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Measurement of liquid flow in open channels under tidal conditions

*Mesure de débit des liquides dans les canaux découverts — Mesurages
dans des conditions de marée*

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

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

International Standard ISO 2425 was prepared by Technical Committee ISO/TC 113, *Hydrometric determinations*, Subcommittee SC 1, *Velocity area methods*.

This second edition cancels and replaces the first edition (ISO 2425:1974), which has been technically revised.

Annexes A, B and C of this International Standard are for information only.

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Introduction

The measurement of flow in tidal channels poses problems additional to those encountered in unidirectional streams. A tidal river reach will exhibit a range of conditions, from the backwater effect, when the flood tide impedes the freshwater river flow, through to the complete flow reversal.

The duration and extent of the tidal influence in an estuarial measurement station depend on the actual location of the station in the estuary.

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Measurement of liquid flow in open channels under tidal conditions

1 Scope

This International Standard provides a summary of a selection of recommended methods available for the measurement of liquid flow in tidal channels, special consideration being given to those techniques that are either unique to or particularly appropriate for measurement under tidal conditions, including treatment of errors.

Reference is also made, where appropriate, to methods developed for measurement in non-tidal channels, but in such cases attention is drawn to their limitations with respect to practicality and/or accuracy.

This International Standard does not describe alternative methods, such as weirs, flumes, dilution gauging, salt velocity and floats, although they may be suitable under certain conditions, especially where the effect of tides only impedes and does not stop or reverse the passage of stream flow. These methods are described in detail in other International Standards.

The standard comprises two parts:

- a) techniques for single measurements of tidal flow;
- b) techniques appropriate for continuous measurement of tidal flow.

The cubature method of measurement, although currently not used, is included in annex A. Annex B presents methods suitable for measurement for tidal conditions, and annex C gives an example of the computation for a single vertical. Similar computations may be made for other verticals.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 748:1997, *Measurement of liquid flow in open channels — Velocity-area methods*.

ISO 772:1996, *Hydrometric determinations — Vocabulary and symbols*.

3 Terms and definitions

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

4 Principles of methods of measurement

4.1 General

Tidal-flow measurement can be an instantaneous rate of flow or a total volume of flow during a flood or ebb tide. The unsteady nature and change in direction of flow under tidal conditions create problems of measurement additional to those associated with the measurement of the discharge of unidirectional streams. The methods specified in ISO 748, ISO 1100, ISO 4369, ISO 9123, ISO 9823 and ISO 9825 cannot therefore always be applied to tidal channels. Any change in water quality brought about by tidal conditions may affect the methods specified in ISO 6416 and ISO 9213.

For various reasons, direct measurements of velocity in tidal channels are more liable to large errors than are those made under conditions of unidirectional flow.

The methods of measurement included in this International Standard may be grouped into either single or continuous measurements.

4.2 Single measurement methods

4.2.1 Velocity-area method

At a chosen gauging site, the velocity of flow and the area of cross-section of the channel are measured. The product of these measurements at any instant is the rate of flow or discharge past the gauging site at that instant. It is referred to as the Velocity-Area method and includes the following techniques:

- a) current meter from a fixed station;
- b) current meter from a moving station (moving boat).

4.2.2 Cubature method

In an area which includes a stretch of river channel and its flood plain, surface areas and rise in water level of stored water are measured at known time intervals. Volumes of stored water are computed, and the flow into the upstream stretch of river is estimated, from which the average rate of flow is determined (see annex A).

4.3 Continuous measurement methods

4.3.1 Ultrasonic method (ISO 6416)

Transducers are positioned on each bank of the river channel, such that the flight path is at an oblique angle to the direction of flow. The time taken for a pulse of sound to travel in both directions is measured and compared. From these two times, the mean velocity can be computed.

4.3.2 Electromagnetic method (ISO 9213)

A horizontal coil is constructed above or below a river channel. A magnetic field is generated by an alternating current and voltages are induced in the flowing water which acts as an electrical conductor. After calibration, measurements of electrical parameters and water depth provide a means of measuring the discharge.

4.3.3 Unsteady-flow models

Unsteady-flow models may be used for computing continuous records of discharge in open channels in both tidal and non-tidal conditions. These models, however, are not applicable where a longitudinal density gradient, such as a salt-water wedge, is present.

Unsteady-flow models are based on the numerical solution of non-linear partial differential equations that describe gradually varied unsteady flow in open channels. The available models employ one or more of several numerical computation techniques. Data requirements, which can be substantial, depend on the numerical techniques employed by the model selected. It is necessary that techniques for the application of unsteady-flow models and the data requirements be clearly defined and understood for successfully computing discharges.

5 Special considerations and choice of method

5.1 Special considerations

Changes in water level at the mouth of a river due to tidal action cause backwater effects in the channel. These may alter water level only, or both water level and direction of flow. The whole flow may be reversed in direction, or only some of the flow may be reversed due to differences in density.

Most flow-gauging techniques are generally best suited to conditions closely approximating steady flow, but unsteady flow causes additional difficulties as follows.

- a) At any section, water levels continuously change;
- b) at any point on a vertical, velocities continuously change either with or without change in direction;
- c) in any vertical, the continuously changing velocities usually create greater velocity gradients than in channels with steady uniform flow;
- d) during the period of transition in flow direction (flood to ebb or ebb to flood), zero velocity occurs at a succession of points over the changing velocity profile;
- e) high water and low water may not take place at the same time as the reversal in flow direction;
- f) the change in direction of flow does not take place at the same time throughout the wetted cross-section;
- g) when the direction of flow changes, the characteristics of the approach conditions from the upstream and the downstream may be different and may result in divergence (when the angle between the flood and the ebb flow is other than 180°) between the flood and ebb flow;
- h) flow may be stratified, with liquids of different densities in each layer. While the liquid in the upper stratum may flow in one direction, the more dense liquid in the lower stratum may flow at a different speed in the same or opposite direction. When such density difference due to a salt water wedge occurs, the maximum velocity in each layer may occur at different times;
- i) at any section in a channel, variations in water level may cause changes in width and cross-section of flow;
- j) an increase in the number of measurements required to make an estimate of discharge;
- k) during a tidal cycle there may be variations in salinity leading to changes in the speed of sound and conductivity of the water, and these may adversely affect ultrasonic and electromagnetic methods.

5.2 Choice of method

5.2.1 General

In channels with steady flow, one of the main factors affecting the choice of gauging method is the frequency of measurements of discharge in the channel. Observations may be repeated over months or years (continual or repeated measurements), or occasionally, often once only (occasional measurements). Under variable or unsteady conditions, the frequency of measurement, although affecting the cost of each gauging and important economically, may not be compromised. The physical conditions of flow and waterway dominate the choice.

5.2.2 Physical conditions

The physical conditions which affect the choice of gauging method are:

- a) tidal range;
- b) width of channel;

- c) variation in width along a channel and with time;
- d) depth of channel;
- e) shape of channel;
- f) change in flow direction during ebb tide or flood tide;
- g) density of river traffic;
- h) the number of experienced staff available;
- i) the number of boats and gauging equipment available;
- j) environmental considerations;
- k) the intrusion of a salt-water wedge;
- l) a temperature gradient in the water;
- m) the incidence of seiches and wind-induced waves;
- n) health and safety of personnel (including the availability of lighting during hours of darkness);
- o) the number of observations to be made, e.g. the velocity-area method requires a considerable number of observations at one cross-section;
- p) flow reversal or only a backwater effect.

The principal methods of measurement and the effect of physical conditions on the selection of the gauging method are summarized in annex B, table B.2.

5.2.3 Selection and demarcation of site

5.2.3.1 General

The site should contain all stages of flow which occur or which need to be measured.

Ideally, sites should conform to the following requirements.

- a) Sites where weeds grow should be avoided or kept free from weeds to ensure there is no obstruction to the gauging operation, unless the method is tolerant to the presence of weeds, e.g. electromagnetic method;
- b) There should be no vortices, dead water or strong cross-currents;
- c) Sites where ice accumulates should be avoided;
- d) The site should be accessible for staff and equipment at all stages of flow.

5.2.3.2 Preliminary reconnaissance surveys

A preliminary reconnaissance survey of all potential sites should be made to eliminate those which are unsuitable, and to ensure that the hydraulic and topographic features of the remainder conform to the requirements of the International Standards pertaining to the method of measurement to be used.

Inspections under different flow conditions may be necessary to ensure that conditions unsuitable for the method of measurement do not occur when observations are being made.

5.2.3.3 Survey of chosen site

A permanent benchmark should be established and related to a standard datum in general use in the area. All subsequent levelling surveys should be reduced to the standard datum.

A topographical survey of the channel at the proposed gauging site should be made. This should include a plan of the site indicating the width of the water surface at a stated stage, date and time, the edges of the natural banks of the channel or channels, the line of any definite discontinuity of the slope of these banks, and the toe and crest of any artificial flood bank.

The survey of the stretch of channel should be extended through the floodway to an elevation above the highest anticipated flood level. The spacing of levels or soundings should be close enough to reveal any abrupt change of the contour of the channel. The bed of the channel should be examined for the presence of rocks or boulders, particularly near positions where measurements will be made.

6 Measurement of tidal flow

6.1 Techniques for single measurements of tidal flow

6.1.1 Measurement of tidal flow by velocity-area methods

6.1.1.1 Site requirements

The following International Standards provide details of the methods: ISO 748, ISO 1100-1, ISO 3454, ISO 4366, ISO 4369, ISO 4375, ISO 7178, ISO 8363 and ISO 9209.

The conditions indicated in ISO 748 for selection of site may be difficult to achieve for tidal rivers, since the flow is unsteady and may reverse. Reversal of flow implies different approach conditions for flood and ebb at the measuring cross-section, making it difficult to obtain the idealized flow conditions specified in ISO 748. However, the site for measurement of tidal flow should be chosen to have as far as possible the following features.

- a) The direction of velocities at all points, particularly during the period of maximum flow, should be at right angles to the measuring section;
- b) the channel upstream and downstream of the gauging site should be straight and of uniform cross-section;
- c) the depth of water in the selected length should, at low stages of flow, be sufficient to provide for the effective immersion of current meters (ISO 748);
- d) the view from the gauging site should be unobstructed by trees or other obstacles;
- e) the bed of the channel should not be subject to significant changes during the tidal cycle;
- f) the location of cross-sections, particularly the measuring cross-section, should be marked with clearly visible and readily identifiable markers of sufficient durability to last the lifetime of the gauging station;
- g) one or more staff gauges should be installed to provide a means of measuring all stages of flow. The gauge should be related by precise levelling to the standard datum;
- h) where there may be a significant difference in the level of the water surface between the two banks, an auxiliary gauge should be installed on the opposite bank, particularly in the case of wide rivers. The mean of the measurements taken from the two gauges should be taken as the mean level of the water surface.

6.1.1.2 Measurement of cross-sectional area

ISO 748 shall be applied without alteration.

6.1.1.3 Measurement of velocity by the fixed current-meter method

6.1.1.3.1 Measurement procedure

International Standards ISO 748, ISO 4375 and ISO 5168 provide details of the method, equipment and uncertainties in the results.

When using a current meter to measure velocities at chosen locations across a channel subject to tidal flow, speed of measurement is important. Many procedures considered essential to achieve accuracy in unidirectional flow measurements may have to be abandoned for practical and economic reasons in favour of those which will accelerate the gauging procedure.

An alternative but less reliable method of determining the direction of flow is to use a subsurface float. Since the direction of flow may not be the same at different levels in the channel, the depths at which the directions of the flow are measured should also be recorded, and the measurements may be made at a number of points (at least surface, mid-depth and bed) in the vertical. To limit the risk of error due to changes in the direction of flow, the use of a direction-indicating current meter is recommended.

Velocity measurements should be made at as many verticals as practicable depending on the availability of staff, instruments and equipment. Measurements should be made at not less than three verticals, using the following procedure.

- a) Synchronize the watches and clocks of all observers;
- b) survey the gauging cross-section;
- c) mark the positions of the selected verticals with mooring buoys using both flood and ebb anchors to restrict the movement of the buoy, if the gauging is to be carried out from a boat. If gauging is to be carried out from a bridge or cableway the positions should be marked on the structures. If gauging is by wading (rarely possible except in the upper reaches of small tidal rivers), each gauging position should be marked by driving a stake into the river bed;
- d) measure the depth of water and the clock time at the first vertical;
- e) measure velocities, in magnitude and direction, near the surface, at depths of 0,2; 0,4; 0,6 and 0,8 of the total depth and near the bed.

Repeat the measurement near the surface. If the depth exceeds about 15 m, measure velocities at intervals of one tenth of the depth between 0,1 and 0,9 of the total depth, and repeat the measurement at 0,1 of the depth. Record the clock time of every measurement;

- f) measure depth of water and clock time at the first vertical again, and then move the gauging equipment as quickly as possible to the second vertical;
- g) repeat the measurements of depth, velocity and time at the second vertical as described in d), e) and f), before proceeding to the third vertical to repeat the procedure. Continue this procedure until measurements have been made at all verticals. Return to the first vertical to repeat the procedure;
- h) if more than one gauging team is available, measurements may be made at two or more verticals simultaneously. Each team should carry out observations on pre-selected verticals to avoid interfering with one another as specified in items d) to g);
- i) the measurements of depth, velocity and time at the verticals should be continued for a period of at least two hours longer than the tidal cycle (i.e. one hour before and one hour after the tide cycle). Where there is diurnal inequality, observations should be taken over at least 25 h;
- j) at intervals of not more than 15 min, observe water level and clock time. These observations should begin before the survey of the cross-section is started, and should continue until after the last measurement on a vertical has been made;
- k) resurvey the cross-section;
- l) where oblique flow is unavoidable, the angle of the direction of flow to the perpendicular to the cross-section shall be measured and the measured velocity corrected. Special instruments are available for measuring both angle and velocity at a point simultaneously.

Where these instruments are not available and there is insignificant wind, the angle of flow throughout the vertical may be taken to be the same as that observed on the surface. If the channel is very deep, or if the local

bed profile is changing rapidly, this assumption shall not be accepted without checking. If the measured angle to the perpendicular is γ , then:

$$V_{\text{corrected}} = V_{\text{measured}} \cos \gamma$$

6.1.1.3.2 Computation of discharge for fixed current-meter method

For each set of verticals, the following calculations and plots are necessary.

- a) Choose a convention for flow direction. For each vertical, adjust the values of measured velocities to the time of the first velocity measurement, and calculate the mean velocity over the vertical.

$$V_{na} = V_n + \frac{V_1 - V_r}{V_r} \cdot \frac{t_n - t_1}{t_r - t_1} \cdot V_n$$

$$V_m = \frac{1}{r-1} (V_{1a} + V_{2a} + \dots + V_{(r-1)a})$$

where

t_1 = time of first observation at surface;

t_n = time of n th observation;

t_r = time of repeat observation at surface;

V_1 = first measured velocity at surface;

V_n = measured velocity at time t_n ;

V_r = repeat measured velocity at surface;

V_{na} = adjusted value of measured velocity V_n ;

V_m = mean of adjusted velocities;

$r-1$ = number of points in the vertical.

- b) plot cross-sections;
- c) plot depth of each vertical against time;
- d) tabulate mean velocities for each vertical against clock times of first and last observations of velocity in that set;
- e) for each vertical, plot mean velocity against the mean of the clock times for each set of velocity measurements;
- f) for clock times at intervals of not more than 30 min, tabulate:
- 1) clock time;
 - 2) water level;
 - 3) area of cross-section (computed from cross-section and water level);
 - 4) mean velocity on each vertical [interpolated from plot in e) above]; and

- 5) discharge at each clock time calculated from:

$$Q = (V_1A_1 + V_2A_2 + \dots V_nA_n)$$

where

Q = rate of discharge at specified clock time

n = number of verticals

A_1 = area of cross-section 1

A_2 = area of cross-section 2

V_1 = mean velocity at vertical No.1

V_2 = mean velocity at vertical No. 2, etc.

- g) plot discharge against clock time.

The volume of water passing the gauging section is equal to the area under the discharge/time plot during the period of flood tide or ebb tide.

NOTE The volume of ebb flow should normally exceed the volume of flood flow by an amount $q \cdot T$ unless there is a significant seepage out of the banks, where

q = freshwater flow measured upstream of the limit of tidal influence (m^3/s),

T = duration of tidal cycle

Annex C shows a typical tabulation for one segment, but methods of utilizing computing aids can be evolved.

6.1.2 Measurement of tidal flow by the moving boat method

ISO 4369 describes this method of measurement using a moving boat.

This method is suitable for gauging flow in tidal rivers which are wide and deep enough to permit the use of a small powered boat. The relationship between surface and mean velocity should be established as described in ISO 4369.

The direction of the flow may be measured as specified in 6.1.1.3.1. This introduces much additional work, which the moving boat method is designed to eliminate. A simpler but less accurate method is to anchor three or more buoys in the channel.

The position of a buoy relative to the cross-section will indicate whether the net direction of flow is land or seaward. This method will not indicate the difference in the direction of flow near the surface and the bed.

6.2 Techniques appropriate for continuous measurement of tidal flow

6.2.1 Measurement of tidal flow by the ultrasonic method

Refer to ISO 1100-1 and ISO 6416 for specifications on the requirements for gauging stations using ultrasonic equipment.

Ultrasonic gauging stations may be constructed specifically for the purpose of measuring reverse flow in a narrow channel. The following features are necessary:

- a) electric power should normally be available, although some new designs can operate from batteries or solar cell and battery systems;

- b) abrupt bends in the channel should be avoided, if possible, but these may be acceptable provided that condition (c) is satisfied;
- c) at cross-sections taken in the area between the positions of the upstream and downstream transducer mountings, the velocity distribution should be similar under all flow conditions both positive and negative;
- d) the bed should not progressively scour or accrete, and preferably should not show appreciable changes in its level over the range of flows;
- e) measurement may not be possible if concentration of suspended sediment exceeds about 1000 mg/l. Annex B, Table B.3 gives the relationship between pathlength, transducer frequency and suspended solid concentrations;
- f) the water should be well mixed and should not contain pockets of saline water or waters of different temperatures;
- g) the water should be free of bubbles such as occur downstream of a weir or sluice;
- h) width: depth ratio should not exceed 50:1.

ISO 6416 provides details of ultrasonic gauging equipment and methods.

Time series data from an ultrasonic gauging station provides the basic information for computing the volume of flood or ebb flow past the station.

6.2.2 Measurement of tidal flow by the electromagnetic method

ISO/TR 9213 provides specifications on the requirements for gauging stations using the electromagnetic method.

The station should not be located at a point where there is a saline wedge or where rapid changes in electrical conductivity of the water occur, and should be:

- a) at least 100 m from sources of electrical interference (power cables, electric railways, etc.);
- b) at least 3 km from a longwave public broadcast radio station;
- c) upstream of the limit of saline intrusion, including saline density differences, and at a point where the specific conductivity is low;
- d) able to access a 1 kW source of electrical power;
- e) able to be calibrated by another method of gauging (see 6.1).

Time series data from an electromagnetic gauging station provides the basic information for computing the volume of flood or ebb flow past the station.

6.2.3 Computations

- a) Tabulate:
 - 1) clock time at intervals of 15 min for a period of a tidal cycle plus 2 h;
 - 2) discharge at clock times.
- b) Plot discharge against clock time.

The volume of flow past the gauging station over a flood tide or an ebb tide is equal to the area under the discharge/time plot during the period of the flood tide or ebb tide respectively.

NOTE The volume of ebb flow usually exceeds the volume of flood flow by an amount $q \cdot T$, unless there is significant seepage of water into or out of the channel between the seaward section and the inland section, where

q = freshwater flow measured upstream of the limit of tidal influence, and

T = duration of ebb flow.

7 Uncertainties in tidal flow measurement

7.1 General

Reference should be made to ISO 748 for information on the calculation of the uncertainty in the velocity-area method of measurement and to ISO 1088, ISO 5168 and the ISO Guide to Expression of Uncertainty in Measurement. The following clauses contain additional information on the computation of uncertainties for the velocity area method (current meters).

7.2 Uncertainties in measurement by velocity area method

7.2.1 Sources of uncertainty

Reference should be made to clause 10 of ISO 748:1997, in which the necessary definitions and a general outline of the method of calculation are given. The following extends the method to tidal flow. Estimates of the magnitude of the additional error components cannot be given with the present state of knowledge.

The generalized form given in ISO 748 for determining the discharge, Q , is extended to read:

$$Q_t = \sum_{i=1}^{i=m} (b_i d_i v_i \cos \lambda_i)_t$$

where

Q_t is the discharge at one particular moment of the tidal cycle;

λ is the mean in a vertical of the angles between the single measured velocity and the normal to the cross-section.

The overall uncertainty in the tidal (ebb or flood) volume is then composed of the following uncertainties, expressed as percentage random uncertainties:

- a) uncertainties in the assessment of width;
- b) uncertainties in the assessment of sounding of depth, both of individual soundings and readings of the water level;

These should be determined having regard to ISO 748.

NOTE Uncertainties originating from the variation of depth and width with time may be neglected.

- c) uncertainties in the determination of individual velocities;

These will depend on the accuracy of the equipment, the technique employed (ISO 748) and the irregularity of the velocity distribution with time and space, and on the magnitude of dv_i/dt , i.e. the rate of change of the average velocity v_i with time.

NOTE These uncertainties occur, particularly during the slack-water period, due to the limitation of the current-meter in measuring velocities below 0,15 m/s.

- d) uncertainties in the use of the velocity-area method, particularly those concerned with the number of verticals and the number of points in each vertical.

These uncertainties will also depend on the width of the channel, the ratio of width to depth, and on the method of computation used.

- e) uncertainties in the determination of the angle (in a horizontal plane) between the single velocity vector and the normal to the cross-section;
- f) uncertainties due to the reduction of the individual measurements in the vertical to the same instant;
- g) uncertainties arising from interpolation to the same instant of mean velocities in the vertical, in cases where the velocity distributions are not measured simultaneously;
- h) uncertainties arising from the reduction of mean velocities from one tide to another tide.

7.2.2 Individual components of errors

In ISO 748, the following components have been presented and remain essentially the same:

- uncertainties in width (X'_{b_i});
- uncertainties in depth (X'_{d_i});
- uncertainties in the determination of local point velocities (X'_{v_i});
- uncertainties in the determination of the mean velocities composed of:
 - 1) number of points (X'_{o_i});
 - 2) mean velocity in a vertical ($X'_{\bar{v}_i}$), to be derived from:

$$X'_{\bar{v}_i} = \sqrt{X'_{\bar{v}}^2 + X'_{o_i}^2}$$

- 3) number of verticals (X'_{m_i});

To these components, the following shall be added for tidal flow;

- uncertainties in the mean of the angles between the velocity vectors and the normal to the cross-section ($X'_{\bar{\varphi}}$).

If X'_{φ} is the uncertainty in the angle of a single velocity, then the uncertainty $X'_{\bar{\varphi}}$ for a vertical is determined from:

$$X'_{\bar{\varphi}} = \sqrt{\frac{\sum X'_{\varphi}^2}{m}}$$

where m is the number of velocities measured in the vertical.

- uncertainties arising from insufficiencies in the applied method (X'_{s_i}).

Under this heading are considered the uncertainties under f), g) and h) of 7.2.1 and indicated by $X'_{(i)}$, $X'_{(ii)}$, and $X'_{(iii)}$, respectively. (X'_{s_i}) is to be determined from:

$$X'_{s_i} = \sqrt{X'_{(i)}^2 + X'_{(ii)}^2 + X'_{(iii)}^2}$$

Each of the constituent uncertainties in this formula may be omitted when not applicable. $X'_{(i)}$ is usually negligible. $X'_{(iii)}$ may be large; this implies that the method it arises from should only be used if $X'_{(iii)}$ is known. $X'_{(ii)}$ is to be derived from:

$$X'_{(ii)} = X'_{\bar{v}_t} = X'_t \frac{d\bar{v}}{dt}$$

where

$X'_{\bar{v}_t}$ is the uncertainty in the mean velocity \bar{v} of a vertical for which \bar{v} has been determined by interpolation;

X'_t is the uncertainty of time measurement (percentage error relative to the time interval between measurements of verticals, and due to synchronization of watches, etc.);

$\frac{d\bar{v}}{dt}$ is the slope of the velocity-time curve.

The uncertainty arising from taking "limited number" of discharge measurement during the tidal period can be disregarded.

7.2.3 Resultant random uncertainty in measurement of flow

The percentage resultant random uncertainty X'_{Q_t} in measurement of flow at time t shall be calculated in accordance with ISO 748, as follows:

$$X'_{Q_t} = \sqrt{X'^2_m + \frac{\sum_{i=1}^{i=m} (b_i d_i \bar{v}_i \cos \bar{\varphi}_i)^2 \left(X'^2_{b_i} + X'^2_{d_i} + \frac{X'^2}{v_i} + \frac{X'}{\varphi_i} \tan^2 \varphi_i \right)}{\sum_{i=1}^{i=m} (b_i d_i \bar{v}_i \cos \bar{\varphi}_i)^2} + X'^2_s}$$

The use of a simplified formula based on that presented in ISO 748 is not recommended.

7.2.4 Resultant systematic uncertainty in measurement flow

The above equations are satisfactory for estimating the precision of the measurement but do not take account of the possibility of systematic errors. Systematic errors which behave as random uncertainties shall be estimated separately and may be combined as follows:

$$X''_Q = \sqrt{X''^2_b + X''^2_d + X''^2_{\bar{v}} + X''^2_{\bar{\varphi}}}$$

where X''_b , X''_d , $X''_{\bar{v}}$ and $X''_{\bar{\varphi}}$ are the percentage systematic uncertainties in b , d , \bar{v} and $\bar{\varphi}$ respectively.

NOTE It is a question here of systematic errors due to the instruments, which vary randomly from instrument to instrument, and not of systematic errors inherent in the type of instrument or measurement which can be eliminated or determined only if a superior instrument or improved method is available.

7.2.5 Combined uncertainty at the 95 % confidence level

The overall estimate of the uncertainty of the discharge will then be:

$$X_{Q_t} = \sqrt{X'^2_{Q_t} + X''^2_Q}$$

This value shall be doubled to give the uncertainty on the measurement of the discharge at the 95 % confidence level, as indicated in ISO 748.

7.2.6 Combined standard error in the determination of the tidal (ebb or flood) volume

If S_{vol} and S_{Q_t} , are, in absolute values, the standard errors in the measurements of the tidal volume and discharge respectively ($S_{Q_t} = Q_t X_{Q_t}$), and if T is the constant time interval between successive moments p at which Q_t is determined, the following relation holds:

$$S_{vol} = T \sqrt{\sum_{i=1}^{i=p} S_{Q_{t_i}}^2}$$

This value shall be doubled to give the uncertainty at 95 % confidence level, in absolute value, on the determination of the tidal volume, as indicated in ISO 748.

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Annex A (informative)

Measurement of tidal flow by the cubature method

A.1 Site requirements

The cubature method has not been described in other International Standards, and is thus covered in detail below.

This method is intended for the measurement of the volume of tidal inflow or outflow, or the average rate of tidal inflow and outflow over a long period (hours). It is not normally suitable for determining nearly instantaneous rates of flow.

The method is best suited for narrow channels, of nearly constant width, and affected by tidal range over a short distance only. Channels which present additional practical difficulties in the measurement of tidal volume are those which are:

- a) very wide (not confined to a narrow channel or valley);
- b) very variable in width along the channel; and
- c) affected by tides over an extended distance.

Select a cross-section (the seaward section) through which the flood tide or ebb tide will pass, and upstream of which the change in tidal volume is to be measured.

At regular intervals along the tidal channel upstream of the seaward section and on both sides of the channel, set markers outside the limits of tidal inundation. Continue to set out markers at the extremities of each section until a section unaffected by high spring tides is reached (inland section). The sections may be spaced approximately two channel widths apart, or more if the channel is uniform.

The longitudinal distance between adjacent markers (along both banks) and transverse distances between pairs of markers should be measured. If the features of the channel necessitate computation of the tidal volume by cubature method II (A.4) the position of all markers should also be fixed by triangulation.

A unidirectional gauging station should be established at the inland section, if one does not already exist sufficiently close for there to be no significant difference between the flow at the two sites (ISO 1100-1).

Staff gauges and/or water level recorders should be established at the seaward section, the inland section and at some of the sections between these limits. They should be related by precise levelling to the standard datum.

A.2 Field measurements

- a) At a chosen time, measure at each section the distances of the edges of the water surface from the established markers, and record the clock time.
- b) Measure the water level at all gauges along the channel and record the clock time. Water level observations should be made at two or more of the stations at intervals of not more than 15 min.
- c) Measure the freshwater flow at the upstream section.

The features of the site, and the availability of staff, transport and communication equipments affect the speed at which the series of measurements a) to c) can be made, and the choice of the subsequent method of analysis (A.3 or A.4). Aerial photography will produce a set of simultaneous measurements of channel width. Survey by staff moving along the river or the river bank will produce a sequence of measurements of channel width extending over a period of time.

The measurements of channel width and water level should be repeated as frequently as practicable over the flood or ebb tide or over the whole tidal cycle as required.

The measurement of freshwater flow should also be repeated if significant variations in flow are expected to occur during the period of measurement of tidal volume.

A.3 Computation — Method I

The method is suitable for narrow channels of fairly constant width.

- a) For each section, calculate the water-surface width from measurements of the distance of the edges of the water surface from the established markers;
- b) for each section, plot the water-surface width against clock time;
- c) from the width/time plots for each section, determine the water-surface widths at chosen clock times;
- d) for each water level gauging station plot the reduced water level (stage) against clock time;
- e) from the stage/time plots for each water level station, deduce by interpolation the stages corresponding to the chosen clock times in c);
- f) by interpolation, compute for each chosen clock time the corresponding stage at each section. This step is necessary because the water-level gauging stations will not necessarily be located at all sections or even at any section, and the water level at each section is required;
- g) from the flow gauging carried out at the inland section, compute the freshwater flow as specified in the relevant International Standard, using the following symbols:

$b_1, b_2, \dots b_n$	=	simultaneous channel widths at cross-sections between seaward section (1) and inland section (n) at clock time t ;
$b'_1, b'_2, \dots b'_n$	=	simultaneous channel widths at clock time t' ;
$h_1, h_2, \dots h_n$	=	simultaneous stages at cross-sections between seaward section (1) and inland section (n) at clock time t ;
$h'_1, h'_2, \dots h'_n$	=	simultaneous stages at clock time t' ;
t	=	clock time;
t'	=	subsequent clock time;
$1_{1-2}, 1_{2-3}, \text{ etc.}$	=	distance between markers on sections 1 and 2, 2 and 3, etc.;
$V_{1-2}, V_{2-3}, \text{ etc.}$	=	change in tidal volume between sections 1 and 2, 2 and 3, etc., during time interval $t' - t$;
V	=	change in tidal volume between seaward and inland sections during time interval $t' - t$;
T	=	duration of flood tide or ebb tide;
q	=	freshwater inflow rate.

NOTE Ebb flow and freshwater flow in a downstream direction are positive. Flood flow in an upstream direction is negative.

- h) Calculate mean channel width between sections 1 and 2.

$$B_{1-2} = 0,5 (b_1 + b_2)$$

$$B'_{1-2} = 0,5 (b'_1 + b'_2)$$

- i) Calculate mean water levels between sections 1 and 2.

$$H_{1-2} = 0,5 (h_1 + h_2)$$

$$H'_{1-2} = 0,5 (h'_1 + h'_2)$$

- j) Calculate change in tidal volume between sections 1 and 2.

$$V_{1-2} = 0,5 (B'_{1-2} + B_{1-2}) (H'_{1-2} - H_{1-2}) 1_{1-2}$$

- k) Repeat computations h) to j) for remaining pairs of adjacent sections, and calculate change in tidal volume upstream of seaward section during time interval $t' - t$.

$$V = V_{1-2} + V_{2-3} + \dots + V_{(n-1)-n}$$

The tidal volume, at the seaward section, over a complete flood phase or ebb phase is the algebraic sum of the tidal volumes over all time intervals between the time of reversal of flow from landward to seaward and seaward to landward.

A.4 Computation — Method II

The method is applicable to wide channels of irregular width. If the water-surface widths are large and vary greatly along the channel, the assumptions made in A.3 j) may introduce appreciable errors, and the procedure outlined below should be followed.

- a) For each section, plot the distances of the edge of the water from the established markers against clock time.
- b) From the water's edge distance/time plots for each section, determine by interpolation the distances of the water's edge at chosen clock times.
- c) On a plan of the channel mark the locations of the sections and plot the simultaneous positions of the water's edge at the chosen clock times. Draw the line showing the water's edge at each clock time. Using a planimeter or squared paper compute the surface areas between sections at each chosen clock time.
- d) Follow the steps described in A.3 d) to g), using the symbols defined in A.3 g), and where

$a_{1-2}, a_{2-3}, \dots, a_{(n-1)-n}$ is the simultaneous water-surface areas between sections 1 and 2, and 2 and 3 etc. from the seaward section 1 to the upstream section n at a chosen clock time.

$a'_{1-2}, a'_{2-3}, \dots, a'_{(n-1)-n}$ is the simultaneous water-surface areas at the subsequent clock time.

- h) Follow steps in A.3 i).
- i) Calculate change in tidal volume between sections 1 and 2

$$V_{1-2} = 0,5 (a'_{1-2} + a_{1-2}) (H'_{1-2} - H_{1-2})$$

- j) Repeat computations i) and j) for remaining pairs of adjacent sections, and calculate change in tidal volume upstream of seaward section during the time interval $t' - t$.

$$V = V_{1-2} + V_{2-3} + \dots + V_{(n-1)-n}$$

Annex B (informative)

Flow measurement methods suitable for tidal conditions

This annex provides a summary of the flow measurement methods described in the text of this International Standard (Table B.1) and a guide to the selection of an appropriate method (Table B.2).

Table B.1 — Flow measurement methods

Single measurements	
Velocity area	— current-meter fixed station
	— moving boat
Continuous measurements	
Velocity area	— ultrasonic station
	— electromagnetic station

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Table B.2 — Guide to the selection of gauging method

Parameter	Current meter	Moving boat	Ultrasonic	Full-width electromagn.
Depth < 1 m	✓	x	✓	✓
> 1 m	✓	✓	✓	✓
Width: Depth ratio < 30	✓	✓	✓	✓
> 30	✓	✓	1)	✓
Width < 30 m	✓	x	✓	✓
30 m to 200 m	✓	✓	2)	x
> 200 m	✓	✓	x	x
Tidal range > 1 m	✓	3)	✓	✓
Width variation < 10 m	✓	✓	✓	✓
10 m to 30 m	✓	4)	6)	5)
> 30 m	x	4)	✓	x
Dense traffic	x	7)	8)	x
Limited number of staff	x	✓	✓	✓
Limited number of equipment	x	✓	✓	✓
Salt wedge	9)	9)	10)	x
Temperature gradient	✓	✓	x	✓
Wind seiches	✓	3)	✓	11)
✓ Method is recommended for this parameter. x Method is not recommended for this parameter.				
1) Minimum distance between path and the surface or bed is: $27 \sqrt{\frac{\text{Path length (m)}}{\text{Transducer frequency (Hz)}}}$				
2) In wider rivers, problems of signal loss from suspended solids and temperature gradients become important. See ISO 6416.				
3) Measurements shall be taken quickly, so that measured velocity is representative of that over full depth.				
4) Measurement in shallow water not possible.				
5) Method not suitable if total width exceeds about 30 m.				
6) Mounting of transducers, and keeping paths free of weed becomes difficult.				
7) Risk of accidental collision.				
8) Loss of record when boats are in the measurement section and for up to 3 min after they leave the section.				
9) Water velocities may be in opposing directions above and below the interface. Meters should be direction-sensing.				
10) Is not recommended for use in nonhomogeneous water; but may be able to measure velocities in the freshwater region and in the salt-water region. It will not measure in the interface (see ISO 6416).				
11) Surface waves may generate spurious signals and cause the measurements to be very variable.				