 9	26 to 10,5	29 to 12	33 to 13
5) Medium to dense brush (with foliage)	0,070 to 0,160	14 to 6,5	17 to 7,5	19 to 8	21 to 9
d) Trees					
1) Cleared land with tree stumps, no sprouts	0,030 to 0,050	33 to 20	39 to 23	44 to 26	49 to 29
2) Same as above, but with heavy growth of sprouts	0,050 to 0,080	20 to 12	23 to 14	26 to 16	29 to 18

Table A.2 *(continued)*

Type of bed material	Manning's coefficient n	Chezy's coefficient C for the following values of R_h			
		R_h = 1 m	R_h = 2,5 m	R_h = 5 m	R_h = 10 m
3) Heavy stand of timber, a few felled trees, little under-growth, flood stage below branches	0,080 to 0,120	12 to 8,5	14 to 9,5	16 to 11	18 to 12
4) Same as above, but with flood stage reaching branches	0,100 to 0,160	10 to 6,5	12 to 7,5	13 to 8	15 to 9
5) Dense willows, in mid-summer	0,110 to 0,200	9 to 5	10,5 to 6	12 to 6,5	13 to 7,5

Annex B
(informative)

Approximate value of Strickler-coefficients k_{St} for natural streams

An alternative formula for fluid motion was developed by Albert Strickler[20] based on data collected from gravel-bed streams in Switzerland and France, and fixed-bed laboratory data, see Tables B.1 to B.4. It is very similar to the Manning formula except the Strickler roughness coefficients (k_{St}) are the reciprocal of the Manning coefficients (n), as shown by Formula (B.1):

$$Q = A k_{St} R_h^{\frac{2}{3}} S^{\frac{1}{2}} \quad \text{(B.1)}$$

where

A is area, in m^2;

k_{St} is the Strickler roughness coefficient, in $m^{\frac{1}{3}}/s$;

R_h is the hydraulic radius, in m;

S is the energy slope.

Table B.1 — Strickler-coefficients k_{St} in natural streams — Earth-channels, tortuous flow course and slowly flowing

Channel bed conditions	Strickler coefficients $[m^{\frac{1}{3}}/s]$
Without weed growth	33,5 to 43,5
Grass, weak weed growth	30 to 40
Strong weed growth or water plants in deep channels	25 to 35,5
Channel bed stony, banks overgrown with grass or weed	25 to 40
Channel bed of stones, banks without grass or weed	20 to 33,5

Table B.2 — Strickler-coefficients k_{St} in natural streams — Rivers and brooks with width < 30 m, at the highest water level — In the plain

Channel bed conditions	Strickler coefficients $[m^{\frac{1}{3}}/s]$
Straight flow, full flow section, no gravel bars and no scours	30 to 40
Straight flow, some stones and some brushwood	25 to 33,5
Spiral course, some gravel bars and some shallow areas	22 to 30
Spiral course, some stones and some brushwood	20 to 28,5
Spiral course, more stones	16,5 to 22
Spiral course, low water depths	18 to 25
Slow flowing sections, with brushwood and deep scours	12,5 to 20
Very thickly covered sections with brushwood, deep scours	6,5 to 13,5
Floodplain with deep stock of trees and undergrowth	6,5 to 13,5

Table B.3 — Strickler-coefficients k_{St} in natural streams — Rivers and brooks with width < 30 m, at the highest water level — In the mountains

Channel bed conditions (No vegetation at the channel bed, steep banks, vegetation at the flooded banks)	Strickler coefficients $[m^{\frac{1}{3}}/s]$
Channel bed consists of gravel, stones and few stone blocks	25 to 33,5
Channel bed consists of stones with large stone blocks	22 to 30

Table B.4 — Strickler-coefficients k_{St} in natural streams — Rivers with width > 30 m at the highest water level

Channel bed conditions	Strickler coefficients $[m^{\frac{1}{3}}/s]$
Regular section with stone blocks and brushwood	16,5 to 40
Irregular and rough section	10 to 28,5