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ET DE LA LUTTE CONTRE
LES CHANGEMENTS CLIMATIQUES

Sampling Guide for Environmental Analysis

Book 7

Flow Measurement Methods

3rd edition

Votre gouvernement

Québec

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FOREWORD

Book 7 of the *Sampling Guide for Environmental Analysis* addresses recognized techniques for evaluating water flow and volumes withdrawn or discharged by companies, industries, municipalities and/or other bodies that hold authorizations issued by the Ministère de l'Environnement et de la Lutte contre les changements climatiques (MELCC) and are required to report their water withdrawal and/or discharge values to it.

This publication addresses both the theoretical aspects and best practices regarding flow measurement and collates information from recognized technical publications and the practical experience of water flow technicians and other professionals that collaborate on environmental monitoring in Québec. It is meant for workers in the area of streamflow measurement or who use this type of service. This book was written both to bolster understanding of the theoretical bases of flow measurement and to oversee and standardize methods to facilitate fieldwork.

The current edition of Book 7 is a thorough update that takes account of new technologies and updates of hydrometry references, including International Organization for Standardization (ISO) standards. More complete than the preceding version, this new edition covers all types of water flow, whether free surface or pressurized.

A variety of user comments received by the authors since the first edition of this work has been taken into account in the current version in order to update content and adapt the work in the light of recent developments and actual field conditions. For this reason, flow measurement professionals were consulted and we sincerely thank them for their input.

Please address all comments and/or questions to the following address: guide.echantillonnage@environnement.gouv.qc.ca.

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ABOUT THE SAMPLING GUIDE FOR ENVIRONMENTAL ANALYSIS

The *Sampling Guide for Environmental Analysis* is a series of publications that deal precisely with sampling in a variety of environmental settings. It sets out best practices for planning and conducting sampling to ensure both the quality of samples and the validity of the scientific data garnered from them. As such, it can be considered as a reference work that assembles general information on recognized sampling practices.

Regulations, guidelines, policies and other relevant Ministère de l'Environnement et de la Lutte contre les changements climatiques (MELCC) documents refer to one or more publications mentioned in this guide.

The Centre d'expertise en analyse environnementale du Québec (CEAEQ) publishes the *Sampling Guide for Environmental Analysis* series and coordinates updates in its role as the ministerial body in charge of the publication.

Whenever approval from the Ministère is required pursuant to any part of the sampling guide, requests should be addressed to the appropriate regional office.

GLOSSARY

For the purposes of this publication, the following definitions apply. Readers are invited to refer to Appendix 1 for notions of metrology.

Approach channel (approach section)

Channel reach immediately upstream of the gauging station where appropriate discharge conditions need to be established to ensure measurement accuracy: This can be an artificial (concrete) or natural channel (ditch).

Conservation of energy principle

A physics principle stating that the total energy in a closed system does not change over time. Total initial energy of a closed system is therefore equal to total final energy, meaning that energy can move from one form to another during the phenomenon, but no energy will be created or destroyed.

Flow conditioner (stiller)

A mechanical device that subdivides flow, which then transits through narrow annular passages so as to reduce turbulence and disruptions in the flow path (e.g., bends) or that arise due to an obstacle upstream or near the measuring device, enabling errors to be reduced to a minimum.

Free flow (modular)

Flow over or through a structure when the upstream level is independent of the downstream level for a given discharge.

Gauging

All of the operations necessary for measuring discharge.

Head loss

The difference in total head between two sections.

Example: A weir causes a significant upstream rise in water level and modifies discharge conditions, leading to major head loss.

See Appendix 2.

Hydraulic radius (r_h)

In a free surface channel, the ratio of the cross-sectional area (A) divided by the wetted perimeter that is in contact with the liquid (P).

$$r_h = \frac{A}{P}$$

Invert

The lowest part of the cross-section of a natural or artificial channel.

Linear

A sensor is considered linear when its measurement sensitivity range remains constant.

Liquid level recorder

A device that records liquid level continuously.

Examples: pneumatic liquid level recorders (also called "bubble gauges") equipped with a piezoelectric pressure or ultrasound sensor.

Measuring transducer

A device, such as a pH electrode, used in measuring that translates entry to exit quantity in accordance with a predetermined law of physics.

Non-modular (submerged) flow

Flow over or through a structure, when it is affected by changes in the water level downstream.

Reach (headrace)

Length of a channel between two defined cross-sections.

Sensor (probe)

The part of a **measuring instrument** that provides data about a quantity to be measured

Example: A water level measuring device float.

Stage-discharge relation

A curve, equation or table that expresses the relationship between the stage and the discharge in a free surfacechannel for a given cross-section and at a specific time.

Water level gauge

The basic part of a water level gauging and recording device, most often comprising a vertical or inclined stage gauge located near the device's liquid level recorder on which the water level is read.

ACRONYMS AND STANDARD SYMBOLS[1]

α:	Angle (rad)
Δ:	Difference between two values of the same quantity (variable dimension)
***A*:**	Area (surface) (m^2)
***B*:**	Range (width) (m)
***F_r*:**	Froude number (dimensionless)
***g*:**	Gravitational acceleration (m/s^2)
***K (ou C)*:**	Constant (variable dimension)
***l*:**	Length (m)
μ, η:	Dynamic viscosity (Pa·s)
***n*:**	Rotational velocity (rad/s)
***P*:**	Height of a weir (m)
***ρ*:**	Mass per unit volume (density or specific mass) (kg/m^3)
***Q*:**	Flow (m^3/s)
Q_m:	Mass flow
***Q_V*:**	Volumetric flow
***r*:**	Radius (m)
***R_e*:**	Reynolds number (dimensionless)
***r_h*:**	Hydraulic radius (m)
***S*:**	Slope, bed slope (dimensionless)
***t*:**	Time (s)
***v*:**	Velocity (m/s)
***V*:**	Volume (m^3)
$\acute{x}$:	Average value (variable dimension)

Other symbols shown in various sections of this book are used to identify specific items and are not necessarily ISO standard symbols. In such cases, the meaning in the relevant section of the publication takes precedence over the meaning in the above list of acronyms and symbols.

[1] Based on ISO 772–Hydrometry–Vocabulary and symbols.

1 INTRODUCTION

Accurate and consistent flow measurement methods are required in a variety of settings with effluent, be they industrial, municipal or agricultural, among others. Flow measurement is used to achieve many goals.

For example, it makes it possible to determine the pollution load of discharge; establish the effluent discharge or load variation over time; calibrate equipment used for measuring and processing effluent and feed water; measure, locate, analyze and resolve water network collection and distribution issues; evaluate treatment equipment performance; and determine the quality of bodies of water and the quantity of available water resources.

From an environmental viewpoint, flow measurement is also required in implementing laws and regulations. More precisely, in self-monitoring programs, it makes it possible to measure withdrawn, consumed or discharged volumes of water; measure effluent pollutant load; and check the accuracy of *in situ* measurement systems based on verification methods approved by the Ministère.

The acquired data enables status reports to be subsequently prepared and improve the regulatory framework to ensure water stakeholder accountability, help implement the user-pay principle and abide by intergovernmental agreements.

This publication is meant to aid in understanding the principles of flow measurement; contribute to setting up a consistent *in situ* measurement system; and provide a framework for checking measurement system accuracy, whether by means of visual inspections or instantaneous flow measurements that make it possible to determine discrepancies between the installed measurement system and a reference method.

Flow measurement can be used by many categories of clients, including municipal, industrial and agricultural operators, consultants that check the accuracy of flow measurement systems as well as inspectors, technicians and professionals employed by the Ministère.

2 OVERVIEW

2.1 DEFINITION OF FLOW

In hydraulics, flow (Q) is defined as a volume (V) of liquid flowing through a cross-section of a channel or pipe in a unit of time (t):

$$\boldsymbol{Q = \frac{V}{t}} \qquad (1)$$

Flow can be calculated using the following general equation:

$$\boldsymbol{Q = A \times v} \qquad (2)$$

Where Q Flow (i.e. m^3/s)
v Flow velocity (i.e. m/s)
A Area of the wetted section perpendicular to the flow (i.e. m^2)

Flow can be measured in different types of channels, with measurement methods varying according to discharge channel and magnitude of flow.

2.2 CHANNEL TYPES

Three channel types are used for water withdrawal, transport and/or discharge: open channel (such as rivers), partially covered channel (such as culverts) and closed conduit (such as drinking water distribution networks). These channels may be natural (such as streams and rivers) or artificial (such as flumes, drainage ditches, and water distribution or sewage networks). Channel type directly influences the discharge encountered at a given facility.

2.3 DISCHARGE TYPES

There are two categories of discharge: free surface and pressurized.

2.3.1 Theorical concept of free surface flow

The term “free surface flow” applies whenever the surface of discharge is in direct contact with the surrounding air. In such cases, the water surface is subjected to atmospheric pressure. The discharge then depends on the gradient of the channel’s slope and the frictional resistance of the walls. Given that the result of the previously stated equation 2 is constant, the equation’s variables must adjust based on the conservation of energy principle.

In this type of discharge, velocity (v) and area (A) are the two variables that must be measured to evaluate flow (Q) where no measuring device is installed in the free surfacechannel. This is expressed by equation 2, where the wetted section area (m^2) of a rectangular channel is as follows:

$$\boldsymbol{A = h \times B} \qquad (3)$$

Where h discharge level (such as in metres)
B sectional width (such as in metres) (constant value)

This makes it possible to obtain the following long-form formula:

$$\boldsymbol{Q = v \times h \times B} \quad (4)$$

According to this equation, if we presume that flow remains constant, whenever a change in velocity is imposed or induced (for example, inside a primary structure), discharge depth has to adjust to comply with the equation. Whenever discharge accelerates and energy is converted into velocity, the level drops. Inversely, whenever velocity is reduced, the level rises. The resulting lower discharge water surface level is called the drawdown.

A Parshall flume is an example of a primary measuring structure and a good illustration of the phenomenon of depth changing when velocity increases. When water enters a channel, it accelerates in the convergent section to reach maximum velocity when transiting the control section (constriction) which slopes downward, thereby causing a significant drop in water level at the constriction.

The principle of equation 4 can be applied to various forms of free surface channels.

Free surface flow is usually seen in channels such as irrigation canals but may also be found in partially covered channels such as culverts, where the discharge is below channel capacity (Figure 1).

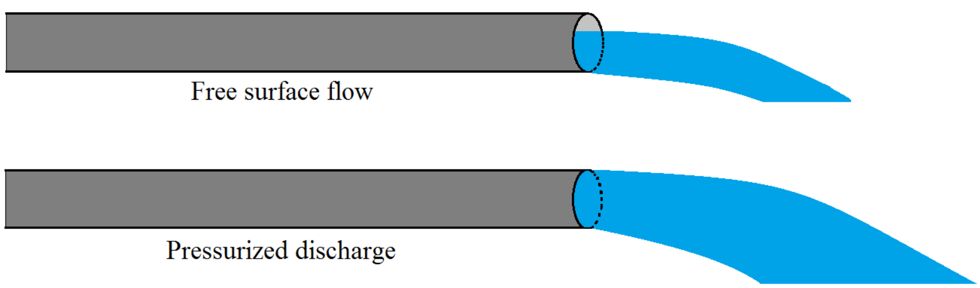


Figure 1: Free surface and pressurized flow in a partially covered channel.

2.3.2 Theoritical concept of pressurized (closed conduit) flow

Discharge is referred to as pressurized (or “loaded”) when the liquid is confined in a closed channel and subjected to pressure that exceeds atmospheric pressure, such as in water conveyance and drinking water distribution systems.

However, a partially covered channel can turn into a pressurized discharge channel when discharge is at its maximum run-full capacity (Figure 1). In such cases, discharge in the channel is no longer a function of air pressure but rather of water pressure exerted upstream from the channel. The discharge is thereby greater than if it occurred in a free surface channel.

A culvert in which discharge is at maximum channel capacity is an example of a partially covered channel that displays the characteristics of pressurized discharge.

The following example of a water tank can help in understanding this phenomenon (Figure 2). Flow in a pipe at the bottom of a full tank exceeds flow in a pipe at the top due to higher water pressure. The flow velocity is therefore also higher in the exit pipe at the bottom of the tank.

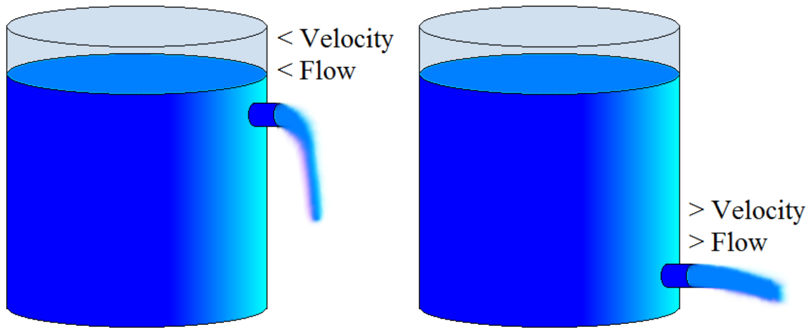


Figure 2: Characteristics of pressurized discharge in a partially covered channel.

In closed conduit or partially covered channels, changes in pressure translate into a variation in discharge velocity, while the area of the wetted section remains constant.

In the case of a cylindrical pressurized pipe (Figure 3), the volume (*V*) of a section is determined by multiplying the area (*A*) by the length (*l*) of the section in question. In such cases, *A* is constant and corresponds to πr^2, where *r* is the inside radius of the pipe.

$$A = \pi r^2 \tag{5}$$

$$V = A \times l \tag{6}$$

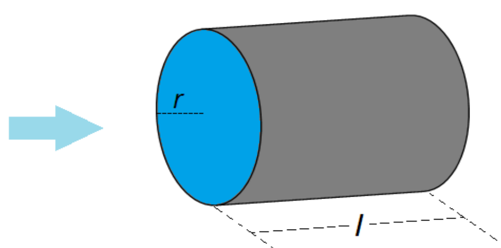


Figure 3: Calculation of volume in a pressurized cylindrical pipe.

2.4 Volumetric and Mass Flow

To express volumetric flow (Q_V), one of the variables must be a function of time. If we presume that the area *A* is constant, the other variable *l* is expressed as distance travelled over time. The expression of distance travelled Δl, as a function of time Δt, gives *v*, which is the discharge velocity through the channel:

$$v = \frac{\Delta l}{\Delta t} \tag{7}$$

In equation 6, if variable (*l*) is replaced by its value as determined in equation 7, the equation then becomes:

$$\boldsymbol{V} = \boldsymbol{A} \times \boldsymbol{v} \times \Delta \boldsymbol{t} \qquad (8)$$

As well, if (*V*) is replaced in equation 1 by its value as determined in equation 8, the flow equation reverts to equation 2.

Volumetric flow is generally expressed in units of volume per unit of time. The recommended measurement unit is m^3/s.

While flow measurement is most often associated with volumetric flow, flow can also be used to express the passage of a quantity of matter (mass) through a section in each unit of time. To express mass flow (Q_m), equation 2 must be modified to include the density of the measured fluid, which may differ from the density of water, i.e. 1,000 kg/m^3. It may be equally important to consider the temperature of the fluid, since it influences the density factor value. The equation therefore becomes:

$$\boldsymbol{Q_m} = \boldsymbol{\rho} \times \boldsymbol{A} \times \boldsymbol{v} \qquad (9)$$

Where	Q_m	Mass flow (kg/s)
	ρ	Liquid density factor (kg/m^3)
	A	Sectional area (m^2)
	v	Velocity of the liquid through the sectional area (m/s)

This equation can be used whenever the mass of the fluid is required for particular purposes such as determining the mass of liquid mine tailings discharged into an accumulation area.

2.5 Ways to Determine Water Flow and Volume

Water flow and volume can be determined by continuously measuring the quantity of water circulating in a discharge facility or by estimating it with instantaneous measurement.

2.5.1 Instantaneous measurement (estimate)

An instantaneous measurement takes place at a specific point in time, generally covering a very short period of no more than a few minutes. As such, it only reflects the period of time in which it was conducted. However, a value derived from an instantaneous flow measurement can be associated with a somewhat longer period of time if we presume that discharge was constant throughout the interval of time separating the two measurements.

Essentially, instantaneous measurements are used in the following cases:

- Checking the compliance of hydraulic structures such as gauging flumes.
- Determining the capacity of a measuring system such as a pump.
- Determining the instantaneous flow of steady discharge such as effluent transiting the outlet of an extended aerated basin for extrapolation purposes.

- Quickly determining the discharge rate.
- Determining the dimensions of hydraulic equipment needed for carrying or treating water.

Figure 4 illustrates the generally employed methods used for this type of measurement, i.e.:

- Volumetric.
- Dilution with trace elements.
- Velocity-area.
- Reference instrument.
- Pump capacity.
- Instantaneous measurement of water level in the primary element of a hydraulic structure.

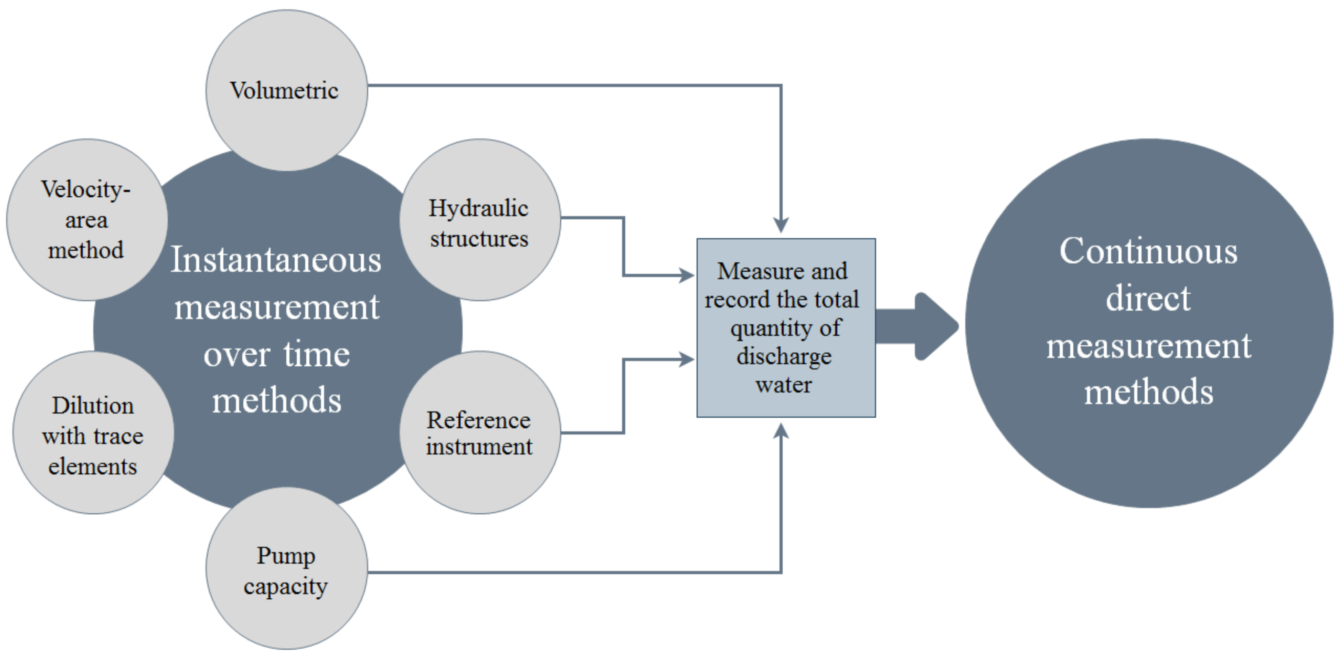


Figure 4: Instantaneous and continuous direct measurement methods.

2.5.2 Continous direct measurement

The principle of continuous direct measurement of flow is based on the assumption that all discharged water is measured and recorded or collated within acceptable limits of accuracy.

Continuous direct measurement is comprised of an array of instantaneous measurements taken over short periods of time (a few seconds) using devices capable of recording the values obtained during the entire duration of measurement. In certain specific cases, it is also possible to record other representative parameters, such as water mass and velocity, and convert them to water volume and flow.
This means that the instantaneous method used in conjunction with the measurement of the

total water volume can become a continuous measurement method (Figure 4). This is the case for methods using a primary temporary or permanent hydraulic structure, a reference instrument, pump capacity or the volumetric method.

The advantage of continuous direct measurements stems from the fact that they may extend over a given period of time such as several hours or even days and therefore reveal all variations of flow during the period. As such, the acquired information is more complete.

2.6 FLOW MEASUREMENT BASED ON DISCHARGE TYPE

Figure 5 shows the relationship between discharge types and the (instantaneous or continuous) measurement method used.

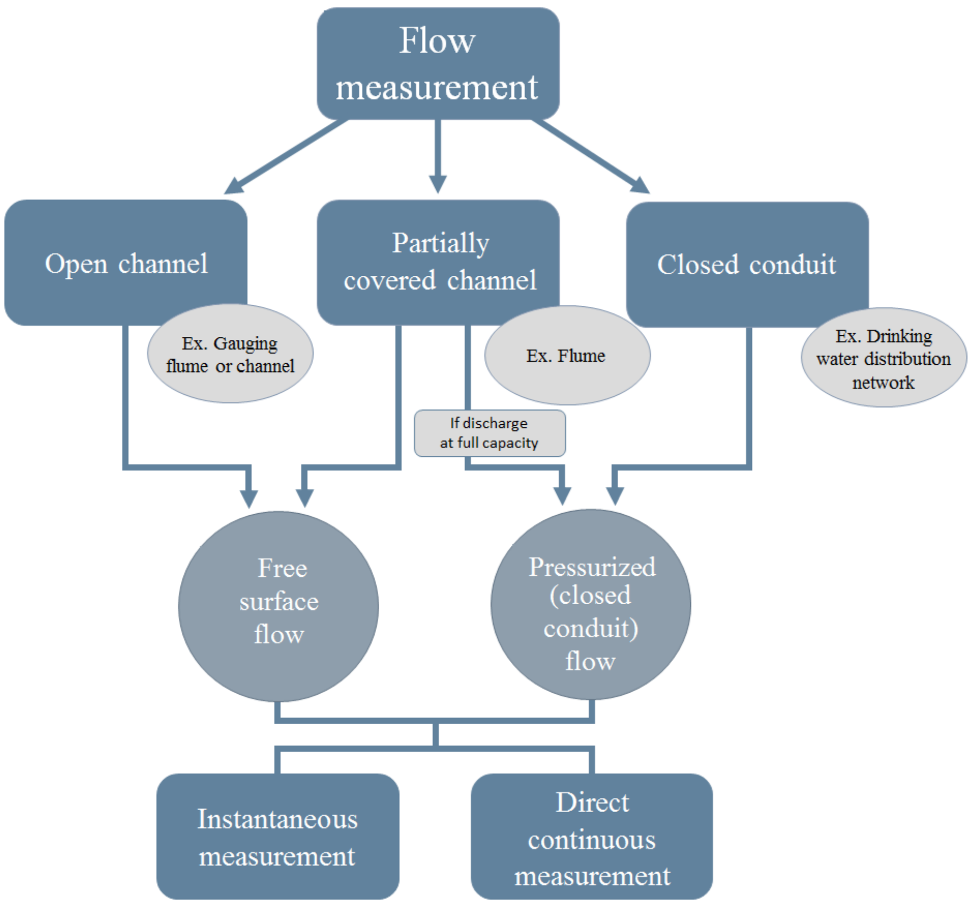


Figure 5: Relationship between discharge type and measurement method.

2.6.1 Discharge measurement in free surface flow

One of the simplest and quickest ways of determining discharge in free surface flow conditions is to use a primary structure such as a flume whose stage-discharge curves or flow tables are already known.

The flow tables in the 8th (or later) edition of the *ISCO Open Channel Flow Measurement*

Handbook (Teledyne ISCO) or the ones supplied by the manufacturer are examples of tools that can be used for this purpose.

The instantaneous or continuous measurement of discharge level with a flowmeter alone makes it possible to determine flow. The required physical conditions of the facility must be met since the curves and flow tables are based on standard values. Any physical changes that result in failure to meet the criteria will require the accuracy of the primary structure to be checked.

The other way to measure flow consists of measuring the average discharge velocity and the area of the wetted section. Equation 4 is required to calculate the flow in this case. However, measuring the discharge velocity requires a current-meter or similar device capable of measuring velocity based on mechanical, ultrasonic, Doppler Effect or electromagnetic principles. Developing a gauging curve on the basis of measurements taken for various flow ranges will then enable the stage-discharge relation to be determined. In conjunction with a water level measuring device, the stage-discharge relation can calculate the continuous flow.

2.6.2 Measurement of flow in pressurized discharge

Measurement of flow in a closed conduit with pressurized discharge can be achieved with flowmeters or counters. In this type of discharge, flow measurement is based on principles that will vary with the type of installed equipment that must be adapted to the range of flow measured and type of liquid.

Counters provide the cumulative total volume over a given period of time, such as 24 hours. Flowmeters take a large number of instantaneous measurements of water volume per unit of time at short intervals, such as one second, and compile them. The volume of water displaced per unit of time and the compilation of all flow measured during each interval represent the total volume of water displaced during the period in question.

In addition, flowmeters equipped with or linked to a data acquisition system make it possible to reveal all variations in flow that occur in a given period of time, such as minimum, maximum and average flow, something that counters cannot accomplish.

The choice between a counter and a flowmeter will be based on the specific effluent monitoring needs and requirements.

In the case of flowmeters, the method used to determine flow can be based on the difference in pressure created by a constriction in the channel. The pressure is measured upstream and at the constriction, where velocity increases and pressure drops. Venturi, orifice plate and V-cone flowmeters make use of this principle. Flow measurement can also be based on the intensity of electric current. Here, a magnetic field is created around a section of the channel, perpendicular to the discharge. Water transiting the magnetic field generates an induced current that is proportional to flow. The magnetic (or electromagnetic) flowmeter is another example of a flow measurement device based on the transmission frequency or speed of sound (high-frequency sound in ultrasonic flowmeters) captured by a sensor. Flowmeters that are compatible with free surface facilities are described in section 3.3, while those used for pressurized discharge are detailed in section 4.

Counters can measure water volume based on the rotational velocity of a mobile device that is proportional to water velocity. This is the case for turbine and propeller-based counters. Measurement can also be based on counting filling operations (as in volumetric positive displacement counters) or on alternating hydraulic counting (as in fluid oscillation electronic counters). However, this type of equipment is not addressed in this publication.

2.7 SAMPLE FLOW MEASUREMENT INSTALLATIONS IN FREE SURFACE CHANNELS

A system for measuring flow in a free surface channel is generally comprised of two components: primary structures and secondary devices. The primary structure can usually read the instantaneous flow of the discharge. Parshall and Palmer-Bowlus flumes and weirs are examples of primary structures.

The secondary device is a flowmeter that continuously measures discharge from the primary structure. It accomplishes this through a known stage-discharge relation and can also compile and record flow measurement data.

Section 3 provides a more detailed description of primary structures and secondary devices, as well as the particular requirements for their use in free surface channel facilities.

2.8 SAMPLE FLOW MEASUREMENT INSTALLATIONS IN PRESSURIZED CONVERED CONDUITS

Similar to flow measurement in free surface channels, flow measurement systems in pressurized covered conduits (pipes) are generally comprised of a primary structure and a secondary device. The primary structure produces and measures a signal that is proportional to flow. This signal is extracted and converted to a standard output signal by the secondary device. Primary structures include a stilling tube, an apparatus that creates the desired signal and others that create the desired effect, as well as electrodes to measure the signal. The secondary device in this case is usually the apparatus that displays and transmits the acquired data.

The continuous recorder in the flowmeter is usually integrated into the device, although it may also be separate and simply connected to the measurement apparatus. The addition of a computer to this system enables data to be conserved over a longer period of time and processed with specialized software.

Section 4 provides a more detailed description of flow measurement in a pressurized (closed conduit) flow.

2.9 SELECTION CRITERIA FOR MEASURING EQUIPMENT BASED ON EASE OF OPERATION, MAINTENANCE, ACCURANCY CHECKING AND CALIBRATION

2.9.1 Selecting measuring equipment

Optimizing the choice of method is required when measuring effluent flow with precision. Measuring equipment must, therefore, be adapted to the type of water withdrawal, carriage or *in situ* discharge facility. For example, while a water counter can only be used for pressurized channels, certain types of flowmeters are appropriate for both free surface and closed pipes.

Moreover, the prevailing conditions at the measuring point will be determinant in choosing optimal equipment. As such, an initial *in situ* characterization is required for the following:

- Characteristics of the water (physicochemical properties, suspended matter, algae, sediment, etc.).
- Characteristics of the discharge (velocity, turbulence, pressure, temperature, conductivity, etc.).
- Discharge type (free surface or pressurized, continuous or intermittent).
- Flow measurement interval to determine minimum, maximum and average flow.
- Access to the measuring equipment for maintenance, accuracy checking, adjustments and data reading purposes.
- Environmental conditions that could affect the functioning of the equipment, such as cold weather, snow or ice.
- Facility constraints such as available space, the shape and dimensions of a channel or pipe, the presence of a source of electricity, etc.
- Acceptable load loss[2] (check whether the current configuration of the facility tolerates a higher water level upstream caused by the measuring device).
- Sensitivity needed to detect and measure water level variations associated with changes in minimum flow.
- Desired measurement accuracy.

Given the large number of devices on the market and the multiple parameters that can influence which one is acquired, it is recommended to leave the choice of measuring equipment to an experienced colleague. At the time of purchase, the full range of information required to operate and maintain the equipment must be in hand, as well as the certification and calibration documents, which should remain accessible for use in equipment maintenance.

In the case of devices that are built on-site, such as weirs, it is important to ensure that the flow measurement system can be adequately operated, maintained, checked and adjusted.

2.9.2 Installation, accuracy checking, adjustement, calibration and maintenance

Installation

Measuring system devices must be installed by qualified and experienced staff in compliance with all technical characteristics and requirements specified by the manufacturer. It is preferable to know that a device is being operated in compliance rather than attempt to estimate the effects of non-compliant conditions and correct the values obtained therein.

For example, depending on any predetermined local risk factors, measuring devices may need to be protected from fire, freezing, electrical discharge, hot water, steam, overheating, pressure surges, physical damage or vandalism.

[2] Total load and head loss concepts are described in Appendix 2.

Measuring systems should be installed so as to enable inspection, checking, adjusting and calibration. For example, a flume must never be permanently covered. A drift should be planned in pipes to make it easier to remove the flowmeter.

Accuracy checking, adjustement and calibration

Appendix 1 clarifies a number of notions and lists metrology terms used in accuracy checking and calibration.

Purchase and deployment of a calibrated primary structure

Primary structures come with calibration certificates that attest to their accuracy under theoretical conditions. Calibration conditions are usually not the same as *in situ* ones. This means that accuracy checking is essential when a measuring system is placed into service and must be conducted on-site as soon as possible after installation and under normal discharge and operational conditions.

Checking is achieved by comparing the data collected by the *in situ* measuring system to the data provided by methods approved by the Ministère, such as volumetric, velocity-area, reference instrument, etc. These methods are described in sections 7 to 11. Accuracy checking should be conducted by qualified, experienced staff.

Recalibrating a primary structure

Recalibrating a primary structure is needed whenever it is not in compliance with the manufacturer's norms or if it deteriorates, becomes horizontally or vertically warped or whenever an accuracy check fails to meet maximum permissible variance requirements. In such cases, calibration determines the relationship between flow and water level at different discharge levels in free surface channels, or pressurized pipe discharge conditions as measured by the primary structure.

A new empirical stage-discharge or other relation based on the type of installed equipment can then be determined over the range of measurement likely to be used by the primary structure.

Free surface channel primary structure calibration is usually conducted *in situ*, while pressurized pipe flowmeter calibration (such as electromagnetic) is carried out on a test bed.

Flow measuring system adjustment and accuracy checking

Primary structure adjusting and accuracy checking remain essential even after calibration, all the more so since test bed and *in situ* conditions are unlikely to be identical, and therefore lead to errors that need to be taken into account.

Secondary device accuracy checking is conducted by comparing device and manual flow measurement, as explained in detail in section 3.3. The frequency of checks will vary in accordance with regulatory requirements. Subject to any applicable requirement that takes precedence over the information found herein, primary structure accuracy checking should be annual and employ another reference method approved by the Ministère, described in sections 7 to 11.

Accuracy checking for secondary measuring devices that are part of a free surface channel measuring system is recommended weekly. Whenever required, adjustments need to be made without delay. In closed conduit, distinguishing secondary devices from primary structures may be more difficult. Recommended monthly checks are described in the following section that deals with flow measuring system maintenance.

Section 12 provides details on reporting requirements.

Maintenance

Inspection and maintenance should be periodically conducted on all primary structures at least monthly (or more often depending on discharge conditions, such as when there is a lot of suspended matter in the effluent). Proper maintenance will increase the useful life of the equipment and the accuracy of measurement, as well as reduce maintenance or replacement costs. It is important that users refer to manufacturer recommendations for the maintenance instructions of the device. Inspection and maintenance may include the following:

- Free surface channel:
    - Check the structural integrity for longitudinal and transverse problems, breakage, warping, cracks, leakage, joint issues, etc.
    - Clean all sections of the primary structure (weir invert, walls and edges, connecting flume, stilling well and all approach and waste channels in order to avoid any accumulation of sediment, grass, silt, debris and ice).
    - Clear plants at the outlet of the channel.
    - Check discharge conditions to ensure that water is calm and well-distributed at all times.
    - When there is a secondary device, check measurement accuracy and make any necessary adjustments.
- Covered conduit:
    - Check all electronic components, such as 4 to 20 mA output signal transmitters and connectors, then zero the device.
    - Compare current flow trends to observed preceding-day historical data in the production or treatment of water during the time period under study. Unexplained variance in measured flow values could indicate malfunction, requiring an investigation to determine the cause of the problem and identify any necessary corrections.
    - Check whether the electronics include an alarm or error signal.
    - In the case of effluent loaded with suspended matter, cleaning may become necessary, particularly if the equipment is not optimized for conditions (such as when a diaphragm used for effluent is heavily loaded with suspended matter).
    - If insulating materials have been deposited on the electrodes or tube sidewalls by the liquid conductor, then mechanical, electrical or chemical cleaning is warranted to remove then. This could include removing the electrodes, using a mechanical scraper, electrolysis, etc.
    - A device with moving parts has a greater likelihood of deteriorating over time

and with use. Some models are manufactured so as to enable the removal of parts (such as the mechanical part of a paddlewheel flowmeter) for maintenance or replacement purposes or to repair defective sensors.

Flowmeter and data transmission maintenance programs are detailed in section 3.3. Sample checklists for primary structure inspection are shown in Appendix 3.

Flow measurement…

… is based on:

volume, i.e., in the measuring section;
measurement duration;
discharge velocity.

May be **instantaneous** or **continuous direct.**

Varies with discharge type (**free-surface** or **pressurized**).

Accuracy of a measuring station is directly related to:

Choice of appropriate equipment for *in situ* conditions
Compliance with installation instructions
Maintenance
Accuracy checking

3 MEASURING EQUIPMENT INSTALLATION FOR FREE SURFACE FLOW

3.1 FREE SURFACE FLOW CLASSIFICATION

Free surface flow measurement is generally based on the stage-discharge relation, which depends on discharge conditions and hydraulic behaviour. In free surface flow, the water surface is in contact with the ambient air and is therefore subject to atmospheric pressure.

Before reading water level in discharge conditions that are appropriate and representative of flow, it is important to understand the hydraulic behaviour of the discharge.

Figure 6 illustrates the various types of free surface flow.

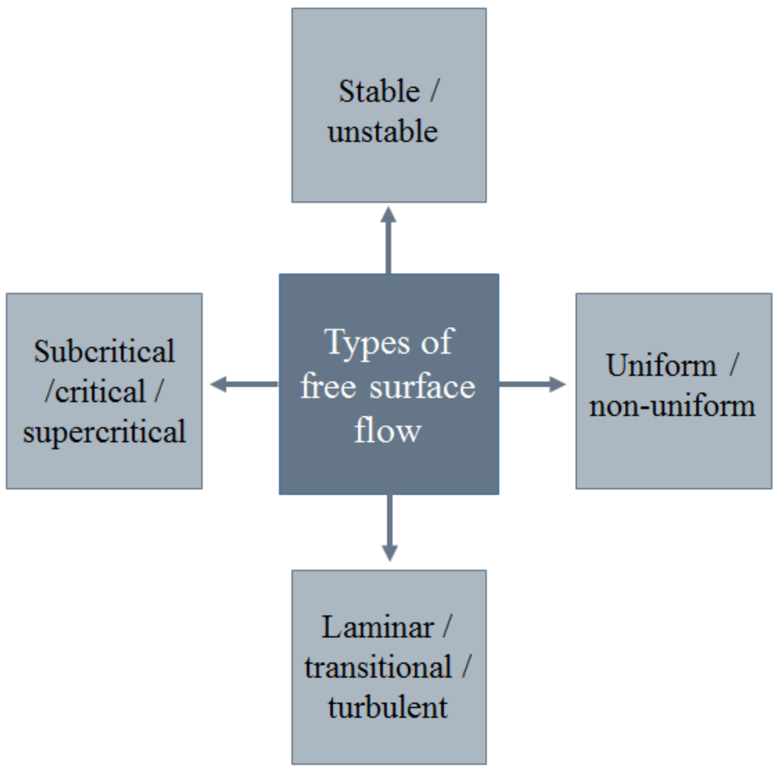


Figure 6: Types of free surface flow.

3.1.1 Stable and unstable discharge

This criterion relates to variability over time. Stable discharge (also called permanent, stationary or established) is in a state where velocity and level do not vary over time. When the characteristics of the discharge in a section of the channel change over time, it is termed unstable (also called non-permanent or transitional).

Discharge is rarely stable in channels, but variations over time can be sufficiently small for the discharge to be considered as a series of stable regimes. Stable discharge can be uniform or non-uniform, while unstable discharge is solely non-uniform.

3.1.2 Uniform and non-uniform discharge

This criterion relates to spatial variability. Uniform discharge is characterized by constant water level and velocity throughout the channel. This can only occur under conditions where the slope and cross-section are constant, meaning that the channel surface is parallel to the invert (Figure 7). Truly uniform channel discharge is quite rare but may be induced by a long, regular-shaped channel.

Non-uniform discharge may increase or decrease in relation to discharge velocity. The change may be gradual (Figure 7, section B) or rapid (Figure 7, section C).

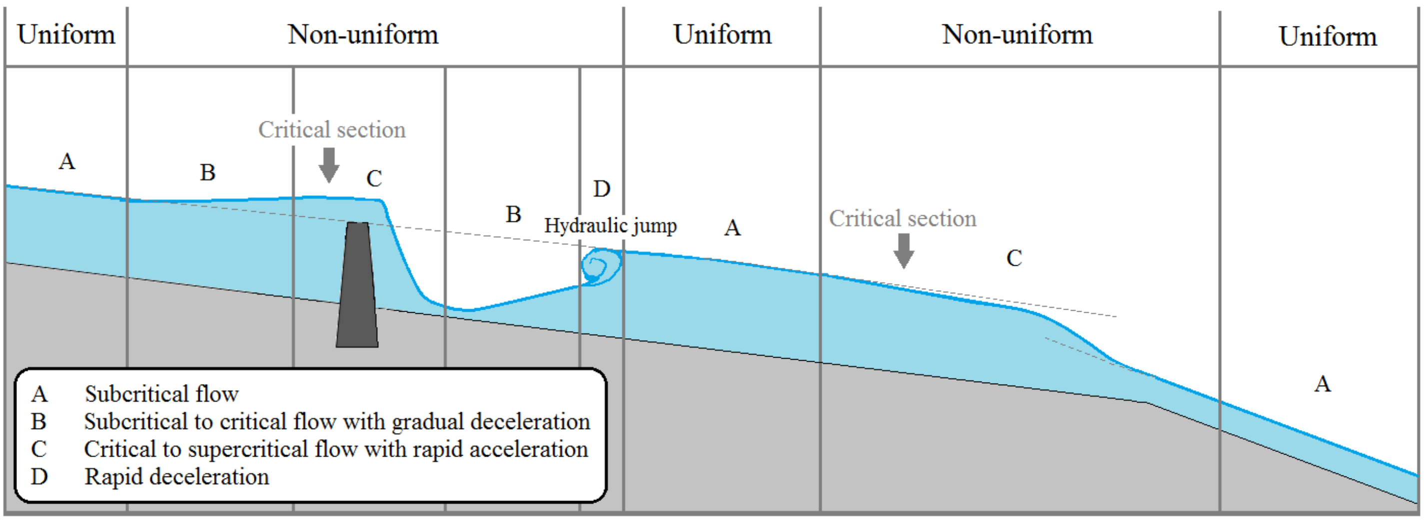


Figure 7: Uniform and non-uniform flow.

3.1.3 Laminar, transitional and turbulent flow

This characteristic is based on a physical phenomenon. Laminar flow is characterized by the parallel displacement of water runnels that do not mix, contrary to turbulent flow (Figure 8). Laminar conditions are unusual in watercourses and even in man-made channels, both usually displaying a certain level of turbulence.

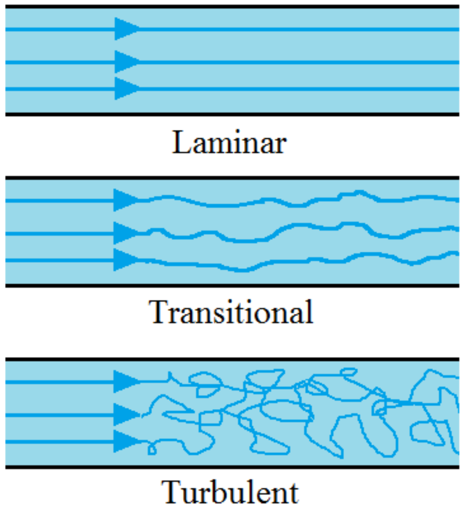


Figure 8: Laminar, transitional and turbulent flow.

The Reynolds number (R_e) can distinguish laminar from turbulent discharge:

$$R_e = \frac{v_{moy} r_h}{\eta} \tag{10}$$

Where	v_{moy}	Average velocity of the liquid (m/s)
	r_h	Hydraulic radius of the cross-section (m)
	η	Kinetic viscosity of the liquid (m^2/s)

Reynolds numbers are dimensionless. They express the relationship between inertial and viscous forces. As the number rises, so does turbulence in the discharge. Reynolds numbers differ between free surface flow and pressurized (closed conduit) flow.

Three discharge regimes can be identified on the basis of their increasing Reynolds numbers:

1. In visual terms, a laminar regime (Figure 8) displays low particle velocity and well-defined streamlines that are parallel to the channel walls. In such cases, $R_e < 500$ and the viscosity forces determine discharge. The velocity profile is hyperbolic, as illustrated by the red lines in Figure 9.

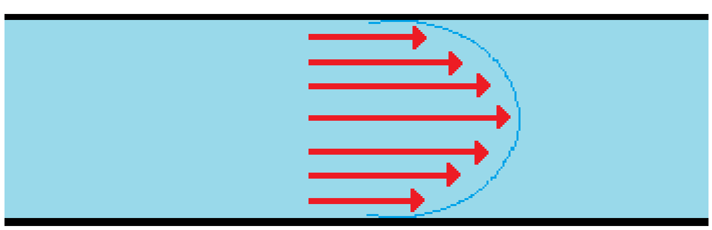


Figure 9: Velocity profile of a laminar regime.

2. A transitional regime (Figure 8) is characterized by instability arising from disturbance amplification and the dominant effect of subsiding laminar regime viscosity. The transition between laminar and turbulent regimes can arise whenever the R_e value is between 500 and 1,000.

3. A turbulent regime is characterized by increased instability to a point where discharge is so chaotic that systemic organization is unclear (Figure 8). In such cases, $R_e > 1{,}000$. The displacement of sizable eddies in many directions occurs whenever the velocity is greater than the viscosity forces.

   Head loss arising in this regime is essentially due to viscous friction among particles located close to the channel walls (red lines in Figure 10).

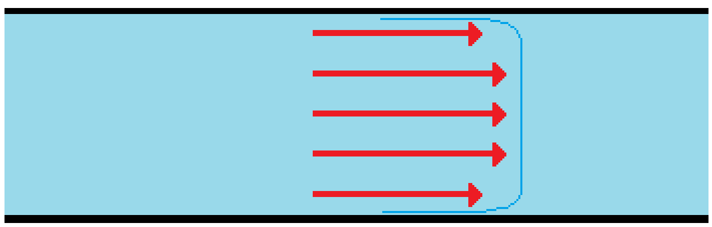


Figure 10: Velocity profile of a turbulent regime.

3.1.4 Subcritical, critical and supercritical discharge

This characteristic is also based on a physical phenomenon. It is evaluated at the water level measuring point and is a function of the Froude number (*Fr*), which relates discharge velocity to gravitational acceleration and discharge level as expressed in the following equation:

$$Fr = \frac{v}{\sqrt{gh}} \qquad (11)$$

Where
- v Discharge velocity (m/s)
- g Gravitational acceleration (m/s^2)
- h Discharge depth (m)

As its name suggests, the velocity of subcritical (also called fluvial) discharge is below critical velocity. This type of discharge is known for low velocity, greater depth and an *Fr* number < 1 (Figure 7, section A).

In critical discharge, $Fr = 1$ (Figure 7, section B), which is the minimum discharge energy for a given flow.

In supercritical (also called torrential) discharge, $Fr > 1$ and gravity is the dominant factor. Velocity is high and level, low (Figure 7, section C).

Moving from a subcritical to supercritical state of discharge can be seen when a structure such as a weir induces a smaller discharge area or change in slope.

Moving from supercritical to subcritical discharge often arises when there is a change in slope but occasionally when discharge contracts then widens and is characterized by the appearance of a hydraulic jump (Figure 7, section C). Hydraulic jumps are turbulent zones of varying extent that are characterized by extreme variations in water level.

3.2 PRIMARY STRUCTURES

3.2.1 Overview

In the case of a open channel or partially covered channel where discharge is not at maximum capacity (and therefore not pressurized), flow is usually measured with a hydraulic primary structure.

Primary structures are used to change water discharge so as to generate particular discharge conditions that enable users to identify appropriate and reliable measurement locations for establishing the streamflow. Flow measurement is, as such, measured at the hydraulic structure that enables a unique stage-discharge relation to be determined. The streamflow can, therefore, be obtained from a single measurement of the water level at the primary structure reading point.

One of the main benefits of this type of installation over closed conduits is that it makes it possible to visualize the discharge conditions at any time. This enables users to quantify magnitude even in poor conditions; make corrections as quickly as possible; and take appropriate measurements.

Two main categories of primary structures are used to measure free surface flow: flumes and weirs. Individual types of flumes and weirs have their own specific structure, form and stage-discharge curve. Flow can therefore be determined by means of the theoretical formula or the appropriate flow table that is itself determined by the shape and dimensions of the structure.

3.2.2 General design criteria and installation guidelines for primary structures

Some general criteria need to be considered when selecting and installing primary structures. Firstly, the structures must be sufficiently strong and resistant to erosion to deal with discharge conditions and storms that may occur at the selected location. The dimensions must also correspond to the flow measurement period, and installation must comply with the manufacturer's recommendations.

No branching, curves, falls or rapid changes to the invert are to be employed in primary structure approach channels. Discharge at the approach point must be well-dispersed and relatively free of turbulence, waves and eddies, while the downstream section must enable free-flow with no backwash or submergence. Irregular sides or beds are also to be avoided in approach channels since they can play a negative role in generating irregular discharge profiles and, as such, affect measurement accuracy.

It should be noted that whenever water is loaded with sediment or suspended matter, it is preferable to use a flume, which retains less suspended matter than a weir.

Finally, the selected location for installing these structures must be easy to access to enable *in* *situ* readings and stage-discharge curve checks, as well as inspection and maintenance. Regular visual inspection is of paramount importance. The use of a steel or concrete plate to cover an installation and thereby limit access to the measuring point is not appropriate. As such, primary structures must not be installed in spaces that limit access. The relative costs of checking accuracy in non-optimal installation conditions must also be considered. Accuracy checks in an inaccessible approach channel or one that is located in a closed space come with major costs and the risk of significant errors involving other checking methods that can be tricky or difficult to repeat.

In cases where the location prohibits the installation of a open channel discharge measurement system, closed conduit installation should be envisaged.

3.2.3 Measuring point and stilling well

The measuring point should be located where the effect of the rise in water level occurs, i.e. the elevated portion where the head line is seen throughout all parts of the installation, including the primary structure, approach channel and outlet channel (Figure 11). The line that is transverse to the longitudinal axis of the primary structure at the measuring point constitutes the correct theoretical location for measuring streamflow. There are no common or standard locations of this point among the various types of primary structures. Individual structures have their own measuring point. The use of consistent measuring point locations for a given primary structure is of paramount importance, due to the fact that inappropriate locations can lead to reduced measurement accuracy.

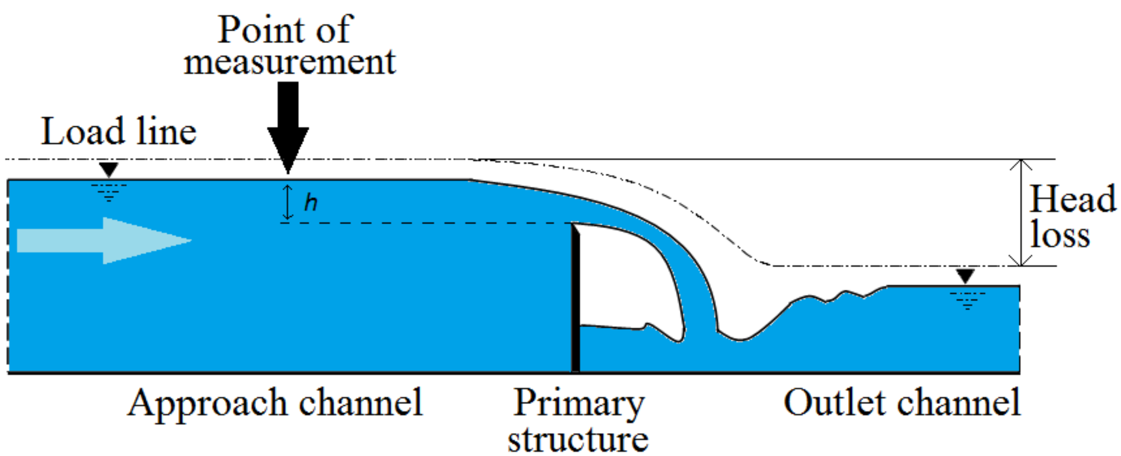


Figure 11: Head line and measuring point in a weir.

Ideally, primary measurement structures should be equipped with a stilling well installed at the measuring point. The well makes it possible to read water level in relatively calm conditions by reproducing what occurs in the primary structure.
The well is perpendicularly connected to the primary structure by means of a conduit or slot whose opening is approximately equivalent to 1/10 the diameter of the well, allowing for a fast reaction time to changes in water level while abating any oscillation caused by surface waves.

It is important to ensure that the conduit meets the well wall and primary structure at right angles to avoid readings being flawed. The well should also have sufficient depth to accommodate the entire range of water levels. The well invert should be located below the lowest water level that is to be measured, or the zero level of the primary structure. It is however mandatory for the measured water below the invert of the flume or the zero of the measuring device at floor level to be subtracted from that value, so as to avoid overestimation of the water level.

The diameter of the well must be sufficient for utilization and maintenance to occur without interfering with any other installed measuring devices such as flowmeter level detectors. Draining and rinsing a well will keep it free of sediment or debris that could lead to inaccurate measurements.

Even if a stilling well is used, manual readings taken in the gauging section of the channel are also recommended for counter-checking purposes. In addition, a water level gauge should also be permanently installed at the measuring point, for reference purposes.

While stilling wells can be useful, their periodic maintenance (including the flume and connector) is recommended weekly when effluent contains a lot of suspended matter or debris. Moreover, adjustments may be required in winter to ensure that water does not freeze in the connectors. Finally, stilling wells must be installed as close as possible to the flume to avoid any major lags that reflect deficient management of oscillation in flume water. Figure 12 illustrates a stilling well installed in a Parshall flume, at the measurement point.

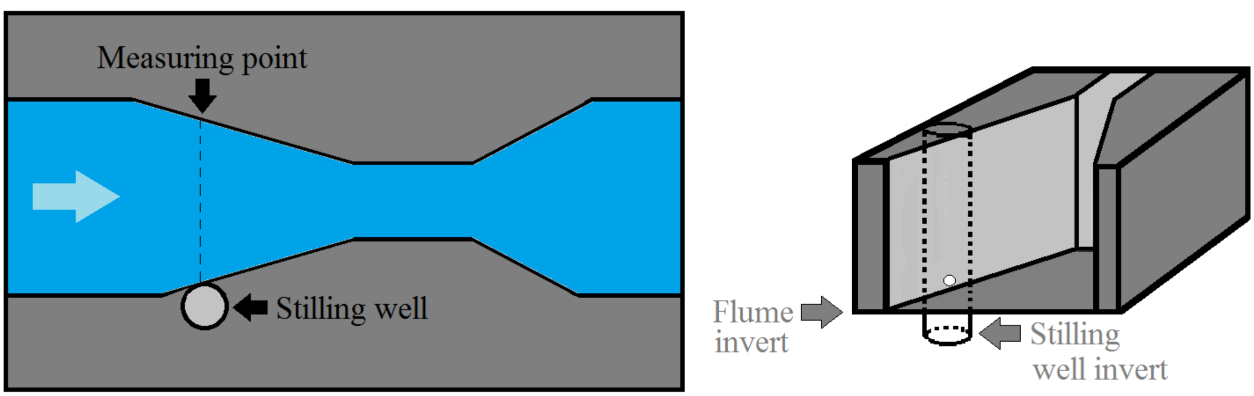


Figure 12: A Parshall flume stilling well.

3.2.4 Accuracy

The installation and configuration quality of a primary structure, its maintenance and existing discharge conditions are all factors that can influence measurement accuracy. The following factors should be considered with a view to maximizing the accuracy of gauging flumes and weirs:

- Select a primary structure whose characteristics suit site conditions, for example by opting for a flume rather than a weir when effluent contains a high sediment load.

- Install equipment whose dimensions are appropriate to discharge conditions, ensuring that they will enable discharge to flow freely in all hydraulic regimes that are within the constraints of the installation. Dimensioning needs to be based on a recent study or on recently measured values. The goal here is to select a primary structure that will cover the greatest variation of *in situ* water levels at the measurement point or to choose a site that provides great stability of flow, such as an aerated pond.
- Abide by standard dimensions when constructing a primary structure.
- Take all required precautions during the installation process.
  - Ensure that the structure is transversely and longitudinally level. If the base of the channel is not level with the transverse axis, average water level must be used to conserve the stage-discharge relation, i.e., the level must be measured on all sides to determine the average.
  - Install the hydraulic structure parallel to the approach channel in flumes and perpendicular to discharge in weirs.
  - During weir installation, ensure that the structure is not warped, that it retains its original dimensions and shape and that there is no sign of expansion at the channel floor, wall flaring or crest rounding.
  - Avoid obstructions in all sections of the primary structure as well as in the approach and outlet channels. When liquids meet an obstruction, they are forced to flow over it, which increases the water level at the measuring point and overvalues the streamflow.
  - Ensure that the structure does not leak and that all discharge is captured.
- Ensure appropriate approach channel length. If it is too short it will be unable to adequately correct any major distortions in the approach and distribution velocity.
- Use a standard measuring instrument, such as a ruler.
- Comply with instructions for locating the measuring point and zero calibration when measuring water level.
- Comply with standard primary structure measurement intervals, because errors will increase whenever the flow does not meet minimum manufacturer recommendations.
- Ensure that the rise in water level is sufficient to clearly establish the stage-discharge relation.
- Ensure that installation makes it possible to determine a uniform and constant discharge regime upstream from the primary structure, for all ranges of measurement.
- Make certain that discharge velocity is sufficient to ensure free-flow or ventilation.
  - When a channel is in non-modular (submerged) flow, accuracy will decrease in accordance with the submergence discharge conditions ratio (h_2/h_1) upstream and downstream.
  - It is important that users are able to recognize when a facility is in non-modular (submerged) flow.
  - It is important to adopt a two-point measurement technique for non-modular (submerged) flow.
- Regularly maintain the equipment, removing sediment deposits, grass and other debris that can accumulate upstream of an approach channel or at the base of a weir

in gauging sections and at the throat of a flume, crest of a weir, or outlet.

- Regularly inspect the structure to ensure that there are no signs of warping or cracks caused by leaks.
- Use the flow equation appropriately and ensure that the constants are correct.

Measurement errors in gauging flumes and weirs are greatly influenced by the quality of installation of the primary structure and by discharge conditions. As such, theoretical measurement errors are variable. As a general rule, the theoretical margin of error in primary structures is ± 3% for gauging flumes and ± 2% for weirs. However, experience shows that even when an installation meets manufacturer recommendations, errors can be as high as ± 5%. This value will rise and accuracy drop whenever the flow is at the lower end of the measurement range.

In free surface flow…

…the pressure of the air-water interface = atmospheric pressure.

Flow is mainly influenced by gravity.

Flow features are as follows:

- time variables: stable/unstable
- spatial variables: uniform/non-uniform
- are functions of physical phenomena:
  - laminar/transitional/turbulent
  - subcritical/critical/supercritical

The primary structure (gauging flume or weir) will modify flow and create a precise level/discharge ratio to the extent that it is:

- Adapted to *in situ* conditions
- Installed in compliance with requirements
- Appropriately maintained.

3.2.5 Gauging flumes – overview

Gauging flumes are usually prefabricated devices that are temporarily or permanently inserted into a discharge channel. They are moulded hydraulic structures that reduce the discharge area or change the incline angle of the channel bed to induce a change in the hydraulic regime, moving it from subcritical to supercritical (Figure 13).

If the flow of liquid is constant and the discharge area drops, the discharge velocity will increase, leading to a lower water level. This works according to the Venturi principle.

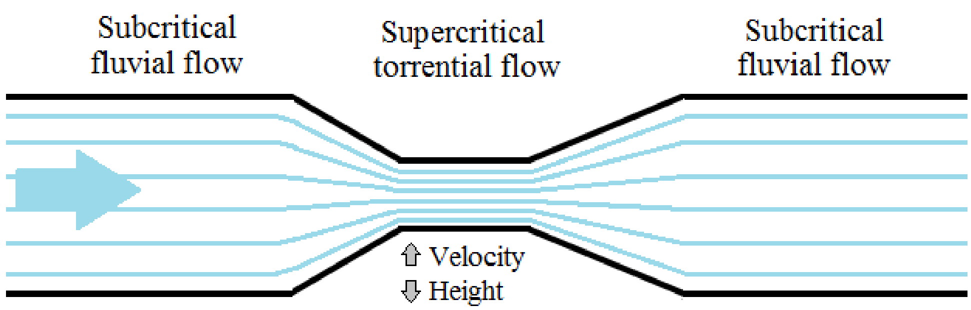


Figure 13: Top view of a Venturi flume.

This type of flume generally has convergent, control (constriction or throat) and drift sections.

Flow is determined by measuring water level at a specific location within the flume or upstream from it. The level of water transiting the flume is a function of streamflow.

Dimensions vary by the type and shape of the flume. In practice, it is recommended that manufacturer-provided calibration curves be used to establish true flow in the flume.

The type of flume selected depends on several factors, including the flow measurement interval; maximum permissible variance; acceptable head loss; whether or not the discharge leads to sedimentation; and economic factors. Gauging flumes have both benefits and drawbacks, which are shown in Table 1.

The following sections deal with the most common types of gauging flumes for permanent and temporary measurement sites. Other types of gauging flumes may be acceptable, as long as they meet *in situ* conditions and are installed and used per the manufacturer's recommendations and with the correct conversion formula.

Table 1: Advantages and drawbacks of gauging flumes

Benefits	Drawbacks
• Low head loss • Wide range of flow measurement • Discharge velocity generally sufficient to prevent sedimentation. As such, they are self-cleaning. • Accurate reading in free-flow conditions	• Generally expensive to install • Setup requires great care • Requires a solid waterproof base • Discharge must be well-distributed upstream and at the inlet with little turbulence so as to ensure that measurements are representative. • Measurement in non-modular (submerged) flow is difficult and not recommended.

Gauging flumes…

… are hydraulic structures that are specially moulded to restrict flow and/or modify inclination so as to change the hydraulic regime from subcritical to supercritical.

Q is constant, so reducing the flow area raises velocity and lowers the water level.

Q is a function of the water level at the point of measurement.

Individual models of gauging flumes have standard dimensions and precise water level measuring points that must be used.

3.2.5.1 Parshall flume

The Parshall flume was invented near the end of the 1920s to measure irrigation water flow. Now it is often used to measure wastewater flow in permanent or temporary installations.

Description

The Parshall flume includes a convergent section, a control section (also called the throat, collar or constriction) and a drift section (Figure 14). Parshall flumes come in a wide range of constriction widths, from as little as .0254 m (1 in) to 15.2 m (50 ft) Table 2.

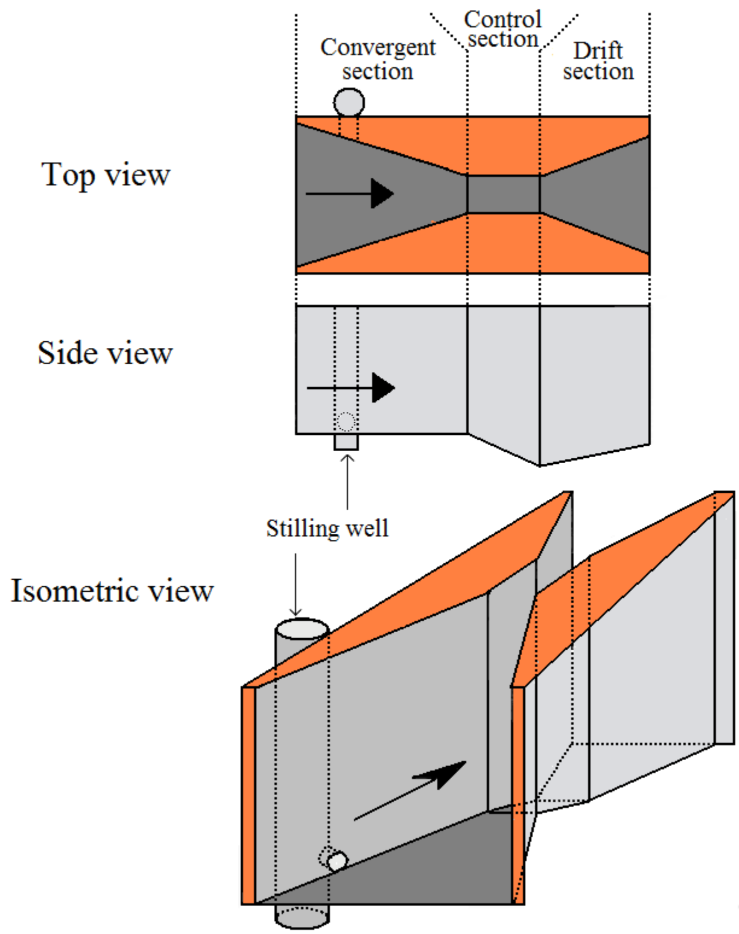


Figure 14: Illustration of a Parshall flume.

The convergent section is characterized by a horizontal invert, while the lateral vertical walls form a funnel toward the control section.

The bottom of the control section is inclined downstream and has a 3:8 slope. The lateral walls are vertical and parallel to the longitudinal axis of the channel. The intersection line of the invert's convergent section and control section is called the channel threshold.

The bottom of the drift section has a 1:6 upward inclination as well as divergent lateral vertical walls.

While they are not really part of the Parshall flume, the approach and outlet channels are essential for the proper functioning of the installation and must be capable of meeting maximum permissible variance values.

Applications

Though originally designed to measure flow in free surface natural channels such as rivers, streams and drainage ditches, Parshall flumes are frequently used to measure flow in open manufactured channels for storm drainage and in home drainage systems; inlets and outlets at municipal or industrial wastewater facilities, etc.

Parshall flume geometry and functional principle make it a very good tool for measuring flow containing solids. As well, with their weak load loss, Parshall flumes can be easily adapted to existing sewer networks.

Functional principle

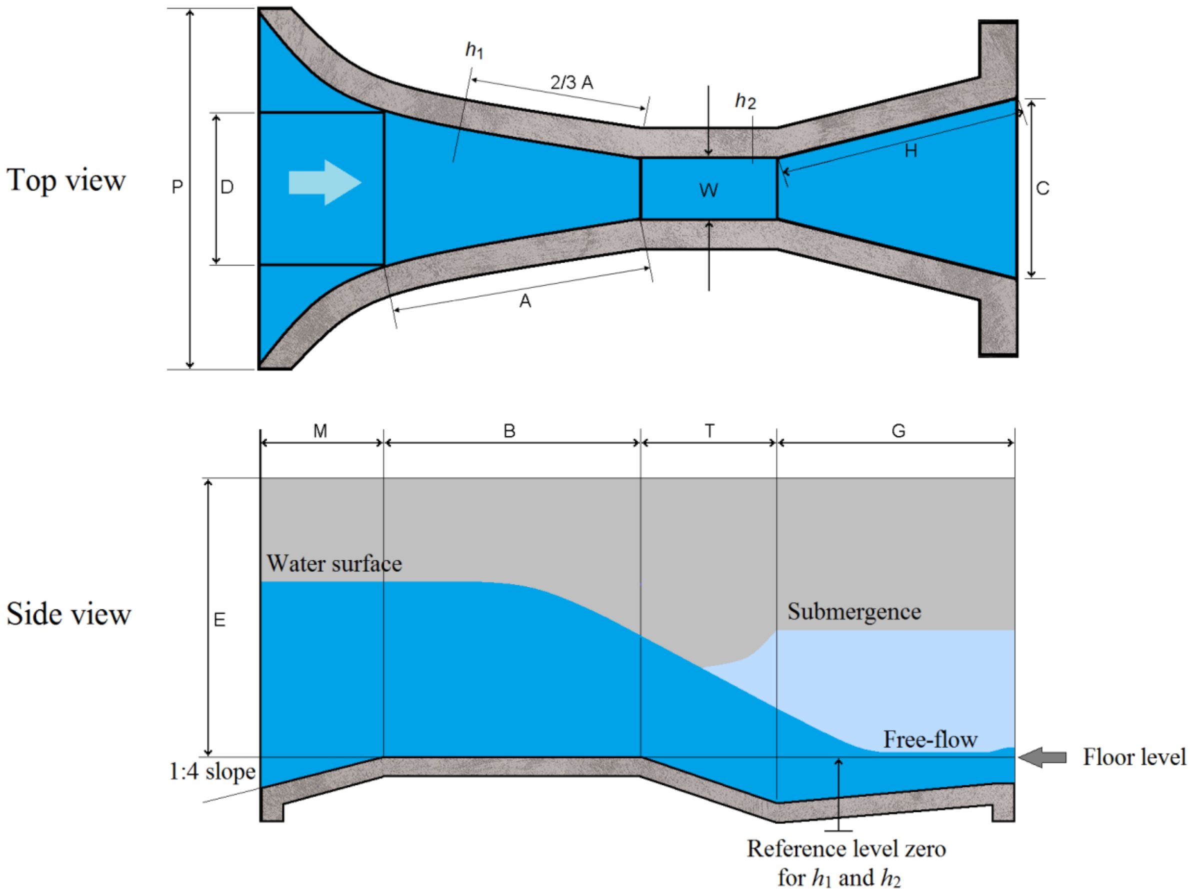
Parshall flumes use the Venturi principle (Figure 13). Due to their lateral constrictions, Parshall flumes reduce the discharge area, which raises the water level upstream from the control section. Any sudden major drop in water level in the control section therefore increases the discharge velocity.

Flow can thus be easily determined by the water level in a Parshall flume measurement section (2/3A) since it is known that water level varies in proportion to the flow in standard discharge conditions.

Standard dimensions

Parshall flume dimensions are defined by the width of the control section or constriction (W in the illustrations). Figure 15 shows the physical characteristics of the channel and discharge and Table 2 shows the dimensions for each standard-width Parshall flume.

It is important to rigorously abide by standard dimensions when using known empirical tables to accurately determine flow. Moreover, channel dimensions must enable the flume to work most of the time in a range of flow from 20 to 80% of its capacity. When dimensions are excessive, the accuracy of low flow measurement will decrease. Inversely, when the dimensions of the flume are too small, the accuracy of heavy flow measurements will be lower. As such, it is preferable to restrict the use of Parshall flumes to the above range to comply with requirements.



Key		
Approach channel	M P	Length of the slope at the Parshall flume inlet Width of the approach channel
Convergent section	D E A 2/3A h_1 B	Width at the inlet of the convergent section Depth of the convergent section channel Length of the convergent section wall Length measured from the constriction Water level upstream Length of the convergent section
Control section	T W h_2	Length of the control section Width of the control section (dimensions of the channel) Water level downstream
Drift section	C G H	Width of the drift section outlet Length of the drift section Length of the drift section wall

Figure 15: Physical characteristics of Parshall flume discharge.

Table 2: Standard Parshall flume dimensions (m)[3]

W		A	$^2/_3$A	B	C	D	E	G	H	M	P	T
m	in/ft											
.0254	1"	.363	.242	.356	.0929	.167	.152 - .229	.203	.206			.0762
.0508	2"	.414	.276	.406	.135	.214	.152 - .254	.254	.257			.114
.0762	3"	.467	.311	.457	.178	.259	.305 - .457	.305	.309			.152
.152	6"	.621	.414	.610	.394	.397	.610	.610		.305	.902	.305
.229	9"	.879	.587	.864	.381	.575	.762	.457		.305	1.08	.305
.305	12"	1.37	.914	1.34	.610	.845	.914	.914		.381	1.49	.610
.457	18"	1.45	.965	1.42	.762	1.03	.914	.914		.381	1.68	.610
.610	2'	1.52	1.02	1.50	.914	1.21	.914	.914		.381	1.85	.610
.914	3'	1.68	1.12	1.64	1.22	1.57	.914	.914		.381	2.22	.610
1.22	4'	1.83	1.22	1.79	1.52	1.94	.914	.914		.457	2.71	.610
1.52	5'	1.98	1.32	1.94	1.83	2.30	.914	.914		.457	3.08	.610
1.83	6'	2.13	1.42	2.09	2.13	2.67	.914	.914		.457	3.44	.610
2.13	7'	2.29	1.52	2.24	2.44	3.03	.914	.914		.457	3.81	.610
2.44	8'	2.44	1.63	2.39	2.74	3.40	.914	.914		.457	4.17	.610
3.05	10'		1.83	4.27	3.66	4.76	1.22	1.83				.914
3.66	12'		2.03	4.88	4.47	5.61	1.52	2.44				.914
4.57	15'		2.34	7.62	5.59	7.62	1.83	3.05				1.22
6.10	20'		2.84	7.62	7.32	9.14	2.13	3.66				1.83
7.62	25'		3.35	7.62	8.94	1.7	2.13	3.96				1.83
9.14	30'		3.86	7.92	1.6	12.3	2.13	4.27				1.83
12.2	40'		4.88	8.23	13.8	15.5	2.13	4.88				1.83
15.2	50'		5.89	8.23	17.3	18.5	2.13	6.10				1.83

[3] *Teledyne ISCO Open Channel Flow Measurement Handbook* (2017) and openchannelflow.com

Measurement range

Parshall flumes can measure flows of between 22.7 m^3/d for a 25 mm (1-in) flume and 7,344,000 m^3/d for a 15.2 m (50-ft) flume. Table 3 shows the minimum and maximum recommended flows for various dimensions of this type of free-flow flume. In this section, only data applicable to flumes whose dimensions are between 0.0254 m (1 in) and 3.66 m (12 ft) are listed.

Table 3: Minimum and maximum recommended flow for free-flow Parshall flumes[4]

Flume size		Minimum depth (h_1) m	Minimum flow		Maximum depth (h_1) m	Maximum flow	
m	in/ft		l/s	m^3/h		l/s	m^3/h
.0254	1"	.03	.263	.948	.20	4.98	17.9
.0508	2"	.03	.526	1.90	.25	14.1	5.7
.0762	3"	.03	.778	2.80	.35	34.8	125
.152	6"	.03	1.50	5.39	.45	108	389
.229	9"	.03	2.50	9.01	.60	245	882
.305	12"	.03	3.32	12.0	.75	446	1,605
.457	18"	.03	4.80	17.3	.75	678	2,443
.610	2'	.045	11.7	42.0	.75	915	3,293
.914	3'	.045	17.0	61.2	.75	1,390	5,011
1.22	4'	.06	34.9	125	.75	1,876	6,750
1.52	5'	.06	42.9	155	.75	2,364	8,514
1.83	6'	.075	72.6	261	.75	2,857	10,290
2.44	8'	.075	95.2	343	.75	3,850	13,860
3.05	10'	.09	158	570	.85	5,754	20,720
3.66	12'	.10	223	801	1.05	9,578	34,480

Installation

Parshall flumes should be installed in a straight section of the channel that is free of obstruction and bed disparity. Placing objects such as measuring probes, tubes or pumps in a Parshall flume is not recommended.

During setup, it is important to ensure the integrity of the original physical characteristics of the Parshall flume. It has to be rigid, impermeable and capable of tolerating maximum flow without being damaged by upstream overflow or erosion. A solid structural foundation will help avoid displacement or warping.

[4] *Teledyne ISCO Open Channel Flow Measurement Handbook* (2017)

The invert of the convergent section of the flume must be higher than the invert of the approach channel, which must itself be connected to the invert of the convergent section by a 1:4 inverted vertical/horizontal slope section (Figure 15).

The installation of a Parshall flume requires both approach (inlet) and exit (outlet) channels. The approach channel must fulfill the following conditions:

- The axis of the Parshall flume must be aligned with the direction of the discharge in the approach channel, which itself must be straight and uniform over a length of between five and ten times the width of the surface of the water in Table 2, section D. Additionally, an inflow pipe should not be inserted into the convergent section of the channel (Figure 16).
- The approach channel must have a minimum width that complies with dimension “D” in Table 2, and a maximum width that does not exceed dimension “P” of the same table.
- To avoid discharge disturbances at the entry of the convergent section of the Parshall flume, it must be connected to the approach channel by vertical walls that are angled at 45° to the axis of the Parshall flume or curved, and having a radius greater than twice the maximum height of the discharge.
- However, for smaller flumes (control section width less than .5 m), the approach channel connector walls may be placed perpendicular to the axis of the channel. For flume widths that exceed .5 m but are less than 2.44 m, the connector walls between the approach channel and the convergent section can be rounded (**Erreur ! Source du renvoi introuvable.**, top view) while for larger flumes they can be vertically angled at 45° to the axis.
- The surfaces of the flume, connector and approach channel must be smooth.
- Discharge in the approach channel must have symmetrical velocity distribution. The best way of accomplishing this is through a long, uniform, straight approach channel section that is free of obstacles that could influence discharge conditions. If in doubt about the discharge conditions and symmetry of velocity distribution in the approach channel, a full assessment of distribution and velocity range will be required (may be carried out using a rotating current meter).
- Discharge in the approach channel must be non-turbulent with no eddies or waves, so as to increase the accuracy of measurements taken in the gauging section of the flume.
- The approach channel slope must be less than 1%. It is important to avoid excessive inclination, which could result in a jump in the convergent section of the flume (see Figure 17) that could increase velocity and restrict the water level from rising in the convergent section. The slope of the bed must ensure that the discharge regime is calm or fluvial. This type of regime is mainly characterized by low to moderate discharge velocity and deep water.

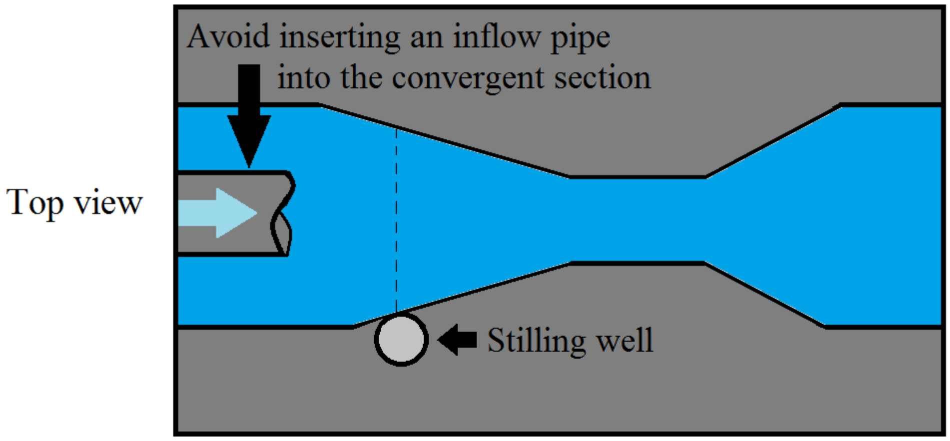


Figure 16: Avoid inserting an inflow pipe into the convergent section.

The upstream discharge conditions of the structure are significant because they regulate the level of water upstream, which could influence how the Parshall flume functions. The outlet channel must meet the following conditions:

- The slope must be sufficient to allow water to exit quickly (at least 2%).
- It must be designed so as to not create any narrowing that would lead to non-modular (submerged) flow in the channel.
- There must be no sharp curves that could restrict discharge and cause non-modular (submerged) flow.
- The drift section must generally be the average of the convergent section walls in length, and the angle of the walls must exceed the angle of the walls of the drift to prevent erosion caused by falling water.

All sections of the channel must be easily accessible for regular inspection and maintenance. A gauge should be permanently installed on one of the walls of the convergent section in the measuring section (2/3A). Finally, it is recommended that a stilling well be installed whenever the highest possible accuracy is required of the depth-measuring device or secondary structure.

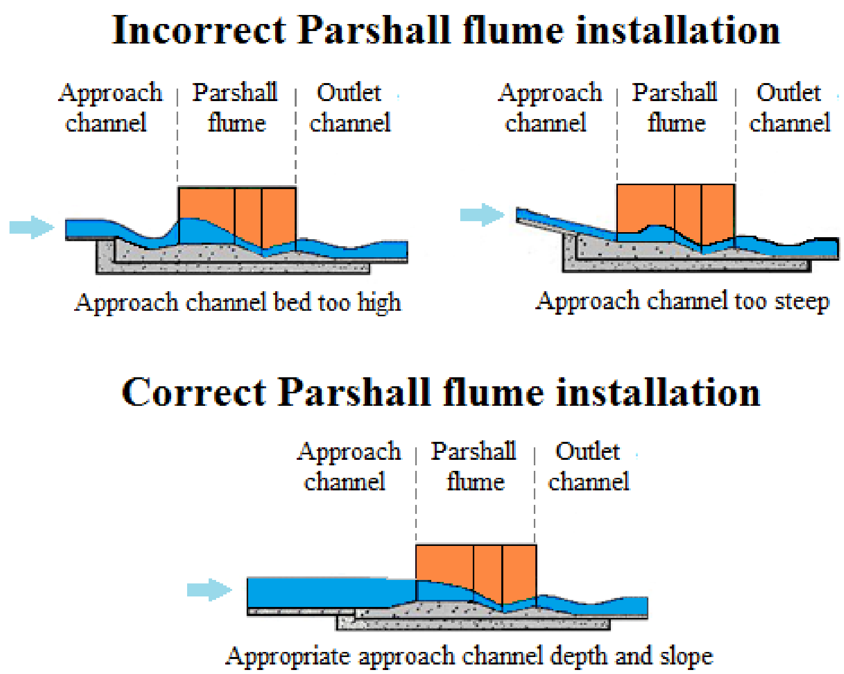


Figure 17: Parshall flume approach channel installation.

Measuring point

The rate of flow through a flume is determined by measuring the water level (also termed "water level" herein) in the convergent (h_1) and control (h_2) sections. The need to measure one or both depends on the discharge conditions.

In a free-flow regime, only h_1 (a point located at 2/3 of the length of Section A, the distance being measured along the wall from the beginning of the control section) needs to be measured. This measurement can be taken with a vertical gauge placed over the interior face of the wall, at the water level measuring point. The zero of the gauge must correspond to the horizontal invert of the convergent section of the channel. However, in cases where greater accuracy is needed or whenever continuous recording or depth sensors are used, the installation of a stilling well must be envisaged.

When a channel is in non-modular (submerged) flow, two piezometric water level measurements are required (h_1 and h_2). The measuring point of h_2 must be located in the control section at a depth that corresponds to the convergent section invert. In non-modular (submerged) flow, it is not advisable to use a vertical gauge to measure h_2, but rather a stilling well, due to the fact that discharge at the constriction is turbulent and can cause significant water surface fluctuation.

A stilling well is a solution that can be considered to facilitate reading water level in turbulent conditions (see Section 3.2.3 for more information on installing stilling wells).

Free-flow

Discharge in a Parshall flume is considered as free-flow when it is not influenced by variations in the upstream water level. Under good conditions, the surface of the water in each section of the channel appears smooth and without hydraulic jumps or afflux.

Parshall flumes work satisfactorily at high submergence ratios. However, whenever the level of water upstream (h_2) (control section) is greater than the threshold in the convergent section, upstream (h_1) and (h_2) downstream readings must be taken. The flow measurement will not be distorted as long as the h_2/h_1 ratio expressed as a percentage does not exceed the values shown in Table 4.

Table 4: Maximum submergence ratio (%) based on Parshall flume dimensions

Channel dimensions		Submergence ratio
m	in/ft	%
.025, .051 and .076	1, 2 and 3 in	50
.152 and .229	6 and 9 in	60
.305 to 2.438	1 to 8 ft	70
2.438 to 15.240	10 to 50 ft	80

Free-flow equation

In free-flow conditions, the streamflow can be read at a single measuring point (h_1). As such, the flow equation resulting from the stage-discharge relation is as follows[5]:

$$\boldsymbol{Q = K\, h^n} \qquad (12)$$

Where
- Q Flow (value as a function of the selected unit of measurement)
- h Water level (m) (h_1)
- K Constant (a function of the constriction dimensions and the selected unit of measurement)
- n Constant of the exponent (value is a function of the dimensions of the constriction)

Table 5 shows the flow equations for free-flow Parshall flumes in litres per second (l/s) and cubic metres per hour (m^3/h).

[5] *Teledyne ISCO Open Channel Flow Measurement Handbook* (2017)

Table 5: Parshall flume free-flow equations[6]

Channel width (W)		Flow equation	
m	in/ft	l/s	m^3/h
.0254	1"	$Q = 60.36\ h^{1.550}$	$Q = 217.3\ h^{1.550}$
.0508	2"	$Q = 120.7\ h^{1.550}$	$Q = 434.6\ h^{1.550}$
.0762	3"	$Q = 176.5\ h^{1.547}$	$Q = 635.5\ h^{1.547}$
.152	6"	$Q = 381.2\ h^{1.580}$	$Q = 1{,}372\ h^{1.580}$
.229	9"	$Q = 535.4\ h^{1.530}$	$Q = 1{,}927\ h^{1.530}$
.305	12"	$Q = 690.9\ h^{1.522}$	$Q = 2{,}487\ h^{1.522}$
.457	18"	$Q = 1{,}056\ h^{1.538}$	$Q = 3{,}803\ h^{1.538}$
.610	2'	$Q = 1{,}429\ h^{1.550}$	$Q = 5{,}143\ h^{1.550}$
.914	3'	$Q = 2{,}184\ h^{1.566}$	$Q = 7{,}863\ h^{1.566}$
1.22	4'	$Q = 2{,}954\ h^{1.578}$	$Q = 10{,}630\ h^{1.578}$
1.52	5'	$Q = 3{,}732\ h^{1.587}$	$Q = 13{,}440\ h^{1.587}$
1.83	6'	$Q = 4{,}521\ h^{1.595}$	$Q = 16{,}280\ h^{1.595}$
2.44	8'	$Q = 6{,}115\ h^{1.607}$	$Q = 22{,}010\ h^{1.607}$
3.05 to 15.2	10' to 50'	$Q = (2{,}293\ W + 473.8)\ h^{1.6}$	$Q = (8{,}255\ W + 1{,}706)\ h^{1,6}$

Non-modular (submerged) flow

One might expect to see non-modular (submerged) flow as soon as water reaches the convergent section threshold, but this is not the case. As described in the "Free-flow" section, Parshall flumes work satisfactorily in situations of high submergence. However, whenever flow is sufficient for upstream discharge to affect flow, the threshold is deemed "submerged." Visually speaking, when a hydraulic jump is observed at the surface of the discharge at the constriction, this indicates that measurement of the submergence ratio is required. This submergence instance is shown in pale blue in **Erreur ! Source du renvoi introuvable.**.

Discharge is considered submerged whenever the h_2/h_1 submergence ratio exceeds the values shown in Table 4. Non-modular (submerged) flow does affect the accuracy of flow readings compared to free-flow situations. For this reason, the conversion tables should not be used to assess flow in such cases, because calculating the stage-discharge relation would no longer be sufficient. Accurate equations have been developed to calculate flow in non-modular (submerged) flow. For this type of situation, flow may be determined on the basis of the selected equation. Any results based on such equations should be corroborated by another way of

[6] *h* corresponds to the h_1 measuring point, expressed in metres
Source: *Teledyne ISCO Open Channel Flow Measurement Handbook* (2017)

measuring flow, such as the volumetric method. Given the application issues related to these equations, they are not shown in a detailed manner in this publication. Readers should refer to the appropriate ISO standards for more information.

Since the calculated flow is a function of the simultaneous measurement of two water level variables (h_1 and h_2), continuous direct measurement would involve the installation of two measuring devices and the transmission of these values to a computer system for incorporation into the flow calculation equation.

Parshall flumes stop behaving as flow measurement structures and become inoperable whenever the h_2/h_1 submergence ratio reaches or exceeds 95%, because the difference between h_1 and h_2 is then so small that even minor errors of measurement can lead to great uncertainty of results. For all of these reasons, it is advised to choose the flume dimensions wisely and avoid using Parshall flumes in non-modular (submerged) flow conditions.

Parshall flume modifications

The drift section can be modified without affecting the obtained values. One available version of this flume does not include a drift section and can also be used as a portable device for widths of up to 76 mm and as a temporary measuring device, but only in free-flow conditions.

Since the use of modified flumes is strongly discouraged, this subject is not addressed in detail in this publication.

Parshall flumes…

- Comprised of three sections: convergent, control and drift.
- Dimensions are between .0254 m (1 in) and 15.2 m (50 ft) and correspond to the width of the control section.
- Should be sized to operate most of the time at 20-80% of capacity.
- Require regular inspection based on the sample field checklist in Appendix 3.

3.2.5.2 Palmer-Bowlus flumes

The Palmer-Bowlus flume was designed in the 1930s following research by engineers Harold Palmer and Fred Bowlus, who wanted to adapt Venturi channels for use in sanitary sewage systems. The goal was to build an inexpensive flume that was simple to use and could be easily adapted to common round or U-shaped channels.

Description

Palmer-Bowlus flumes include a control section (also called “throat” or “choke”) that is attached to two transitional sections, one upstream and the other, downstream. Compared to Parshall flumes, these two sections are identical in shape and are placed at identical heights.

The shape of the flume makes it possible to narrow the channel and accelerate the discharge in the control section (Venturi effect). The control section of the flume is uniform in width, with length equal to the diameter.

Independent of flume size, Palmer-Bowlus dimensions are only related to the diameter (D) of the channel. Once the diameter of the flume is defined, the other dimensions fall into place in proportion.

Various narrowing shapes have been designed, but most common is the trapezoidal, due to its greater accuracy in both low flow and for maximum peaks. This publication only refers to the trapezoidal type, shown in Figure 18.

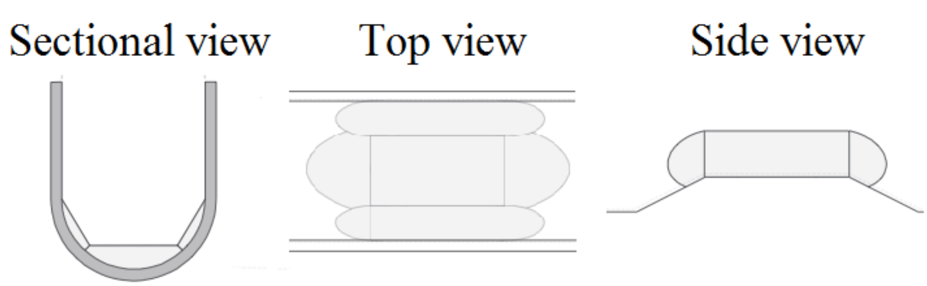


Figure 18: A trapezoidal Palmer-Bowlus flume.

Palmer-Bowlus flumes are usually prefabricated with plastic-reinforced fibreglass, PVC or stainless steel, and come in dimensions that vary from .102 m (4 in) to 1.83 m (72 in). Larger flumes can be special-ordered, up to 2.44 m (96 in) in width.

Contrary to Parshall flumes, Palmer-Bowlus flumes have greater design flexibility, with different manufacturers offering a wide variety of dimensions and configurations.

Different configurations have been designed to meet special requirements. For example, the approach channel may be incorporated into the prefabricated structure to remedy a poorly defined channel that does not provide good approach conditions. This publication only refers to installations where the approach sections are not incorporated into the fibreglass structure.

This type of flume is usually cast in concrete for channels whose dimensions are similar and that display good approach conditions.

Applications

Palmer-Bowlus flumes are designed to measure flow in sewage systems and can be easily installed in existing pipes. As such, they may be a useful option whenever the goal is to measure localized network flow to obtain results that are global to the system. Moreover, flumes with a width less than .381 m may be inserted into standard sewers, with no need to adapt the existing configuration. Palmer-Bowlus flumes are often used as temporary devices for collecting flow data that will be used to select the width of a permanently installed primary structure.

The Palmer-Bowlus interval of measurement between minimum and maximum flow is quite small compared to other types of flumes. For example, for a given interval of flow measurement, the Parshall flume is more efficient at reading changes in the water level than the Palmer-Bowlus, which means that more sensitive measuring equipment is required for the latter.

Palmer-Bowlus geometry and functionality make it an attractive choice when measuring flow containing solids.

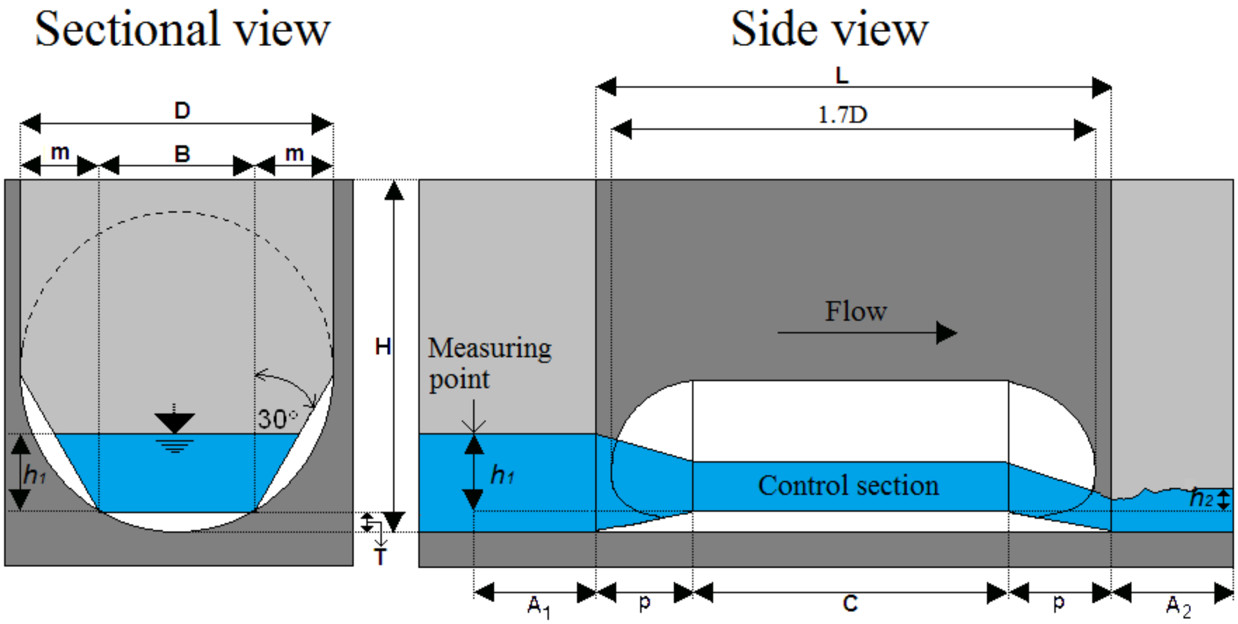
Functional principle

Elevation of the floor of the control section and vertical contraction of the lateral walls of the flume reduce the discharge area and raise the water level upstream of the control section and lower it in the control section (throat) in Palmer-Bowlus flumes. This is accompanied by an increase in the discharge. Flow is determined by simply measuring the water level upstream of the flume, since it is known that it varies in proportion to flow.

It is recommended to use this flume solely in free-flow conditions. The notions of free and submerged discharge will be discussed later in this publication.

Standard dimensions

The dimensions of Palmer-Bowlus flumes depend of the diameter (D) of the channel in which they are installed. However, to improve accuracy, the flume width should be determined by the flow to be measured rather than the diameter of the existing pipe. Selecting an oversized flume may reduce the accuracy of measurement in low flow conditions, while an undersized flume could lead to non-modular (submerged) flow. The width of the flume should enable maximum discharge to correspond to approximately 70% of maximum capacity.



Key	
A1	Length enabling h_1 measuring point to be located (D/2)
A2	Length enabling h_2 measuring point to be located (D/2)
B	Width at the base of the control section of the flume (D/2)
C	Length of the control section of the flume (throat) (corresponds to the width of the pipe)
D	Width of the flume (corresponds to the diameter of the pipe)
H	Height of the flume (D + approximately .0508 m or 2 in)
L	Total length of the base of the flume (2D + approximately .0508 m or 2 in)
m	Distance between the base and the sides (D/4)
p	Length of the entry and exit sections (D/2)
T	Difference in water level between the base of the control section of the flume and the invert (D/6) (corresponds to the h_1 and h_2 zero)

Figure 19: Free-flow Palmer-Bowlus flumes (Plasti-Fab).

As previously mentioned, the dimension and configuration of this type of flume are not uniform, so greater flexibility can be exercised in the construction process. It is important to make use of the flume manufacturer's flow tables for accuracy purposes. The main difference among flume manufacturers is the way they treat vertical contraction of the lateral walls at the throat.

Commonly available Palmer-Bowlus flumes are manufactured to Plasti-Fab norms. Figure 19 and Table 6 show flume shapes and dimensions.

Table 6: Standard Palmer-Bowlus flume dimensions (m) (Plasti-Fab)

C and D		B	H	T	A_1 and A_2	p	L	m
m	in							
.102	4"	.051	.153	.017	.051	.051	.255	.026
.152	6"	.076	.203	.025	.076	.076	.355	.038
.203	8"	.102	.254	.034	.102	.102	.457	.051
.254	10"	.127	.305	.042	.127	.127	.559	.064
.305	12"	.153	.356	.051	.153	.153	.661	.076
.381	15"	.191	.432	.064	.191	.191	.813	.095
.457	18"	.229	.508	.076	.229	.229	.965	.114
.533	21"	.267	.584	.089	.267	.267	1.117	.133
.610	24"	.305	.661	.102	.305	.305	1.271	.153
.686	27"	.343	.737	.114	.343	.343	1.423	.172
.762	30"	.381	.813	.127	.381	.381	1.575	.191
.914	36"	.457	.965	.152	.457	.457	1.879	.229
1.067	42"	.534	1.118	.178	.534	.534	2.185	.267
1.219	48"	.610	1.270	.203	.610	.610	2.489	.305
1.524	60"	.762	1.575	.254	.762	.762	3.099	.381

Measurement interval

Depending on their dimensions, Palmer-Bowlus flumes can operate over a broad interval of measurement. Table 7 shows the levels and minimum and maximum recommended flow for Palmer-Bowlus flumes in free-flow conditions. Values in parentheses represent maximum recommended flow. Above these values, uncertainty increases.

Table 7: Palmer-Bowlus flume height and flow intervals[7]

Flume width (D)		Measurement intervals [level]* MIN. – MAX.**		Measurement intervals [flow]* MIN. – MAX.**	
in	m	ft	m	CFS[8]	m^3/h
4	.102	.04 – .31 (.25)	.012 – .095 (.076)	.004 – .180 (.121)	.41 – 18 (12)
6	.152	.04 – .47 (.35)	.012 – .143 (.107)	.006 – .512 (.295)	.61 – 52 (30)
8	.203	.04 – .63 (.50)	.012 – .192 (.152)	.008 – 1.058 (.690)	.82 – 108 (70)
10	.254	.04 – .78 (.60)	.012 – .238 (.183)	.009 – 1.836 (1.119)	.92 – 187 (114)
12	.305	.05 – .94 (.70)	.015 – .287 (.213)	.016 – 2.092 (1.676)	1.63 – 213 (171)
15	.381	.06 – 1.17 (.90)	.018 – .357 (.274)	.027 – 5.292 (3.086)	2.75 – 539 (315)
18	.457	.08 – 1.31 (1.05)	.024 – .399 (.320)	.051 – 6.968 (4.614)	5.20 – 710 (470)
21	.533	.09 – 1.53 (1.25)	.027 – .466 (.381)	.067 – 10.14 (7.043)	6.83 – 1,034 (718)
24	.610	.10 – 1.76 (1.40)	.031 – .536 (.427)	.096 – 14.33 (9.465)	9.79 – 1,461 (965)
27	.686	.11 – 1.97 (1.60)	.034 – .601 (.488)	.126 – 19.07 (13.09)	12.84 – 1,944 (1,334)
30	.762	.13 – 2.19 (1.75)	.040 – .668 (.533)	.131 – 24.76 (16.52)	13.35 – 2,524 (1,684)
36	.914	.15 – 2.63 (2.01)	.046 – .802 (.613)	.246 – 39.23 (17.28)	25.08 – 3,999 (1,762)
42	1.067	.18 – 3.07 (2.45)	.055 – .936 (.747)	.389 – 57.65 (38.34)	39.65 – 5,877 (3,908)
48	1.219	.20 – 3.39 (2.80)	.061 – 1.033 (.853)	.532 – 75.74 (53.54)	54.23 – 7,721 (5,458)
54	1.372	.23 – 4.20 (3.14)	.070 – 1.280 (.957)	.768 – 122.3 (70.36)	78.29 – 12,467 (7,173)
60	1.524	.25 – 4.24 (3.50)	.076 – 1.292 (1.067)	.783 – 132.4 (93.51)	79.82 – 13,497 (9,532)
66	1.676	.25 – 4.60 (3.85)	.076 – 1.402 (1.174)	1.016 – 162.6 (116.5)	103.57 – 16,576 (11,876)
72	1.829	.30 – 5.08 (4.20)	.091 – 1.548 (1.280)	1.415 – 208.5 (147.6)	144.25 – 21,255 (15,046)

*Values are rounded to simplify presentation in the table.
**Values in parentheses correspond to maximum recommended level and flow. Above these values, uncertainty increases.

Installation conditions

During installation, ensuring the integrity of the original physical characteristics of the flume and planning inspection and maintenance access for all of its sections, is vital.

Palmer-Bowlus flumes must be installed level, both lengthwise and transversely. This type of flume is generally installed directly into the pipe, preferably in its centre, and firmly attached to the invert to avoid warping. The control section of the flume is where protection from warping is most important. In temporary installations, flumes will often be incorporated into

[7]Plasti-Fab, *Palmer-Bowlus flow equations* (www.plasti-fab.com).
[8]Cubic ft/sec.

sandbag dams. The Palmer-Bowlus flume is relatively easy to install as it requires no upstream/downstream invert differential.

Discharge must be calm and uniformly distributed at the measuring point, with no waves at the surface. Palmer-Bowlus flume functionality is optimal in laminar discharge conditions. At zero-flow, the water level is the same as at the bottom of the control section invert. Water level can then be measured from this level (D/6) and not from the bottom of the flume.

In order to optimize discharge conditions and measurement accuracy, the following characteristics upstream of the flume are considered during installation:

- Whenever the flume width is less than the diameter of the channel, it must be equipped with a transitional section whose length is equal to at least four times the diameter of the channel in which it is installed. Ideally, the transitional section will be connected to the flume by a reduction section whose angle does not exceed 30°.
- In cases where the slope of the channel is too steep, the flume can be slightly raised to reduce its effects. This will increase water level upstream of the flume and cut velocity, as long as the diameter of the inflow pipe is sufficient for the water level upstream of the flume to not exceed recommendations, i.e. 90% of the height of the channel (h_T).
- Installation must make it possible to raise the water level upstream of the flume over an upstream distance of at least ten times the diameter of the pipe.
- Turbulence, obstructions, elbows or junctions must be avoided in the approach channel over a length equivalent to at least 25 times the diameter of the inflow pipe. Discharge in the approach channel should show little turbulence and be well-distributed over its entire width.
- The slope of the approach channel must be below 2% for small flumes and below 1% for flumes whose width is at least 762 mm (30 in). An overly steep slope in the upstream channel will decrease accuracy due to turbulence at the measuring point.
- The slope of the approach channel must ensure that the discharge is not turbulent and that its velocity upstream is less than in the control section. In the opposite case, discharge at the measuring point will be overly turbulent and preclude the accurate measurement of the water level.

Installation of this flume must also be completed with the following downstream features:

- A steep slope is not required, even though it could help maintain critical discharge throughout the control section, thus encouraging free-flow conditions at the exit point of the flume.
- The slope of the channel should be greater than or equal to the slope of the approach channel.
- Any sharp curve or equipment placed at the outlet of the flume must be at a distance of 5 to 20 times the width of the flume; otherwise it could restrict discharge and induce non-modular (submerged) flow.

Measurement point

The ideal location for measuring the water level is upstream of the inlet to the flume and at a distance equal to half the diameter of the pipe (D/2). However, the location can vary slightly as long as the measurement point is located before the upstream transitional section and in a section where the water level remains relatively constant over a distance equivalent to the width of the channel.

Permanently installing a gauge over the walls at the measuring point is recommended to facilitate instantaneous measurement of water level and to check the accuracy of the flowmeter, whenever required.

Readings are taken at the centre of the flume in relation to the transverse axis. Water level is measured from the level corresponding to the virtual extension of the invert in the control section of the flume and not from the channel bed itself. At zero-flow, the water level upstream of the flume is the same as at the control section invert. The water level at the measurement point in zero-flow conditions is equal to one-sixth of the diameter of the pipe (D/6). Adjustments to the flow measurement device must, therefore, take this particularity into account. In practical terms, it is common to measure water level at the invert then reduce the theoretical or measured value of D/6.

Discharge at the measurement point must be parallel to the walls and free of surface turbulence. Otherwise, the accuracy of the measured level could be negatively affected.

A stilling well is an option that should also be considered, as it can reduce the effect of discharge turbulence on water level measurement.

Free-flow

Discharge upstream of the flume must be calm, free of waves, and have a velocity that is less than the observable velocity in the control section. Moreover, even a small increase in the water level upstream of the control section proves that critical discharge has been reached in the primary structure.

In Palmer-Bowlus flumes, water must flow quietly, without showing any marked turbulence, and the surface profile must decrease all along the channel. If major turbulence is observed, adjustments to the setup will be required to ease the discharge.

Upstream, torrential discharge should be favoured. To maintain free-flow, a slight inclination at the exit of the structure is strongly recommended.

Free-flow equation

Flow equations will slightly vary in accordance with different sources. It is therefore recommended to refer to the flume manufacturer’s conversion tables and formulas.

In free-flow conditions, a single measuring point (h_1) is sufficient, based on the principle expressed in the following equation[9]:

$$\boldsymbol{Q = K\, h_1^n} \qquad (13)$$

Where	Q	Flow (m^3/s or l/s)
	n	Exponent in free-flow conditions (1.9)
	h_1	Water level at the measuring point (m)
	K	Coefficient in free-flow conditions (varies by flume width)

This equation is based on flume size and discharge level. As such, use of the manufacturer's tables is required.

For example, Table 8 shows Plasti-Fab flow equations: Two equations are provided for most sizes of Palmer-Bowlus flumes. The short-form equation gives a flow of acceptable accuracy, close to the table's theoretical values. However, given uncertainty at the higher and lower ends of the curves, the long-form equation should always be preferred, since it provides good accuracy at all flow levels.

[9] *Teledyne ISCO Open Channel Flow Measurement Handbook* (2017)

Table 8: Free-flow Plasti-Fab equations

Width		Short- and long-form equations Q = CFS x 101.940648 for m^3/h
in	m	
4	.102	$Q = 1.73 \times (h + .00588)^{1.9573}$
		$Q = -.000491374 + .052219h + 1.815283h^2 - 3.352818h^3 + 7.682511h^4 + 79.0388h^5 + 113.3232h^6 - 2711.151h^7 + 5131.661h^8$
6	.152	$Q = 2.071 \times (h + .005421)^{1.9025}$
		$Q = -.000252012 + .051932h + 2.872653h^2 - 5.988129h^3 + 5.207215h^4 + 69.2287h^5 - 89.3457h^6 - 348.922h^7 + 572.806h^8$
8	.203	$Q = 2.537 \times (h + .01456)^{1.9724}$
		$Q = -.002211174 + .144056h + 2.644594h^2 - 2.468403h^3 + 1.537941h^4 + 18.920840h^5 + 4.9486h^6 - 123.611h^7 + 119.943h^8$
10	.254	$Q = 2.843 \times (h + .01610)^{1.9530}$
		$Q = -.002568036 + .157007h + 3.717063h^2 - 7.279155h^3 + 12.957680h^4 + 10.044620h^5 - 30.7575h^6 - 3.989h^7 + 20.724h^8$
12	.305	$Q = 3.142 \times (h + .017)^{1.9362}$
		$Q = +.001285249 + .160814h + 4.074878h^2 - 4.868885h^3 + 5.194802h^4 + 5.391436h^5 - 2.3493h^6 - 15.932h^7 + 11.682h^8$
15	.381	$Q = 3.574 \times (h + .01682)^{1.9062}$
		$Q = -.005446241 + .321892h + 3.703519h^2 - 1.430430h^3 + 2.165814h^4 - 10.406070h^5 + 32.1713h^6 - 36.007h^7 + 13.225h^8$
18	.457	$Q = 3.988 \times (h + .01875)^{1.8977}$
		$Q = +.010862620 + .005188h + 6.702144h^2 - 7.621502h^3 + 5.159058h^4 + 3.082969h^5 - 1.4116h^6 - 3.676h^7 + 1.957h^8$
21	.533	$Q = 4.223 \times (h + .039)^{1.9619}$
		$Q = -.027504770 + .689056h + 4.144363h^2 - 1.761823h^3 + 1.672703h^4 - .342789h^5 + 1.6492h^6 – 2.110h^7 + .656h^8$
24	.610	$Q = 4.574 \times (h + .0408)^{1.9497}$
		$Q = -.002225281 + .420895h + 5.930978h^2 - 3.470244h^3 + .746696h^4 + 3.182714h^5 - 2.1110h^6 + .058h^7 + .141h^8$
27	.686	$Q = 4.97 \times (h + .038)^{1.9269}$
		$Q = -.009705140 + .354086h + 6.791781h^2 - 3.986792h^3 + 1.071059h^4 + 2.255546h^5 - 1.3530h^6 - .005h^7 + .084h^8$
30	.762	$Q = 5.022 \times (h + .0625)^{1.9663}$
		$Q = -.200116800 + 2.238534h + 2.207354h^2 + 1.185735h^3 + .374370h^4 - .386049h^5 + .2800h^6 - .168h^7 + .033h^8$
36	.914	$Q = 5.462 \times (h + .08)^{1.991}$
		$Q = -.084205270 + 1.359937h + 5.845147h^2 - 1.647873h^3 + .509795h^4 + .413952h^5 - .0570h^6 - .105h^7 + .0261h^8$
42	1.067	$Q = 6.12 \times (h + .078)^{1.9628}$
		$Q = -.083333500 + 1.431028h + 7.047561h^2 - 2.475667h^3 + 1.037684h^4 + .102303h^5 - .0446h^6 - .035h^7 + .008h^8$
48	1.219	$Q = 6.626 \times (h + .085)^{1.9586}$
		$Q = -.053395340 + 1.441452h + 7.813287h^2 - 2.012471h^3 + .265820h^4 + .384576h^5 - .0875h^6 - .020h^7 + .005h^8$
54	1.372	$Q = 7.210 \times (h + .08625)^{1.9450}$
60	1.524	$Q = 7.183 \times (h + .126)^{1.9833}$
		$Q = -.614242800 + 4.007510h + 6.591763h^2 - 1.186873h^3 + .318855h^4 + .215911h^5 - .0987h^6 + .012h^7 - .000h^8$
66	1.676	$Q = 8.536 \times (h + .07820)^{1.9100}$
72	1.829	$Q = 7.839 \times (h + .155)^{1.9871}$
		$Q = -.358481400 + 3.418848h + 8.675141h^2 - 1.269805h^3 + .156454h^4 + .085580h^5 - .0048h^6 - .005h^7 + .001h^8$

Non-modular (submerged) flow

Non-modular (submerged) flow arises whenever resistance to discharge at the flume outlet reduces velocity and increases the water level in the control section and hence at the measuring point. Non-modular (submerged) flow is always the result of a problem upstream of the flume, such as when the channel is larger or smaller than the flume or when it is obstructed.

This type of installation must only be used in free-flow conditions. The measurement of flow remains acceptable as long as the submergence ratio (h_2/h_1) is less than 85%. If the ratio exceeds 85%, the flume ceases to function as a flow measuring structure.

Every precaution must be taken during the installation process to ensure that this situation is avoided. As such, it is recommended to choose a flume whose dimensions preclude functioning in non-modular (submerged) flow.

Modifications

Whenever the velocity of discharge is slightly too high it can be reduced by increasing the height of the flume's threshold. This is accomplished by raising the entire flume in relation to the invert of the channel.

Palmer-Bowlus flumes…

Well-adapted to flow containing suspended matter. Low load loss.

At the same discharge interval, generate smaller changes in water level than Parshall flumes.

Comprised of a control section connected to upstream and downstream sections; the length of the control section is equal to the diameter of the pipe at a width (D) of .102 m (4 in) to 2.44 m (96 in).

Water level measurements are taken from the invert of the control section, not the channel.

Dimensions should ensure that maximum flow corresponds to around 70% of maximum flume capacity.

Require regular inspection based on the example shown in the field checklist in Appendix 3.

3.2.5.3 H flumes

H flumes were designed in the mid-1930s by the U.S. Department of Agriculture Soil Conservation Service.

Description

H flumes combine the physical and mechanical characteristics of weirs and flumes. In shape, they resemble a triangular weir, while mechanically they offer the advantage of being capable of removing solids, just like classic flumes.

H flumes are available in aluminum, fibreglass and galvanized and stainless steel. The choice of material should be related to the desired characteristics, including cost. Aluminum H flumes are light and easy to transport, but are more expensive, while those made of stainless steel resist corrosion and abrasion.

There are three types of H flumes : HS, H and HL. The type and size are a function of the water level in section D of the flume. Short-width H flumes are called HS, standard-sized ones are simply known as H and larger ones are called HL. The HS model has a narrower outlet that increases the accuracy of measurement in low-flow situations. The HL model has a slightly bigger opening and is more efficient when flow is anticipated to exceed the capacity of standard H flumes.

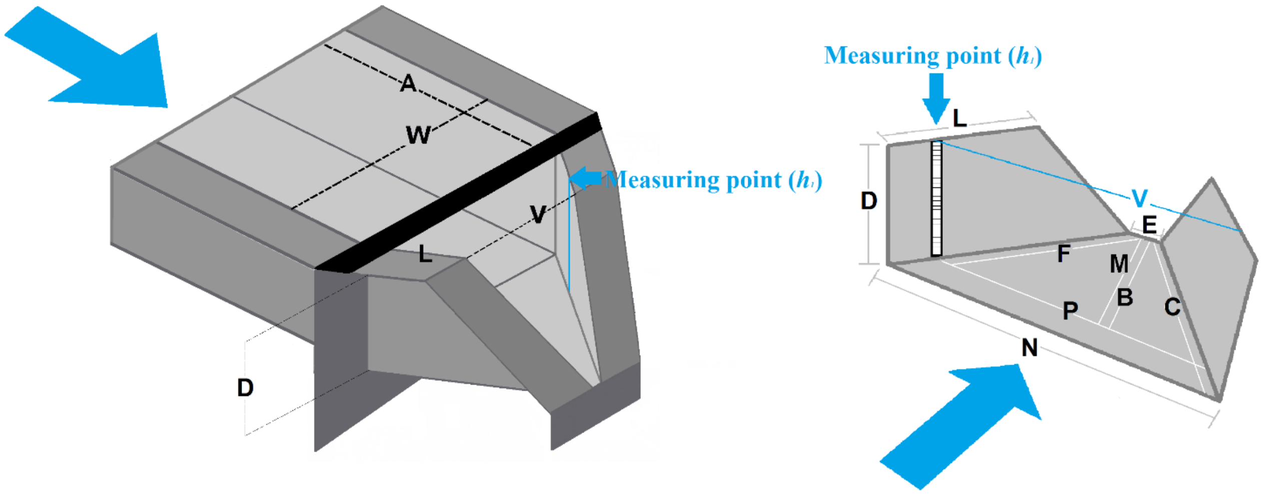
The sections of an H flume are shown and described in Figure 20. All three types have the same sections. The letters identifying the sections are used to facilitate comprehension and are not based on any standard nomenclature.

Les Figure 22, Figure 23 et Figure 24 show sections W and N, as well as their widths (1.05D for an HS flume, 1.9D for an H flume and 3.2D for an HL flume). The width of the approach channel is generally the same as the total width of the flume, particularly when the approach channel is part and parcel of the prefabricated structure.

H flumes do not have drift sections, just approach channels and control sections (Figure 21). The approach channel may be part and parcel of the structure when it and the control section are moulded in fibreglass, or be built on-site. This is the case for a concrete rectangular approach channel attached to the control section.

H flumes have a rectangular cross section and a V-shaped throat similar to the indentation in triangular weirs.

The sidewalls have a trapezoidal mouth, narrow at the base and wide at the apex. H flumes and their approach channels have flat floors, but a slight inclination can be envisaged to facilitate the evacuation of solids whenever flow is weak.



Key	
A	Length of the approach channel
B	Length of the base of the flume in the flume axis
C	Length of the base of the flume with respect to the wall
D	Flume height (corresponds to the flume dimensions)
E	Width of the base of the control section at the flume outlet
F	Location of the measuring point with respect to the wall
L	Length of the walls at their highest point
M	Location of the measuring point in the flume axis
N	Total width of the flume
P	Width of the base at the measuring point
V	Width of the control section at its maximum height
W	Width of the approach channel

Figure 20: Illustration of various sections of an H flume.

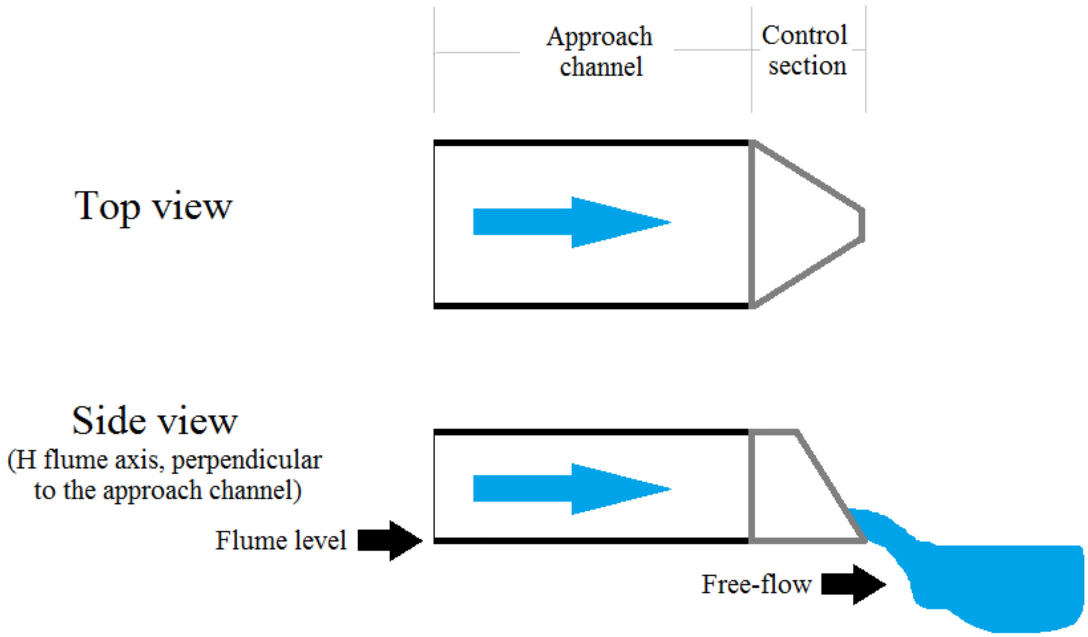


Figure 21: Top and side views of the approach channel, the contro section and the outlet of an H flume.

Applications

H flumes enable the accurate measurement of effluent flow over a wide range of intervals, more so than any other type of flume. They offer considerable sensitivity in low-flow conditions and higher measurement capacity in strong-flow situations.

They are frequently used in wastewater processing and to measure industrial discharge, retention basin overflow, and sanitary effluent or surface runoff.

The flat floor of H flumes and width of the control section (E) base at the outlet enables the evacuation of sediment-laden effluent without risk of blockage. However, it is not generally recommended to use smaller HS and H flumes for effluent containing sanitary solids or large-sized debris that could become lodged in the narrowest part of the flume outlet.

H flumes are suitable for temporary measurement set-ups as long as the installation instructions are followed.

Functional principle

H flumes use the Venturi principle. Due to their lateral constraints, H flumes reduce the discharge area and raise the water level upstream of the control section. The flow can be determined by simply measuring water level since it is proportional.

While it is possible to use this type of flume in non-modular (submerged) flow, it is strongly recommended for use in free-flow conditions because in such cases, the flow can be determined by a single measuring point, while in non-modular (submerged) flow, measurement of the water level is also required upstream of the control section. The notions of free and submerged discharge are developed further on in the text.

Standard dimensions

No national or international standard dimensions exist for H flumes. However, in order for the manufacturer's stage-discharge tables to be properly used and for flow measurement to be accurate, the normative dimensions of each section must be rigorously met during assemblage and installation.

Figure 22, Figure 23 and Figure 24 show the dimensions of HS, H and HL flumes, as well as their physical characteristics and the dimensions of each of their sections. The meaning of the letters used to represent the various sections is listed in Figure 20.

The dimensions of each section are a function of the value of D, the height of the flume. For example, HS flumes are available in the following heights: .122 m, .183 m, .244 m and .305 m. We can thereby calculate the dimensions of each section of a .305-m HS flume by replacing D with .305 m. For example, if Section W is 1.05D it should measure .3203 m (W = 1.05D = 1.05 x .305 m = .3203 m), and so on and so forth for each section.

While five widths of HL flumes are available (.610-m, .762-m, .914-m, 1.07-m and 1.219-m), only the 1.219-m flume is recommended since lower flow is measured with more accuracy by standard H flumes.

H flume dimensions should enable the device to work most of the time in flow conditions of between 70 and 100% of capacity. Oversized flumes should be avoided because they are less accurate in low-flow conditions.

HS flume height (D)	
ft	m
.4	.122
.6	.183
.8	.244
1	.305

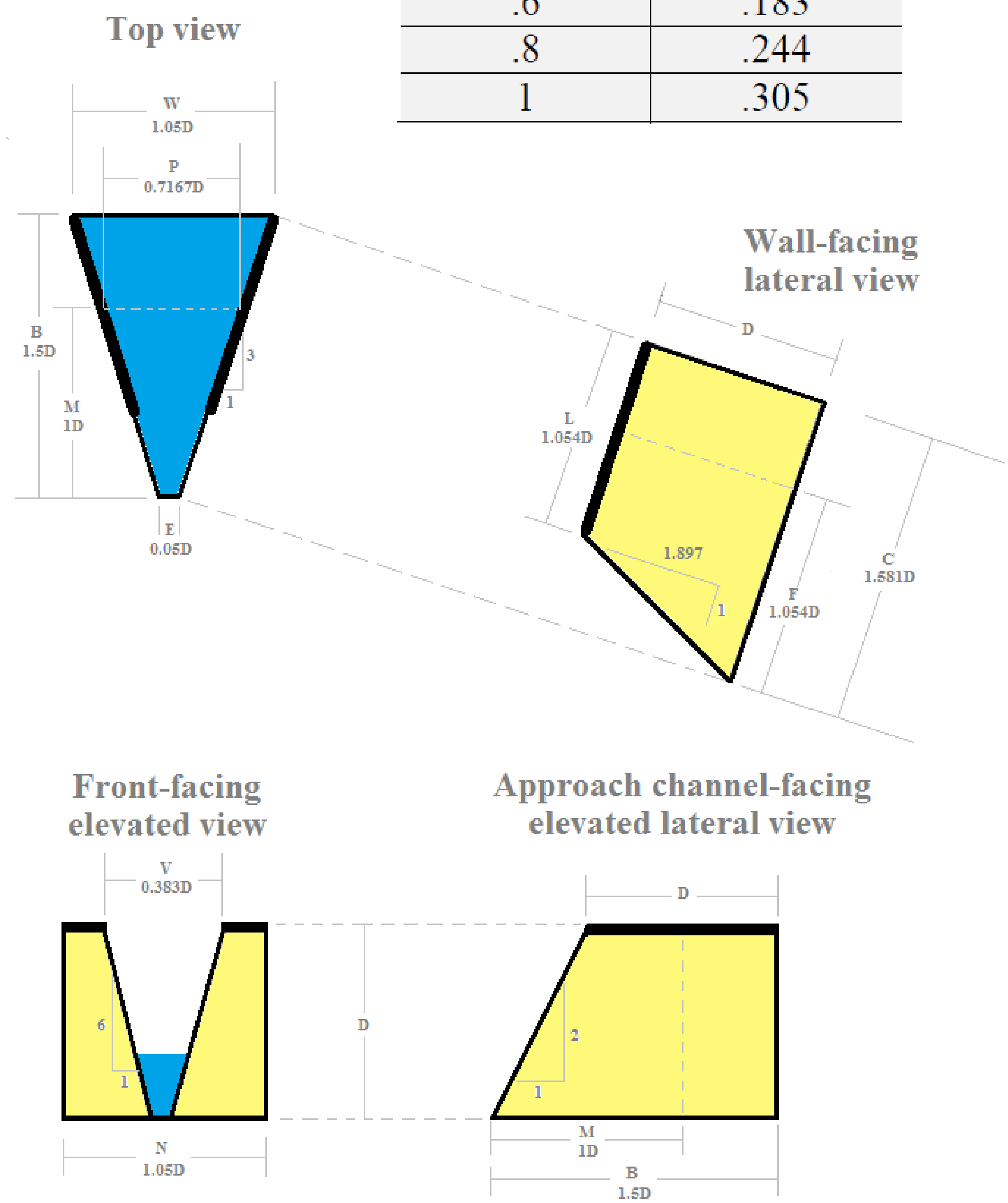


Figure 22: Physical dimensions of an HS flume.

H flume height (D)	
ft	m
.5	.152
.75	.229
1	.305
1.5	.457
2	.610
2.5	.762
3	.914
4.5	1.37

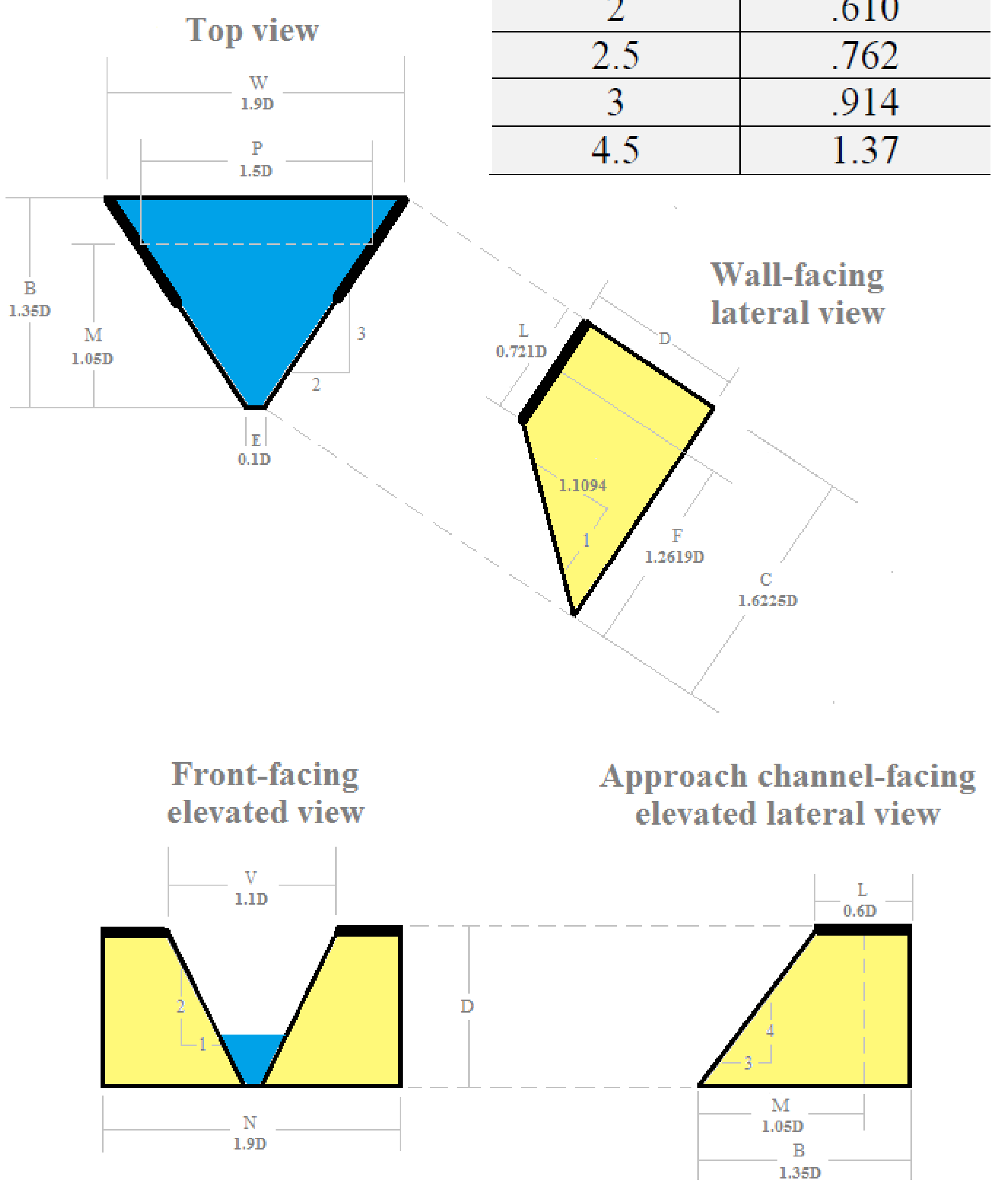


Figure 23: Physical dimensions of an H flume.

HL flume height (D)	
ft	m
2	.610
2.5	.762
3	.914
3.5	1.07
4	1.219

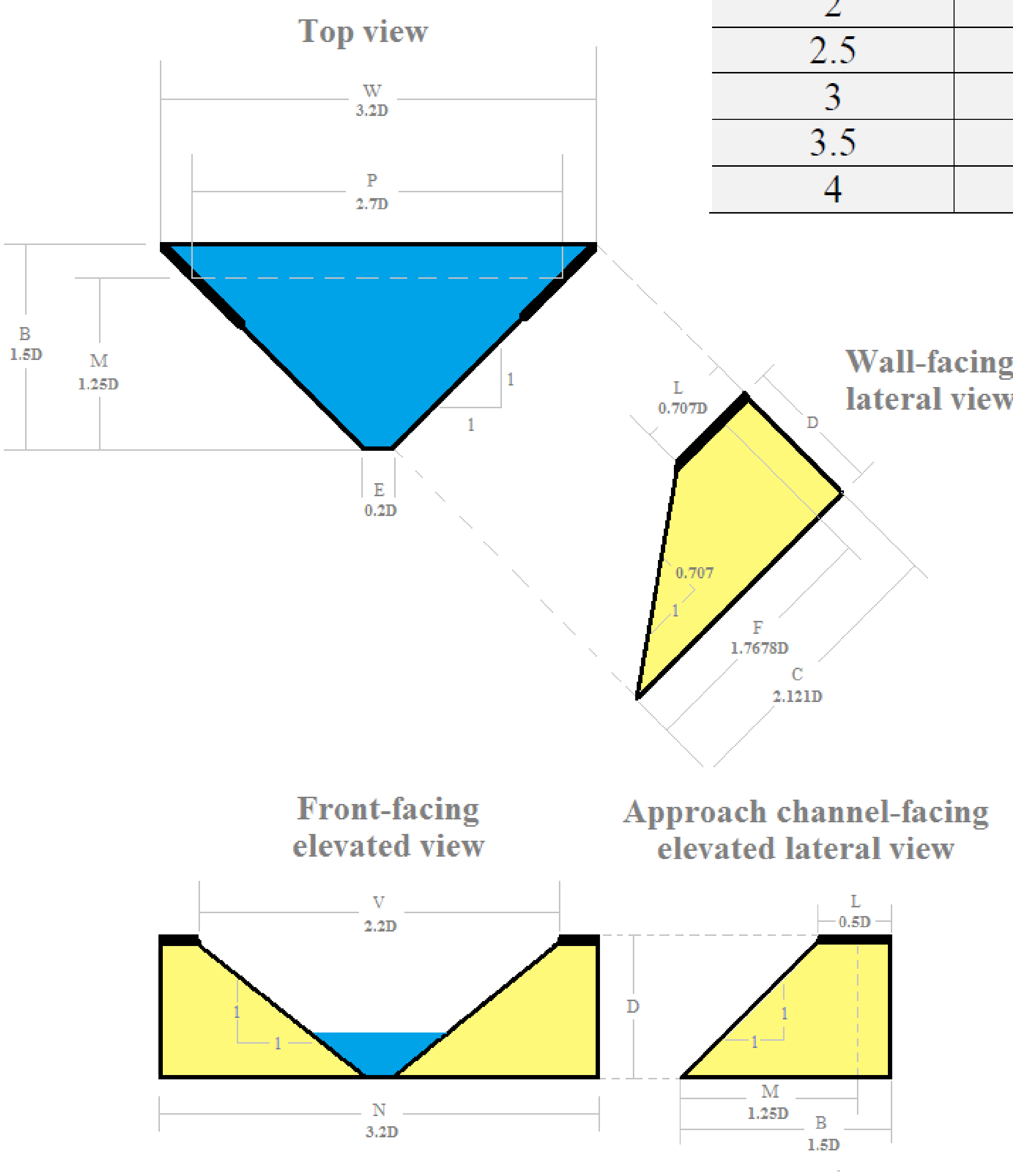


Figure 24: Physical dimensions of an HL flume.

Measurement interval

Table 9 shows the water level and minimum and maximum recommended flow for the HS, H and HL flumes in free-flow conditions.

The three types of H flumes can measure flow between .3216 m^3/day (.0134 m^3/h) for a .122-m (.4 ft) HS flume and 284,160 m^3/day (11,8403 m^3/h) for a 1.219-m (4 ft) HL flume.

Only data for a 1.219-m HL flume is shown since lower flow is measured more accurately by standard H flumes.

Table 9: Minimum and maximum recommended HS, H and HL flume width flow values in free-flow conditions[10]

Flume width (D)			Minimum water level	Minimum flow		Maximum water level	Maximum flow	
	m	ft	m	l/s	m^3/h	m	l/s	m^3/h
HS	.122	.4	.005	.0037	.0134	.120	2.322	8.359
	.183	.6	.005	.0053	.0190	.180	6.268	22.56
	.244	.8	.005	.0070	.0251	.240	12.84	46.22
	.305	1.0	.005	.0085	.0307	.300	22.44	80.77
H	.152	.5	.005	.0093	.0334	.150	9.465	34.07
	.229	.75	.005	.0139	.0502	.225	26.09	93.92
	.305	1.0	.005	.0157	.0567	.300	53.52	192.7
	.457	1.5	.005	.0250	.0901	.455	151.6	545.6
	.610	2.0	.005	.0325	.1170	.605	308.9	1,112
	.762	2.5	.005	.0418	.1505	.760	545.3	1,963
	.914	3.0	.005	.0483	.1737	.910	856.5	3,083
	1.370	4.5	.005	.0715	.2573	1.370	2,384	8,582
HL	1.219	4.0	.005	.1161	.4180	1.215	3,289	11,840

Table 10 shows flow in m^3/h for various water levels and HS, H and HL flume widths.

[10] *Teledyne ISCO Open Channel Flow Measurement Handbook* (2017).

Table 10: Flow table (m^3/h) for various water levels and HS, H and HL flume heights[11]

Flume height (D) (m)		Flow (m^3/h)												
		HS				H								HL
		.122	.183	.244	.305	.152	.229	.305	.457	.610	.762	.914	1,37	1,219
Water level (m)	.005	.0134	.0190	.0251	.0307	.0334	.0502	.0567	.0901	.1170	.1505	.1737	.2537	.4180
	.100	5.512	6.048	6.684	7.381	13.21	14.70	16.21	19.23	22.16	25.20	28.22	37.13	67.59
	.150		14.93	16.05	17.29	34.07	36.34	39.19	44.74	50.18	55.71	61.25	77.67	140.7
	.200			30.48	32.42		71.16	74.69	83.21	91.70	100.3	108.8	134.0	243.9
	.250				53.42			125.4	136.6	148.8	160.1	172.3	208.0	377.2
	.300				80.77			192.7	205.9	221.2	237.5	252.8	299.5	548.9
	.350								294.4	312.8	332.2	351.5	410.5	752.8
	.400								403.1	422.5	447.0	470.6	543.0	993.0
	.450								531.0	555.4	581.5	610.1	696.3	1,276
	.500									710.6	738.1	771.8	872.7	1,601
	.550									888.4	920.4	956.1	1,075	1,966
	.600									1,090	1,130	1,160	1,301	2,382
	.650										1,360	1,401	1,552	2,851
	.700										1,623	1,664	1,827	3,362
	.750										1,907	1,957	2,131	3,925
	.800											2,282	2,455	4,533
	.850											2,626	2,818	5,202
	.900											3,004	3,207	5,934
	.950												3,638	6,719
	1.000												4,098	7,544
	1.050												4,590	8,442
	1.100												5,120	9,418
	1.150												5,677	10,450
	1.200												6,274	11,520
	1.250												6,912	
	1.300												7,581	
	1.350												8,281	

Installation

The original physical characteristics of the flume must be ensured during the installation process. The complete structure should be installed on a solid support to avoid invert and wall warping under heavy-flow conditions.

H flumes must be installed in a straight section of the open surface channel, whose bed must be smooth and free of obstruction. Placing objects such as probes, tubes or pumps in the flume is not recommended.

[11]*Teledyne ISCO Open Channel Flow Measurement Handbook* (2017).

The flume must be installed centred in the discharge.

The approach channel is rectangular and usually has the same width (N) and height (D) as the inlet of an H flume. When installing flumes that are wider than the inlet, an approach channel with 45° lateral walls is called for to direct discharge into the flume. The connection between the H flume and the approach channel must be smooth and leak-proof.

It is important to place an inflow pipe directly into the approach channel or control section of the flume (Figure 25).

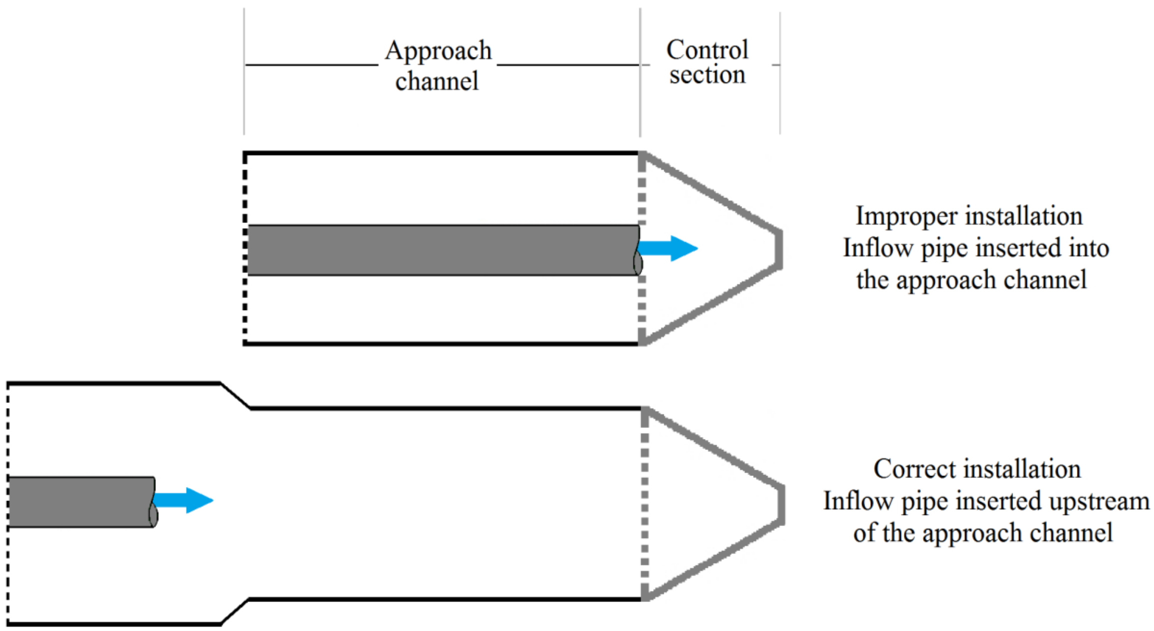


Figure 25: Examples of inflow pipe installation.

The approach channel must be rectilinear over a distance corresponding to at least three to five times the height of the flume (D), to minimize measurement errors related to poor discharge conditions.

The approach channel invert must be level. The slope of the approach section must be less than 1%. An excessive slope will result in a jump occurring in the control section of the flume (Figure 17) or in excessive velocity that will prevent water from rising in the control section, and, as such, should be avoided.

Discharge in the approach channel must be calm, subcritical and uniformly distributed.

If deflectors are used to correct or quieten flow, they must be placed upstream of the flume and at a distance of at least ten times the maximum water level. However, deflectors are not recommended for discharge that is heavily loaded with sanitary solids or debris.

There must be no sharp curves that could restrict discharge at the flume outlet, where water should fall and flow freely without backflow in order to not induce submerged conditions. The slope of the channel outlet must be sufficient (at least 2%) to enable the immediate evacuation of water.

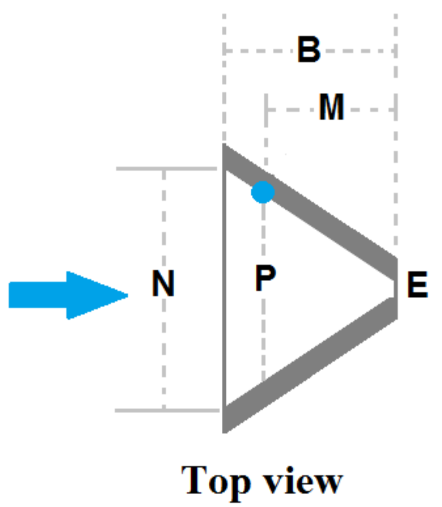
The location of the measuring points (F and M) must meet the manufacturer's specifications (Figure 22, Figure 23 and Figure 24) because H flumes are highly sensitive to minor measuring point location errors.

All sections of the flume must be easily accessible for regular inspection and maintenance. A gauge must be permanently installed over the walls of the control section at the point where water level is measured. Finally, a stilling well is recommended whenever water level measurement by a secondary device requires a high degree of accuracy.

Measuring point

The measuring point (h_1) is located in the control section of the flume (Figure 20 and Figure 26) and is based on its maximum permissible water level (D). The location of the measuring point varies with the type of H flume used, as shown in Figure 22 (HS), Figure 23 (H) and Figure 24 (HL). The location of the measuring point (h_1) can be determined by measuring the distance of section M from the flume outlet (E) or on the basis of the difference between sections B and M as measured from the entrance of the control section (N) (Figure 26).

The continuous measurement "secondary" device in H flumes should be installed either directly over the flume discharge or in a connected stilling well.



Type	Location of h_1
HS	.5D
H	.3D
HL	.25D

Figure 26: Measuring point location for each type of H flume.

Free-flow

Due to their narrow control section and absence of drift section, HS, H and HL flumes are easily influenced by the effects of submergence.

For an H flume to work as expected, discharge must be free flowing and not limited by upstream conditions. Whenever upstream resistance rises above a given value and flow velocity in the flume drops, a water backwash effect is created. Discharge could then slow down to the point of complete stagnation, causing the primary structure to no longer work as a hydraulic structure.

Flow measurement does remain possible whenever discharge in the flume is in a state of transition between free-flow and non-modular (submerged) flow. The situation can be identified by calculating the submergence ratio (water level downstream h_2/water level at the main measuring point h_1) (Figure 27).

The submergence ratio in H flumes is comparatively lower than in other types of flumes capable of carrying flow of the same magnitude. The submergence ratio expressed as a percentage is 25% for HS and H flumes, and 30% for HL.

Even if a structure was originally designed to work in free-flow conditions, changes to the discharge caused by plant growth upstream of the flume, sedimentation, added hydraulic structures, reconfiguration of the installation or increase in flow may cause submergence.

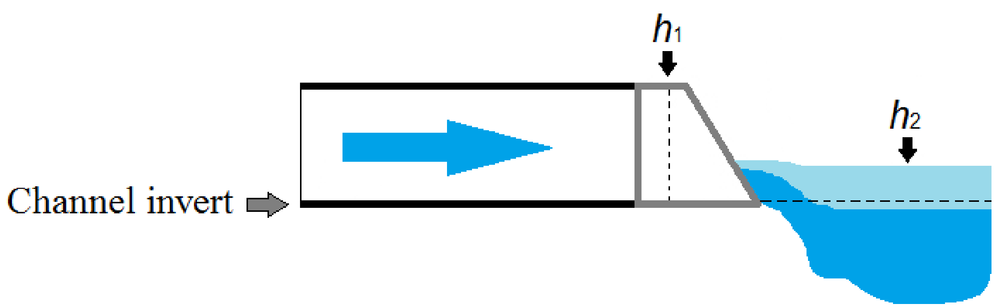


Figure 27: Location of h_1 and h_2 water level measuring points.

Free-flow equation

The following general simplified flow equation conceived by BOS determines flow for all three types of H flumes:

$$\log Q = A + B \log h_1 + C [\log h_1]^2 \quad (14)$$

Variables A, B and C are shown in Table 11. The expected rate of errors encountered in using the equation is 3% or less.

Table 11: Various values used in the BOS flow equation for free-flow conditions[12]

Type of flume	D		Maximum flow	Variable values		
	m	ft	$m^3/s \times 10^{-3}$	A	B	C
HS	.122	.4	2.27	-.4361	+2.5151	+.1379
	.183	.6	6.14	-.4430	+2.4908	+.1657
	.244	.8	12.7	-.4410	+2.4571	+.1762
	.305	1.0	22.3	-.4382	+2.4193	+.1790
H	.152	.5	9.17	+.0372	+2.6629	+.1954
	.229	.75	26.9	+.0351	+2.6434	+.2243
	.305	1.0	53.5	+.0206	+2.5902	+.2281
	.457	1.5	150	+.0238	+2.5473	+.2540
	.610	2.0	309	+.0237	+2.4918	+.2605
	.762	2.5	542	+.0268	+2.4402	+.2600
	.914	3.0	857	+.0329	+2.3977	+.2588
	1.37	4.5	2,366	+.0588	+2.3032	+.2547
HL	1.219	4.0	3,298	+.3160	+2.3466	+.2794

Stage-discharge tables are also available[13] for all H flume types and widths and should be used to directly determine flow based on water level (h_1). Referring to the theoretical equation and the manufacturer's stage-discharge table will minimize flow value errors as much as possible.

Non-modular (submerged) flow

The submergence ratio of H flumes is defined as the ratio between water level measured upstream of the flume (h_2) and at the measuring point (h_1), expressed as a percentage. The zero level for measurements of h_1 and h_2 refers to the HS, H or HL flume invert.

Calculating flow in non-modular submerged conditions is possible, but due to the complexity of the calculation method, HS and H flumes should be installed in ways that limit the submergence ratio to less than 25%. For HL flumes, the ratio should be less than 30%.

Modifications to flumes

The theoretical dimensions of H flumes must be followed, failing which primary structure recalibration becomes necessary in order to validate the stage-discharge ratio.

Since the use of modified flumes is strongly discouraged, this subject is not addressed in detail in this publication.

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[12] *Discharge measurement structures* (BOS, 1989).
[13] *Discharge measurement structures* (BOS, 1989).

H flumes…

Three types: HS, H and HL

Cover discharge rates between .3216 m^3/d (HS starts at .122 m) and 284,160 m^3/d (HL is 1,219 m).

Combine the physical and mechanical features of weirs and classic flumes.

The acceptable water level in Section D determines the flume type and dimensions.

Should be used at 70-100% of capacity. Avoid the use of oversized flumes.

Regular inspection is required per the sample field checklist shown in Appendix C.

3.2.6 Weirs – overview

Weirs are overflow structures built perpendicular to the direction of the flow in a open channel. They may be used to control the upstream surface water level as well as to measure streamflow.

Weirs can raise the water level upstream, acting like dams. Water must pass over a notch whose shape and size define the type of weir that is used. This structure can induce a significant loss of load, particularly in flat channels without inclination, and, consequently, lead to major discharge disturbances.

The level of water passing over the structure is proportional to the flow. Therefore, flow can be determined by measuring vertical height from the base of the crest to the surface of the water at a distance upstream of the weir, calculated using the equation or table that is appropriate to the shape and size of the weir.

Weirs are simpler and less expensive to build than other primary structures. Construction can be customized as long as norms are dutifully met. Weirs provide accurate flow measurements if construction, installation and maintenance are appropriate.

Weirs are named based on the shape of their discharge control section. This publication deals with thin-plate and broad-crested weirs, including how to distinguish between the two by the length of the weir in the direction of discharge (l) and the water level measured at the upstream measuring point (h):

$$\text{Broad-crested weir} = h < 1{,}6l$$
$$\text{Thin-plate weir} = h > 2l$$

When neither of the two definitions applies, no classification is possible and a field study is required.

Weir components and related phenomena are shown in Figure 28 (thin-plate weirs) and Figure 38 (broad-crested weirs) and are described in Table 12.

Table 12: Identification and description of weir components

Identification	Description
Crest	Edge over which water flows
Notch	Angled slot through which water flows
Blade (*p*)	Difference between the crest and floor of the weir, in metres
Nappe	Curtain of water spilling over the weir
Ventilation	Air pocket below the nappe on the downstream side of the weir
b	Width of the weir, perpendicular to the direction of discharge (also known as the length of the weir crest, in metres)
B	Width of the weir, in metres
h_{max}	Maximum acceptable weir height, in metres
h (or h_1)	Water level measured at the upstream measurement point (m)
h_2	Water level measured at the downstream measurement point (m)
l	Length of the weir in the direction of the discharge (m)
Point of measurement (*Pm*)	Location of the water surface level measuring point
Lowering of the surface	Local drop of water level in the approach channel due to discharge accelerating while passing over an obstacle or through a reach

3.2.6.1 Thin-plate weirs, also known as thin-crested weirs

Description

The plate or crest of this type of weir is a thin metallic vertical blade. In free-flow conditions, the outlet blade only touches the crest on a thin line. In comparison to broad-crested weirs, the flow line over the crest is strongly curved and the water flowing over the crest is deep compared to the thickness of the crest (Figure 28).

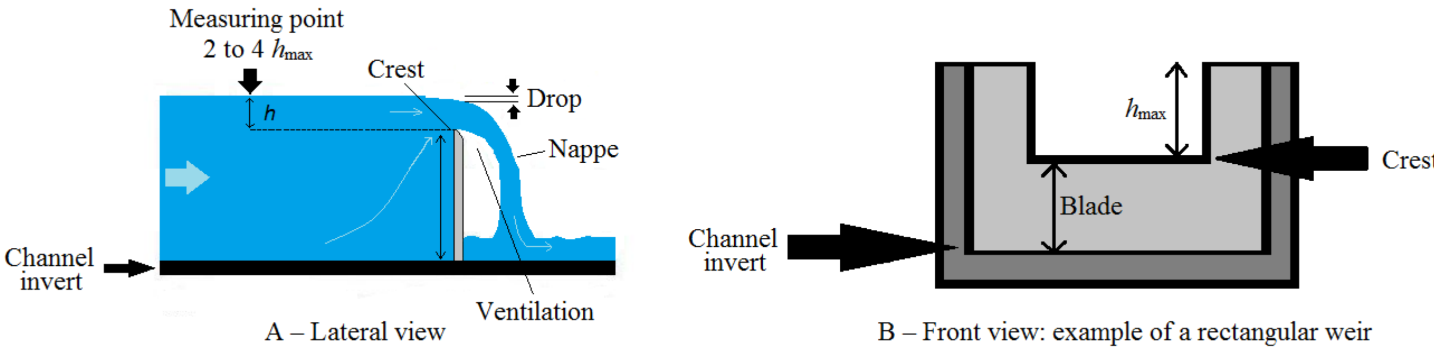


Figure 28: Components of a thin-plate weir in free-flow conditions.

Thin-plate weirs are classified on the basis of the shape of their notch. Weirs with no lateral contraction (also called restricted weirs) with outlet blades offering no lateral contraction are common, as are rectangular (with contraction) and triangular weirs. Trapezoidal (also known as Cipoletti) and circular weirs also exist (Figure 29).

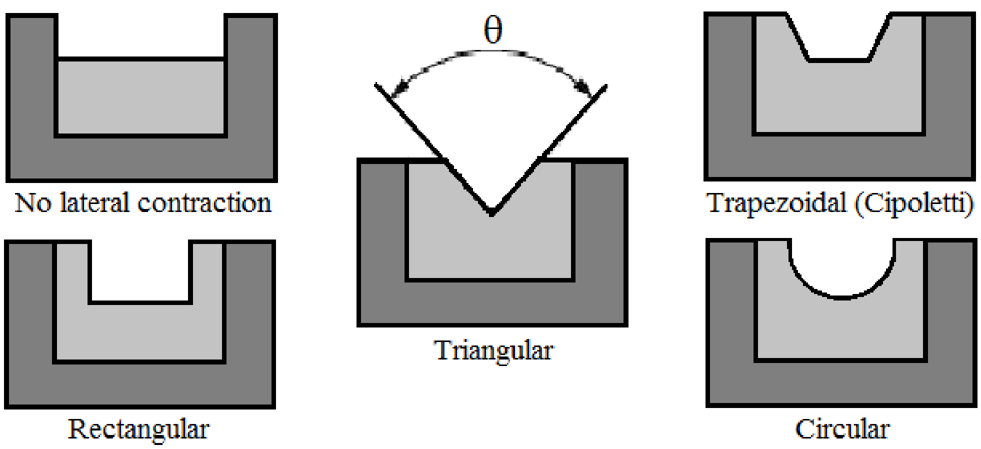


Figure 29: Types of thin-plate weirs based on notch shape.

Applications

Due to the variety of their geometric shapes and sizes, weirs are capable of measuring a very wide range of flow. The characteristics of the known or expected effluent should be taken into account when selecting a weir. For example, the tight angle of triangular weirs enables low flow to be measured with less uncertainty, plus this type of weir has a higher level of sensitivity than rectangular or trapezoidal weirs.

Weirs are usually installed on a temporary basis, but can also be permanent. They are mainly used for small channels or watercourses. Weirs work well for effluent where the impact of load loss is minor but are not recommended for water with a high level of suspended matter. If this is the case, constant attention must be paid to blockage from heavy deposits of solids upstream of the weir.

Functional principle

Thin-plate weirs enable a curtain of water to flow over them, controlling the discharge. In free-flow conditions, flow through the weir can be quantified by using the ratio between the upstream flow and the height of the blade. The water nappe flows freely in the downstream direction due to a ventilation air pocket (Figure 30 a), which implies that the water level upstream of the weir is independent of the downstream level.

Pressure is unstable in non-aerated nappes and in nappes that do not flow freely over the crest of the weir (Figure 30 b and Figure 30 c). Situations where aeration is insufficient (submerged from below) due to the elevated water level beneath the nappe (Figure 30 d) are to be avoided.

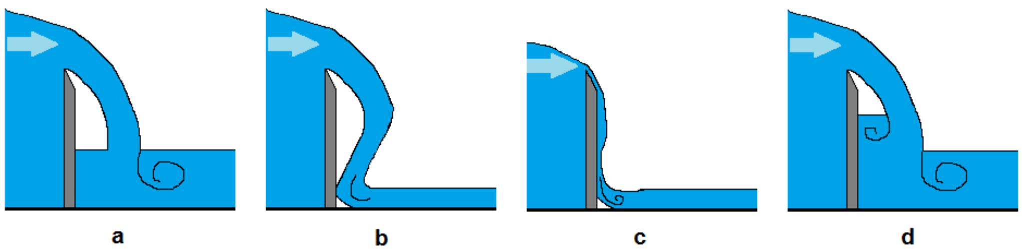


Figure 30: Examples of nappes flowing over thin-plate weirs.

The measurement of flow depends on the depth of water in the weir, but also on the weir's shape and size, the geometry of the approach channel, the dynamic properties of the water, the aeration of the nappe and an experimentally-determined coefficient of flow.

Standard dimensions

Weir size should be selected following preliminary studies to determine the expected flow measurement interval. The weir must be capable of dealing with maximum discharge of between 70 and 100% of its capacity. Oversized weirs may lead to less accuracy in weak-flow conditions, while undersized weirs may quickly induce non-modular (submerged) flow in heavy-flow conditions.

The standard dimensions of thin-plate weirs depend on the type in use.

Rectangular weirs include lateral contraction capacity, meaning that the notch over the crest is narrower than the width of the channel into which it flows ($b/B \neq 1$) (Figure 31).

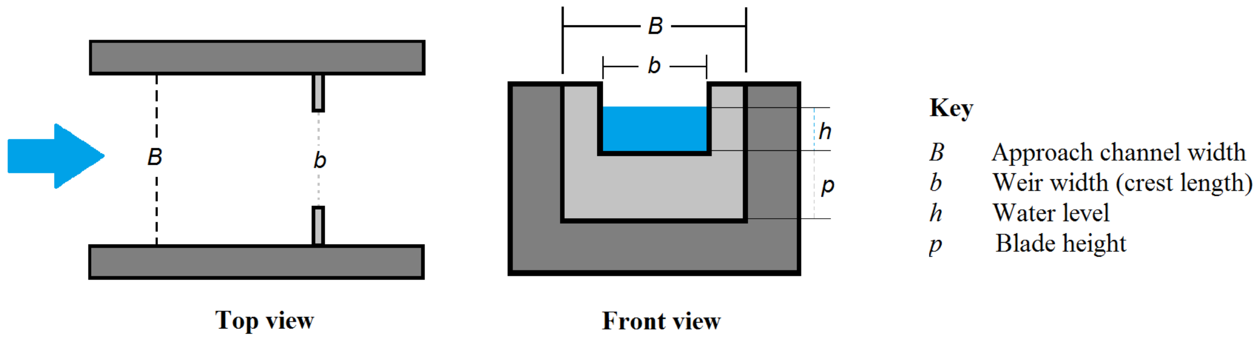


Figure 31: Characteristics of a rectangular weir.

This standard base shape can be without lateral contraction. In such cases, *b*/*B* = 1.0, whenever the width of the weir (*b*) is equal to the width of the approach channel (*B*) (Figure 32).

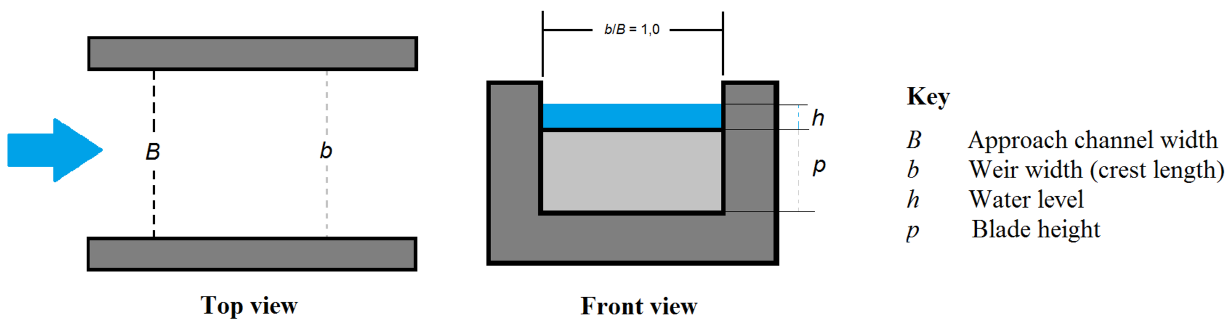


Figure 32: Characteristics of a weir without lateral contraction.

The triangular weir shows contraction along the two sides of the angled notch (Figure 33). The most common angle for the triangular weir is 90°, while other angles also exist, including 22½°, 30°, 45° and 120°.

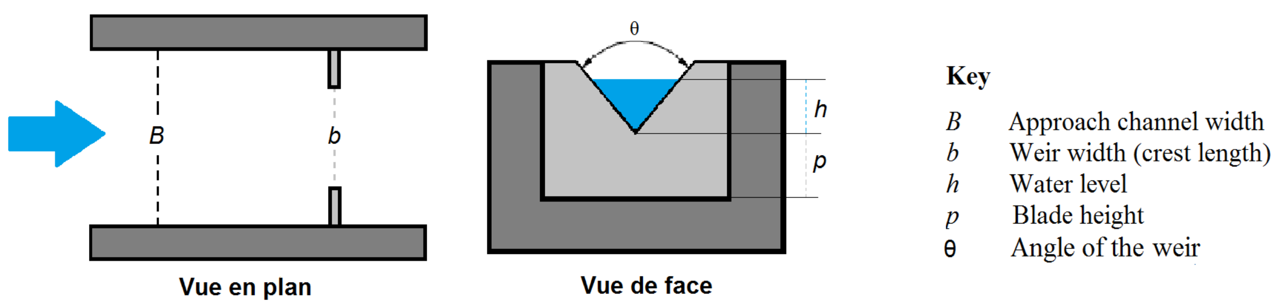


Figure 33: Characteristics of a triangular weir.

The correct proportions and dimensions of the sections of a weir must be met during the design process so as to enable optimal discharge and accuracy of flow measurement:

h	The minimum water level required to avoid the "clinging nappe" phenomenon (Figure 30 c) that arises under very weak-flow conditions.
h/*p*	Given the difficulties in measuring water level and errors caused by backwater and waves in the approach channel, the *h*/*p* (water level/blade height) ratio establishes the maximum permissible value.
b	The width of the notch (*b*) shows limitations due to errors caused by the combined effects of viscosity and surface tension.
p and *B* – *b*	Limitations on the height of the blade (*p*) and the ratio of the width of the channel to the notch (*B* – *b*) are put into place to determine any instabilities stemming from parasitic currents (backwater, eddies, etc.) that show up between the channel and the weir whenever the values of (*p*) and (*B* – *b*) are low.

In addition to the need to consider these criteria when designing a weir, they also represent application limits for some flow equations, as described in Table 14.

Measurement interval

Contrary to certain primary structures like the Parshall flume, weirs are not prefabricated with standard dimensions that correspond to specific intervals of flow measurement. For a given water level, established flow may differ due to the fact that in addition to water level, the equation considers other variables, such as the weir width and flow coefficient.

Various relationships mentioned in the literature enable flow to be calculated on the basis of the geometry and dimensions of the weir. It is important to dutifully abide by the design criteria (including the dimensions) of each section of the weir, as well as the minimum and maximum recommended water levels in order to obtain accurate flow measurement.

The minimum length of the crest (*b*) of a rectangular weir with or without contraction should be at least .3 m. If this is not possible, a triangular weir is the better choice since it offers greater accuracy in weak-flow conditions.

Theoretically, no maximum crest length exists for rectangular weirs and weirs without contraction. Any constraints will, therefore, be of a practical and/or economic nature. However, in order for the stage-discharge relation to remain within acceptable values, the water level over the crest must not exceed half the crest length (i.e., for a crest whose length is 1 m, maximum water level must not exceed .5 m).

Installation

Thin-plate weirs are particularly dependent on correct installation to regulate the distribution of velocity in the approach channel and construction of the crest of the weir to standard specifications.

Weirs must be installed in a straight section of the channel. The length of the approach channel must be at least five times the width of the nappe at maximum discharge. Otherwise, the approach velocity can be overly high and as a consequence, the measurement of water level and flow probably over-evaluated. The approach channel should be rectilinear, smooth and horizontal to encourage uniform and stable discharge and good distribution of velocity, without curves, falls or branching.

Appropriate control of the approach velocity is very important, since measurement errors can increase by more than 20% when velocity is too high. Deflectors may be used to encourage adequate velocity distribution as long as their location meets the minimum distance upstream of the weir. Approach velocity can also be easily corrected by increasing the blade height.

Weir plates are usually manufactured in stainless steel or other rigid materials that are resistant to corrosion or covered with protective film. Plate thickness must be between 1 and 2 mm. If the thickness is greater, the plate must have a bevelled edge with a minimum angle of 45° on the downstream side of the weir in order to reduce the crest thickness to 1 to 2 mm (Figure 34).

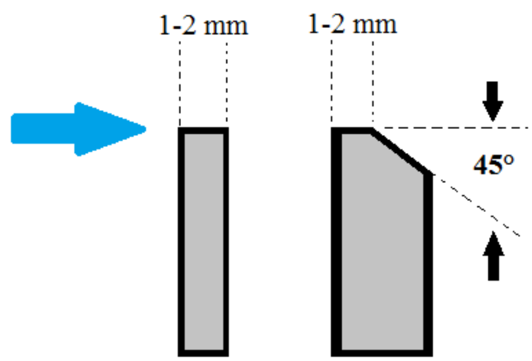


Figure 34: Details of a thin-plate weir crest.

Weirs must be solidly installed to resist the strongest anticipated flow without warping or damage, and perpendicular to the walls of the discharge channel. The vertical and transverse axes must be level. The geometric shape of the weir must be cut accurately. The surface of the crest must be level over its entire length, smooth, and show a sharp edge at its intersection with the upstream face of the weir plate. The notch must be symmetrical and equidistant with respect to the walls of the discharge channel.

The joints between the weir plate, sides and floor of the channel must be resistant and leak-proof so that all water is channelled by the weir.

The nappe of water must only touch the upstream side of the crest, i.e., not the wall downstream of the weir. Ventilation between the blade and the nappe is an indication of free-flow (Figure 30 a).

To avoid non-modular (submerged) flow caused by backflow, the capacity of the outlet channel must be sufficient to enable the immediate evacuation of water at maximum flow.

The maximum water surface level upstream must be no higher than 5 cm below the crest, failing which the nappe must be continuously ventilated over its entire length to prevent non-modular (submerged) flow.

When installing a weir, it is important to plan accessibility for inspection and maintenance. It is preferable to build a weir to code rather than estimate the effects of field conditions and subsequently attempt to correct obtained values.

Measuring point

Water level corresponds to the difference between the crest and the water surface at the measuring point. Point zero of the weir, therefore, corresponds to the height of the crest when the water level is not measured directly over it. That value must be precisely transposed at the point of measurement by means of a level and a ruler or square (see Figure 35).

In free flow conditions, the measuring point must be located upstream of the weir, at a distance of two to four times the maximum permissible depth at the weir to avoid measurement being influenced by the water surface level lowering effect. It is advisable to measure water level in a stilling well. The stilling well must be installed in compliance with the criteria described in section 3.2.3. A reference ruler must be permanently installed at the measuring point.

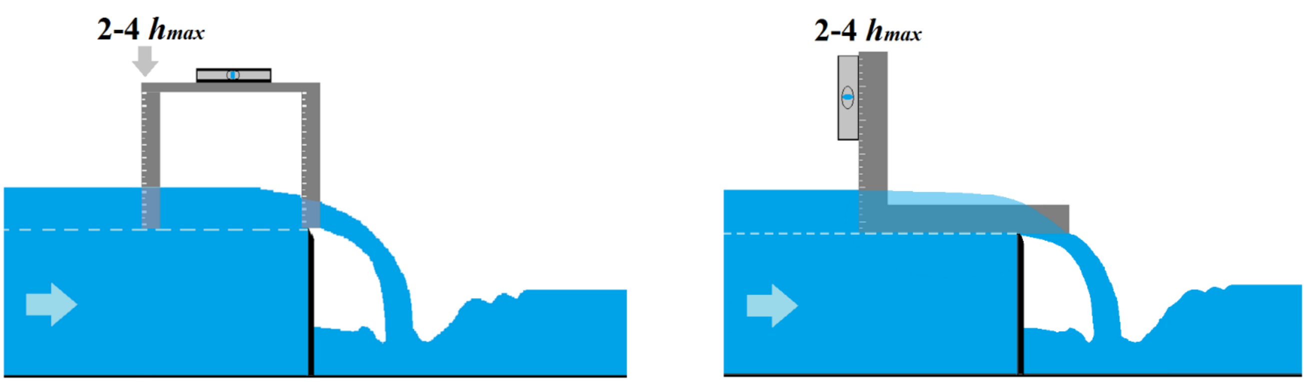


Figure 35: Examples of methods for measuring water level upstream of the zero point in a weir without contraction.

Free flow

In order for the equation associated with the weir to accurately calculate flow, discharge must be in free flow conditions. Discharge in a weir is considered as free (or critical) whenever the water levels upstream and downstream are independent of each other. This means that the water level downstream is sufficiently low to not affect ventilation under the nappe (minimum of 5 cm below the crest) and that discharge is sufficiently distant from the blade to enable air to circulate freely under the nappe.

Flow equation in free flow

In free flow, the water level downstream has no effect on the level upstream and, as such is not included in the flow equation. As a result, flow in the weir is influenced in a major way by the physical characteristics of the primary structure and the approach channel.

Ideally, the flow equation should reflect all influencing factors. No universal equation exists for this type of weir that takes account of all factors that regulate discharge and is applicable to every installation. The simplified equations are valid for an ideal weir with low approach velocity and where flow is not submerged. More elaborate equations can calculate flow with a higher level of precision. These equations rely on the use of charts or figures to determine the variables of the equation. Caution should be taken when using these equations, particularly whenever water level over the crest is very low compared to the level at the downstream face of the blade. In such cases, minor water level uncertainty can lead to major uncertainty with respect to flow. The flow equations and expression of the flow coefficient also depend on the aeration of the nappe and only apply when it is in free flow. Contrariwise, any resultant loss of energy will produce additional flow measurement errors.

Application limits of equations based on weir dimensions are shown in Table 13.

Table 13: Equation showing the application limits for various types of weirs

Type	Simplified equation	Recommended equation
Rectangular	$h > 1/3\ b$ $p = 2h_{max}$ minimum Length of each lateral contraction = $2h_{max}$ minimum	$h/p \leq 2.5$ $h \geq .03$ m $b \geq .15$ m $p \geq .10$ m $(B - b) / 2 \geq .10$ m
Without contraction	$h < 1/3\ b$ $p = 2h_{max}$ minimum	$h/p \leq 4.0$ $.03 \leq h \leq 1.0$ m $b \geq .30$ m $p \geq .06$ m
Triangular	$p = 2h_{max}$ minimum Length of each lateral contraction = $2h_{max}$ minimum	$h/p \leq .4$ $h/B \leq .2$ $0,05 \leq h \leq .38$ m $p \geq .45$ m $B \geq 1$ m

Table 14 shows the simplified and recommended equations for a rectangular weir. The recommended equation includes a coefficient (C_d) that is determined by the type and shape of the weir and by the relationship between b/B, θ and β as shown in Table 15. The intermediate values of b/B may be extrapolated linearly. A sample calculation of these two equations is shown in Table 16.

Table 14: Free flow equations for a rectangular weir

Simplified equation[14]	Recommended equation[15]
$$Q = C(b - 0,2h)h^{1.5}$$ Q = flow (m³/h or l/s) C = constant, a function of the units 1,838 if Q is in l/s 6,618 if Q is in m³/h b = weir width (m) h = water level (m)	$$Q = \frac{2}{3}\sqrt{2g}C_d b_e h_e^{1.5}$$ Q = flow (m³/s) g = gravitational acceleration (9.81 m/s² or $\sqrt{2g}$ = 4.43) C_d = coefficient, a function of the type and shape of the structure, per equation $$C_d = \theta + \beta\, {}^{h}/_{p}$$ θ and β = depend on the ratio of b/B (Table 15) h = water level (m) p = blade height (m) $$b_e = b + .003\ m$$ $$h_e = h + .001\ m$$

Table 15: Ratios between b/B, θ and β[16]

b/B	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
θ	.588	.589	.590	.591	.592	.593	.594	.596	.598	.602
β	-.002	-.002	.002	.006	.011	.018	.030	.045	.064	.075

[14]Francis equation. Constant described in the *Teledyne ISCO Open Channel Flow Measurement Handbook*, 2017.
[15] Kindsvater-Carter equation. Coefficient (C_d) described in *Streamflow Measurement*, Herschy, 2009.
[16] *Streamflow Measurement*, Herschy, 2009.

Table 16: Sample flow calculation for a rectangular weir

	Simplified equation	Recommended equation
Weir configuration	b = 1 m B = 2 m	h = .2 m p = .4 m
Verification of limitations	Per Table 13	
Determination of flow	$\boldsymbol{Q = C(b - .2h)h^{1.5}}$ $Q = 6618[1-(.2\times .2)].2^{1.5}$ Q = **568.25 m³/h**	$\boldsymbol{Q = \frac{2}{3}\sqrt{2g}C_d b_e h_e^{1.5}}$ $C_d = \theta + \beta\,\frac{h}{p}$ (A function of b/B, see Table 15) $C_d = .592 + .011\,\frac{.2}{.4} = .5975$ $b_e = 1 + .003 = 1.003$ $h_e = .2 + .001 = .201$ $Q = \frac{2}{3}\times 4.43\times .5975\times 1.003\times .201^{1.5}$ Q =.1595 m³/s (**574.18 m³/h**)

The simplified and recommended equations for weirs without contraction are stated in Table 17. The recommended equation includes a coefficient (C_d), which is a function of the .602 + .083 h/p equation. A sample calculation of these two equations is shown in Table 18.

Table 17: Flow equations for a weir without contraction in free flow conditions

Simplified equation[17]	Recommended equation[18]
$\boldsymbol{Q = Cbh^{1.5}}$ Q = flow (m^3/h or l/s) C = constant function of units 1,838 if Q is in l/s 6,618 if Q is in m^3/h b = weir width (m) h = water level (m)	$\boldsymbol{Q = C_d\frac{2}{3}\sqrt{2g}\,b\,h_e^{1.5}}$ Q = flow (m^3/s) C_d = coefficient of flow $C_d = .602 + .083\frac{h}{p}$ h = water level (m) p = blade height (m) g = gravitational acceleration (9.81 m/s^2 or $\sqrt{2g}$ = 4.43) b = weir width (m) h_e = h + .0012 m

17Francis equation. Constant described in the *Teledyne ISCO Open Channel Flow Measurement Handbook*, 2017.
18Kindsvater-Carter equation. Coefficient (C_d) described in *Streamflow Measurement*, Herschy, 2009.

Table 18: Sample flow calculation for a weir without contraction

	Simplified equation	Recommended equation
Configuration of the weir	b = 1 m h = .2 m B = 1 m p = .4 m	
Verification of limitations	Per Table 13	
Determination of flow	$\boldsymbol{Q = Cbh^{1.5}}$ $Q = 6618 \times 1 \times .2^{1.5}$ Q = **591.93 m³/h**	$\boldsymbol{Q = C_d \frac{2}{3}\sqrt{2g}\, b\, h_e^{1.5}}$ $C_d = .602 + .083\left(\frac{.2}{.4}\right) = .6435$ $\sqrt{2g = 4.43}$ $h_e = .2 + .0012 = .2012$ $Q = .6435 \times \frac{2}{3} \times 4.43 \times 1 \times 0.2012^{1.5}$ Q = 0.21715 m³/s **(617 m³/h)**

The simplified and recommended equations for a triangular weir are shown in Table 19. The simplified equation includes a coefficient (C), which is a function of the angle of the notch and the unit of measurement (l/s or m^3/h). The values of this coefficient are shown in Table 20.

The coefficient (C_d) of the recommended equation is also a function of the angle of the notch and is determined by Figure 36. For a 90° weir, both the coefficient and the flow are directly related to the water level. Several references are available in the literature, on the Internet or from the manufacturer, which directly determine the coefficient from the conversion table on the basis of the water level (e.g., *Flow Measurement*).

Table 19: Flow equations for a triangular weir in free flow conditions

Simplified equation[19]	Recommended equation[20]
$\boldsymbol{Q = C\, h^{2.5}}$ C Constant, a function of the angle of the weir and the unit of measurement (Table 20)	$\boldsymbol{Q = \frac{8}{15}\sqrt{2g}\, C_d \tan\frac{\theta}{2} h^{\frac{5}{2}}}$ g gravitational acceleration constant 9.81 m/s² ($\sqrt{2g}$ = 4.43) C_d Coefficient determined by the angle of the weir (Figure 36). When the angle is 90°, refer to the appropriate conversion table.

[19]Francis equation. Constant described in the *Teledyne ISCO Open Channel Flow Measurement Handbook*, 2017.
[20]British Standards Institution (BSI) equation. Coefficient (C_d) described in *Streamflow Measurement*, Herschy, 2009.

Table 20: Value of coefficient "C" by angle of measurement[21]

Angle	l/s	m³/h
22.5°	$Q = 274.4\ h^{2.5}$	$Q = 987.8\ h^{2.5}$
30°	$Q = 373.2\ h^{2.5}$	$Q = 1{,}344\ h^{2.5}$
45°	$Q = 571.4\ h^{2.5}$	$Q = 2{,}057\ h^{2.5}$
60°	$Q = 796.7\ h^{2.5}$	$Q = 2{,}868\ h^{2.5}$
90°	$Q = 1{,}380\ h^{2.5}$	$Q = 4{,}969\ h^{2.5}$
120°	$Q = 2{,}391\ h^{2.5}$	$Q = 8{,}606\ h^{2.5}$

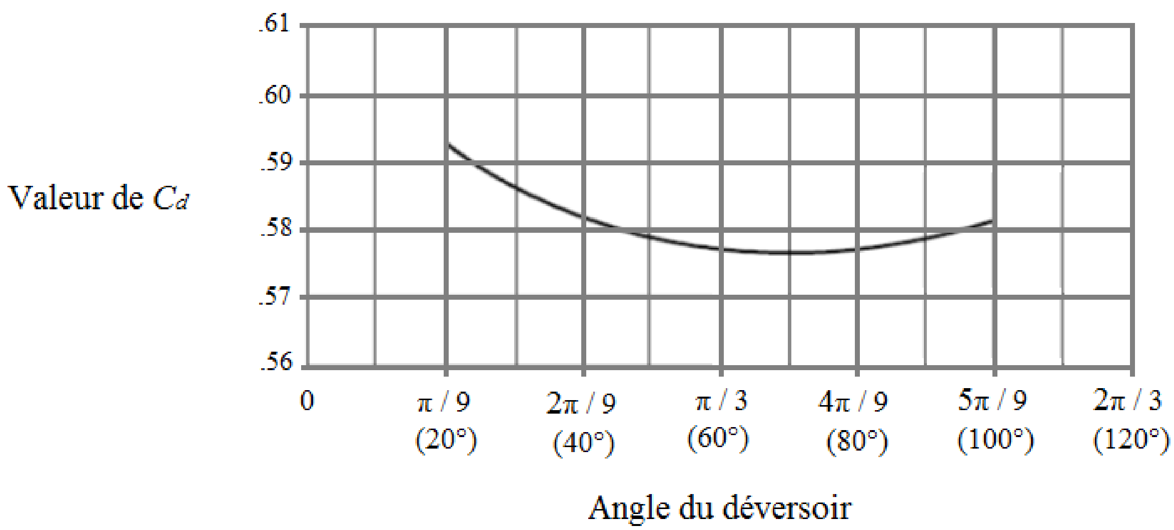


Figure 36: Ratio of coefficient (C_d) based on weir angle[22]**.**

A sample calculation for these two equations is shown in Table 21.

[21]*Teledyne ISCO Open Channel Flow Measurement Handbook*, 2017.
[22]Adapted from *Streamflow Measurement*, Herschy, 2009.

Table 21: Sample calculation of flow for a triangular weir

	Simplified equation	Recommended equation
Configuration of weir	$b = .8$ m $B = 1.2$ m $h = .2$ m	$p = .6$ m $\theta = 45°$
Verification of limitations	Per Table 13	
Determination of flow	$\boldsymbol{Q = Ch^{2.5}}$ $Q = 2057\,(.2^{2.5})$ $Q =$ ***36.80*** **m³/h**	$\boldsymbol{Q = \frac{8}{15}\sqrt{2g}\,C_d \tan\frac{\theta}{2}\,h^{\frac{5}{2}}}$ $\sqrt{2g} = 4.43$ $C_d = 0.58$ $\tan\frac{\theta}{2} = .4142$ $h^{\frac{5}{2}} = .01789$ $Q = \frac{8}{15}\sqrt{2g}C_d \tan\frac{\theta}{2} h^{\frac{5}{2}}$ $Q = .01015$ m³/s **(36.56 m³/h)**

Non-modular (submerged) flow

Discharge in a weir is considered submerged when it is affected by upstream conditions.

First, the water level upstream drops to the point where air no longer circulates under the nappe (Figure 37 a). Water level downstream (h_2) eventually exceeds the zero water level upstream (h_1) (Figure 37 b). This kind of situation distorts measurements because the pressure upstream of the weir is insufficient. Consequently, velocity is too low and measured water level, too high.

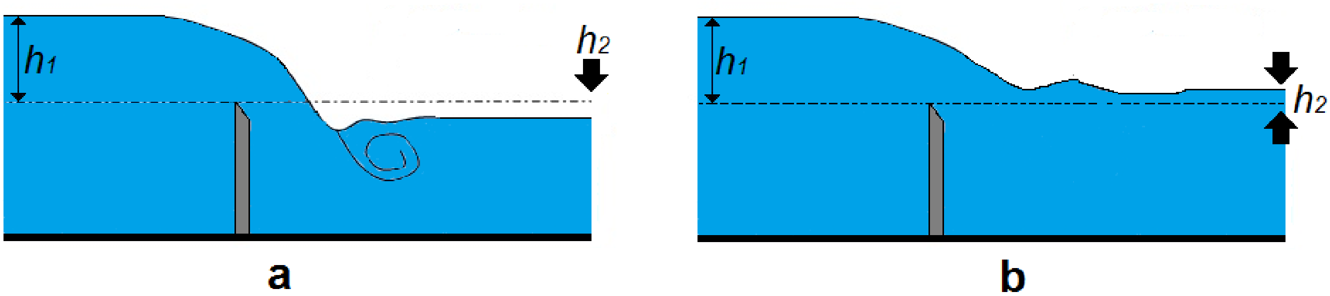


Figure 37: Illustration of non-modular (submerged) flow.

This condition affects the accuracy of flow measurement. Non-modular (submerged) flow (non-ventilated) conditions are not recommended and must be avoided. Moreover, weirs are unusable when the water level upstream submerges the crest of the weir (Figure 37 b). The size and installation of a weir have to enable ventilation and free flow conditions at all times.

Using a weir in submerged conditions is not a good practice and should be avoided. A special formula is required for calculations in non-modular (submerged) flow conditions because h_1 and h_2 must be included.

However, the only way to correct this situation is to modify the measurement installations and/or the discharge (whenever possible) or to simply change the measurement device to foster free flow.

Since this latter procedure is not advisable and in fact exceptional, users should refer to ISO 1438 for more information.

Thin-plate weirs…

Thin-plate weirs are characterized based on the form of their notch.

The choice of weir type should be based on discharge (e.g., a triangular weir can measure weak-flow with a lower level of uncertainty).

Not recommended where effluent is highly sedimented, due to the danger of blockage and clogging or where load loss is to be avoided.

Weir dimensions must enable maximum flow to correspond to between 70 and 100% of capacity.

The nappe has to flow freely downstream and have a ventilation pocket.

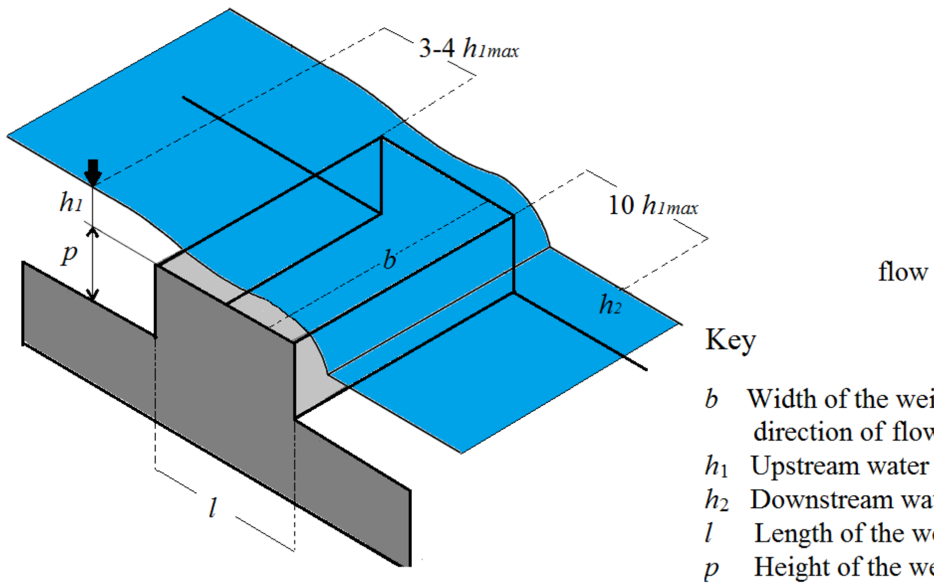
The zero point corresponds to the height of the crest and the measuring point must be two to four times the maximum water level (h_{max}) in the weir.

Inspection must be made regularly on the basis of the field checklist in Appendix 3.

3.2.6.2 Broad-crested weirs

Description

A broad-crested weir is characterized by a shallow upstream water level (h_1) in comparison to the thickness of the crest (l) (Figure 38), when $h_1/l < 1.6$.



Key

- *b* Width of the weir crest perpendicular to the direction of flow (m)
- h_1 Upstream water level measurement point
- h_2 Downstream water level measurement point
- *l* Length of the weir in the direction of flow
- *p* Height of the weir (difference in metres between the floor of the channel and the crest)

Figure 38: A broad-crested rectangular weir.

In addition to their various geometric configurations, thin-plate and broad-crested weirs can be distinguished on the basis of their distinct stage-discharge relation and their coefficients C_d.

The International Organization for Standardization (ISO) describes four types of broad-crested weirs: rectangular, round-nose, trapezoidal (Cipoletti) and V-shaped (Figure 39). Since it is the most common type, the broad-crested rectangular weir will be considered in this section. The crest of this type of weir is a horizontal rectangular plane surface and of which the upstream face forms a sharp right-angled corner at its intersection with the plane of the crest.

For information on other types of broad-crested weirs, refer to the applicable ISO standards:

ISO 4374 – Liquid flow measurement in open channels — Round-nose horizontal broad-crested weirs

ISO 4377 – Hydrometric determinations — Flow measurement in open channels using structures — Flat-V weirs

ISO 4360 – Hydrometry — Open channel flow measurement using triangular profile weirs

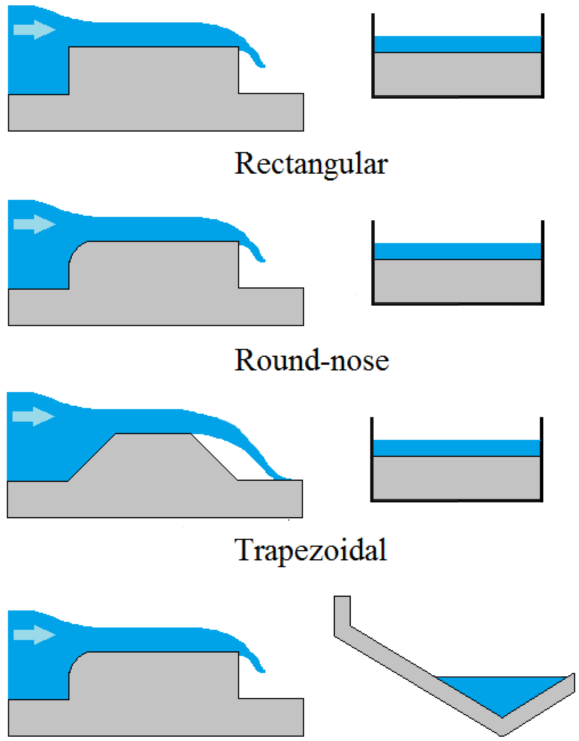


Figure 39: Types of broad-crested weirs – side (left) and sectional views (right).

Applications

Broad-crested weirs are more robust than thin-plate weirs and are mainly used for large channels or rivers in natural settings. These weirs function over a broad range of flow coefficients and are among the easiest to build in the field. However, as with other weir types, they cause loss of load and induce silt and debris accumulation.

Functional principle

The full measurement system includes an approach channel, a measurement structure and a downstream channel. The state of the three components influences overall measurement accuracy.

As is the case for thin-plate weirs in free flow, discharge in broad-crested weirs flows in the approach channel until it becomes critical close to the weir and eventually spills to the downstream side in a supercritical nappe.

Installation

The site selected for installing broad-crested weirs must offer the following:

- Stable banks.
- An unobstructed channel bed.

- A uniform approach channel that is horizontal and rectilinear of a length at least five times the width of the discharge.
- Deflectors (whenever required) installed at a distance greater than ten times the maximum water depth.
- Smooth discharge that is free of disturbances and with normal velocity distribution over the cross-section of the approach channel.
- A location capable of dealing with the effects of load loss at all flow levels.
- An outlet channel upstream of the weir enabling the immediate evacuation of water at maximum flow.

The weir itself must have the following characteristics:

- A rigid leak-proof structure that resists discharge without warping or rupturing.
- It must be perpendicular to the direction of flow.
- Its crest must be horizontal, flat and smooth.
- Its upstream face must be at a right angle to its intersection with the crest, since rounding the angle notably increases the flow coefficient (C).
- The width of the crest (b) (perpendicular to the direction of flow) must be equal to the width of the channel in which the weir is installed, therefore $b = B$.

Measuring point

As is the case in thin-plate weirs, the water level corresponds to the difference between the crest and the water surface at the measuring point.

The upstream measuring point (h_1) must be located sufficiently distant from the weir to prevent lowering of the surface while being sufficiently close so as to ensure that loss of energy between the measurement and control sections is negligible.

This distance corresponds to three to four times h_{1max} (Figure 38).

If the weir is used in non-modular (submerged) flow conditions, a measurement of the level downstream (h_2) is required. The measuring point must be located ten times $h_{1\mathrm{max}}$ (Figure 38). At this location, turbulence associated with the dissipation of energy near the weir will have dropped to an acceptable level. The water level measuring point must be located on the interior face of the lateral walls, parallel to the structure of the weir itself.

In certain cases, it may be preferable to measure the water level in a stilling well to reduce the effects of surface irregularities.

Installers should plan for a method of periodically checking the zero level of the water level measuring device to recalibrate if required.

Free flow

For rectangular broad-crested weirs, if the channel upstream of the weir is of even width over a distance equal to the maximum water level downstream (h_2), ventilation of the nappe is not required.

Discharge will be in free flow conditions as long as the modular limit (S_1) is not exceeded. That limit is the submergence ratio ($S = h_2/h_1$) over which the upstream water level will be affected by the downstream level of the weir. The modular limit (S_1) is shown in Figure 40.

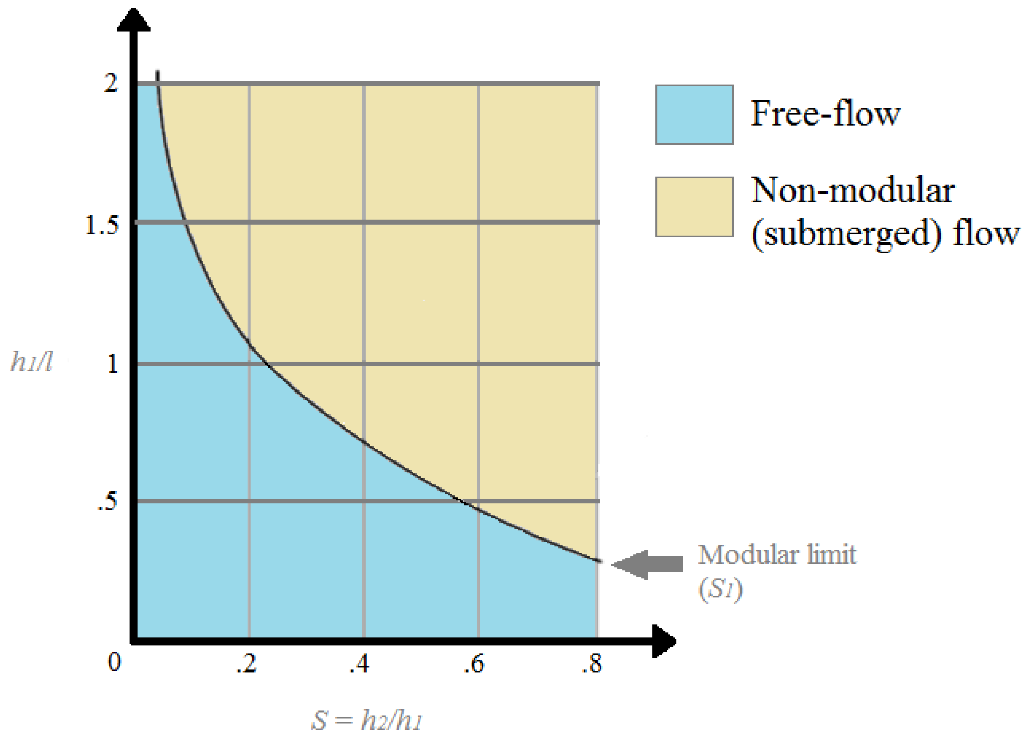


Figure 40: Modular limit (S1) as a function of h1/l[23].

The flow equation in free flow conditions

The application limits of the equation for a rectangular broad-crested weir in free flow conditions based on the dimensions of the weir are shown in Table 22.

[23] Adaptation–ISO 3846.

Table 22: Application limits of the flow equation in free flow conditions

Application limits
$h_1 \geq .06$ m
$b \geq .30$ m
$p \geq .15$ m
$.1 < l/p < 4.0$
$.1 < h_1/l < 1.6$
$h_1/p < 1.6$

The flow equation in free flow conditions for a rectangular broad-crested weir is as follows[24]:

$$\boldsymbol{Q = C\sqrt{2g}\, b\, h_1^{1.5}} \quad \textbf{(15)}$$

Where
- Q Flow (m^3/s)
- g Gravitational acceleration (m/s^2)
- b Width of the weir perpendicular to flow (m)
- C Coefficient of flow in relation to water level $C = .385A_1$ where A_1 is per Table 23
- h_1 Height of the upstream water at the point of measurement (m)

[24] ONEMA, *Contrôle des débits réglementaires*.

Table 23: Determination of coefficient A_1 for a rectangular broad-crested weir[25]

h_1/p	h_1/L																	
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
0.1	.850	.850	.850	.861	.870	.885	.893	0.925	0.948	.971	.993	1.016	1.039	1.062	1.085	1.106	1.130	1.148
0.2	.855	.855	.855	.864	.874	.888	.907	0.930	0.954	.977	1.001	1.026	1.050	1.074	1.096	1.120	1.142	1.159
0.3	.864	.864	.864	.868	.879	.894	.913	0.936	0.961	.986	1.011	1.037	1.061	1.085	1.110	1.132	1.152	1.169
0.4	.873	.873	.873	.874	.885	.901	.920	0.945	0.969	.995	1.021	1.047	1.072	1.097	1.122	1.144	1.163	1.180
0.5	.882	.882	.882	.883	.894	.909	.929	0.954	0.978	1.005	1.032	1.057	1.083	1.109	1.133	1.154	1.173	1.188
0.6	.892	.892	.892	.894	.904	.920	.941	0.964	0.990	1.016	1.043	1.067	1.094	1.120	1.143	1.164	1.182	1.196
0.7	.901	.901	.901	.906	.916	.932	.952	0.975	1.000	1.026	1.052	1.077	1.104	1.129	1.152	1.171	1.188	1.203
0.8	.911	.911	.912	.916	.926	.942	.962	0.985	1.010	1.036	1.062	1.086	1.112	1.136	1.158	1.176	1.194	1.209
0.9	.921	.921	.922	.926	.936	.952	.972	0.996	1.021	1.046	1.072	1.096	1.120	1.143	1.163	1.181	1.199	1.214
1.0	.929	.929	.931	.936	.946	.962	.982	1.006	1.031	1.056	1.081	1.106	1.128	1.150	1.169	1.187	1.204	1.220
1.1	.935	.937	.940	.946	.956	.972	.993	1.017	1.042	1.066	1.092	1.115	1.138	1.159	1.177	1.195	1.212	1.228
1.2	.941	.944	.949	.956	.966	.982	1.004	1.028	1.053	1.077	1.103	1.126	1.148	1.168	1.186	1.204	1.222	1.237
1.3	.946	.951	.957	.966	.977	.993	1.016	1.040	1.063	1.089	1.114	1.136	1.158	1.178	1.196	1.214	1.232	1.250
1.4	.953	.959	.967	.975	.986	1.005	1.028	1.050	1.075	1.101	1.124	1.147	1.168	1.187	1.206	1.224	1.244	1.266
1.5	.961	.968	.975	.984	.997	1.018	1.040	1.061	1.088	1.111	1.134	1.156	1.176	1.196	1.215	1.235	1.258	1.277
1.6	.972	.978	.985	.994	1.010	1.030	1.050	1.073	1.096	1.119	1.142	1.164	1.184	1.204	1.224	1.245	1.268	1.289
Note: Values highlighted in yellow are not recommended.																		

Table 24: Sample calculation of flow for a rectangular broad-crested weir

	Equation	
Configuration of weir	$h_1 = .40$ m $h_2 = .10$ m $b = 10$ m $p = .30$ m	$l = .50$ m $l/p = 1.6667$ $h_1/l = .80$ $h_1/p = 1.3333$
Verification of limitations	Per Table 22	
Determination of flow	$\boldsymbol{Q = C\sqrt{2g}\, b\, h_1^{1.5}}$ $\boldsymbol{C = .385A_1}$, per Table 23, $A_1 = 1.043$ $Q = .4016 \times 4.43 \times 10 \times .40^{1.5}$ $Q = 4.5008$ m^3/s **(16,202.98 m^3/h)**	

[25]Source: ONEMA, *Contrôle des débits réglementaires.*

Non-modular (submerged) flow

Rectangular broad-crested weirs can be used in non-modular (submerged) flow if certain conditions and applicable equations set out in ISO 3846 are met.

Broad-crested weirs…

The ISO lists four types: rectangular, round-nosed, trapezoidal and V-shaped.

The water level is the difference between the crest and water surface at the measuring point.

The measuring point is located between three and four times the maximum acceptable water level of the weir (h_{max}).

Inspection of the weir must be made regularly on the basis of the field grid checklist in Appendix 3.

3.3 SECONDARY DEVICES

Primary structures can only produce the instantaneous measurement of flow by converting water level at the measuring point by means of a theoretical equation or stage-discharge tables. By contrast, direct continuous measurement and recording water level and flow require additional equipment, called secondary devices.

Secondary devices measure physical characteristics like distance and pressure, which correspond to the water level at the measuring point of the primary structure. They can display and save readings, then process and transmit them in order to determine a flow value by applying a known stage-discharge relation.

In free surface flow, the secondary devices used to measure and convert primary structure flow signals are called flowmeters.

3.3.1 Classification of secondary devices

This section refers to devices that are common in industrial and municipal settings, without however offering a full review of all equipment that is available on the market.

Water level measuring devices can be divided into two categories: those that detect level and those that continuously measure it (Figure 41). The first category indicates that a predefined water level has been reached. For example, this could be a high level marker set at 1 m that is connected to an alarm and serves to warn that a reservoir risks overflowing.

Continuous measurement is more sophisticated since it is based on an interval. For example, it could measure water levels of between 0 and 30 cm, which gives more information than measurement at a single point as, for instance, in the previous example.

Figure 41 also illustrates principles of measurement like pressure differential and travel time, which govern continuous head measuring devices (described in greater detail in the following sections).

Area-velocity flowmeters are widely available and can be used with or without primary structures. This is the case for immersed head-velocity Doppler flowmeters and non-contact area-velocity radar flowmeters whose combined water level and velocity measurement capability can determine flow.

This type of equipment is useful whenever the installation of a primary structure is impossible or whenever the channel at issue displays current inversions and/or transient loading. The devices can also be used to determine instantaneous flow, as when checking the accuracy of flow measurement. Section 7 provides further details on this in the framework of accuracy checking.

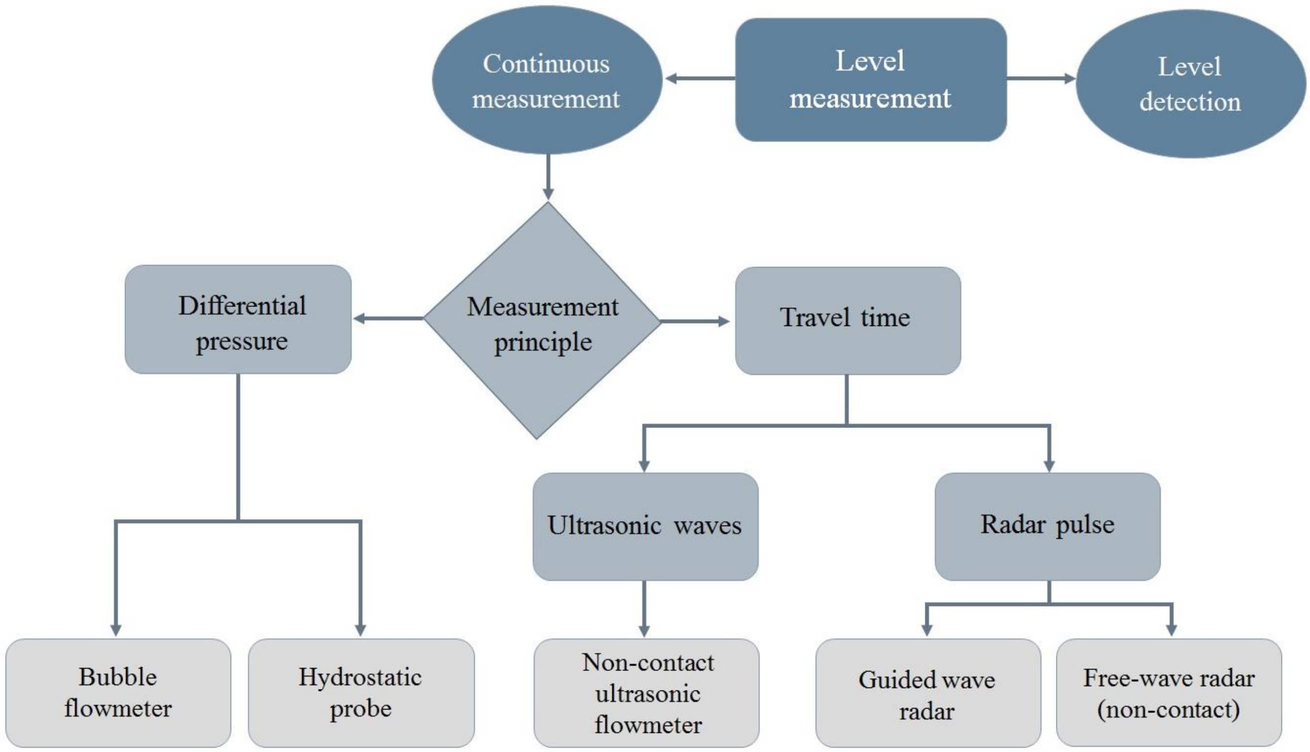


Figure 41: Classification of level measuring devices.

3.3.2 Pressure differential measuring devices

3.3.2.1 Bubble flowmeter

Description and functional principle

The bubble flowmeter is comprised of a pneumatic bubbler pipe installed in the measuring section, which is connected to a compressor set up at a distance from the primary structure, such as on a wall bracket (Figure 42).

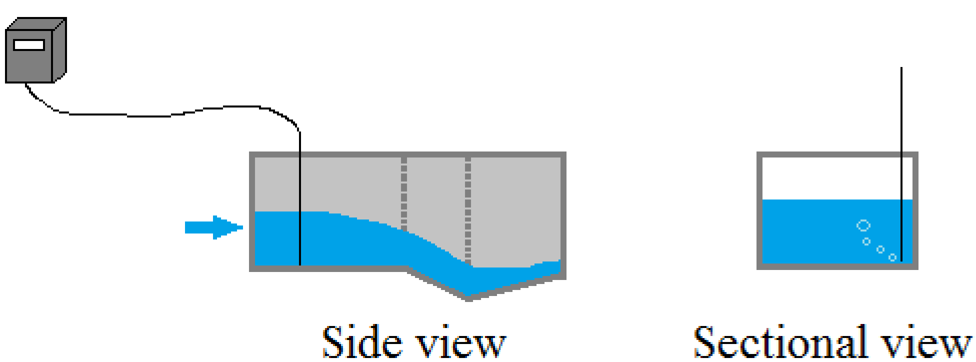


Figure 42: Sample installation of the compressor box of a bubble flowmeter and bubbler pipe in a Parshall flume.

The compressor forces air into the bubbler pipe. The water level is determined by measuring the pressure required to force air out of the pipe against the water pressure. The pressure differential measured by the hydrostatic sensor is proportional to the depth and is converted into flow using the manufacturer's stage-discharge tables per the type of primary structure in use.

Installation

The technical specifications of the selected device must be considered with respect to the characteristics of the effluent to be measured.

- Storage and operational temperature, such as -30 °C < T° < 60 °C.
- Maximum length of the tube between the compressor box and measuring point, such as max. 30 m.
- Minimum and maximum water level, such as 0-30 mm/0-500 mm.
- Flow velocity, such as ≤ 1.5 m/s.
- Suspended matter (e.g., avoid heavy effluent load).

The following conditions must always be met during the installation process.

- The compressor box must not be exposed to vibration, storms or direct sunlight.
- The position of the base of the bubbler pipe must correspond to the zero level at the measuring point of the channel or the installed weir.
- The tube of the bubbler pipe must not be bent, stretched or compressed so as to enable air to pass freely.
- The bubbler pipe must be attached to the channel bank, as close as possible to the wall (2-3 cm from the edge) in order to limit flow disturbance.
- The bevelled edge (extremity of the bubbler pipe) must face the interior of the channel (Figure 43).
- Bubbling frequency equates to airflow of one bubble per second.
- Measurement in a stilling well is preferred due to the fact that it completely avoids disturbances caused by the bubbler pipe and simplifies the zero calibration. The zero level in the measurement section must be considered when installing the stilling well (Figure 12).

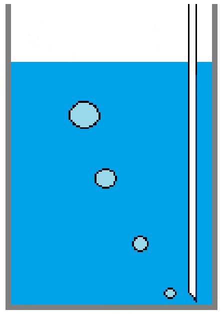


Figure 43: Installation of a bubbler pipe, bevelled edge facing the interior of the flume.

3.3.2.2 Hydrostatic sensor

Description and functional principle

The hydrostatic sensor is immersed at the bottom of the channel and measures pressure (p) to determine water level (h) (Figure 44) by the following formula:

$$h = \frac{p}{\rho \times g} \qquad (16)$$

Where	h	Water level
	p	Total pressure (hydrostatic pressure + atmospheric pressure)
	ρ	Density of the liquid
	g	Gravitational acceleration

The sensor is equipped with a ceramic cell that detects changes in hydrostatic pressure due to variations in water level, while detecting and compensating for changes in atmospheric pressure due to weather (if so equipped). This makes it possible to precisely read the water level in the measurement section, whatever the surrounding conditions (wind, foam, etc.). The probe is linked to a transmitter that converts water level to flow.

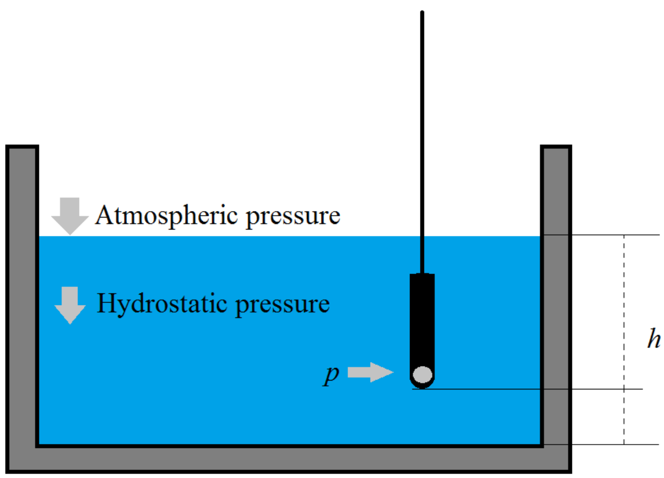


Figure 44: How a hydrostatic sensor works.

Installation

The technical specifications of the device must be taken into account. The selected device must be able to meet effluent characteristics that include interval of measurement, suspended matter, etc. Installation specifications may vary by manufacturer, but the following general instructions apply:

- Adjust the water level interval of measurement *in situ* to match the calibration of the secondary structure.
- Firmly attach the probe using suspension clamps or another manufacturer-recommended tool.

- Install the atmospheric pressure box where it is least likely to risk being submerged.
- Install the tip of the pressure sensor (the cell) at the zero depth of discharge in the primary structure measurement section. Placing the probe at the bottom of the channel should however be avoided when it is located upstream of a weir due to possible sedimentation. The sensor must not touch the channel bed (Figure 44) to avoid any risk of breakage, or require consequent adjustment of the value of the level (h) in the device.
- Protect the probe by placing it inside a PVC pipe or something similar.
- If possible, install the probe in a stilling well to limit the effects of rapid changes in velocity on measurement accuracy.
- Ensure easy access for verification and calibration purposes.

3.3.3 Measuring devices based on travel time

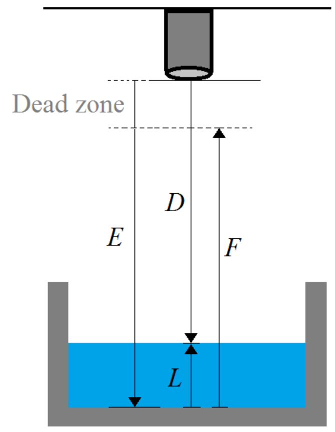
Devices that work on the principle of travel time do not directly measure water level but instead, the distance between the sensor and a reference point. In this case, the water level is obtained by subtracting the distance between the sensor and the discharge surface (Figure 45).

The distance (D) measured by the device is proportional to the travel time (t) of the pulse, where c is the speed of sound (330 m/s) in the case of an ultrasonic sensor or the speed of light (300,000 km/s) for a radar sensor (radar propels radioelectric pulses through air at the speed of light). The following equation applies:

$$\boldsymbol{D = c * \frac{t}{2}} \qquad (17)$$

The distance (E) is known by the system (and corresponds to the zero level), making it possible to calculate water level L:

$$\boldsymbol{L = E - D} \qquad (18)$$



D	Distance between the ultrasonic sensor and the discharge surface
E	Zero level
F	Measurement range
L	Water level

Figure 45: Water level measurement by an ultrasonic sensor.

3.3.3.1 Ultrasonic flowmeter

Description and functional principle

Here, the ultrasonic sensor is suspended above the flow and emits ultrasound pulses in the direction of the water surface. The pulses are reflected back and captured by the sensor (Figure 45). The elapsed time between transmission and capture measures the water level.

When the type of primary structure in use is known (Parshall flume, weir, etc.), the flow can be determined from the water level with one of the conversion tables that come with the device or by using a stage-discharge ratio.

Installation

The technical specifications of the selected device must be taken into account. The device must meet the characteristics of the effluent (measurement interval, temperature, condensation, foam, etc.). Installation specifications may vary by manufacturer, but following these general instructions is mandatory:

- Select a device whose measurement interval (.2-4 m/0-3 m, etc.) matches acceptable primary structure levels.
- Match the location of the measuring point of the primary structure.
- Avoid discharge with foam, floating debris and heavy condensation.
- Check to see that the edges of the measuring section do not distort readings, for example in a narrow channel.
- Centre the sensor between the edges of the measuring section (Figure 46 a but not b).
- Position the sensor perpendicular to the water surface.

- Position the sensor so that measurement can take place at all water levels, unrestricted by the dead zone (Figure 46 c).
- Maintain the free space between the sensor and the water surface so that echo displacement is unobstructed by pipes, structures, etc.
- Meet the guidelines for the maximum distance between the transmitter box and the sensor.
- Whenever possible, install the sensor over a stilling well to reduce the effects of surface discharge turbulence.
- Avoid installing the transmitter box in direct sunlight to protect the electronics from overheating, condensation and storms.

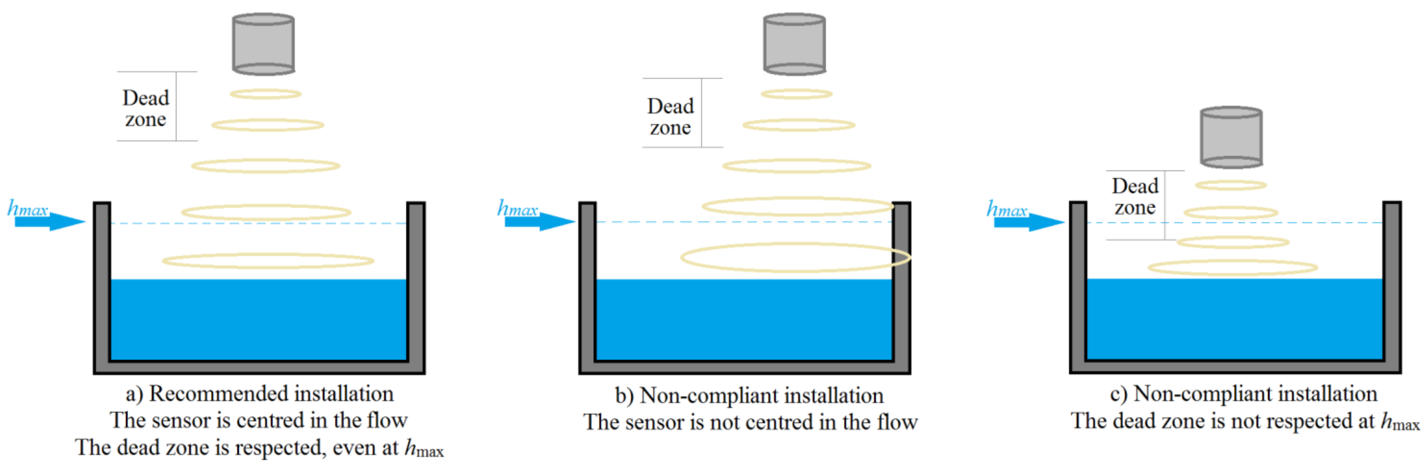


Figure 46: Examples of ultrasonic sensor installation.

3.3.3.2 Radar

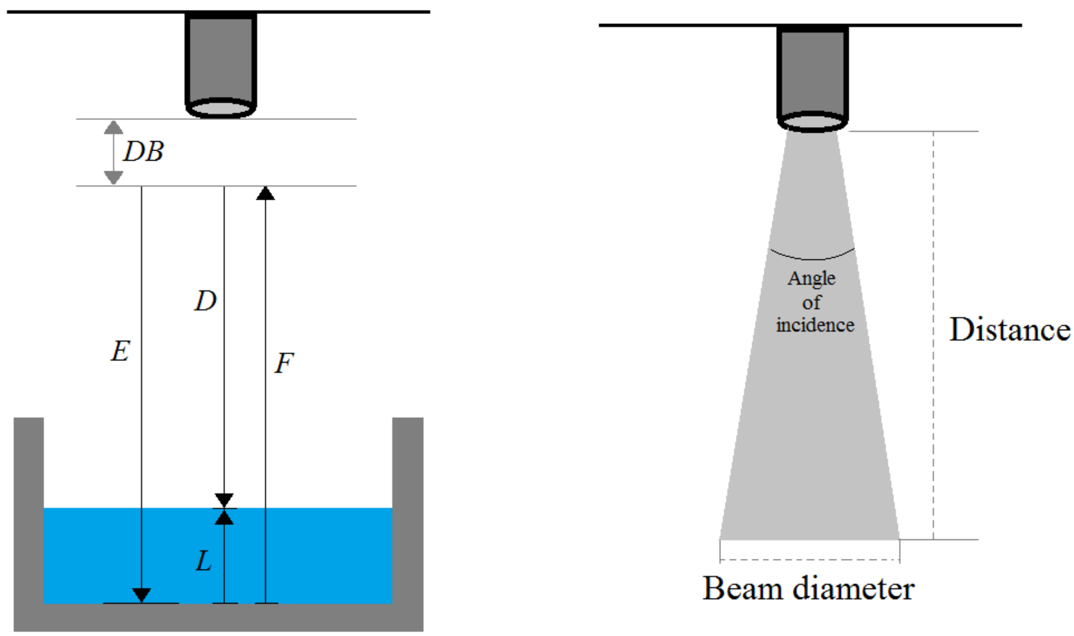
Description and functional principle

Radar measurement of water level can be accomplished either by non-contact free wave or by submerged guided wave radar (also called wire-guided). In non-contact radar, the sensor is installed above the discharge (Figure 47). Guided radar uses a rod or cable that is in direct contact with the liquid (Figure 48).

Non-contact free wave radar

Prior to use, the device is calibrated by entering the zero level (*E*) and its maximum readable level (*F*) (Figure 47). Theoretically, this type of device has no dead zone and can take readings right up to the antenna. In practice, there can be a predefined interference distance (*DB*), within which the signal is not analyzed. This may be used to suppress parasitic signals near the antenna such as those stemming from condensation.

Radar pulses from the antenna are reflected by the surface of the discharge and received by the antenna. A microprocessor analyzes the signals and calculates the level from the radar waves reflected by the surface of the discharge. The travel time of the reflected radar pulse is directly proportional to the distance traveled.



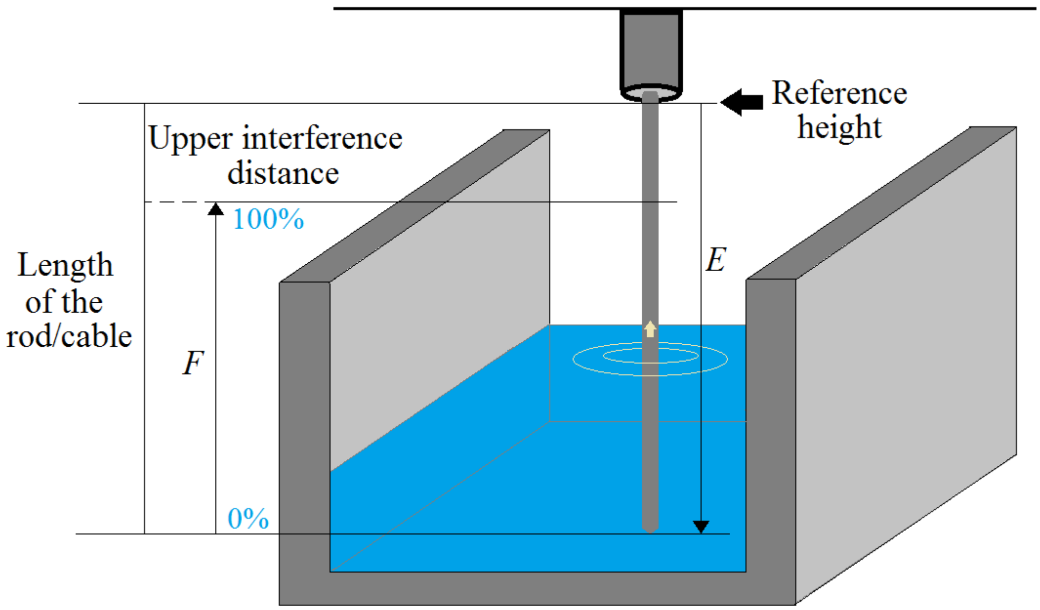
D	Measured distance
DB	Interference distance
E	Calibration at empty (zero level)
F	Calibration at full (measurement range)
L	Water level

Figure 47: Water level measured by free wave radar.

Submerged guided wave radar

Pulses are propelled along a stainless steel rod or cable. When the pulses reach the flow surface, part of the pulse energy is reflected back to the electronic circuit (Figure 48). The time-lapse between signal transmission and echo reception is proportional to the water level.

In this type of device, the interval of measurement depends on the length of the sensor, meaning it can be shortened if need be.



E	Calibration at empty (zero level)
F	Calibration at full (measurement range)

Figure 48: Water level measured by submerged guided wave radar.

Installation

Installation specifications may vary by manufacturer, but the following general instructions are mandatory for both non-contact free wave and submerged guided wave radar devices.

- Install the radar at the measuring point of the primary structure.
- Select a device whose technical specifications match *in situ* conditions such as temperature, pressure, etc.
- Accurately determine the *E* and *F* levels.
- Match the upper interference distance (between the radar reference level and the maximum achievable level) or less, as required.
- For outdoor installation, use a protective weather cover if possible.

The following points apply to non-contact free wave radar:

- Comply with the minimum width of the measuring section (e.g., .5 m) to avoid waves reflecting off the sides of the channel.
- Give preference to calm discharge surfaces without noticeable turbulence.
- Avoid liquids with poor reflectivity.
- Avoid enabling the formation of deposits, high condensation and foam/gel on the sensor.
- Install the antenna perpendicular to the discharge surface.

The following points apply to submerged guided wave radar devices:

- Respect the minimum distance between the device and the sides of the channel (e.g., 10 cm) and clear deposits on the walls, which could reduce the space.
- Avoid contact between the sensor and the bed of the measuring section and comply with the minimum distances set by the manufacturer.
- Install the rod or cable vertically so that it is perpendicular to the discharge surface.

3.3.4 Comparison of secondary devices

Le choix d'un élément secondaire se base sur les spécifications techniques de l'appareil ainsi que sur les conditions *in situ* (ex. : type d'élément primaire, étendue de mesure, présence de vapeur, de mousse, caractéristiques de l'effluent, etc.). Le Table 25 compare les éléments secondaires décrits précédemment sur la base de certaines conditions d'utilisation.

The choice of secondary device is based on its technical specifications and *in situ* conditions. These criteria include the type of primary structure, the measurement range, whether or not there is water vapour or foam, and the characteristics of the effluent. Table 25 compares the previously described secondary devices on the basis of various utilization conditions.

Table 25: Comparison of secondary devices

Utilization	Bubble flowmeter	Hydrostatic probe	Ultrasonic flowmeter	Non-contact radar	Submerged guided wave radar
Type of primary structure	No effect	Flumes > .015 m (otherwise, too many restrictions)	Readings can be skewed by the sidewalls of narrow channels	Readings can be skewed by the sidewalls of narrow channels (≤ .5 m)	No effect, save when the sensor obstructs narrow channels
Wind, water vapour condensation	No effect	No effect	Avoid	Little effect	No effect
Ambient temperature	In general, the available measuring equipment works in industrial and municipal ambient temperatures (e.g., -20 to +60 °C). Refer to equipment specifications to select the model that best matches *in situ* conditions, such as outdoor winter installation. Ultrasonic sensors are influenced by temperature variations and the temperature gradient between the sensor and the water surface.				
Turbulence	No effect but must be solidly attached	No effect but must be solidly attached	Avoid	May be used	Good tolerance

Utilization	Bubble flowmeter	Hydrostatic sensor	Ultrasonic flowmeter	Non-contact radar	Submerged guided wave radar
Foam or debris at the discharge surface	No effect	No effect	Avoid	No or little effect from crest thickness and type of floating objects	Waves guided by the rod can more easily transit through vapour and foam than free wave radar
Suspended particles	May be utilized	Not recommended for liquids with heavy particulate load	No effect	No effect	No effect
Range of water level measurement	Variable by manufacturer/model. Refer to equipment specs to select the best match for *in situ* conditions.				
Range of velocity measurement	Velocity < 1.5 m/s, otherwise stilling well required	No effect	No effect	No effect	No effect
Siltation	No effect	Risk of clogging sensor	No effect	No effect	No effect
Equipment integrity maintenance	No effect; no contact between the measuring probe and the liquid (bubbler pipe)	Sensor may be damaged by chemicals or clogged by debris	No effect; no contact with discharge	No effect; no contact with discharge	No effect but nature of the liquid should be considered
Maintenance	Low cost for the exposed part Dehydrator maintenance Regular cleaning of the bubbler pipe (clogging = risk of pneumatic failure or measurement errors)	Regular cleaning of the sensor to avoid skewed readings	Little maintenance required, non-contact	Little maintenance required, non-contact	Avoid build-up on the cable or rod that could dampen the signal and distort or reduce the interval of measurement
Accuracy (if properly installed)	Variable by manufacturer				
	.1 to 1% of the interval of measurement	.1 to 2% of the interval of measurement	.05 to 3% of the interval of measurement +/- 2-6 mm	.1% of the interval of measurement +/- 1-8 mm	+/- 1-3 mm

3.3.5 Programming the secondary device

These devices use an analog voltage signal to determine a physical value from a related one. For example, a bubble flowmeter determines water level by measuring the pressure required to force air through the bubbler tube against the water pressure.

The analog signal of the device is transmitted at an average current loop of 4-20 mA. This loop makes it possible to transmit the analog signal over a great distance without loss or change.

The sensor measures a physical value such as pressure. The source of the 4-20 mA current converts the value measured by the sensor into a specific current within the 4-20 mA interval. The 0-4 mA current in the loop feeds the transmitter circuit (which therefore must consume less than 4 mA). If the reading drops to 0 mA, the current loop either no longer functions or has errors. As such, the minimum useable value for the 4 mA current output is 0 while the maximum value is 20 mA. The scaled measurement capacity is based on the stage-discharge table of the installed primary structure. As an example, for a .229-m (9-in) Parshall flume, the configuration of the analog output would be as follows:

4 mA	→	0% of the scale	→	0 m^3/h
20 mA	→	100% of the scale	→	882 m^3/h

In order to supply representative values of flow, the flowmeter must take readings at least every minute. If this interval is exceeded, readings become instantaneous and should be treated as estimates. Commercially available flowmeters easily meet this criterion, with most capable of several readings per minute or even per second.

The flowmeter readings for minimum, maximum, average and total flow must be recorded by the device or transmitted to a computer system.

3.3.6 Maintenance, checking and calibration

The following precautions should be taken when the secondary device is switched on, and during routine checks:

- Clean the bed and walls of the channel, as well as the measuring section where the secondary device is installed.
- Remove all instrumentation (sensor, tubing and any other objects) that could interfere with the signal of the secondary device.
- Clean the sensor to avoid siltation and/or grime accumulation.
- Ensure that the reading range of the flowmeter matches the range of the installed primary structure.
- Synchronize the devices for the hour, date, reading range, etc.
- Check the zero of the device.

- Check the accuracy of the flow reading from the secondary device by comparing it to the known reference value, which should be deemed true. This could be, for example:
  - A manual measurement using a permanently installed ruler at the measuring point (Figure 49).

Top view
Ruler attached to the centre of the approach channel at the measuring point of a Palmer-Bowlus flume

Top view
Ruler attached to the wall at a point 2/3 of Section A of a Parshall flume

Figure 49: Sample permanent ruler installations.

  - A movable or permanent reference plate (Figure 50) with rotational capacity can be installed underneath the ultrasonic sensor, enabling it to turn during the checking process. Whether permanent or movable, the reference plate must be level and firmly held when adjusting the secondary device. The height of the plate must be known with precision.

If the value obtained during a check with a ruler or reference plate is the water level, it must be converted to flow prior to comparing it to the value simultaneously obtained by the secondary device. Any observed disparities should be as close to zero as possible and always less than 5%. If this is not the case, an adjustment to the secondary device will be required.

The following example, based on the theoretical equation for a .914-m Parshall flume, shows that the 5% maximum permissible variance can be met when a comparison is made to the water level but may exceed 5% when a comparison is made to flow:

Manual reading of water level: .355 m → 1,553 m^3/h

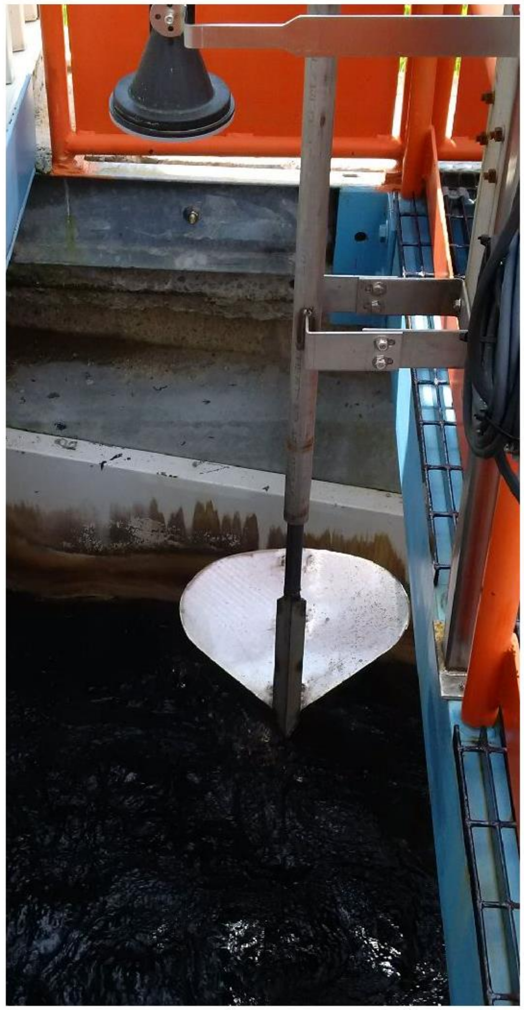
Device reading of water level: .370 m → 1,657 m^3/h

$$\%\ level\ variance = \frac{.355\ m - .370}{.355\ m} \times 100$$

$$\%\ flow\ variance = \frac{1{,}553\ m^3/h - 1{,}657\ m^3/h}{1{,}553\ m^3/h} \times 100$$

- Check data transmission to the computer system. The variance between the values displayed by the local device and the computer system should be as close to zero as possible.

Utilization and adjustment of a temporary reference plate



Sample installation of a permanent, movable reference plate

Figure 50: Sample reference plates.

While secondary structures have a high level of accuracy and problems are rare under laboratory conditions, it is important to note that in-the-field installation and utilization conditions may test performance capacity. As such, accuracy checking and adjustments should ideally be carried out weekly to maintain acceptable accuracy. Device maintenance, adjustment and calibration should be handled by qualified staff to minimize any uncertainty related to human error.

Appendix 3 includes a sample checklist that can be used during the inspection of a secondary device.

Secondary devices…

…are usually flowmeters that measure the value of a physical characteristic corresponding to water level and transforms it into discharge using a known stage-discharge relation.

When choosing a device, consideration should be given to the characteristics of effluent such as particulates, foam, etc.

Installation and utilization conditions may vary on the basis of the functional principles of the device. Manufacturer's recommendations should be followed in all cases.

Regular checks of the device's accuracy are required to ensure that variance between the reading displayed on the device and the transmitted data does not exceed 5% and is as close as possible to 0%.

Regular inspection and accuracy checks should be based on the sample checklist in Appendix 3.

4 MEASURING DEVICE INSTALLATION FOR PRESSURIZED (CLOSED CONDUIT) FLOW

4.1 OVERVIEW

Discharge is considered pressurized whenever liquid is confined in a closed pipe and is subjected to pressure exceeding atmospheric pressure.

As is the case for streamflow measurement in free surface flow, closed pipe systems usually comprise both a primary structure and a secondary device. Primary structures produce a signal that is proportional to the flow and which is taken, measured and converted to a standard output signal by the secondary device. Primary structures comprise a measuring tube, a unit that generates the desired signal and electrodes that read it. Secondary structures are meant to display and transmit acquired data. Contrary to installations in free surface flow conditions, primary structures and secondary devices in closed pipes are harder to distinguish one from the other visually.

In a closed pipe, flowmeters are used to measure flow. Using technology, flowmeters measure various parameters (also called values) such as pressure, induced electrical voltage and ultrasonic wave travel time to determine the value of discharge velocity in the channel. This value subsequently enables the device to calculate flow using equations that are appropriate to the individual method used. This type of equipment can measure both instantaneous and total flow.

4.2 FLOWMETER CATEGORIES

Because of their individual functional methodology, some flowmeters are submerged in the discharge. This is the case for negative-pressure, insertion and mechanical flowmeters that reduce discharge velocity and lead to loss of load (pressure). Other types of flowmeters installed outside the conduit do not affect discharge values.

Insertion flowmeters calculate flow by averaging the readings of a sensor inserted into the discharge. However, measurement principles vary from one type of flowmeter to another. Ultrasonic, electromagnetic and pressure differential flowmeters are available in both non-intrusive and insertion models (Figure 51).

The values measured by flowmeters are mainly based on volumetric flow (Q_v) except for Coriolis flowmeters, where they are based on mass flow (Q_m).

In the majority of measurement principles, average discharge velocity is directly determined or indirectly calculated from a related value. Figure 51 illustrates various pieces of equipment dealt with in this publication on the basis of their measuring principle.

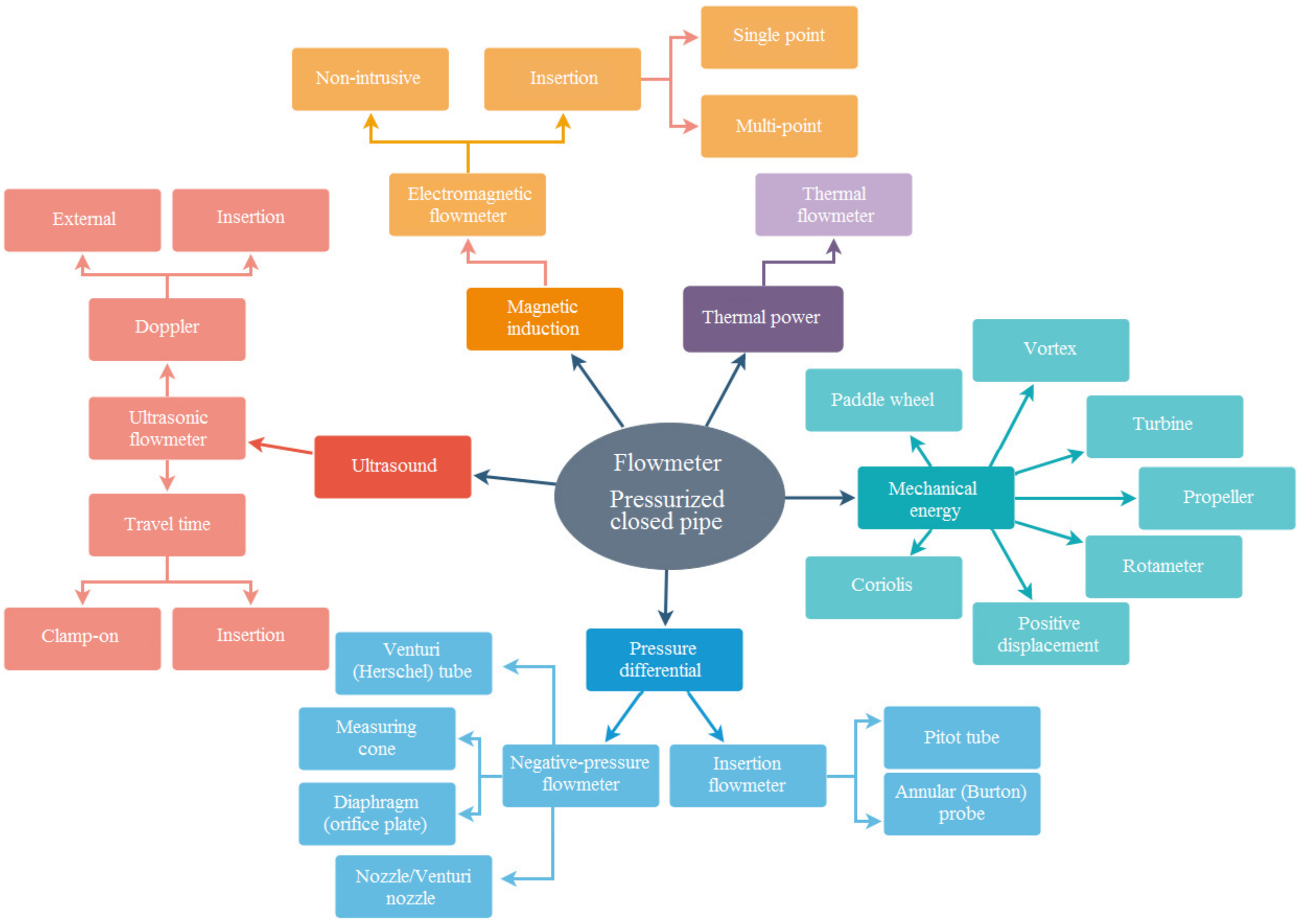


Figure 51: Classification of pressurized closed pipe flowmeters based on their measuring principle.

4.3 ACCURACY

Pressurized closed pipe flowmeters are known for their high accuracy. Manufacturer measurement error data (also called degree of accuracy) is theoretical and therefore based on optimal installation.

For this type of device, measurement errors usually vary between .5 and 3%, meaning that to maintain this range of accuracy, *in situ* conditions must match the reference conditions and values must fall within the manufacturer's recommended limits. As such, it is essential to select equipment that is optimally adapted to the characteristics of the liquid and *in situ* conditions. Installation, utilization and maintenance must also correspond to the manufacturer's recommendations, as well as to applicable ISO standards and generally accepted practices.

4.4 TYPE OF DEVICE BY FUNCTIONAL PRINCIPLE

4.4.1 Differential pressure

This section includes two categories of equipment whose measurement principle is based on pressure differential: negative-pressure and insertion flowmeters.

4.4.1.1 Description and functional principle of negative-pressure flowmeters

This type of flowmeter measures velocity divided by differential pressure. Fluid flows through a negative-pressure geometric constriction that creates a difference in pressure between conditions upstream and downstream of the constriction.

Given that the volume of fluid is the same upstream and downstream of the constriction (conservation of energy principle) and that the total volume of fluid must circulate during the same lapse of time, the velocity of the fluid level must of necessity increase in the constriction area. Since velocity is a function of flow, greater flow means greater velocity and hence a greater pressure differential upstream and downstream of the constriction. This variation in pressure makes it possible to determine the volumetric flow.

This flowmeter has two parts (Figure 52):

- A negative-pressure device that measures differential pressure (Δp) (primary structure) (diaphragm, Venturi, etc.).
- A differential pressure sensor (secondary structure) that calculates pressure difference and measures flow.

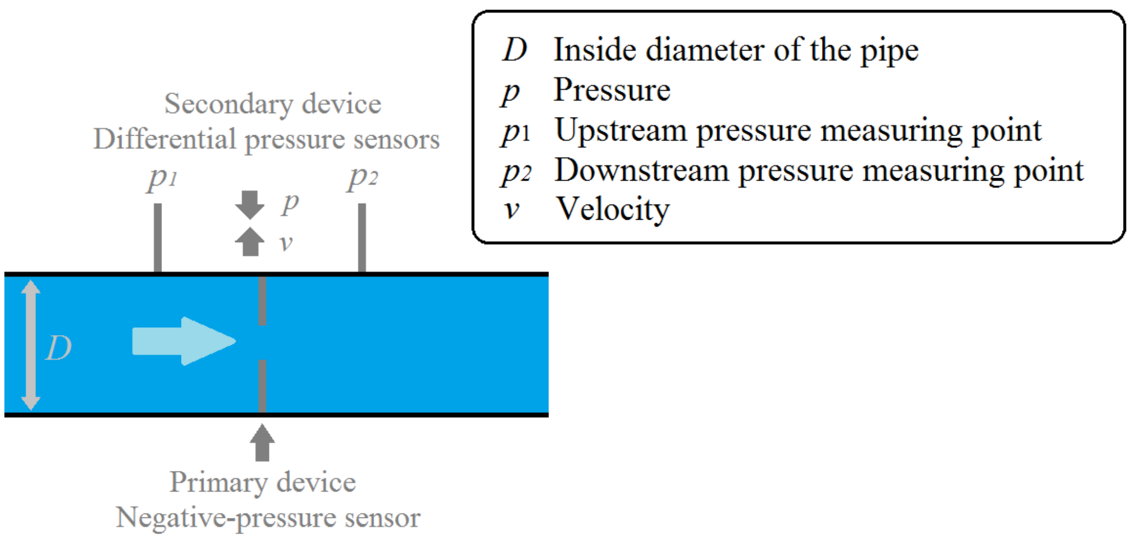


Figure 52: General illustration of a negative-pressure differential flowmeter.

There are four categories of negative-pressure flowmeters, as follows:

Venturi (sometimes called Herschel) tube (Figure 53):

- Converging inlet cone (or choke) where the fluid accelerates.
- Cylindrical neck.
- Diverging outlet cone where the fluid returns to its original pressure.
- Pressure taps upstream and downstream of the constriction (cylindrical neck).

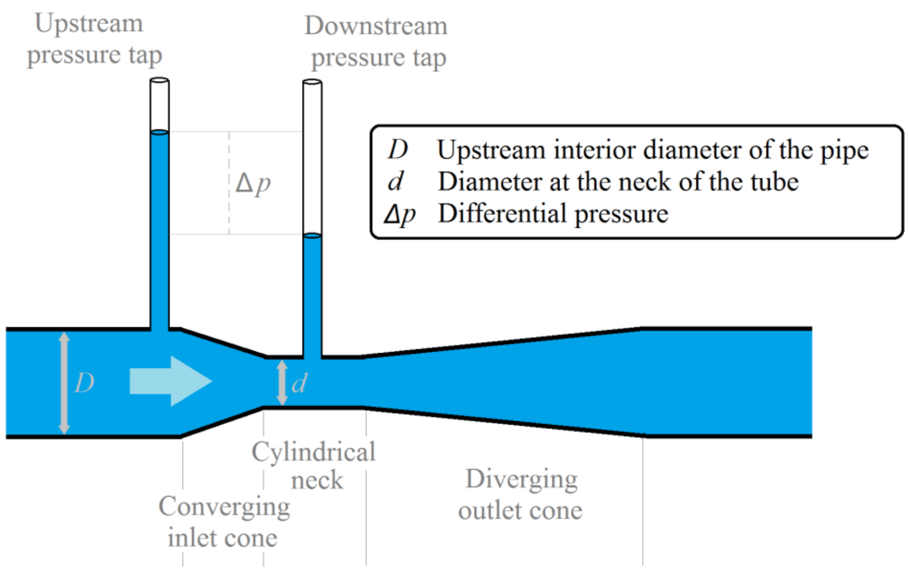


Figure 53: A Venturi (or Herschel) tube.

Diaphragm (or orifice plate) (Figure 54):

- A thin rigid stainless steel plate with an orifice whose diameter and shape are well defined (circular, square, oval, triangular, etc.).
- The plate is inserted into the channel perpendicular to the direction of discharge.
- Pressure is read upstream and downstream of the plate.

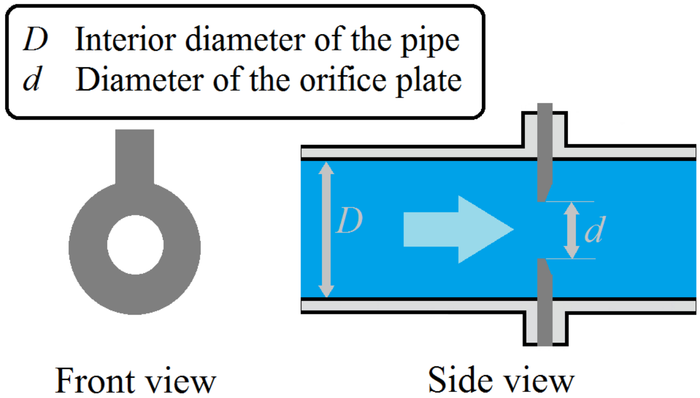


Figure 54: Diaphragm (orifice plate).

Flow (or Venturi) nozzle (Figure 55):

- Rounded constriction.
- Cylindrical neck following the line of the channel.
- No diverging section.
- Pressure is read upstream and downstream of the constriction.
- Considered as a variant of the Venturi tube; characteristics intermediary between the Venturi tube and the diaphragm models.

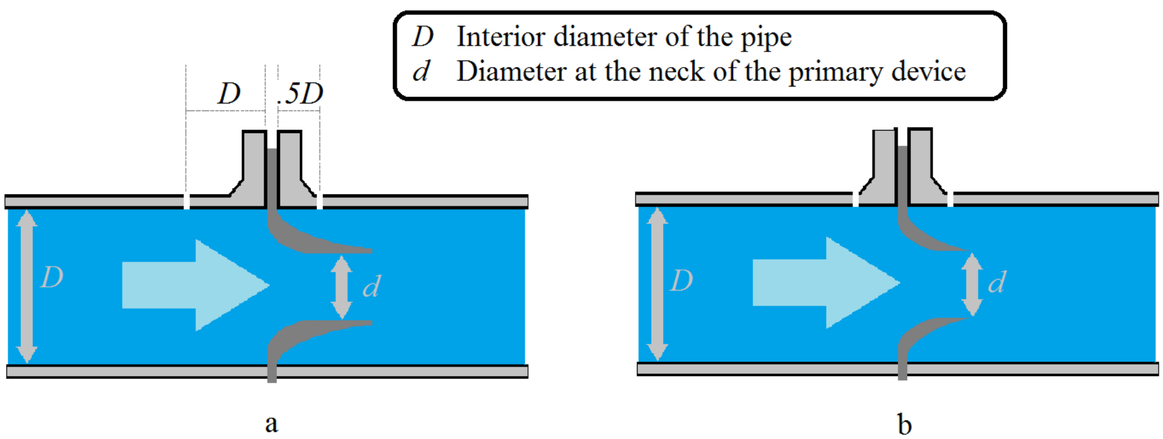


Figure 55: Long radius (a) and ISA (b) flow nozzles.

Measuring cone (Figure 56):

- Flanged discharge tube.
- Section A measuring cone (nose can be flat, sharp, curved or bent), including diameter (*dc*).
- Support structure for maintaining the cone concentric to the centre of the pipe.
- Upstream and downstream pressure-reading taps.

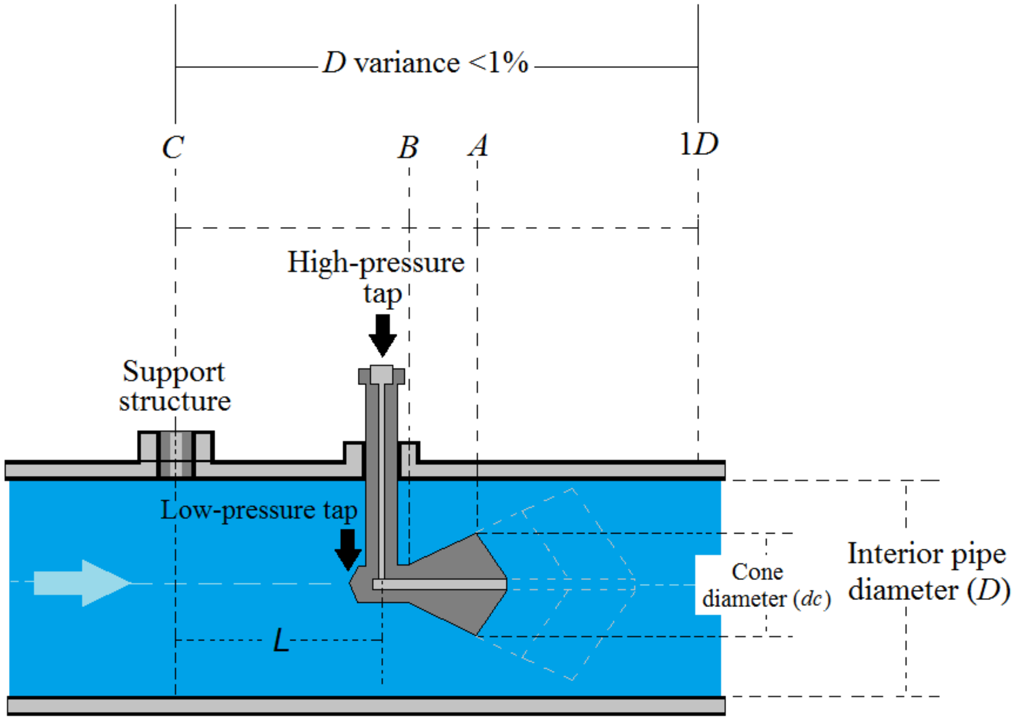


Figure 56: Measuring cone.

4.4.1.2 Insertion flowmeters: description and functional principle

Insertion flowmeters use the principle of differential pressure. They come in two types: Pitot tubes and Annubar (or Burton) sensors. The Pitot tube flowmeter (Figure 57) consists of a tubular sensor inserted directly into the channel. It determines streamflow from the direct measurement of dynamic pressure.

A low-pressure (exterior) tube is installed perpendicular to the fluid discharge. This could be a measuring point facing the downstream side of the discharge, or a tube whose tip is not in direct contact with it. The pressure here, therefore, corresponds to static pressure at one part of the section.

The high-pressure (interior) tube is installed parallel to the fluid discharge and in direct counter-flow contact with it. The tube is inserted so as to slow the discharge. Pressure measured at this point, therefore, corresponds to total pressure, which is the sum of static and dynamic pressure.

A manometer measures the difference between the two (differential pressure), thus making it possible to obtain the dynamic pressure of the discharge and, indirectly, a local estimation of velocity. The outlet pressure of the flowmeter can also be linked to a differential pressure transmitter that provides an electrical signal that is proportional to the velocity of the discharge over the measuring track (Figure 57).

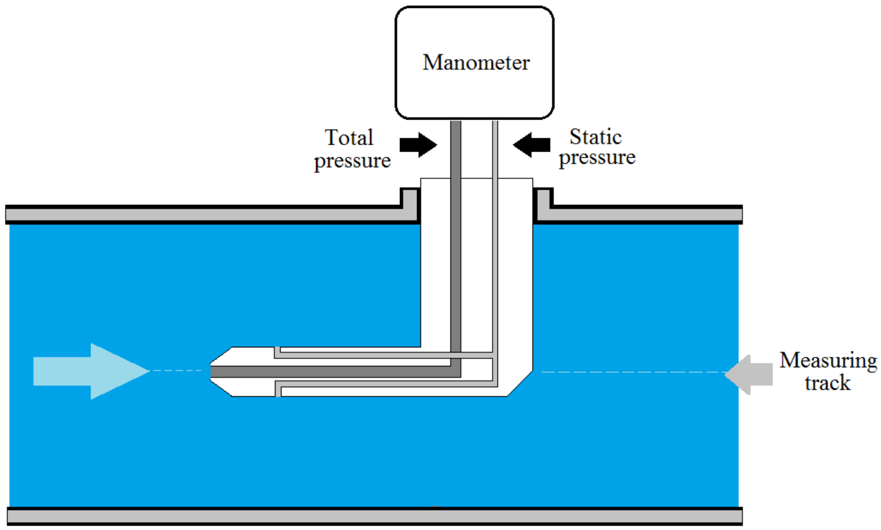


Figure 57: Pitot tube–measuring track readout.

In some models, velocity is measured at a single point of the discharge profile, i.e., over a measuring track (Figure 57). The streamflow is therefore calculated on the basis of instantaneous discharge velocity multiplied by the cross-sectional area. If we postulate that the velocity is uniform throughout the section of the channel, we can determine the streamflow (Q_v). This device must only be used in channels where velocity is well-distributed. Multiple calibrations are required at various flows, due to the fact that the velocity profile can change with the streamflow and also because readouts are no more than samples of local velocity in the channel.

Other Pitot tube and Annubar (or Burton) models (Figure 58) use this functional principle, except that the high-pressure readout is the average of velocity readouts inside the pipe. These instruments are more accurate because they depend neither on the position of the sensor nor the velocity profile of the discharge.

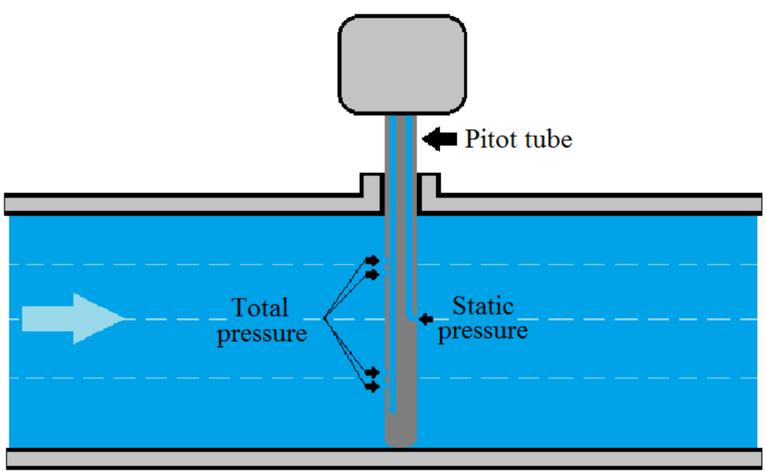


Figure 58: Pitot tube–readout from several pressure taps.

4.4.1.3 Applications

Negative-pressure and insertion flowmeters are made for use with monophasic liquids that are physically and thermally homogenous.

Diaphragm and Pitot tube flowmeters are not recommended for liquids containing suspended matter, given the possibility of sediment accumulation. Flow nozzle and measurement cone instruments may be used in these circumstances, but Venturi tubes are advisable when there is suspended matter.

These instruments can be successfully used for a wide variety of channel diameters (see models and manufacturers). Table 26 shows various diameters available for different types of flowmeters.

Table 26: Channel diameter ranges (mm) for different types of flowmeters

Venturi tube	Diaphragm	Flow nozzle	Measurement cone	Pitot tube
25-3,000	10-1,000	25-630	15-1,800	50-1,800

4.4.1.4 Installation

This section deals with general installation information. Individual instruments have their own special installation instructions, and manufacturer recommendations must be followed.

ISO standards 5167-1 to 5167-5 provide details on Venturi tube and diaphragm, nozzle and measurement cone flowmeter installation, while ISO 3966 addresses Pitot tubes.

The following points must be taken into account when installing the above instruments:

- The measuring section of the channel must be full.
- The position of the device over the channel. A horizontal position is generally recommended. However, that position could lead to accumulation of suspended matter (e.g., upstream of a diaphragm). In such cases, it is required to check whether a vertical position is more acceptable or if a different type of device needs to be selected.

  The vertical position may be acceptable, but the discharge will then need to rise in level in order to maintain fully-pressurized channel flow.
- The straight lengths of a constant-diameter cylindrical conduit and minimum specified constant lengths. These lengths are a function of the diameter (D) of the channel and may run from 3 to 60D upstream and 3 to 5D downstream of the measuring device.

  In some cases, using a discharge conditioner may make it possible to use shorter lengths upstream.

  Minimum lengths will vary by device type, brand and model, but also as a function of discharge disturbance. For example, there may be one or two elbows, an expansion of the channel, a pump, a valve, a filter, etc.

- The number and location of upstream and downstream pressure taps. These may change based on the diameter (D) of the channel, for example, 1D upstream and .5D downstream.
- The characteristics of the device, such as the thickness of the orifice plate.
- The characteristics of the pipe, such as its width and construction material.
- The interior of the pipe must be clean at all times. All metallic defects such as flakes must be removed.
- The primary structure must be installed in the pipe so as to ensure that discharge conditions immediately upstream are calm and free of disturbances.

4.4.2 Magnetic induction

This section deals with magnetic induction flowmeters, including electromagnetic insertion and non-invasive models.

Description and functional principle of non-invasive and insertion electromagnetic flowmeters

A non-invasive electromagnetic ("sleeve") flowmeter generates a magnetic field that is perpendicular to the discharge by a set of electromagnetic coils placed on each side of the channel, as well as two electrodes that are drilled transversally into the conduit. These electrodes are flush with the internal surface of the pipe and touch the liquid without affecting the discharge or causing any loss of load.

Figure 59 illustrates how a non-invasive electromagnetic flowmeter works when installed outside a pipe.

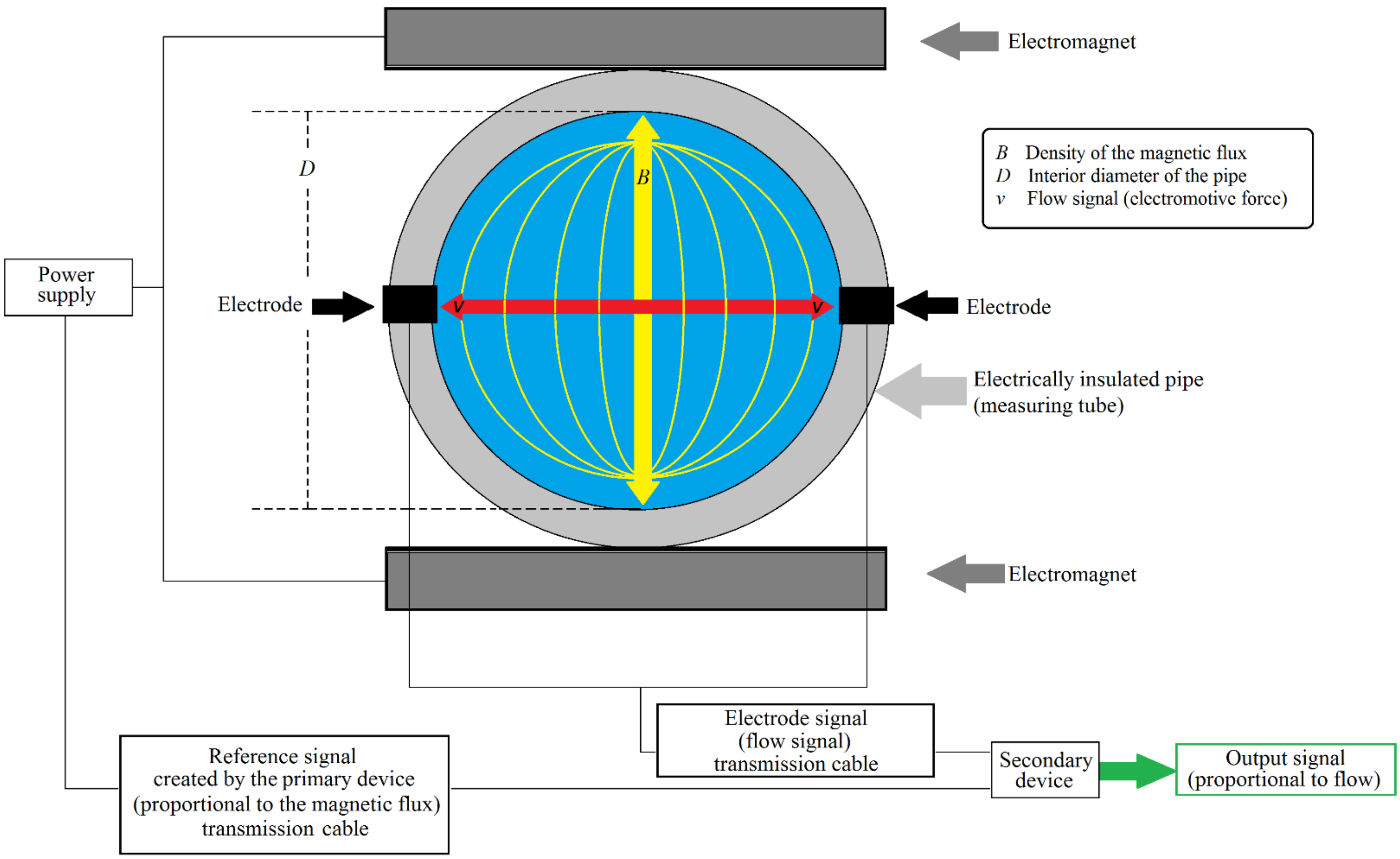


Figure 59: Cross-sectional view and functionality of a non-invasive electromagnetic flowmeter.

Electromagnetic flowmeters are also available as insertion models, where the calculation of average velocity can be handled by either a single measuring point or by multiple measuring points. In the first case, the flowmeter measures v_{max}, which is then corrected to $v_{avg.}$ In the second, the device reads velocity at several points in the diameter of the pipe and calculates the average.

Electromagnetic insertion flowmeters have a sensor inserted at the centre of the pipe or, for very large diameter pipes, at a point 1/8 of the diameter, making it possible for readings to occur at a single point (Figure 60). The magnetic field is therefore confined to the tip of the sensor. Installation at the centre of the pipe should always be preferred.

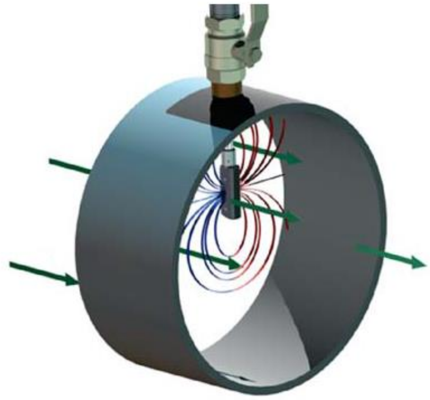


Image: Greyline Instruments

Figure 60: An insertion electromagnetic flowmeter (AVI 5.0).

Several electrodes may also be placed over the body of the sensor in a multi-point array. In this setup, the average flow is obtained over the entire diameter of the pipe (Figure 61). This type of equipment has the advantage of compensating for unequal discharge profiles that may be caused by an insufficient approach length (e.g., elbows) or vortex discharge conditions. This type of equipment is mainly chosen for clean liquid applications since the sensor may obstruct the flow of suspended matter and debris.

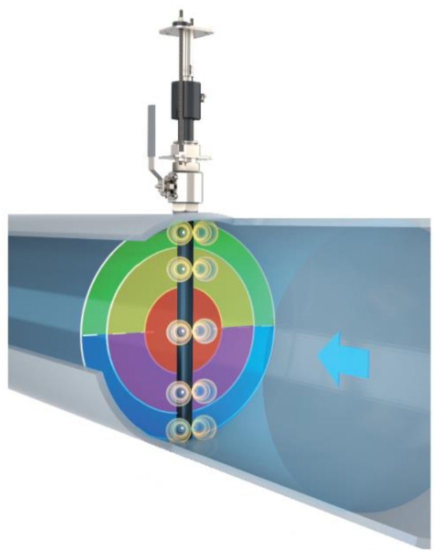


Image: Flow-Tronic, Belgium

Figure 61: An insertion electromagnetic flowmeter (TORPEE-MAG).

Electromagnetic flowmeters include a primary and one or more secondary devices, which can be combined, but this can make it difficult to visually distinguish the component parts.

The primary device produces a signal that is proportional to flow and, in some cases, also produces the reference signal. It includes the following components:

- A closed measuring pipe that is electrically insulated and made of or covered by a non-magnetic material through which the conducting liquid flows.
- One of more pairs of diametrically opposed electrodes that measure the signal generated in the liquid.
- Magnetic coils (electromagnets) that are powered by alternate or direct current and generate a magnetic field in the pipe (yellow lines in Figure 59). The coils may be set up outside the pipe or incorporated into the piping (non-invasive flowmeter) or along the flowmeter rod (insertion flowmeter).

The secondary device comprises all instruments that extract the flow signal from the signal generated by the electrodes and amplify and convert it to a standardized output signal that is proportional to the flow.

This section is based on ISO 6817 and deals with electromagnetic flowmeters using alternating or pulsed direct current that measure the streamflow of a liquid conductor in a closed pipe running full.

4.4.2.1 Applications

Electromagnetic flowmeters are able to calculate bidirectional velocities. The velocity interval *in situ* varies with the diameter of the pipe and must correspond to the instrument's velocity interval, which can vary by device type (insertion or not)–for example, from .2 to 10 m/s. It is advisable to select the diameter of the pipe so that the velocity of the liquid at minimum flow is as high as possible to optimize accuracy and stability at the zero. Specifications on this point can be manufacturer-specific.

The conductivity of the liquid must also be higher than the minimum conductivity of the selected device (e.g., 20 µS/cm) and uniform throughout the discharge.

Available diameters vary by flowmeter make and model (25-3,000 mm). The variety of installation options (pipe diameter, electrodes, assembly without obstruction, insertion, etc.) enables adaptation to different types of discharge, from clean liquids to sludge, but excluding hydrocarbons and distilled water. This type of instrumentation works efficiently for both small and very large volumetric flow.

4.4.2.2 Installation

Commercially-available electromagnetic flowmeters have satisfactory accuracy. However, to conserve the theoretical performance of a device, the following must be considered during the installation process:

- Avoid installing the unit near an electrical facility that could affect the flow signal.
- Carefully align the axes of the primary device and the tubing.
- The interior diameter of the pipe upstream/downstream can usually be identical to the measuring tube. However, if average velocity at maximum flow is less than the manufacturer's recommended value, it is advisable to use a primary device with a

smaller diameter. If the diameter of the flowmeter is undersized compared to the diameter of the pipe, it must be connected with conically-shaped, coaxial pieces.

- There are no theoretical limits to the vertical or horizontal position of the primary device, as long as the pipe remains full at all times. However, depending on discharge conditions, the choice of location may need serious reflection. If there are doubts about whether the pipe is running full, an angled installation may be envisaged (e.g., 45°).
- Vertical assembly is preferable if there is abrasive matter in the discharge, so as to ensure uniform wear-and-tear on the interior of the pipe. Vertical assembly is also recommended in situations where particulates in the discharge may become attached. Otherwise, a purging system will be required.
- Electromagnetic insertion flowmeters are sensitive to air bubbles around the electrodes. As such, an appropriate choice of installation location is vital.
- The device should be installed in a section of the pipe that has a fully developed turbulent discharge profile. The discharge profile may, however, vary considerably due to variations in flow over the network and conditions at each point of installation, becoming laminar at low velocity. As such, serious consideration should be given to the effects of these profile variations on the accuracy of the flowmeter.
- The importance of applying the manufacturer's recommendations for upstream and downstream discharge free of disturbances cannot be overstated. If no manufacturer's recommendations are available, 10 DN upstream and 5 DN downstream distances must be used, DN being the nominal diameter of the pipe. ISO 6817 specifies that an obstruction-free distance of 10 DN upstream of the electrodes is required to ensure that the performance of a device is not modified by more than 1%.
- Spiral flow may influence the signal and change the calibrating factor. It may be difficult to foresee its size and distribution and, as such, a device to eliminate spiral flow may have to be installed upstream of the primary structure.
- Installation needs to take account of subsequent access for maintenance, accuracy checking, checking of the zero and/or calibrating, if required. For example, a drift can be envisaged in certain cases for maintenance and verification purposes or to cut off flow in the primary structure in order to adjust the zero.

The installation of the secondary device must also comply with the manufacturer's specifications. In general, the following should be considered when choosing the installation location.

- Ensure that the location is accessible.
- Avoid excessive vibration.
- Comply with the manufacturer's specifications regarding ambient temperature and moisture.
- Avoid direct exposure to sunlight.
- Ensure that the cables carrying the electrode and reference signals are approved by the manufacturer and are also as short as possible while not exceeding the manufacturer's maximum suggested lengths.

- Avoid installing signal cables near high-voltage power lines.
- Ensure that the following are shown on the device or an identification plate: device type, serial number, electrical power (voltage, amperage and wattage), output signals and maximum impedance.

4.4.3 Ultrasound

This section includes instrumentation based on transit time and the Doppler Effect.

4.4.3.1 Description and functional principle of ultrasonic flowmeters (external and insertion)

The principle of transit time is based on the speed of a wave through moving water. The sensors may be placed outside the pipe ("clamp-on") (Figure 62) or can be intrusive (insertion) (Figure 63).

Generally speaking, ultrasonic insertion devices have greater accuracy than clamp-ons, but installation is more complicated. This option may be required when the pipe is not permeable to ultrasound waves. The measuring principle is the same for insertion and external devices.

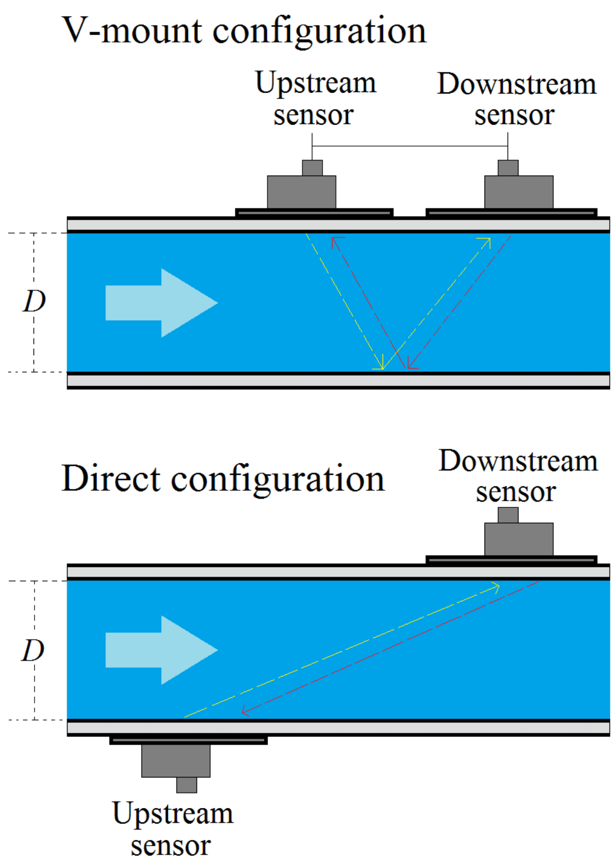


Figure 62: Sample installations of clamp-on transit time ultrasonic flowmeters.

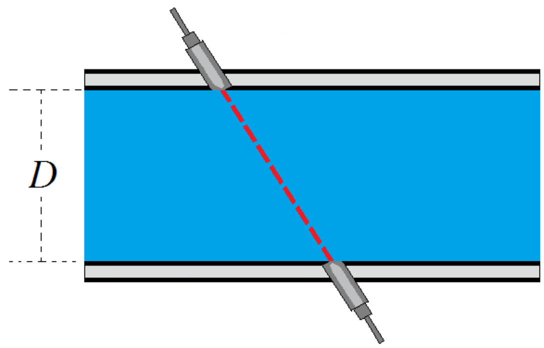


Figure 63: Ultrasonic insertion flowmeter.

The acoustic signal (impulse or pulse) is sent diagonally to the axis of the pipe by the upstream and downstream sensors, which alternate between signal transmitters and receivers.

If there is no discharge, transit time will be the same in both directions. However, as the discharge velocity increases, the velocity of the acoustic signal in the direction of the discharge increases and the velocity of the signal in the opposite direction decreases (Figure 64).

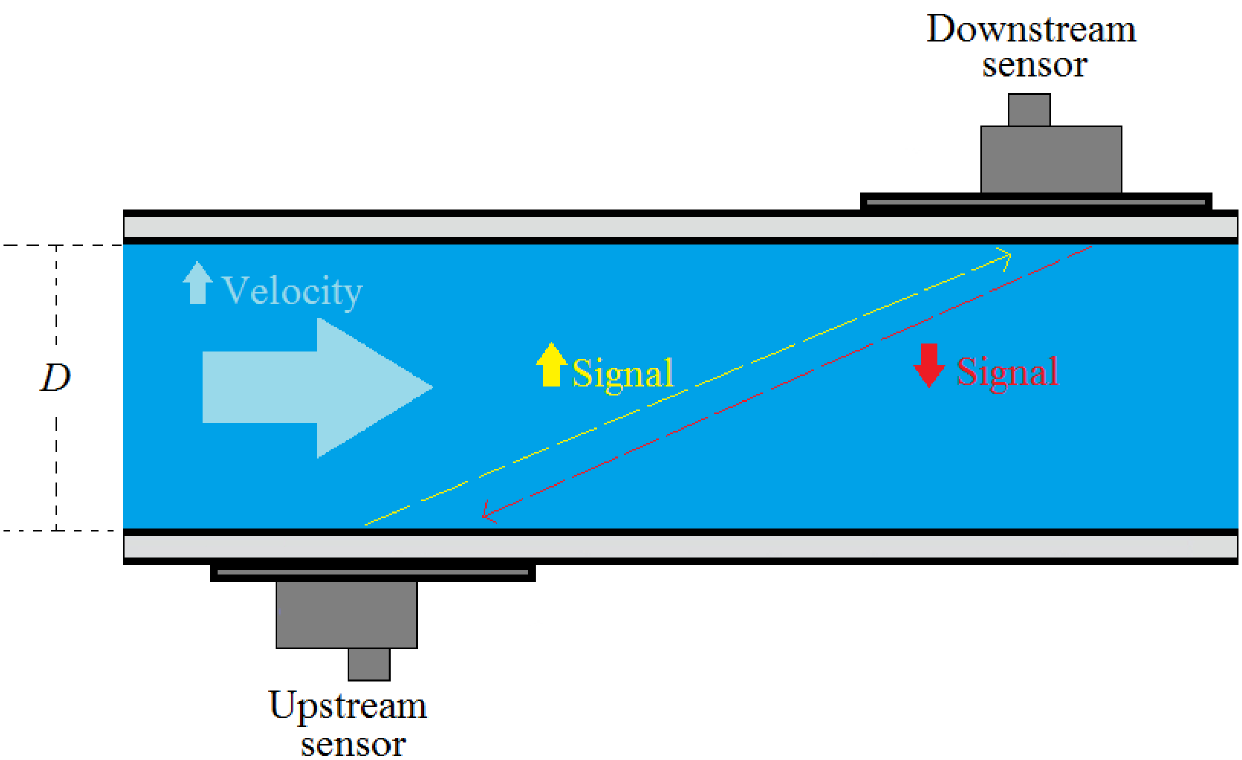


Figure 64: Signal modification due to variations in the velocity.

The difference in transit time between the acoustic waves directed downstream and upstream is proportional to the velocity of the liquid in the pipe, enabling average velocity and therefore streamflow to be determined.

As illustrated in Figure 62, the sensors may be assembled in a V-mount configuration, installed side by side over the pipe: The signal is bounced back by the pipe itself; or in direct configuration (Z- shaped) where the sensors are installed on both sides of the pipe. A third mode exists, the W-shaped configuration, but it is rarer and only used in small pipes.

4.4.3.2 Description and functional principle of external and insertion Doppler flowmeters

The Doppler Effect is based on the frequency variation of reflected waves. These types of flowmeters generally have two ceramic sensors that alternate between transmission and reception.

The transmitter sends a wave or vibration through the discharge, which captures the presence of particulates or air bubbles (Figure 65) that act as reflectors, returning the ultrasound waves to the receiver for recording. If the reflectors are moving, the reflected acoustic waves show a change or shift in frequency called the Doppler Effect (or shift) that is different from the emitted frequency. The difference between the two frequencies is directly proportional to the velocity of the reflectors and hence to the velocity of the discharge, from which the streamflow can be calculated.

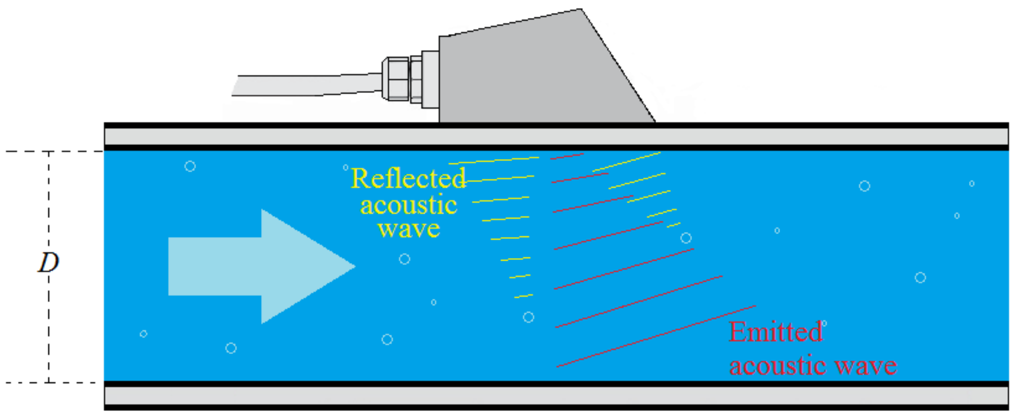


Figure 65: Illustration of how an ultrasonic Doppler flowmeter works.

4.4.3.3 Applications

Transit time ultrasonic flowmeters can be used with monophasic, acoustically conductive liquids that can carry ultrasound. Most clean liquids and liquids with small amounts of particulates or gas bubbles are good candidates.

Water conductivity does not impact the use of this type of flowmeter which, however, is sensitive to water quality, since the fluid to be measured cannot contain a lot of bubbles or solids. If it does, the sound wave frequency will decrease and be unable to travel all the way through the pipe.

The measuring principle of the Doppler flowmeter requires gas or particulates in the discharge to work properly.

Commercially available flowmeters of this type (external or insertion) and model can be installed over a wide range of pipe diameters. Transit time flowmeters have a range of from 10 to 9,000 mm, while the range of Doppler flowmeters is from 10 to 1,000 mm. The recommended discharge velocity range for transit time flowmeters is from .1 to 25 m/s, and from .05 to 12 m/s for Doppler devices.

4.4.3.4 Installation

The manufacturer's recommendations must be met during equipment installation. The following must be considered based on the type of equipment:

Transit time:

- The pipe must be made of a material that favours ultrasound wave propagation. Porous materials such as concrete and cast iron are to be avoided.
- The pipe must be full at all times.
- The measuring section must not be located in proximity to hydraulic disturbances such as elbows, valves and sluice gates or immediately downstream from pumps, etc.
- Installation over pipes with backflow rich in air or gas bubbles likely to disturb the propagation of ultrasonic waves should be avoided.
- The flowmeter may be installed vertically or horizontally. However, the latter option comes with a higher risk of sediment accumulation.
- Caution must be taken to guarantee a perfectly accurate orientation of the transmitter and receiver sensors.
- This type of equipment is sensitive to velocity profile changes, and velocity readout accuracy can be compromised by distortions in the profile. As such, this type of flowmeter must only be installed in locations where the discharge profile is fully developed.
- Installation requirements include a straight length of between 5 and 20 DN upstream and 3 to 5 DN downstream in compliance with the manufacturer's recommendations and disturbance type, such as a pump.

This type of flowmeter can measure flow even under very poor conditions, and air in the pipe will not lead to noticeable data loss or impairment. In addition to the installation conditions, minimum signal quality and strength should always be met to enable proper interpretation of data.

Doppler:

- The material of the pipe over which the sensor is installed must enable the transmission of ultrasound. If this is not the case, the sensor can be inserted into the pipe.
- The pipe must be full at all times.
- The measuring section must not be located in proximity to hydraulic disturbances such as elbows, valves and sluice gates or immediately downstream from pumps, etc.
- The sensor must be installed at the centreline of the discharge.

- The average axis of the discharge in the measuring section must always be parallel to the walls of the pipe.
- The flowmeter may be installed vertically or horizontally. However, the latter option comes with a higher risk of sediment accumulation.
- For outdoor installation, the sensor should be set flat over the outside wall of the pipe.
- Installation requirements include a straight length of between 10 and 15 DN upstream and 5 DN downstream in compliance with the manufacturer's recommendations and the actual type of disturbance, such as a pump.

4.4.4 Mechanical energy

This type of instrument is often seen as an indicator of flow, and is as effective as a flowmeter. The models shown below are for informational purposes.

4.4.4.1 Description and functional principle of paddlewheel and vane flowmeters

The paddlewheel flowmeter (Figure 66) must first be distinguished from the vane flowmeter (Figure 67). In the latter model, fluid discharge, its mass and eventually the spring exert force on the vane. The balanced position of the vane is a function of the streamflow and can be converted to an electrical signal by a potentiometer whose axis is the same as the vane. Vane flowmeters are not described in detail in this publication.

Paddlewheel insertion flowmeters use the mechanical energy of the discharge liquid to turn the wheel, whose rotation is proportional to the discharge velocity. The rotation can be detected mechanically or by a magnetic pulse. In the latter case, the pulse transmitter processes the signal to determine the streamflow of the discharge.

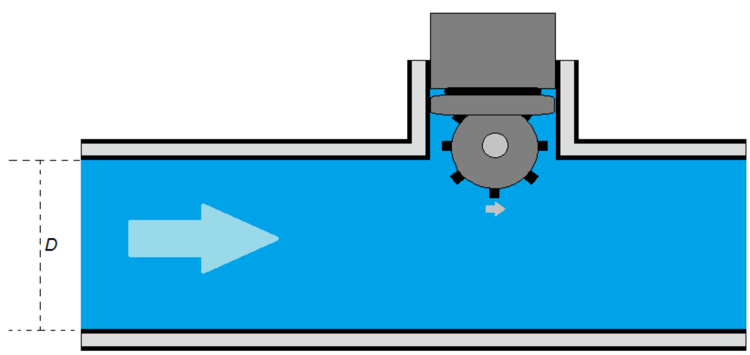


Figure 66: Paddlewheel flowmeter.

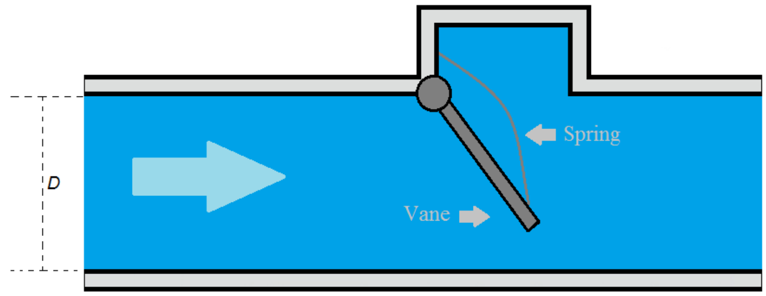


Figure 67: Vane flowmeter.

4.4.4.2 Description and functional principle of vortex flowmeters

Vortex insertion flowmeters measure the volumetric flow of the discharge.

A series of vortices (or eddies) is induced upstream of a bluff obstacle called a vortex tube, set in the discharge (Figure 68). The measuring principle is based on how the vortices move around the obstacle. This phenomenon is similar to what is seen in a river when flow is disturbed by a bridge pillar.

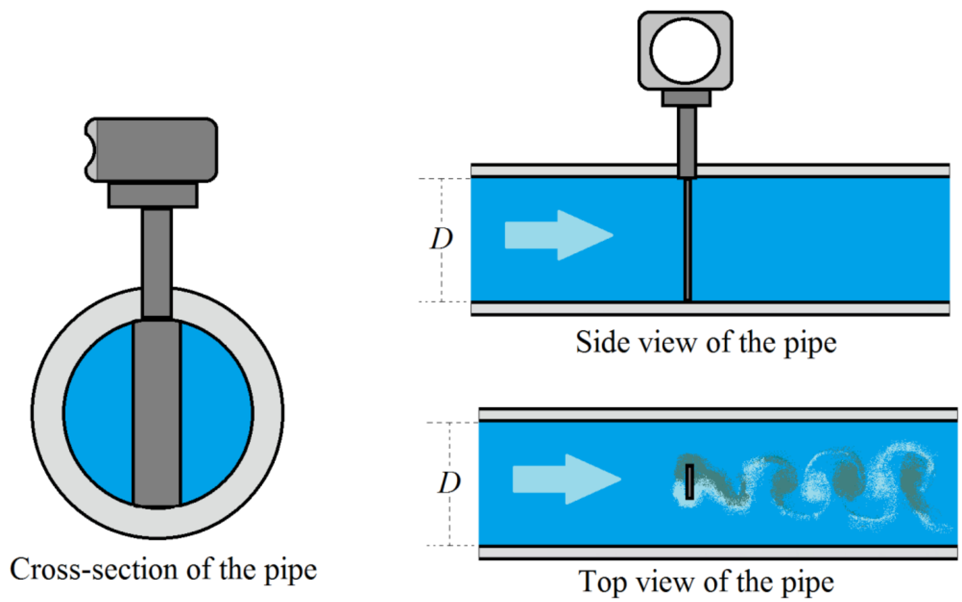


Figure 68: Vortex flowmeter.

When a vortex detaches, it causes unsymmetrical flow that changes the distribution of pressure. The changes are detected and measured by a sensor. The frequency of the vortices is directly proportional to the velocity of the discharge. The digital processing capability of the instrument counts the number of vortices and converts that into velocity using a 4-20 mA output signal.

4.4.4.3 Description and functional principle of the turbine flowmeter

The turbine flowmeter has three main components:

- The turbine sensor (current meter/blade rotor), installed in the pipe along the central axis.
- A transducer (also called the output or transmitter) that transforms the rotation of the turbine into an electrical signal that can be used by the display.
- A flow or volume display.

The mechanical energy of the discharge rotates the turbine, whose rotational velocity is proportional to the discharge velocity and hence to the streamflow (Figure 69).

As the liquid transits the flowmeter, it rotates the blades of the turbine around the instrument's central axis. The angular (rotational) velocity of the rotor is directly proportional to the velocity of the liquid transiting the turbine. The output is measured by a transducer mounted over the flowmeter and converted to a signal that is proportional to the instantaneous flow.

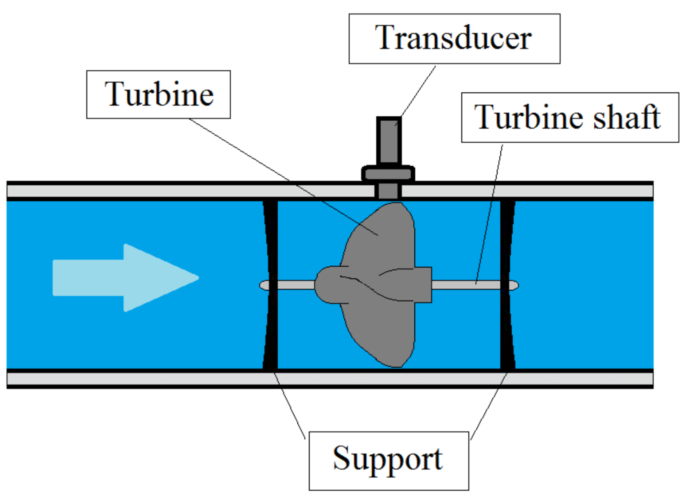


Figure 69: Turbine flowmeter.

Given its working principle, this device is best adapted to moderate, constant-velocity flow. In fact, it provides less accuracy at low flow levels due to the inertial slowdown of the rotor and is also not recommended in high-velocity flow due to the risk of premature wear-and-tear of the rotors (utilization < 5% of the maximum streamflow).

4.4.4.4 Description and functional principle of the Rotameter/variable area flowmeter

A Rotameter consists of a small float inserted into a vertical conical tube (Figure 70). The measuring instrument comprises both a variable area machined tube and the float. The length of the tube is between 110 and 350 mm.

The liquid enters the measuring tube, rising. When the streamflow increases, the liquid generates increased force and pushes the float upwards until equilibrium is reached among all the forces at work (friction, weightlessness and floatability). Once the float is stable, the upward force of the flow is in equilibrium with the mass of the float. Since streamflow is proportional to the displacement of the float, each measurable position of the float corresponds to a particular flow value, the averages of which are marked on the tube.

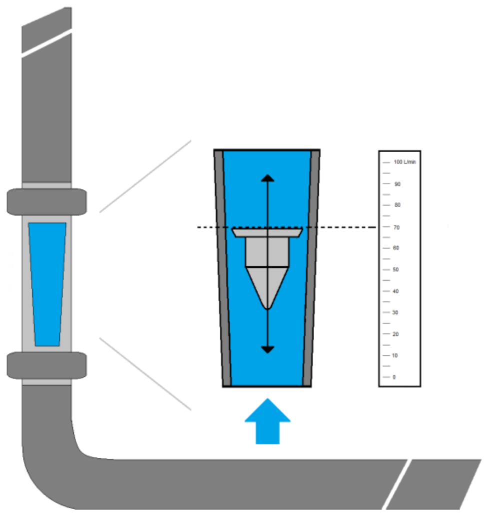


Figure 70: Rotameter.

4.4.4.5 Description and functional principle of the positive displacement flowmeter, also known as the geared flowmeter

Contrary to instruments that measure a related value such as velocity, the positive displacement flowmeter directly measures the volume of liquid transiting the device.

This type of flowmeter within a high-precision chamber. This can be compared to repeatedly filling a beaker with and pouring the contents downstream while counting the number of times the beaker is The rotating components are connected by moving joints (*Source: Macnaught USA* Figure 71). A variety of geometrical types of positive displacement flowmeters are commercially available.

Source: Macnaught USA

Figure 71: Functional principle of the positive displacement flowmeter.

Rotation is mechanically detected and the transmitter processes the signal generated by the rotation to determine the streamflow. As the velocity of the liquid increases, the rotating gears turn proportionally faster.

The rotators are designed so that the joints are able to prevent the liquid from transiting the flowmeter without any slippage.

4.4.4.6 Description and functional principle of the Coriolis (or mass/inertial) flowmeter

Mass/inertial flowmeters use one of two technologies: thermal and Coriolis. Since thermal flowmeters are mainly used to measure gas flow, they are not described in this publication.

A mass/inertial flowmeter measures flow based on mass, not volume. As such, it measures the quantity of matter transiting the instrument, which must often be corrected to the density of the liquid. Variations in temperature and pressure do not affect mass. The accuracy of the Coriolis flowmeter is often considered superior to volumetric devices, which are nonetheless reliable as long as operational conditions match calibration ones.

This type of device is composed of a transmitter and a sensor that together form a single mechanical unit. Depending on the manufacturer, the Coriolis flowmeter may come in the form of a single, double or straight U-shaped tube (Figure 72). It measures the mass acceleration of the liquid moving toward or away from the centre of rotation.

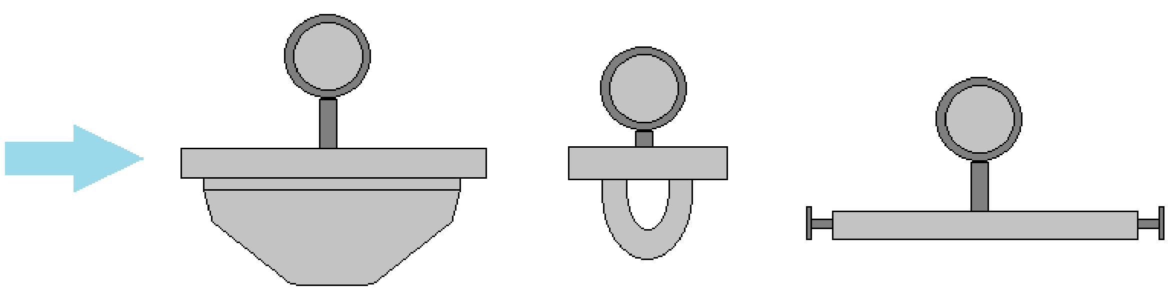


Figure 72: Examples of Coriolis flowmeters.

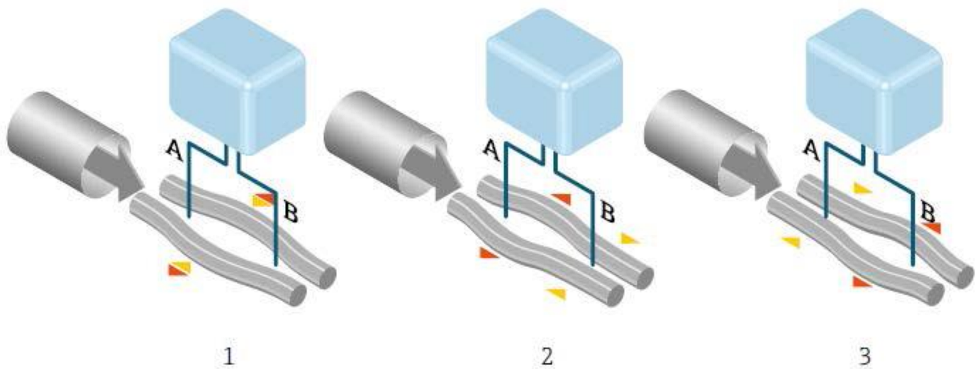
In the Coriolis flowmeter, the amplitude of force depends on the mass in movement and its oscillation speed. Energy is applied to the tube by means of a steady vibration. When the liquid enters the tube(s), the impulse of the mass flow induces a change in the vibration of the tube, which oscillates and causes a change in phase that is proportional to the quantity of matter that transits the tube. As such, a linear output proportional to the streamflow can be calculated by measuring the oscillation.

Endress & Hauser (technical information – Proline Promass E300)

Figure 73 illustrates the change in the oscillatory phase in a sensor comprising two parallel tubes. At streamflow zero, the tubes oscillate in phase (*Endress & Hauser (technical information – Proline Promass E300)*

Figure 73, 1). The difference in phase measured at points A and B increases in proportion to mass flow, where oscillation decelerates at the entry and accelerates at the exit (Endress & *Hauser (technical information – Proline Promass E300)*

Figure 73, 2 and 3). Sensors record both oscillation values and output a linear streamflow signal.



Endress & Hauser (technical information – Proline Promass E300)

Figure 73: Functional principle of a sensor comprised of two parallel tubes.

4.4.4.7 Applications

Table 27 summarizes the applications for which various mechanical flowmeters are suitable.

Table 27: Mechanical flowmeter applications

	Properties	Velocity and flow	Pipe
Paddlewheel	▪ Monophasic ▪ Uniform distribution (the measurement is taken on the walls of the pipe only) ▪ Clean liquid with few particulates to avoid wear-and- tear on moving parts ▪ Lubricant reduces abrasion and reduces the risk of premature wear-and-tear and decreased accuracy	.1-6 m/s Utilization < 5% of the maximum flow to avoid premature wear-and-tear on paddles	10-50 mm
Vortex	▪ Monophasic ▪ Non-sensitive to water quality but can be sensitive to air bubbles ▪ The liquid must not contain long fibres or a lot of abrasives	.3-9 m/s .002 to slightly more than 1 m^3/min	15-300 mm
Turbine	▪ More appropriate for clean liquids with low viscosity	Moderate constant	< 600 mm

	▪ Debris-laden discharge to be avoided, given the risk of obstruction and damage to the sensor	streamflow (< 5% of maximum flow)	
	Properties	**Velocity and flow**	**Pipe**
Rotameter	▪ Relatively clean, sufficiently trans-lucid liquids to visually view the float and ensure that it is not obstructed ▪ Very compact assembly	Ideal for measuring low flow (< 10 m^3/h), such as extraction flow	< 100 mm
Positive displacement	▪ Clean liquids with high viscosity, such as oil ▪ Avoid dirty or abrasive-laden liquids that could damage or clog the bearings ▪ Avoid liquids with gas bubbles unless the latter can be efficiently removed (bubble volume can be mistakenly measured as liquid volume) ▪ Useful for instantaneous flow or volumetric dosing	Adapted to low flow (1-65 l/min)	N.A.
Coriolis	▪ Measuring principle independent of the physical properties of the liquid and discharge profile ▪ Affected by obstructions: For wastewater, straight tube devices should be preferred to U-shaped ones ▪ Do not lead to drops in pressure ▪ Larger than average size ▪ Relative insensitivity to density allows for applications where the physical properties of the liquid are not well-known	It is preferable to use this device in the upper range of the streamflow because its use in low flow conditions can impair accuracy	< 300 mm

4.4.4.8 Installation

The manufacturer’s installation recommendations must be followed for all the devices listed below, and additional factors must be considered:

Paddlewheel
- Installation is quick and easy for most standard pipe diameters.
- Assembly is feasible in almost any position.

Vortex
- Installation is over a horizontal pipe.

- Stopping flow is not required during installation.
- Equipment must be centred in relation to the pipe to avoid parasitic vortices.
- All irregularities on the internal surface of the pipe must be avoided.
- An upstream straight length of between 10 and 40 DN (depending on the type of disturbance) and a minimum downstream straight length of 5 D are required to ensure that vortices are shaped correctly.

<u>Turbine</u>

- Installation can be horizontal or vertical over the pipe, which must run full at all times and not have air bubbles.
- The propeller axis must be horizontal.

<u>Rotameter</u>

- Since the effect of weightlessness can only be vertical, the measuring tube must be placed in a vertical position. However, spring-loaded opposing float designs can enable this type of flowmeter to be installed horizontally because float functionality does not depend on gravity in this case.
- The fluid ascends.
- The float is maintained in a rectilinear position by two guide rails at each extremity of the flowmeter.
- The upstream and downstream sections of the flowmeter pipe should ideally be of the same nominal diameter as the body of the instrument.
- A 5 DN upstream and 2 DN downstream length free of disturbances is recommended.
- There should be no ferromagnetic bodies closer than 100 mm from the display.
- Prior to installing the flowmeter, the pipe must be fully cleaned to eliminate all foreign bodies and/or deposits that could attach to the magnetic float or the guide rails.
- A filter may be installed upstream of the measuring tube to capture any large particles.

<u>Positive displacement</u>

- The viscosity of the liquid used by the device must be similar to the liquid used for calibration due to the fact that varying levels of slippage may lead to measurement errors.
- A filter may be required to remove any deposits in the discharge and avoid wear-and-tear on bearings.
- The choice of construction materials for the rotating parts must be made so as to keep corrosion and abrasion in check. Even small levels of corrosion and/or abrasion can attack sealants and impair measurement accuracy.

<u>Coriolis</u>

- Upstream and downstream straight lengths are not required.

- The flowmeter must be completely filled with liquid.
- Vibration in the tube must be avoided since it could cause equipment breakdown.

Pressurized discharge…

Measuring discharge in a pressurized closed conduit requires a primary device that produces a signal proportional to the extracted discharge, which is then measured and converted to a standard output signal by the secondary device. The primary and secondary devices are difficult to distinguish visually.

The discharge measurement systems may be installed outside the pipe or by insertion.

A wide range of devices are commercially available. They can be categorized by their measuring principle: magnetic induction, ultrasound, differential pressure, mechanical energy or thermal power.

The installed device must be regularly inspected on the basis of the field checklist in Appendix 3.

5 DETERMINATION OF PUMP CAPACITY

The manufacturer's rating curves can be used to determine the capacity of one or more pumps in a pumping station. However, this method may bring about errors that can considerably affect the accuracy of measurement, such as wear-and-tear on the motor or within the pump itself, variations in static water level (depth of water for the zero reference), viscosity of the liquid, etc.

For all the above reasons, it is first required to determine the capacity of the pump at a constant speed (Q_p) (also called "pump flow") rather than setting the pump's capacity on the basis of calibration. This step is sometimes wrongly described as pump calibration, but calibrating refers to establishing a relationship between the streamflow and other variables, such as water level, and involves certification.

5.1 CONDITIONS FOR DETERMINING PUMP CAPACITY

The determination of pump capacity must include the following:

- The calculation of pumping time and volume is made when the pump reaches its permanent functional regime because the starting and stopping process corresponds to a transient flow regime that may vary between zero and maximum flow.
- The pump is used in normal operating conditions (e.g., at normal operational capacity for a variable speed pump).
- The speed of the pump is constant.
- The type of pumping station (isolated or not) (backflow is added to pumping flow in the latter).
- Trials take place when the station is emptied, not during filling.
- The backflow valves are leak-proof to prevent water from flowing back into the pumping station.
- If there is more than one pump, the capacity determination must be performed for each one independently, as well as in combination. For example, if two pumps (A and B) work both together and separately, pump capacity must be determined in three situations: pump A only, pump B only and pumps A and B simultaneously.

5.2 METHOD USED TO DETERMINE PUMP CAPACITY

Pump capacity can be established by the volumetric method or by using a reference instrument. Both methods establish a relationship between the volume pumped and the duration of pumping in order to determine pump capacity.

5.2.1 Volumetric method

The calculation of pump capacity by the volumetric method involves the following steps:

1. Calculation of the surface area of the pumping station (*A*)

The equation for determining the surface area (*A*) of a pumping station is based on its geometry, as shown in Table 28.

Table 28: Equations for determining the surface area of a pumping station

Rectangular station	Circular station
$A = L \times l$	$A = \frac{\pi D^2}{4}$
where A = Surface area of the pumping station in m^2 L = Length in m l = Width in m	where A = Surface area of the pumping station in m^2 D = Diameter in m π = 3.1416

2. Calculation of pumped water level (*h*)

The level (h) of pumped water is the difference between the beginning (h_d) and end (h_f) of the trial (Figure 74). Water level should be measured with precision instruments such as a laser range finder to reduce uncertainty of readings to no more than 1 cm. The following equation describes this:

$$h = h_d - h_f \quad (19)$$

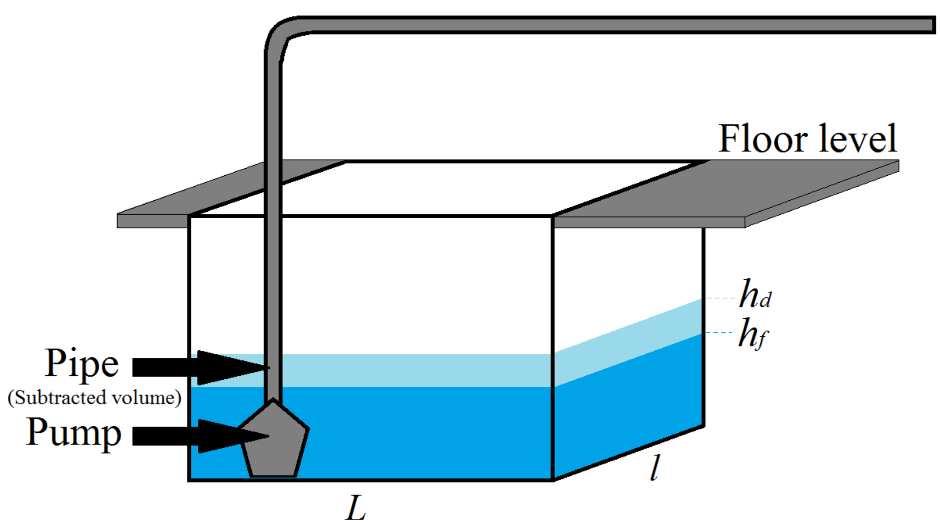


Figure 74: Determining pump capacity using the volumetric method.

3. Calculation of pumping volume (*V*)

To calculate the pumping volume, use the following equation to combine the surface area of the pumping station (A) (m^2) and the pumped water level (h) (m):

$$V = A\,h \qquad (20)$$

To ensure accuracy of results, subtract the volume of the pumps and other accessories from the total volume of the pumping station.

4. Calculation of pumping time (t_p)

The pumping time (t_p) shows the interval of time when the pump is operating, i.e., between the beginning (t_d) and the end (t_f) of the trial, summarized by the following equation:

$$t_p = t_f - t_d \qquad (21)$$

A chronometer capable of reading at least 1/100 second is required (.01%).

5. Calculation of pump capacity (Q_p)

It is preferable to isolate the pumping station when calculating pump capacity (Q_p), i.e., with no water entering the pump well.

The process for calculating pump capacity (Q_p) is different for isolated and non-isolated pumping stations.

Isolated pumping station:

In an isolated pumping station, filling and emptying are separate operations. Pump capacity is determined by the following equation:

$$Q_p = \frac{V}{t_p} \qquad (22)$$

Where	Q_p	True pump capacity (m^3/s)
	V	Volume of water pumped (m^3)
	t_p	Elapsed pumping time (seconds)

Non-isolated pumping station

If a pumping station cannot be isolated, the discharge of water entering the station cannot be eliminated during the emptying process. Therefore, in order to determine pump capacity:

- Firstly, determine the backflow (also called entry flow).
- Ensure that the backflow is constant.

Follow these steps to determine the backflow:

- Turn off the pump.
- Measure the backflow time (t_r), meaning the time for the water in the station to reach a predetermined level (h_r).
- Determine the backflow (Q_r) by means of the following equation:

$$\boldsymbol{Q_r = \frac{V_r}{t_r}} \qquad \textbf{(23)}$$

Where	Q_r	Backflow in m^3/s
	V_r	Backflow volume ($V_r = A\,h_r$) in m^3
	A	Surface area of the pumping station in m^2
	h_r	Backflow level in metres
	t_r	Backflow time in seconds

The backflow is then confirmed by checking it (ideally three times) to ensure consistency. Determining pump capacity then requires the following:

- Determine the pumping volume (V), as previously described ($V = A\,h$).
- Determine the pumping time (t_p), i.e. the time required by the pump to process a predetermined volume of water (V).

The true pump capacity is now determined by the following equation:

$$\boldsymbol{Q_p = Q_r + \frac{V}{t_p}} \qquad \textbf{(24)}$$

Where	Q_p	Pump capacity in m^3/s
	Q_r	Backflow in m^3/s
	V	Volume of pumped water in m^3
	t_p	Pumping time in seconds

The following tables provide examples of real pump capacity in an isolated pumping station (Table 29) and a non-isolated station (Table 30) determined by the volumetric method. The average of the three trials determines the true pump capacity (67.28 l/s for the example in Table 29 and 88.5 l/s for Table 30).

Table 29: Sample volumetric method for determining pump capacity in an isolated station

Trial	1	2	3
Surface area of the pumping station (*A*) (m^2)	6 m x 7.2 m = 43.2 m		
Level of pumped water (*h*) (m)	.60	.53	.58
Subtraction	Submerged pump .3 m^3		
Volume of pumped water (*V*) (l)	25,620	22,596	24,756
Pumping time (t_p) (seconds)	368	354	362
Pump capacity (Q_p) (l/s)	69.62	63.83	68.39

Table 30: Sample volumetric method for determining pump capacity in a non-isolated station

Trial	1	2	3
Surface area of the pumping station (*A*) (m^2)	6 m x 7.2 m = 43.2 m		
Level of pumped water (*h*) (m)	.60	.53	.58
Subtraction	Submerged pump .3 m^3		
Pumping time (t_p) (seconds)	368	354	362
Volume of pumped water (*V*) (l)	25,620	22,596	24,756
Backwater level (h_r) (m)	.14	.17	.16
Backwater volume (V_r) (l)	5,748	7,044	6,612
Backwater elapsed time (t_r) (seconds)	300	300	300
Backflow (Q_r) (l/s)	19.16	23.48	22.04
Pump capacity (Q_p) (l/s)	88.78	87.31	90.43

5.2.2 Reference instrument method

Pump capacity can also be determined by a reference instrument that measures volume continuously over a given period of time as the pump simultaneously empties the pumping station.

As shown in Figure 75, the reference instrument (clamp-on, transit-time or Doppler) is temporarily installed over a closed pipe, upstream of the pumping station.

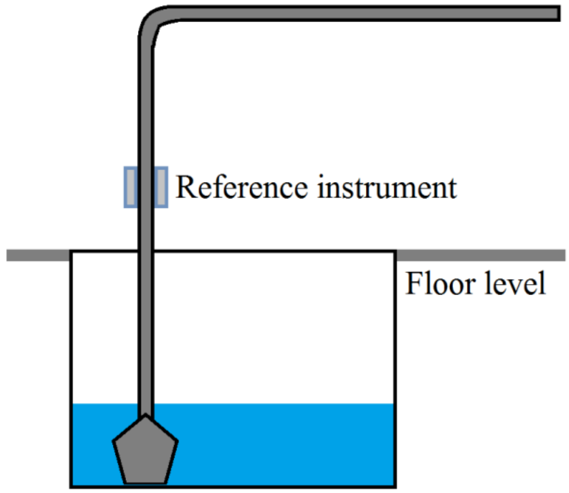


Figure 75: Sample installation of a reference instrument emporarily installed over a closed pipe.

Using a reference instrument obtains a volume which is subsequently used in relation to the chronometer-measured duration of the trial to determine pump capacity. The true pump capacity is determined by the following equation:

$$\boldsymbol{Q_p = \frac{V}{t_p}} \qquad (25)$$

Where Q_p Pump capacity in m^3/s
V Volume of pumped water in m^3
t_p Time of pumping in seconds

This method can be used for both isolated and non-isolated stations. However, for the latter, the previously described backflow (Q_r) needs to be considered.

Table 31 shows an example where pump capacity is determined by the reference instrument method. Here, the average of three 30-minute trials determined the capacity of the pump to be 84.35 l/s.

Table 31: Sample reference instrument method for determining pump capacity

Trial	1	2	3
Total volume measured by the reference instrument (m^3)	151.5	150.8	153.2
Pumping time (seconds)	1,800	1,800	1,800
Pump capacity (Q_p) (l/s)	84.17	83.78	85.11

5.2.2.1 When and how to use a reference instrument

Here's when and how to use a reference instrument to determine pump capacity:

- Measuring errors of the reference instrument must be equal to or less than 2.5% (this type of error usually refers to the notion of precision described by the manufacturer).
- The reference instrument must be used in the conditions prescribed by the manufacturer. Parameters considered will vary by device type and model, but are generally related to:
  - The interior diameter of the pipe.
  - The velocity interval of measurement.
  - Pressure.
  - The upstream and downstream lengths without disturbances (elbow, valve, etc.).
  - The properties of the water (turbidity, conductivity, temperature, etc.)
  - The discharge conditions.
  - The construction material, and the condition and thickness of the pipe.

  The applicable parameters must be checked at the time of the trial and compared with the operational conditions prescribed by the manufacturer.

  The choice of reference instument must always be made so that its measurements are affected by the least possible number of parameters or by the most negligible effects of these parameters.
- The selected reference instrument must be adapted to *in situ* conditions such as installation configuration, normal discharge, etc.
- The reference instrument must be calibrated annually or more frequently when device malfunction is suspected. Calibration must take place at various points over the device's range of speeds.

  Reference instrument calibration must employ recognized procedures such as ISO 4185 (weighing method) and ISO 8316 (method by collection of the liquid in a volumetric tank) or on a rating bench equipped with traceable calibration[26], in which case the calibration certificate is issued by an accredited laboratory.

  The technical specifications of the device and all errors of measurement must be shown on the calibration certificate.
- The calibration laboratory must itself be certified by means of a national or international accreditation such as ISO 17025.
- Before starting the trials, the reference instrument must be stable (around 15 minutes in stable local conditions).

[26]Metrological traceability refers to the property of a result that can be related to a reference through an unbroken documented chain, each step contributing to the measurement of uncertainty (VIM, 2012).

5.3 DURATION OF PUMP CAPACITY DETERMINATION TRIALS

The time-lapse of a trial can be measured by a chronometer capable of reading at least 1/100 of a second (.01%). The volume of pumped water must precisely match the start and stop of the chronometer with the pump in constant operation.

The precision of the trial increases with its duration. Ideally, the duration of a trial must be 30 minutes. If the pumping station is of limited size, minimum trial duration of five minutes may be acceptable.

5.4 NUMBER OF TRAILS NEEDED TO DETERMINE PUMP CAPACITY

In order to determine the capacity of a pumping station, each pump must be subjected to a minimum of three individual trials and three combined trials for combination in use at the pumping station, as applicable.

In addition, for variable speed pumps, three trials must be made at each speed used at the station.

Permissible variance must be less than or equal to 10% between the minimum and maximum values obtained during the three trials, as expressed in the following equation:

$$\%\,\boldsymbol{variance} = \frac{\boldsymbol{min\,flow - max\,flow}}{\boldsymbol{min\,flow}} \times \mathbf{100} \qquad \textbf{(26)}$$

Whenever variance exceeds 10%, the trials must be rerun. Table 32 shows a situation requiring two additional 30-minute trials.

Table 32: Sample calculations of variance between trials

Trial	Variance
Trial 1 = 800 m^3 / 30 min = 26.7 m^3/min Trial 2 = 815 m^3 / 30 min = 27.2 m^3/min Trial 3 = 725 m^3 / 30 min = 24.2 m^3/min	$\frac{24.2\,m^3/min - 27.2\,m^3/min}{24.2\,m^3/min} \times 100 = 12.4\%$
Trial 4 = 732 m^3 / 30 min = 24.4 m^3/min	$\frac{24.4\,m^3/min - 27.2\,m^3/min}{24.4\,m^3/min} \times 100 = 11.5\%$
Trial 5 = 779 m^3 / 30 min = 26 m^3/min	$\frac{26\,m^3/min - 27.2\,m^3/min}{26.0\,m^3/min} \times 100 = 3.8\%$
Conclusion	In this example, trials 1, 2 and 5 are used to determine the capacity of the pump at 26.6 m^3/min.

The average of the three trials used shows the pump capacity.

5.5 Frequency of pump capacity determination

Three or four times a year is appropriate as a test calendar for detecting pump or pump motor problems before a shutdown occurs. As a bonus, the tests will also detect fluctuations in pump capacity.

If there are no regulatory requirements, the capacity of the pump must be re-evaluated at least yearly, or when the following situations occur:

- A new pump is placed into service.
- The working mode of a pump is changed.
- A pump is rebuilt.
- Prior to accuracy checking the flow measurement system that uses the capacity of a pumping station pump.

5.6 Sources of errors when determining of pump capacity

The sources of errors described in the sections dealing with the volumetric method and the method using a reference instrument apply on a case-by-case basis.

The following errors are specific to pump capacity determination situations:

- The calculation of pumping time and volume occurs before the pump has reached is permanent working regime.
- The speed of the pump is not constant.
- The pump's utilization conditions were not taken into account (variable speed, more than one pump, etc.).
- Backwater flow at a non-isolated station was not considered.
- Backwater flow is not constant.
- The calculation of backwater flow is wrong due to inappropriate tools, calculation errors, etc.
- The number and/or duration of the trials is not adequate.
- The pipe's backflow valves are not leak-proof.

Determining pump capacity…

Happens when:

- The pump is used in normal operating conditions and has reached its permanent working regime.
- The speed of the pump is constant.
- The type of station is considered (isolated or not).
- The pumping station is being emptied, not filled.
- There is no backwater in the pumping station.

Two methods:

- Volumetric
- Calibrated reference instrument

Three trials: Each ideally lasting 30 minutes and with a variance of <10% of minimum and maximum values obtained during the three trials

Appendix 4 provides a test checklist.

6 ACCURACY CHECKING A FLOW OR VOLUMETRIC MEASURING SYSTEM

6.1 INTRODUCTION

The flow or volumetric[27] measuring methods described in this section do not require the use of a primary structure, and instantaneously provide the streamflow or accumulated discharge volume.

They use reference methods to check the accuracy of a flow measuring system to validate compliance on the basis of applicable specifications such as regulations, authorizations, directives, guidelines, etc. The reference methods that are recognized by the Ministère and described in the subsequent sections are as follows:

- Velocity-area (section 7).
- Tracer dilution (section 8).
- Volumetric (section 9).
- Pump capacity (section 10).
- Reference instrument (section 11).

The selected reference method applicability conditions must be met in order for the accuracy checking results to be accepted.

Checking a measuring system by combining permanently installed measuring equipment, such as a primary instrument, with official secondary measuring equipment installed upstream or downstream of the equipment being checked is not recognized by the Ministère. In fact, when there is disparity of results between the two, it is often impossible to identify which is defective without re-checking using a different reference method. However, combined checking is possible if the conditions for applying the method with a reference instrument listed in section 11 are met.

Section 12 describes the required content of the report that is required when checking a flow measuring or volumetric system in free surface flowor pressurized flow conditions.

6.2 FLOW MEASURING SYSTEM ACCURANCY CHECKING FLOW CHART

Checking the accuracy of a flow measuring system requires checking all components, whether the system is installed in a open channel or a closed conduit. **Erreur ! Source du renvoi introuvable.** shows the schematic of the accuracy checking process for a flow measuring system, while the individual components are described in detail in the subsequent sections.

[27] Henceforth, “streamflow measurement system” will also refer to “volumetric measurement system.”

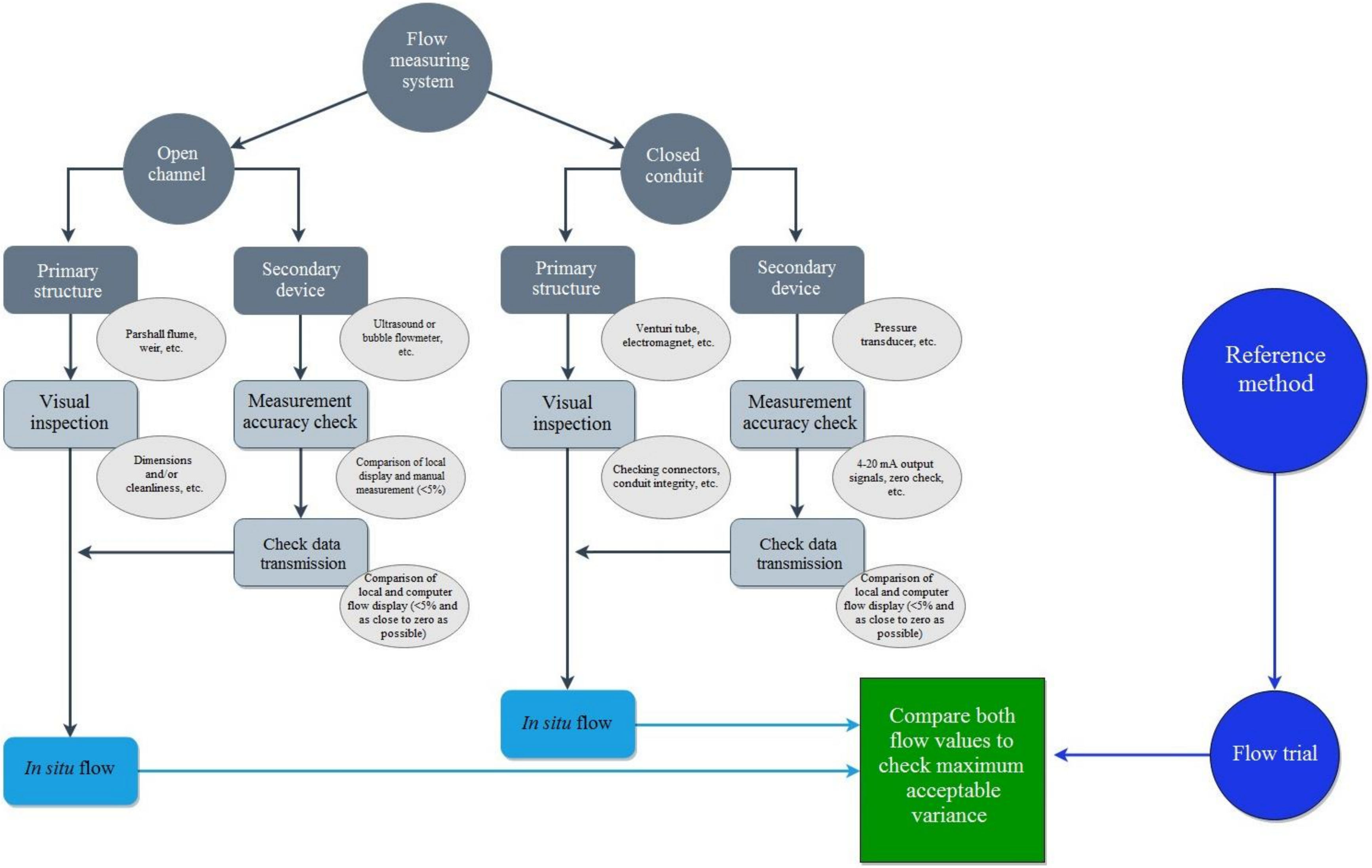


Figure 76: Schematic of the accuracy checking process for open channel and pressurized (closed conduit) flow measuring systems.

6.3 OVERVIEW

6.3.1 Flow measuring system

A flow measuring system is comprised of all component parts, including primary structures and secondary devices; displays; and flow recording and transmission equipment.

The primary structure is the physical unit that varies liquid flow and emits the initial signal that enables streamflow to be determined. The secondary device the value of the physical signal, which could be the water level or the velocity at the primary structure's measuring point, then displays and processes or transmits it to obtain the streamflow.

In a open channel, checking the accuracy of a flow measuring system includes checking both the primary and secondary elements. The checks can be conducted independently of each other. However, when the secondary device *in situ* is used to determine flow during a trial, its accuracy must be checked, and any required adjustments made prior to testing the primary structure. In closed conduits, the secondary structure is more difficult to distinguish from the primary structure, which means that it cannot be used to determine flow during the trial. In such cases, checking the accuracy of the secondary device is part and parcel of checking the accuracy of the primary structure, while as described in section 2.9.2, some routine checks may be performed.

6.3.2 Flow (total volume) during the trial

When checking the accuracy of a flow measuring system, "flow during the trial" refers to the total volume or the instantaneous streamflow measurement made with a reference method that is recognized by the Ministère and which makes it possible to determine the volume of water or flow observed during the test period.

In order to obtain a trial flow that is representative of the discharge conditions, it is vital to abide by the specifications pertaining to the application of the selected method, as described in sections 7 to 11.

6.3.3 In situ flow

When checking the accuracy of a flow measuring system, "*in situ*" flow refers to the total volume or instantaneous streamflow measurement obtained by the measuring system being checked, i.e., the system used by a plant or by a municipality.

Depending on the component equipment used by the flow measuring system, *in situ* flow may be determined by:

- A pumping station where the pump capacity and length of operational time are known.
- A flowmeter installed over a closed conduit.
- A primary structure combined with a permanent secondary device that is part and parcel of a open channel flow measuring system.

- A permanent primary structure being checked, combined with a secondary device that is temporarily installed for the purpose of checking the accuracy of the primary structure.

6.4 Flow measuring system accurancy checking steps

The installation of an *in situ* measuring system must be checked to ensure compliance with manufacturer instructions for dimensions, materials, upstream and downstream lengths, etc.

6.4.1 Visual inspection of the primary structure

In a closed pipe, visual inspection can verify the integrity of the channel and external elements such as connectors.

In open channels, a visual inspection can verify both condition and cleanliness; compare real and theoretical dimensions; confirm that the device's horizontal, cross-section and vertical dimensions are level; and check discharge conditions such as free flow or submerged, preferred current, etc.

6.4.2 Secondary device accuracy checking

The accuracy of a secondary device can be checked by its output signal (4-20 mA, pulsed analog or digital) and zero.

In open channels, this is done by comparing the local display with manually measured values. The variance must be as close to zero as possible and always less than 5%. This check can be performed in wet or dry conditions. Dry checking avoids discharge disturbances that could make it difficult to read the water level with a ruler.

In the first case, true water level is manually measured several times, possibly every 30 seconds for 5 minutes at the measuring point of the primary structure (e.g., with a ruler), while in the second, water level is simulated using a reference plate. The measurements displayed on the secondary device are simultaneously recorded. The greater the number of measurements, the less will be the effects of outlier values and the more representative will be the average, particularly when the water level is variable or when there is turbulence or a delay in transmitting measured values. A minimum of five comparative measurements is recommended. Appendix 3.6 shows an example of inspection and secondary instrument accuracy checking templates.

The calculation of errors must use flow values, not water level. Thus, if the local display only provides water level, it must be converted into streamflow using the theoretical equation or the installed primary structure's stage-discharge curve.

Table 33 shows the raw data for an example of measurement accuracy checking for a secondary device installed over a open channel using a ruler and the local instantaneous streamflow.

Table 33: Example of checking the accuracy of a secondary device with a ruler

Time of measurement (h/min/sec)	Manual level (m)	Theoretical instantaneous flow[1] (m^3/h)	Instrument instantaneous flow[2] (m^3/h)	Variance[3] (%)
09:00:00	.160	75.83	76.00	-0.22
09:00:30	.161	75.58	76.16	-0.77
09:01:00	.161	75.58	76.09	-0.68
09:01:30	.160	75.83	76.01	-0.24
09:02:00	.163	78.09	78.23	-0.18
09:02:30	.165	79.61	80.03	-0.53
09:03:00	.164	78.85	78.97	-0.15
09:03:30	.160	75.83	76.13	-0.40
09:04:00	.159	75.09	76.06	-1.29
09:04:30	.160	75.83	76.20	-0.49
09:05:00	.163	78.09	78.27	-0.23
Average	**.162**	**76.75**	**77.11**	**-0.47**

Notes:

[1] Based on the theoretical formula of the installed primary structure, applied to water level measured manually by a ruler installed at the measuring point

[2] Local measuring device flow values simultaneously recorded with manual water level measurements

[3] The variance as a percentage is obtained by the following equation:

$$\left(\frac{\textit{theoretical instantaneous flow} - \textit{device instantaneous flow}}{\textit{theoretical instantaneous flow}}\right) \times 100$$

If the calculated variance between the values stems from manual measurement and the variance in the values displayed by the instrument is less than 5%, this can be used to measure the flow *in situ* for the purposes of checking the accuracy of a streamflow measuring system. Otherwise, it cannot be used unless it has been adjusted and calibrated and the faulty item has been replaced or repaired.

Temporary instruments are commonly used to measure *in situ* flow. This is acceptable as long as the temporary instrument has been adjusted to the installed primary structure and the measured variance is less than 5%.

Table 34 compares variance when the calculation is based on the water level and streamflow. The example shows that variance of 5% can be achieved when water level is used for the comparison, but might be greater than 5% if streamflow is used. The example confirms the importance of using the flow values instead of the water level.

Table 34: Comparison of water level and streamflow variance for the theoretical equation of a 0.914-m Parshall flume

	Manual measurement	*In situ* measuring equipment	Variance (%)
Water level (m)	.355	.370	4.23
Streamflow (m^3/h)	1,553	1,657	**6.70**

6.4.3 Verification of data transmission to a computer

The flow and volume results for the purposes of the trial are those shown by the *in situ* measuring instrument. It the instrument is connected to a remote data transmission system, an additional check is required to ensure that there is no variance between the *in situ* readout and remote acquired data.

In all cases, checking the accuracy of a flow measuring system involves verifying the accuracy of data transmission to a computer, and that includes time synchronization, downtime, etc. The variance between a permanent local instrument and a computer system display should be near zero and always less than 5%. If this is not the case, adjustments are required before starting the trials.

6.4.4 Primary structure accuracy checking

Checking the accuracy of a primary structure relies on comparing the flow measured by the system being checked (*in situ* flow) with the flow simultaneously obtained using one of the reference methods that are recognized by the Ministère (trial flow). This type of checking cannot be carried out in dry conditions.

6.4.5 Calculation of flow variance in the flow measuring system being checked

The streamflow measured by the reference method (trial flow) is considered as the reference value. If the method's criteria are applied, the measured value is deemed to represent reality, even if it is not deemed a true value on the basis of metrology principles. The calculation of errors between the trial flow and the *in situ* flow makes it possible to determine if the accuracy of the *in situ* flow measuring system being checked meets specifications.

Variance in one component of the system cannot compensate for variance in the other. For example, a variance of -5% in the secondary device cannot be used to compensate for a 15% primary structure variance in order to meet a 10% requirement.

With the result of the trial flow being deemed more accurate, the calculation of the percentage of variance is made using the following formula:

$$\%\ \boldsymbol{variance} = \left(\frac{\boldsymbol{trial\ flow - in\ situ\ flow}}{\boldsymbol{trial\ flow}}\right) \boldsymbol{x\ 100} \qquad \textbf{(27)}$$

The calculation for each trial must incorporate uncertainty, when applicable.

6.5 Number of flow measurement trials and intervals

Checking the accuracy of flow alone can determine the compliance of a primary structure, but only for the streamflow range during the trials. For example, three trials at approximately 85% of flume capacity can determine its accuracy at that particular streamflow, but not when the flume is used at 20% of its capacity.

As such, measurement trials at various flow levels extending over a range of habitual *in situ* discharge intervals is recommended. For example, three levels of flow may be selected, corresponding to minimum, average and maximum flow.

The correct number of trials must be used based on the monitoring specifications for each method (see regulations).

In general, three flow trials are required for each reference method (minimum, average and maximum flow levels) or three trials at a single flow level. The only exception is the velocity-area method, where a single trial is acceptable if all application conditions are met. If they are not all met, three trials are required.

To summarize, three trials must be conducted when checking accuracy at a single flow. If trials can be conducted at different flow levels, a single trial for each level can take place if all required conditions of the method are met. If this is not the case, three trials at each flow level may be required to ensure the validity of results.

6.6 Interpretation of results

Figure 77 shows a sample decision schematic for a streamflow measuring system based on the results of accuracy checking.

If the percentage of the variance between the trial streamflow and the *in situ* rate falls below the maximum permissible value, the *in situ* flow measuring system may be deemed to be in compliance. Minor recommendations may, however, be suggested to improve the installation, such as improving the approach channel.

However, when the percentage of variance exceeds specifications, the method used should be reviewed for its appropriateness *in situ*, for local conditions and for whether the appropriate specifications were met.

On a case-by-case assessment, new full or individual trial checks may be required using the same method or a reference method that is better suited to *in situ* conditions. If the choice of method or its implementation is not suspect, it may be concluded that the measuring system is not in compliance and that recommendations to correct the situation are warranted.

6.7 Assessment of installation compliance

The percentage of variance must comply with the maximum permissible value for each trial and not simply the average of the trials. Table 35 illustrates a case where installation compliance is uncertain, for while the average of 7.5% for the three trials comes in below the regulatory 10%, the 15.0% found in trial 3 exceeds the required ceiling. In a case like this, another trial must be conducted.

Table 35: A sample three-trial result

Trial	Variance (%)
1	3.5
2	4.5
3	**15.0**
Average	**7.5**

6.8 Conclusions and recommendations in the light of accuracy checking a flow measuring system

Accuracy checking a flow measuring system includes formulating a conclusion as to whether the system complies with specifications and provides reliable results. Moreover, recommendations and corrective measures must be stated whenever factually required.

Minor corrective measures such as calibrating a device must take place without delay. Any recalibration on a hydraulic test bed, equipment replacement and/or repairs must take place within a reasonable time frame and comply with applicable specifications. In all cases, accuracy checks must take place again by the regulatory deadline after the corrective measures have been completed, to ensure that the measuring system meets maximum permissible variance.

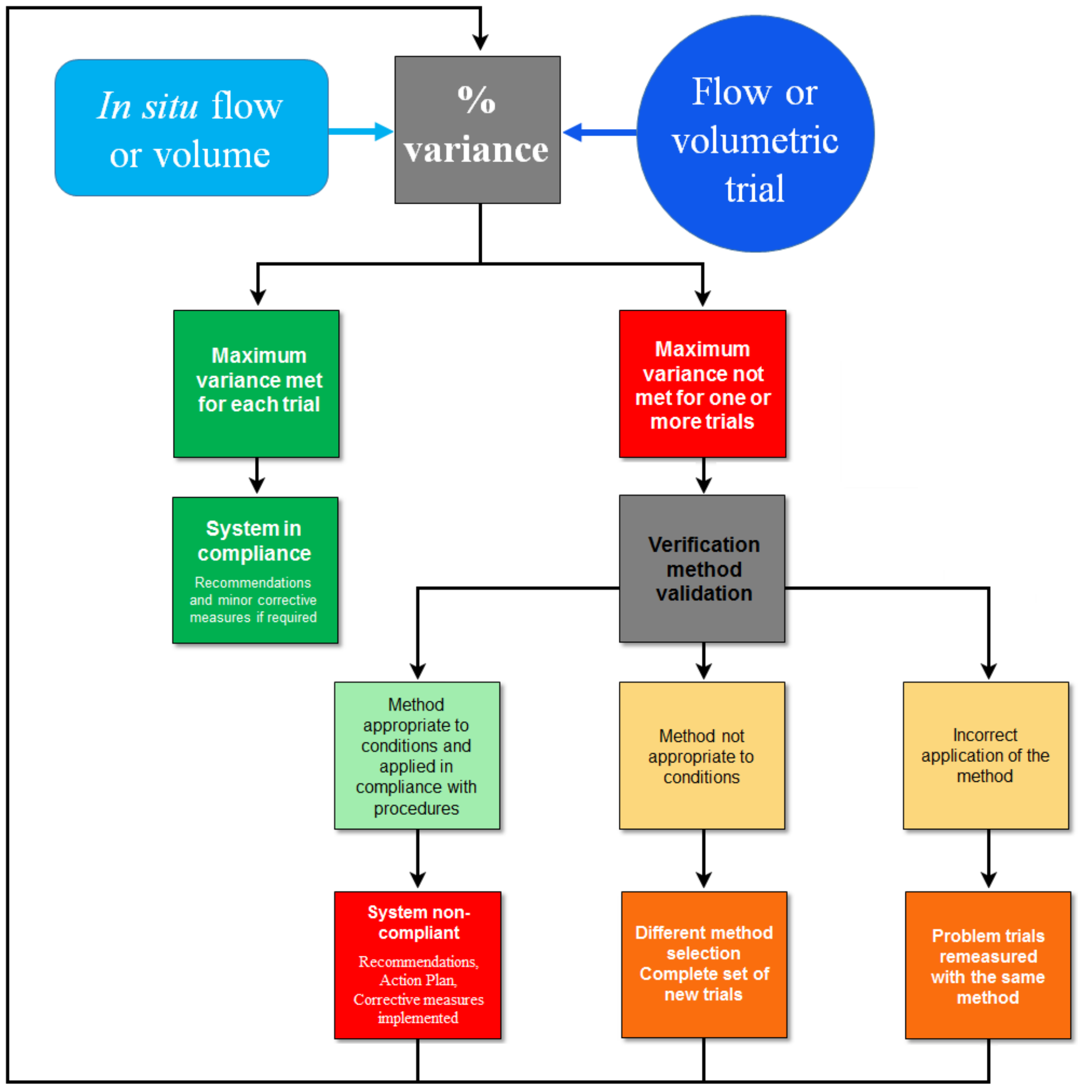


Figure 77: Decision schematic of action required based on the results of accuracy checking a flow measurement system.

Accuracy checking…

Discharge measuring system accuracy checking includes:

- Visual inspection of the primary structure
- Verification of the accuracy of the secondary device
- Verification of data transmission to a computer
- Verification of the accuracy of the primary structure by calculating the variance between the *in situ* system and a reference method that is recognized by the Ministère (velocity-area, tracer dilution, volumetric, pump capacity or reference device).

The number of trials required varies with the selected reference method or the monitoring requirements to be met (see regulations).

The recognized reference methods are listed in sections 7 through 11.

7 VELOCITY-AREA METHOD

The velocity-area method (also known as the velocity distribution method) is used to determine free surface streamflow.

Flow velocity in a given area is not deemed uniform over its full transverse axis. Figure 78 shows examples of velocity distribution in a flow area.

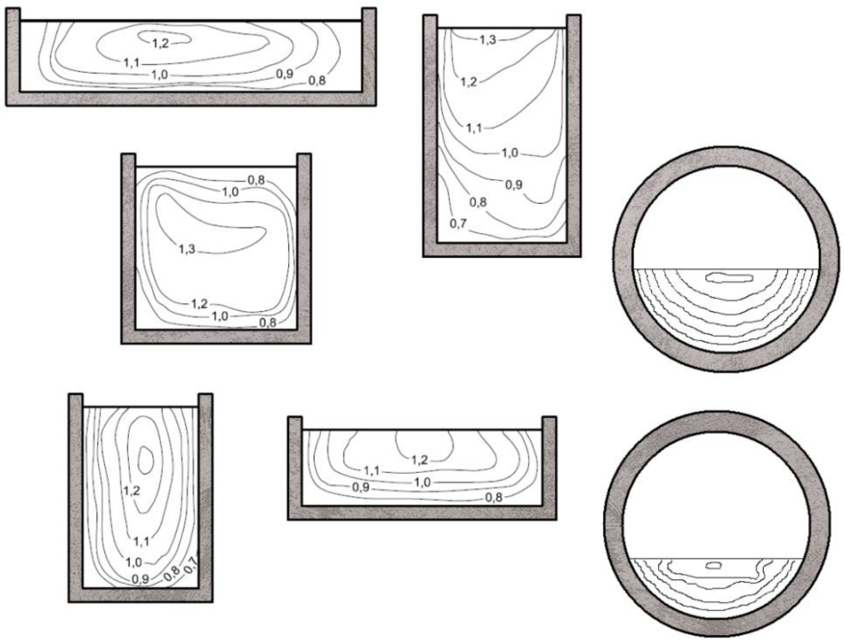


Figure 78: Examples of velocity distribution in a flow area.

The velocity-area method determines the streamflow by means of the transverse area (the product of the width of the wetted section and the level of the discharge) and the velocity of the discharge in the cross-section. Streamflow can then be determined without the use of a primary structure such as a Parshall flume. This can also be used to independently determine flow and can constitute a reference method as part of the process of checking the accuracy of a measuring system.

Whenever the velocity-area method is used in a regularly shaped, well-defined device such as a rectangular flume, the following simplified equation may be employed to calculate the discharge:

$$Q = \bar{v} \times A \qquad (28)$$

Where
- Q Streamflow in m^3/s
- $\bar{v}$ Average velocity of the discharge in the wetted section in m/s
- A Area of the wetted section to be measured, in m^2

In a variable-depth watercourse or structure, total flow is equal to the sum of the individual flow values in each vertical.

Individual streamflow can be determined by a variety of calculation methods including graphic and arithmetic methods for the average and median sections. For more details, see ISO 748.

By applying the velocity-area method to the streamflow in a flume whose shape is well-defined, the stage-discharge relation can be determined by the shape of a rating curve (Figure 79) or a stage-discharge equation or table, which can be subsequently used to determine the streamflow by simply measuring the water level.

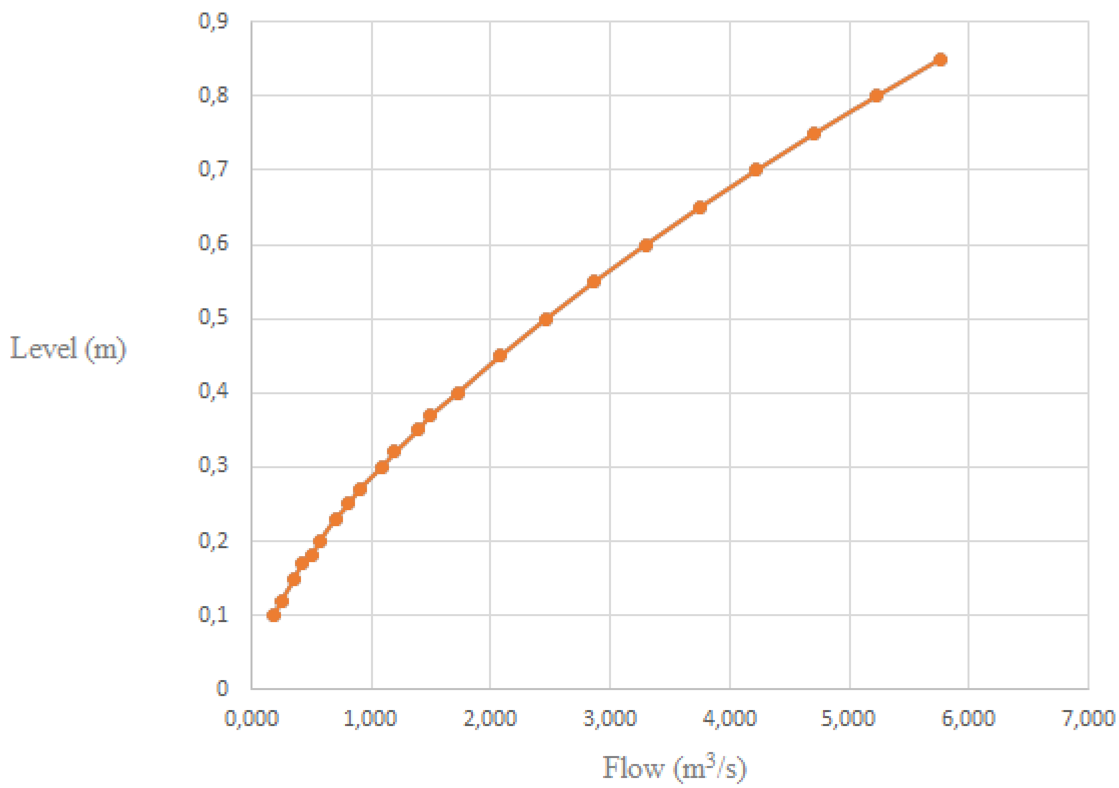


Figure 79: Sample stage-discharge curve.

The velocity-area method can be used with submersible instruments or surface measurements that incorporate average discharge velocity and that take the water level in the measuring section into account. This method enables velocity to be measured in a sampling zone and average discharge velocity to be extrapolated to the entire wetted section.

The sampling zones are based on the dimensions of the flow area and the type, position and characteristics of the reading instrument.

The following kinds of equipment can be used with this method:

- Rotating current meter (also known as a mechanical current meter).

- Electromagnetic current meter.
- Acoustic Doppler Velocimeter (ADV) (also known as an acoustic current meter).
- Area-velocity Doppler flowmeter and acoustic Doppler current profiler (ADCP).
- Area-velocity non-contact radar flowmeter.

Figure 80 summarizes the main characteristics of the measuring instruments described in this section.

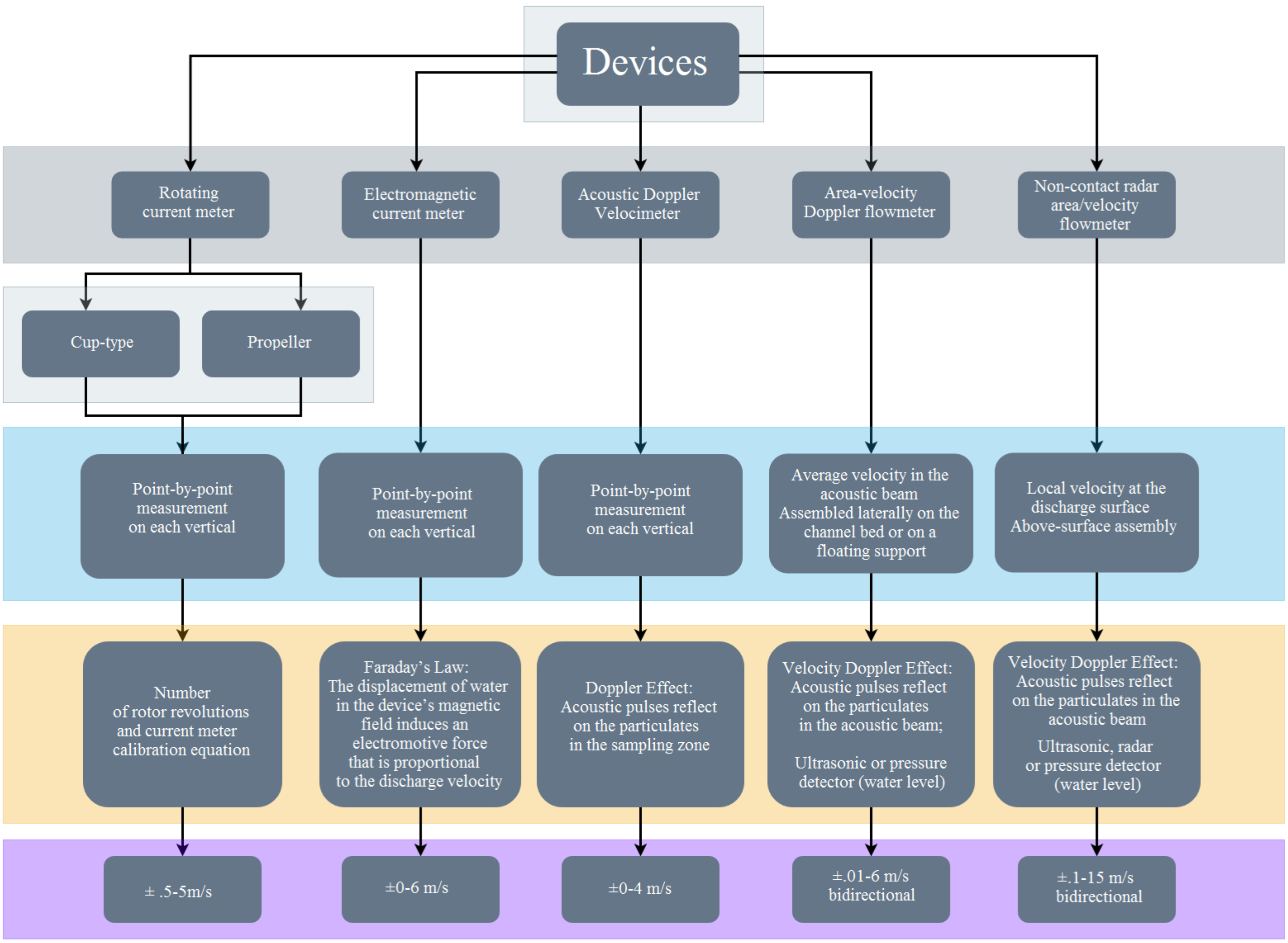


Figure 80: Measuring instrument characteristics.

Other measuring system checking methods exist, but as they are not recognized by the Ministère, they are not discussed in this publication. Among them is float gauging (IS0 748), which should only be used for testing prior to using another measuring method. Measuring velocity by image analysis is another method that can be used to estimate streamflow in real-time, particularly when major flooding occurs and other, more intrusive methods involve risk. For now, this method remains at the exploratory stage.

An example of a field template used to check the accuracy of a streamflow measuring system with the velocity-area method is shown in Appendix 5, along with a template for compiling raw data using the vertical readout method for measuring velocity.

7.1 MEASURING EQUIPMENT FOR USE WITH THE VELOCITY-AREA METHOD

7.1.1 Rotating current meter (also known as the mechanical current meter)

Description

The rotating current meter is an instrument that measures the local velocity of the fluid discharge in which it is submerged. Whenever made possible by the depth of the water, the current meter is installed on a rod, to allow the operator to take readings from a walkway or bridge, or even by walking into the discharge.

Two models of this instrument exist: the cup-type current meter (Figure 81) and the propeller current meter (*Image provided by OTT Hydromet, Germany*
Figure 82). The cup-type current meter rotor usually includes a wheel with six empty or full cups that rotates around a vertical axis when installed in the discharge. The propeller model has two or more blades that can be attached helically, usually rotating around a horizontal axis.

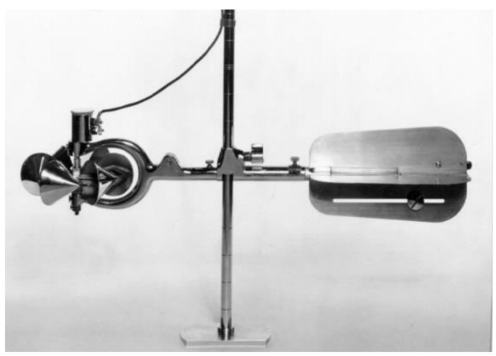


Image provided by the Bureau of Reclamation, U.S. Department of the Interior

Figure 81: Rotating cup-type current meter.

Image provided by OTT Hydromet, Germany

Figure 82: Rotating propeller current meter (OTT C31).

The propeller current meter can be equipped with a single propeller or several interchangeable ones, each with its own individual characteristics (diameter, maximum velocity, angle of incidence, self-adjustment effect, etc.). This instrument can, therefore, measure a variety of velocities and discharge conditions with a single unit as long as the calibration chart is available for each propeller.

Functional principle

The discharge velocity is determined by counting the number of revolutions of the rotor within a given time frame and using the calibration equation of the current meter.

The streamflow of the discharge determined by a rotating current meter uses the following variables:

- The width of the measuring section.
- The water level.
- The velocity of the discharge.

Equation 28 (see above) calculates the trial streamflow in each of the discharge sections by adding up the products of the corresponding velocity/area (average water level during a trial multiplied by the width of the measuring section) for a series of readouts in the measuring section (Figure 83).

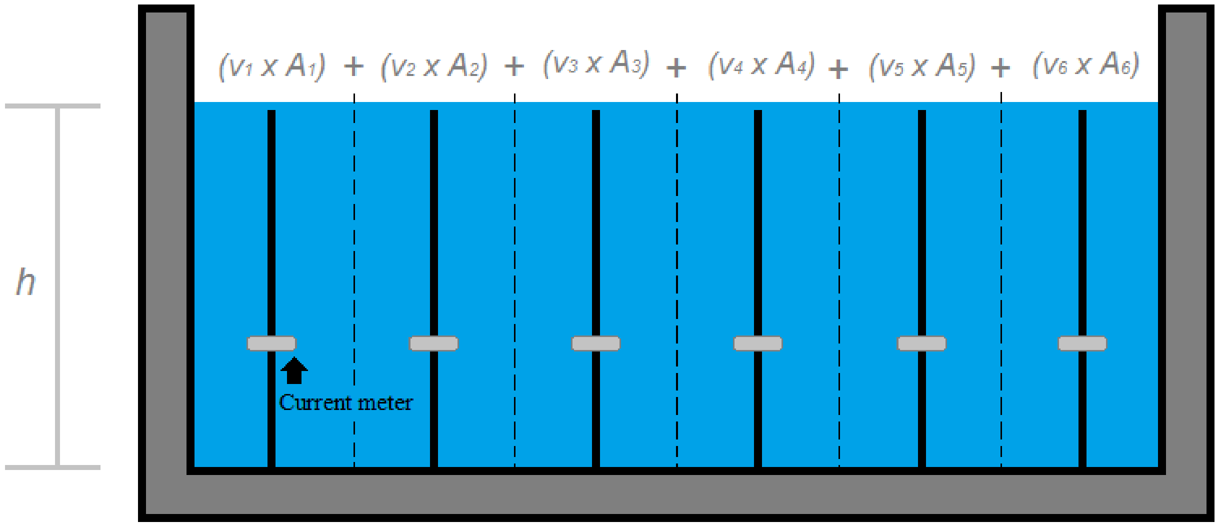


Figure 83: Calculating the trial streamflow using the sum of the flow in the individual vertical sections.

Operating conditions

The current meter manufacturer must provide a calibration table based on tests made at an accredited laboratory.

The functionality of the instrument must be verified prior to each use. For example:

- The rotation of the propeller or cups must be checked by manually turning while observing the movement to ensure that rotation stops gradually, not suddenly.
- All parts must be properly lubricated.
- All rotations must be recorded by the counter.
- The propeller blades must be checked. If their condition is suspect, the instrument must be recalibrated.

Whenever a functionality issue is observed, the instrument must be repaired and calibrated by the manufacturer or at an accredited metrology laboratory such as National Calibration Service or Environment and Climate Change Canada.

During the trials (and usually after each vertical readout), the current meter must be checked to ensure that its propeller rotates freely.

The rotating current meter is not to be used whenever the water level in a vertical is less than four times the diameter of the propeller or the body of the current meter, even if it is larger. The propeller should be selected on the basis of the velocity intervals of the discharge to be measured and must always be used with the current meter that was employed to determine the equation for converting the number of rotations per unit of time into velocity. Measuring errors of the current meter's minimum velocity response are high, which means that the instrument should only be used *in situ* for velocities that are at least twice the minimum response value.

The axis of the rotor must be parallel to the direction of the discharge and level with the water surface. If oblique discharge cannot be avoided, the angle of the discharge to the straight section must be measured and the velocity, corrected (see section 7.7). Some manufacturers offer self-adjusting propellers that take account of the angle of incidence in reading velocity, up to and including the instrument's maximum capacity.

The manufacturer's recommendations as to the instrument's maximum permissible hydrostatic pressure and temperature must be met.

Generally speaking, current meters can be used for velocities within the .5 to 5 m/s range. However, some units can accurately measure velocities outside this range. Users should refer to the instrument's calibration certificate.

7.1.2 Electromagnetic current meter

Description

Like the rotating current meter, the electromagnetic current meter can be used to measure the velocity of water point-by-point, using a rod. The instrument has an electromagnetic sensor attached to a rod (Figure 84). The technician submerges the sensor in the discharge on foot or from a bridge or walkway. The sensor can be used for all velocities listed by the manufacturer.

Contrary to the rotating current meter, the electromagnetic version is less sensitive to suspended matter or debris since it has no moving parts. As such, it has a higher level of durability, and maintenance is easier. This model is preferred to the rotating current meter for low-velocity discharge in that it is theoretically possible to use it for velocities below 5 cm/s (.05 m/s).

Image provided by OTT Hydromet (Germany)

Figure 84: Electromagnetic current meter (OTT MF pro).

Functional principle

The functional principle of the electromagnetic current meter is based on the Faraday Law, which states that the displacement of water in a magnetic field induces an electromotive force that is proportional to the velocity of the discharge.

The streamflow measuring procedure is identical to the one used for rotating current meters.

The electromagnetic current meter delivers a direct measurement of the discharge velocity in a given time frame for velocities in the 0 to 6 m/s range (see manufacturer's specifications).

Operating conditions

The electromagnetic current meter must not be used whenever the water level measuring point is less than three times the vertical dimension of the sensor. The axis of detection of the sensor must be parallel to the direction of the discharge and level with the surface.

The functionality of the sensor must be checked prior to each use and the manufacturer's recommendations must be met. For example, some models can be checked and zeroed by still submersion in a non-metallic receptacle filled with water. Other models require no calibration since they automatically reset to zero when the sensor is no longer submerged.

This type of instrument is temperature-sensitive. As such, it must be submerged for several minutes before starting a trial and never used in proximity to ferrous substances such as reinforced concrete, which can affect readouts.

The digital display in this type of instrument provides a direct readout of the discharge velocity.

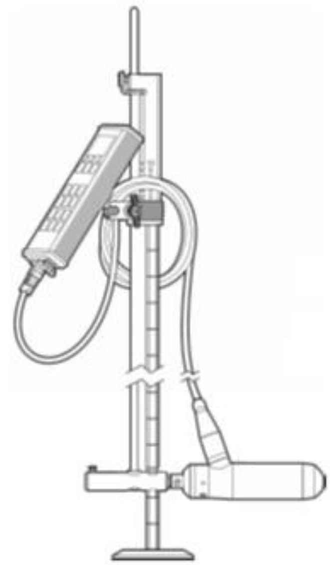
7.1.3 Acoustic Doppler Velocimeter (ADV)–also known as the acoustic current meter

Description

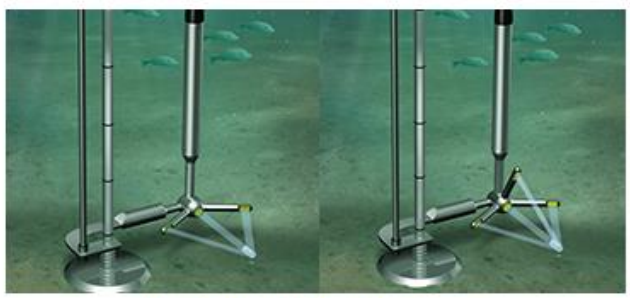
The Acoustic Doppler Velocimeter (ADV) is an instantaneous measuring system used to study fluctuations in water velocity using acoustic signals. Compared to the rotating and electromagnetic current meters, this type of instrument has the advantage of calculating the streamflow immediately after the velocity readouts in the measuring section take place.

The instrument comprises a sensor and a mobile terminal (Figure 85A). The sensor is attached to a rod and deployed in the discharge on foot or from a bridge or walkway. The instrument has no moving parts. Some models are equipped with a pressure sensor that measures both water level and immersion depth. Moreover, it may also make it possible to include the calculation of uncertainty in the final result.

Figure 85 A and B show examples of Acoustic Doppler Velocimeters.



A - Acoustic Digital Current meter (ADC)
Image provided by OTT Hydromet, Germany



B - SonTek® FlowTracker®
Image provided by Sontek, USA

Figure 85: Examples of Acoustic Doppler Velocimeters.

As shown in *Image provided by SonTek USA*

Figure 86, the sensor can include a main transducer that emits acoustic pulses in a narrow beam no more than several millimeters in width (varies by model). The acoustic sensors are mounted on the extensions of the probe, converging toward a common sampling zone that is located at a fixed distance from the sensor (approximately 10 cm). The sampling zone is the physical location where water velocity is measured, providing the spatial and temporal data whose analysis makes it possible to visualize the discharge profile.

Depending on the model, the instrument may have two or three 2-D or 3-D acoustic sensors (see Figure 85 B).

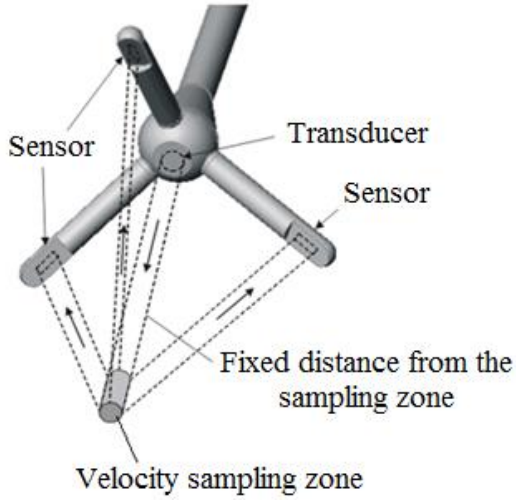


Image provided by SonTek USA

Figure 86: Components of a 3-D (SonTek FlowTracker®) Acoustic Doppler Velocimeter (ADV) showing the ultrasound displacement between the transducer and the sensors.

As shown in *Image provided by OTT Hydromet, Germany* Figure 87, the sensors can function differently based on the instrument model.

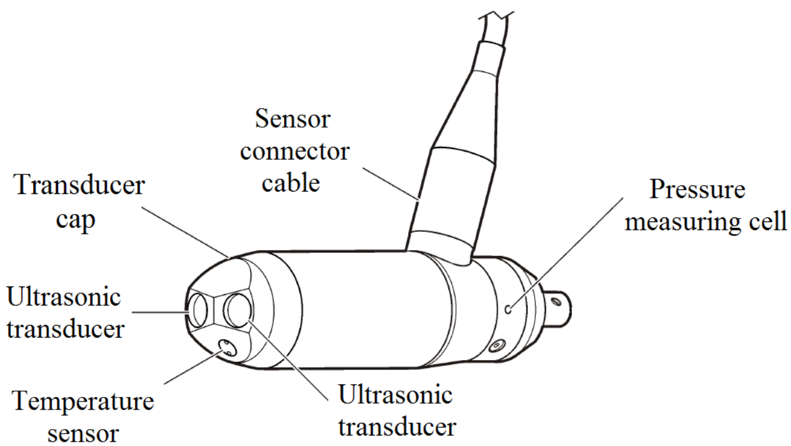


Image provided by OTT Hydromet, Germany

Figure 87: Sensor components of the OTT ADC instrument.

A sensor may also be equipped to read the data required to measure water velocity, level and temperature.

Functional principle

The acoustic velocimeter uses the Doppler Effect as its functional principle. The instrument's transducer sends a short acoustic pulse along the axis of the beam. The resulting ultrasound is reflected in all directions by suspended matter such as sediment, small life forms and air bubbles in the water sampling zone. A portion of the reflected energy moves along the axes of the acoustic sensor beams and is recorded. The sensors measure the frequency of the reflected waves and convert the values into discharge velocity.

The velocity measurement interval varies by make and model of the instrument but may extend up to 4 m/s.

Velocity sampling involves a succession of 2-D or 3-D pings. The values are recorded by the instrument, which also calculates average velocity and records the data for quality control.

An instrument that employs the vertical method with a current meter rod is used to measure the discharge (ISO 748). During the process, it records the distribution of velocity in a vertical, as well as the level of the water and the depth of each submerged sensor. Based on the values measured and the characteristics of the measuring section recorded in the instrument by the user, the instrument calculates average velocity and flow in the vertical. This calculation then makes it possible to obtain the discharge streamflow in the measuring section during the trial.

Operating conditions

Rather than directly measuring the movement of water, this instrument measures the movement of particulates in the water, which is why it is vital that the particulate movement is representative of the water movement.

Prior to starting the measuring process, the technician uses the mobile terminal to enter the measuring station parameters, methodology and desired calculations. The sensor must be mounted on the rod in compliance with the manufacturer's recommendations, and the rod must remain in a vertical position throughout the trial. The instrument will have been calibrated for a particular assembly and must, therefore, be set up in the same way. In addition, since sensor data calibration may have been incorporated into the mobile terminal, some manufacturers may require that the sensor and mobile terminal be used as a single unit.

The ultrasound transducers must be regularly checked for sand and algae, which must be removed to avoid weakening the acoustic signal.

This type of instrument is highly sensitive to discharge density and temperature. A temperature change of as little as 5 °C can cause a change in the speed of sound of around 1%, which can lead to velocity measurement errors of around 2%. As such, an auto-correct temperature/speed of sound sensor is therefore usually added to the instrument. Compensating for sensor temperature in extreme conditions of between 50°C and 5°C may take up to 6 minutes. This means that the sensor should be submerged in water for around 5 minutes before starting a trial. Generally speaking, the water level should be at least three times the vertical length of the sensor unless otherwise required by the manufacturer. The sensor should be positioned against the current and at right angles to the measuring section.

This instrument is not recommended for water with little or no suspended particulates. This is rarely a problem since the level of particulates in natural watercourses or industrial and/or municipal effluent is usually sufficient to enable this method to be used. Also, current technology is such that small quantities of particulates do not interfere with effective measurement.

No obstacles are permitted in the immediate vicinity of the sensor, and the sampling zone should be located so as to avoid interfering structures and/or obstructions.

Ideally, measurement should proceed from a bridge or walkway. If it takes place directly in water, the user must stand off to the side of the instrument at a distance that will not affect the streamflow.

7.1.4 Area-velocity Doppler flowmeter and acoustic Doppler current profiler (ADCP)

Description

Contrary to previously-described equipment that measures instantaneous velocity on vertical segments within the cross-section of a channel, the area-velocity Doppler flowmeter measures average velocity in an acoustic beam. The Acoustic Doppler Current Profiler is another variant of instruments that work by means of the Doppler Effect.

Acoustic Doppler Current Profiler

This instrument usually includes three or four ceramic transmitting/receiving emit divergent acoustic beams vertically to enable the 3-D measurement of the velocity in a vertical (*Image provided by Éditions Quae, France, Hydrologic Measurement by a Doppler Profiler, Le Coz, 2008, Figure 1.6*

Figure 88). The ultrasonic signal is emitted in water by a ceramic transmitter then reflected back from the suspended particulates to calculate velocity, which is deemed to be equal to the discharge velocity. The reflected signals are finally captured by the same ceramic element. This functional model comes with data acquisition delays because the emission and reception of signals use the same piezoelectric ceramic device.

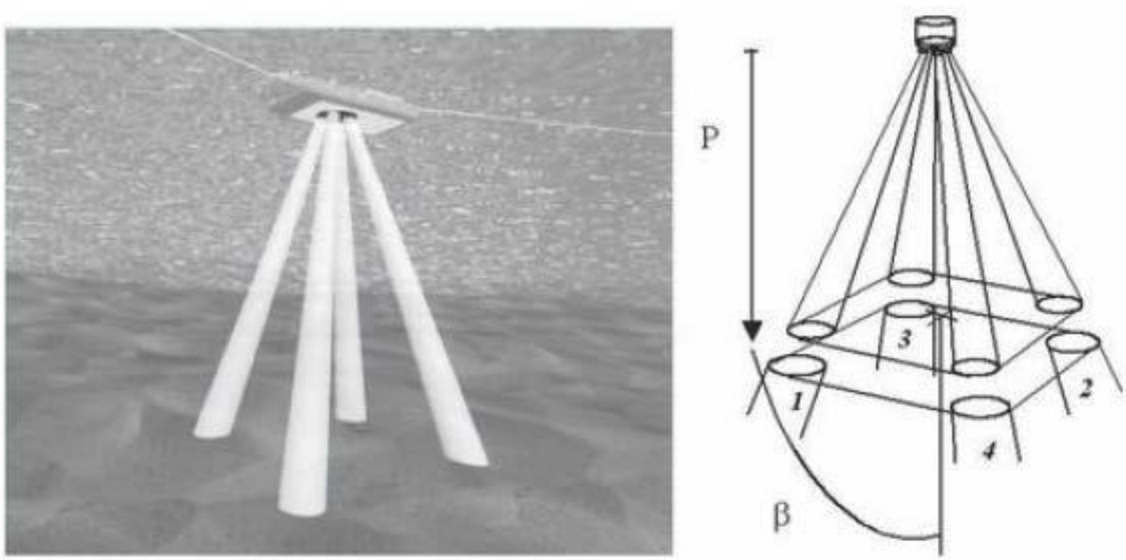


Image provided by Éditions Quae, France, Hydrologic Measurement by a Doppler Profiler, Le Coz, 2008, Figure 1.6

Figure 88: Example of a four-beam monostatic ADCP.

Depending on the model, the ADCP may be deployed in a stationary mode similar to a current meter, but it offers the potential for mobile utilization with floatation equipment that enables travelling to determine the streamflow of a watercourse. The velocities that can be measured by this type of instrument are in the ± 5-20 m/s range.

Given its more frequent use in natural settings and oceanography, the ADCP instrument will not be discussed in further detail in this publication.

<u>Area-velocity Doppler Flowmeter</u>

Depending on the particular features of the selected instrument, Doppler technology can be used to measure the rate of flow in open channel or closed conduits of small or average size. Instruments of this type usually comprise a central unit, a velocity sensor and a water level sensor. Velocity is measured by the Doppler sensor, while, depending on the model, level is read by an ultrasound probe or an internal or external piezoresistive sensor that measures pressure.

While the measurement intervals for velocity vary by manufacturer, bidirectional velocities can range from .01 to 6 m/s.

Some submersed instrument models are made to be attached to the channel bed and mounted laterally over one of its sides or on a floating support (Figure 89). The sensor's shape and material can minimize water resistance and therefore minimize its influence on the discharge profile.

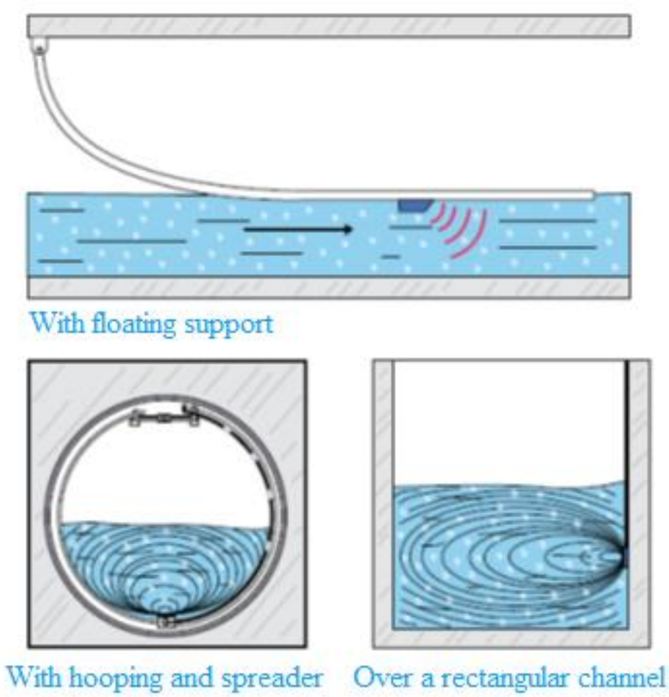


Image provided by Scadalliance Corporation

Figure 89: Sample MainFlo and Hydreka sensor assembly.

The Area-velocity Doppler Flowmeter makes it possible to measure the true average velocity of discharge transiting the acoustic beams (usually two). The streamflow is then calculated from average velocity, water level and area of the wetted section.

Due to technical limitations, the streamflow must at times be extrapolated for unexplored blind zones near the bottom of the instrument or surface zones, on a case-by-case basis. A second sensor may be required to limit the size of blind zones in a large-dimension flume.

Real-time data display makes it possible to visualize the instantaneous velocity of the discharge, as well as the total volume of water. Manufacturer-provided software is used for visualization, data processing and instrument control. In-house software can also be used to process data, but the blind zones must be considered and extrapolated values must be representative of the discharge conditions.

Functional principle

The sensor, which is submerged in the discharge, sends a of a beam at a predetermined oblique angle (20°, 45°, etc.) to the axis of the discharge (*Image provided by Flow-Tronic, Belgium*

Figure 90).

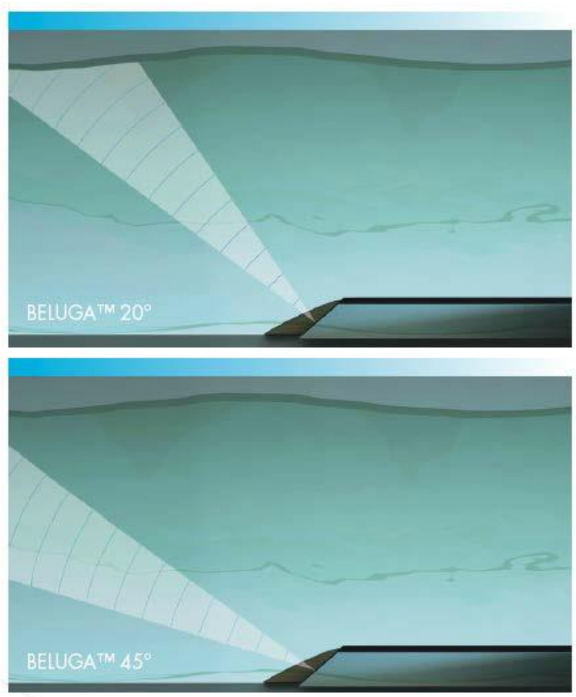


Image provided by Flow-Tronic, Belgium

Figure 90: Sample beam angles (using a Flow-Tronic Beluga).

The sensor, located in the same housing, processes the waves reflected by the suspended particulate in the discharge. Analysis of the waves makes it possible to measure the discharge velocity and convert it to average velocity. At the same time, the water level is continuously measured by a submerged sensor attached to the instrument (such as a pressure sensor or an ultrasound sensor that emits a vertical beam) or an external sensor (such as a non-contact or radar level sensor). The location of the instrument that measures water level must be representative of the discharge conditions in the velocity measuring section.

Water level and dimensions of the flume or diameter of the pipe are converted in the wetted area. Multiplying the area of the wetted section by the average velocity measured by the instrument determines the streamflow.

Operating conditions

Every model has its own specific characteristics and its advantages/drawbacks based on the individual features of the site (e.g., siltation, width and depth of water in the measuring section, blind zone, etc.).

The sampling cross-section will depend on the dimensions of the flume, the position of the instrument and the design characteristics of the sensor. Like the equipment used for area-velocity by vertical deployment, Area-velocity Doppler Flowmeters do not sample all velocities in the measuring section. The overall velocity here is obtained from the partial values. This is especially the case for larger flumes. The instrument location must be as representative as possible of the average velocities, and the following criteria must be considered:

- Give preference to low turbulence discharge where velocities are uniformly distributed.
- Avoid locations with falls or changes in direction immediately upstream of where the sensor is installed (slope < 3%).
- Select a measuring section that is free of obstructions such as trees, aquatic growth, rakes, etc.).
- Avoid installing the instrument in an area where sedimentation is likely to accumulate and ensure that the sensor remains free of loam and algae.
- Ensure that the discharge density (suspended particulates and air bubbles) is sufficient and homogenously distributed.
- Install the sensor so that the angle of the ultrasonic beam is below the surface of the liquid and the cone of the beam reaches the sampling area in a representative manner.

Careful selection of equipment and assembly that meets the manufacturer's technical specifications will produce optimal performances and reduce maintenance. The following items are therefore essential:

- Select an instrument that is capable of measuring in the real conditions of the site (e.g., a free surface channel, a partially full conduit, a loaded closed pipe) and the flume dimensions or pipe diameter.

- Ensure that the assembly is adapted to the type of instrument and discharge conditions. For example, installation at the flume bed leads to debris accumulation, while beams from a laterally assembled instrument may lead to loss of data.
- Comply with the minimum water level required by the manufacturer for use of the instrument.
- Select an instrument whose interval of measurement corresponds to the *in situ* equipment.
- Ensure instrument integrity and cleanliness of the sensor.
- Ensure that the temperature of the discharge is taken into account in the interval of measurement, per the instrument's specifications. If required, include warm-up or cool-down time.
- Select an instrument that can evaluate the quality of the Doppler signal and therefore validate the accuracy of velocity measurement. This may be a digital intelligent sensor. Some instruments can use this information to temporarily modify the flow calculation method, such as moving to stage-discharge mode.
- Select a depth sensor that is appropriate to *in situ* conditions. For example:
    - Pressure sensors are often the most economical option, but since they are submerged in the discharge, they can suffer debris accumulation and require added maintenance.
    - Non-contact ultrasonic sensors are easy to install and have few maintenance requirements but are affected by condensation, foam and objects floating on the surface of the discharge. They also have a blind zone of 20-30 cm between the sensor and the beginning of the measuring section.
    - Non-contact radar sensors can be more expensive but are low-maintenance, not sensitive to floating objects or vapour, and measurement is not constrained by a blind zone.

Processing data to determine the streamflow generally uses software supplied by the manufacturer of the instrument or an in-house program. The following criteria must be met to ensure the validity of measurements:

- The dimensions of the measuring section must be accurately recorded.
- All irregularities requiring that the width of the measuring section is recorded at several water levels must be taken into account.
- In cases where the streamflow must be extrapolated, the blind zones must be reduced to minimum levels (the extrapolation of measurements in the blind zones must reflect no more than 30% of total flow).
- The instruments in use must be synchronized for time, measurement frequency, transmission delays, etc.
- Select a measurement frequency that will obtain data that is representative of the discharge conditions (current trial, continuous 30-minute measurement every 30 seconds at a minimum, etc.).

7.1.5 Non-contact radar area/velocity flowmeter

Description

The non-contact radar area/velocity flowmeter measures velocity at the surface of the discharge without direct contact between the sensor and the discharge itself (Image provided *by Flow-Tronic, Belgium*
Figure 91). The measurement of velocity can also be combined with above-surface ultrasonic or radar depth measurement or with submerged hydrostatic pressure sensors.

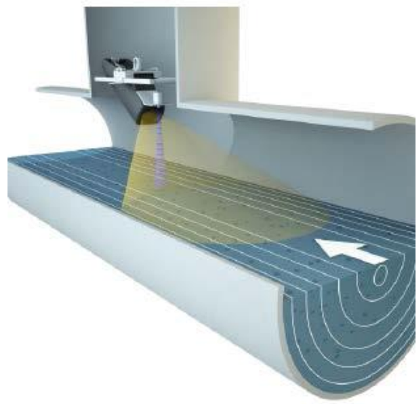


Image provided by Flow-Tronic, Belgium

Figure 91: The Flow-Tronic RAVEN-EYE non-contact radar area/velocity flowmeter

The non-contact radar area/velocity flowmeter is set up above the surface of the liquid to be measured. It suits various types of free flow discharge channels and is installed on bridges or walkways. This type of instrument can provide a solution for measuring flow in difficult discharge conditions, such as when there is a high level of suspended particulates, high temperatures or vapour and corrosive fluids, etc.

The instrument is available in both a fixed version for permanent installation and a portable version, which can be used to check the accuracy of an installed flow measuring system.

Depending on the model, this type of instrument has an interval of measurement for bidirectional velocities in the .10-15 m/s range.

Functional principle

The velocity is measured by a pulsed surface of the liquid, producing a the discharge velocity (*Image provided by Sommer, Austria*

Figure 92).

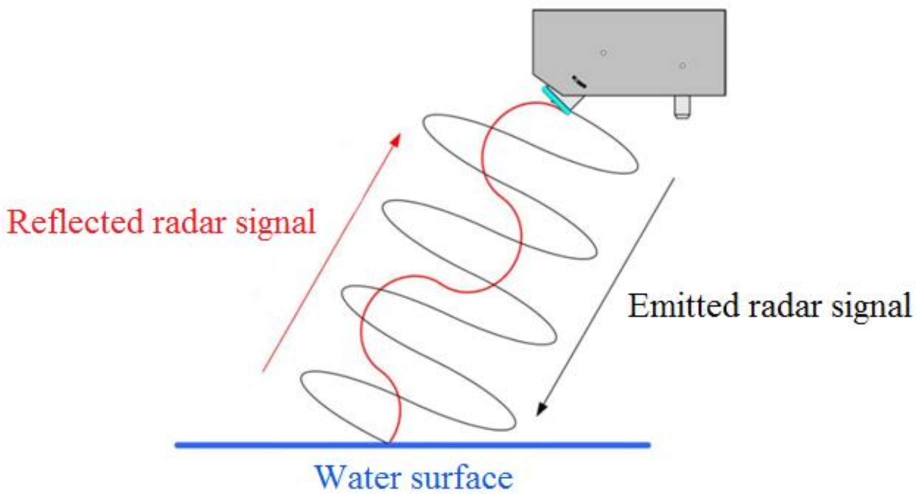


Image provided by Sommer, Austria

Figure 92: Measurement of velocity by the Sommer RQ-30 radar instrument.

The measured surface area is directly surface of the discharge to be measured and the angle of the beam (*Image provided by Flow-Tronic, Belgium*

Figure 93).

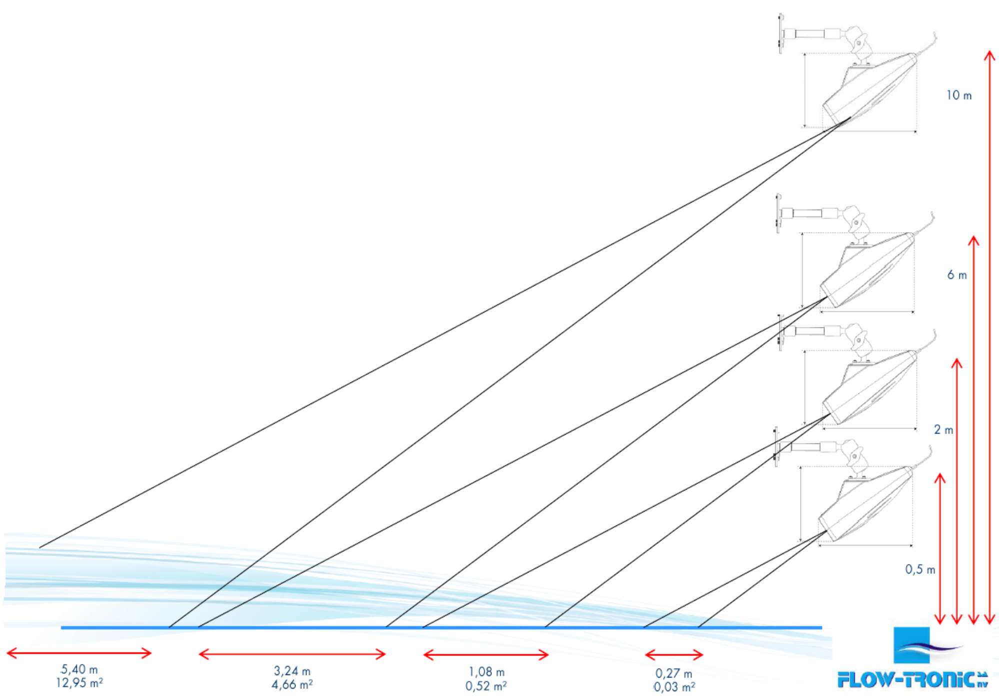


Image provided by Flow-Tronic, Belgium

Figure 93: Angles of incidence of ± 10° and distance of the probe from the

measured surface using the Flow-Tronic RAVEN-EYE instrument.

Water level is simultaneously measured by a pulsed ultrasound or radar or immersed hydrostatic pressure). For radar instruments (*Image provided by Sommer, Austria*

Figure 94), short pulses are emitted perpendicular to the surface of the water. Elapsed time between emission and reflection reception is measured to determine the distance to the water surface and hence the water level.

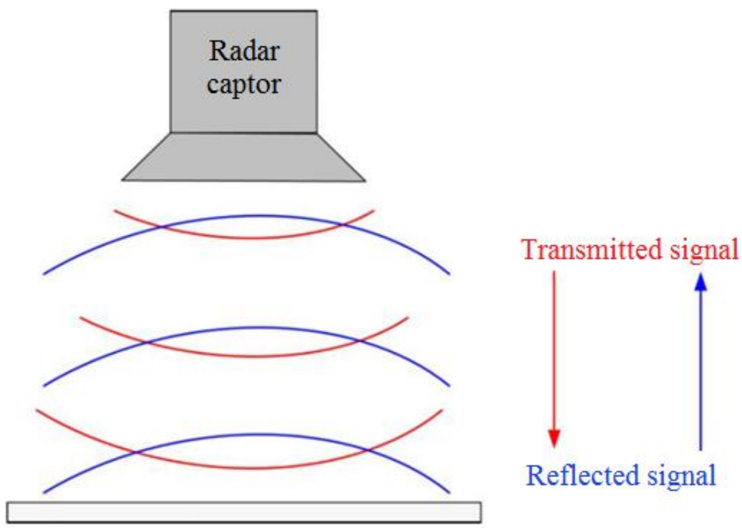


Image provided by Sommer, Austria

Figure 94: Measurement of water level by the Sommer RQ-30 radar instrument.

This instrument uses algorithms to convert the measured velocity at the surface of the discharge to average velocity. The accuracy of the instrument depends in large part on how well the algorithms perform using the manufacturer's recommended methods. Based on the shape of the flume, the instrument converts the water level in the wetted section to streamflow by multiplying the average calculated velocity by the area of the wetted section.

Operating conditions

This type of instrument can be easily adapted to various sizes (at least 100 mm in width) and shapes of flumes or pipes and to high-velocity discharge, and is not affected by turbulent discharge.

Since the instrument measures velocity without contact with the discharge, it has the advantage of being capable of measurements in a wide effluent range without being affected by particulate load, floating debris, corrosive liquids, high temperatures, etc.

When this equipment is set up at the measuring site, the section's profile must be defined to ensure that measurements taken are representative of real conditions. Some models enable pre-programmed geometric profiles or can use a number of geometric points to create complex profiles.

Trials lasting at least 30 minutes with continuous measurement (minimally at 30-second intervals) will be required to obtain flow or volumetric values that are representative of discharge conditions.

As is the case for other equipment, complying with the manufacturer's operational recommendations is essential. In general, the following minimum criteria must be met, particularly with respect to a trial measurement as part of the accuracy checking process of a streamflow measuring system:

- The discharge should be free flow, with no eddies, dead zones, backflow or preferred currents.
- The properties of the channel bed should be stable to ensure consistency of measurement (i.e., avoid gravel beds).
- Discharges with slight surface movement should be preferred to calm surfaces that could reflect beams.
- Favourable upstream discharge conditions that meet the manufacturer's specifications are preferential, for example, an upstream distance of ten times the diameter of the pipe (or width of the flume) is to be preferred over a downstream distance of five times the diameter of the pipe or width of the flume.
- The instrument should be installed parallel to the discharge and centred over the width of the pipe or flume.
- The level sensor should ideally be installed centred to the surface when measuring velocity.
- Metallic objects in the water should be cleared since they could reflect the radar beam.

7.2 MAINTENANCE, ACCURANCY CHECKING AND CALIBRATION

The accuracy of a streamflow measuring system can only be ensured when it is regularly maintained, used and stored according to the manufacturer's recommendations.

Precautions must be taken prior to each use, to ensure proper functionality. Manufacturers suggest periodic control measures, and they must be followed. The instrument manufacturer's user manual detailing this information must be available at all times, in proximity to the equipment.

Checking the instrument can reveal a sensor failure or confirm that the reference values match. Periodic *in situ* comparative control checks with other velocity measuring instruments are also recommended.

Calibration is preferred to instrument verification because it calibrates the equipment's response. This is usually performed by an accredited laboratory on a test bed and must come with a calibration certificate issued by an accredited body, certifying that the equipment is in compliance with ISO standards (in this case, 17025).

Instrument calibration or verification will only be valid if the equipment is properly used and maintained by qualified staff. Users must fully comply with the recommended verification procedures that precede and follow each trial, as described in the manufacturer's user and maintenance manual.

The latest versions of ISO standards, technical reports, guidelines and other technical publications provide more details on equipment calibration, maintenance, usage and transportation and storage specifications. These include the following:

- ISO 748 – Hydrometry — Measurement of liquid flow in open channels using current-meters or floats.
- ISO 1088 – Hydrometry — Velocity-area methods using current-meters — Collection and processing of data for determination of uncertainties in flow measurement.
- ISO 2537 – Hydrometry — Rotating-element current-meters.
- ISO 3455 – Hydrometry — Calibration of current-meters in straight open tanks.
- ISO 15769 – Hydrometry — Guidelines for the application of acoustic velocity meters using the Doppler and echo correlation methods.
- ISO 24578 – Hydrometry — Acoustic Doppler profiler — Method and application for measurement of flow in open channels.

Rotating current meter

Visual verification of the condition of the propellers is recommended prior to each gauging procedure. A record of oil changes and component checks should also be kept and updated after each check.

The current meter must be cleaned after each day of use or after each measurement of the streamflow in highly-sedimented water.

Subject to more stringent requirements, current meter calibration should take place annually or after 300 hours of operation, whichever comes first, as well as whenever a malfunction is suspected. Current meters can only be used within their calibration range and should be installed similarly to the setup used for calibration.

Calibration of a current meter must comply with ISO 3455 and consists of experimentally determining the relationship between the number of revolutions of the rotor per unit of time and a known velocity. This information is used to prepare a calibration curve or table that includes the calibration equation. Minimally, the following information should be kept with the meter when it is used *in situ* or at least be easily accessible: the date of calibration, the make and model of the propeller, the name of the calibrating body and the suspension equipment that was used.

Electromagnetic current meter

It is important to ensure that the electrodes are clean so as to avoid the formation of film that could call measurement values into question. The user must consult the manufacturer's instruction manual and follow its maintenance and verification recommendations to the letter.

ISO 3455 recommends regular calibration of the zero in stagnant water and recording the results in a log. Any abrupt change or constant deviation would suggest that recalibration is warranted.

The zero can be adjusted by submerging the sensor in water, for example, in a receptacle whose dimensions allow the sensor to be 7 to 8 cm from its sidewalls. Calibration should take place when the water is perfectly still.

Calibration of the sensor that measures the force of the magnetic field generated by the velocity of the discharge is required annually, and more frequently when malfunction is suspected. Electromagnetic current meters can be calibrated in the same conditions as the rotating current meter, i.e., on a mobile cart in a straight open tank (ISO 3455).

Acoustic Doppler Velocimeter (ADV)

Generally speaking, basic manufacturer maintenance recommendations for this instrument include cleaning the transducers and other system components such as the LCD display, the USB port, connectors, etc. and inspecting cables and connectors.

While some manufacturers do not call for periodic recalibration, the accuracy of measurement must be periodically validated to ensure that the equipment is used in accordance with the needs of the selected method and as part of the accuracy checking process for a streamflow measuring system.

If annual calibration using a mobile cart in a rectilinear tank is not possible, annual comparative test bed trial verification becomes mandatory. In such cases, the test bed must include a certified traceable benchmark referring to a national or international standard such as ISO 17025, Bureau de normalisation du Québec [BNQ], etc. The details of the verification process and the results must appear on the compliance certificate.

Area-velocity Doppler flowmeter

In general, the following must be part of routine maintenance of this type of instrument: checking the remaining power in the battery and the functionality of all system components (including the power supply and cables), ensuring that the joint seals do not leak and cleaning the velocity and water level sensors. These precautions will avoid any accumulation of sediment and silt on the instrument.

The accuracy of data from the instrument is directly related to the compliance of installation. The user must also ensure that the sensor is firmly attached to the bottom or side of the channel and aligned with the discharge; that the beam is not obstructed by debris, grass, algae, etc.; that all instruments in use are synchronized and that sensor maintenance firmware has been updated.

This type of instrument has no moving parts. As such, manufacturers do not recommend systematic recalibration as the response will only change when there is equipment failure or physical modification. To ensure the validity of the calculation model incorporated into an instrument, yearly comparative checks on a test bed are recommended, in particular when the instrument is used for the needs of the selected method and as part of a streamflow measuring system accuracy check. In such cases, the test bed must include a certified traceable benchmark referring to a national or international standard such as ISO 17025, BNQ, etc. The details of the verification process and the results must appear on the compliance certificate.

Non-contact radar area/velocity flowmeter

This type of instrument is usually designed to have no joints and be leak-proof, increasing its resistance to bad weather conditions. Its above-the-surface installation eliminates issues such as clogging and maintenance, which are part-and-parcel of submerged sensors.

Since the streamflow is calculated on the basis of the geometry of the wetted section, profile validity must be ensured over time, particularly in natural settings where the bathymetric conditions of the site can and do change.

In addition, compliance of the measuring instrument must be validated on a test bed using comparative trials when used for the needs of the selected method and as part of accuracy checking a streamflow measuring system. In such cases, the test bed must include a certified traceable benchmark referring to a national or international standard such as ISO 17025, BNQ, etc. The details of the verification process and the results must appear on the compliance certificate.

7.3 DETERMINING THE LOCATION OF THE MEASURING SECTION

The choice of location of the velocity measuring section must take account of the instrument's operating conditions and the following general criteria, particularly when measuring trial streamflow as part of accuracy checking a streamflow measuring system:

- The location must be easily accessible.
- The upstream measuring section must be straight, free of junctions, obstructions and any other element that could disturb the discharge in order to foster laminar flow. The length of the measuring section must be at least ten times its upstream width and five times its downstream width or per the manufacturer's recommendations.
- The location must have a regular shape, uniform slope and be free of deposits on its walls.
- It must be free of discharge that is divergent, convergent or that has backflow, eddies or no current at all.
- Water level must be sufficient to ensure that the measuring instrument can be submerged in compliance with the instrument's normal operating conditions.
- The discharge velocity must fall within the instrument's minimum and maximum recommended velocities.

The available measuring section choices may be few in number. In such cases, a streamflow method or equipment that is capable of optimally adjusting to *in situ* conditions should be used.

7.4 Measuring the area of the wetted section

The area of the wetted section must be determined level to the measuring section (width and depth of the water).

To check any variation in water level during the measuring period, it is recommended to install equipment that has constant data recording capacity, such as a liquid level recorder, bubble flowmeter or submerged sensor flowmeter, and to note down minimum and maximum levels during each trial.

Whenever the velocity-area method uses the principle of measurement by verticals (rotating current meter, electromagnetic current meter and Acoustic Doppler Velocimeter (ADV), water level measurement in a section whose bed is irregularly shaped must employ intervals that are sufficiently close so as to precisely define the profile of the section.

At a minimum, the number of water level measuring points should correspond to the number of velocity measurement points. Usually, such measurements are made simultaneously. Constant measurement of water level at a single point in the cross-section of the measuring section using a liquid level recorder, bubble flowmeter or ultrasonic probe is acceptable for flumes with irregularly-shaped beds.

In such cases, variance between the lowest and highest water level for the duration of the trial must not exceed 5%. If this is not the case, action will be required to stabilize the streamflow or corrective measures applied to the discharge profile. These may include installing deflectors to correct preferential discharge. Once this is done, the user can undertake a new full set of trial measurements.

A different reference method or other measuring equipment may be required if the discharge cannot be stabilized or corrective measures prove unable to bring water level variance under 5%.

If the velocity-area method is nonetheless retained, a minimum of three complete trials must be conducted to justify the choice. Additionally, the effects of water level variance on the streamflow during the trials must be assessed.

7.5 Measurement of velocity

Some previously-described instruments such as the non-contact radar area/velocity flowmeter and the area-velocity Doppler flowmeter can measure velocity over a minimum of 30 minutes using an algorithm that determines the value for the full wetted section. If this is the case, the information in sections 7.6 to 7.9 should be ignored. Contrariwise, measuring velocity in a vertical is required when using Acoustic Doppler Velocimeters (ADV) or rotating/electromagnetic current meters.

Measurements taken over each vertical are applied over a straight width to the left of the vertical, which means that the application area grows in proportion to the spacing of the verticals (Figure 95). Homogeneous regular discharge for a smaller measuring section width will, in general, require a lesser number of verticals, and vice-versa.

7.6 DETERMINING THE NUMBER OF VERTICALS

The selected number of verticals must be sufficient to take account of area variance due to irregularities in the flume bed. Each vertical must have at least one velocity measuring point.

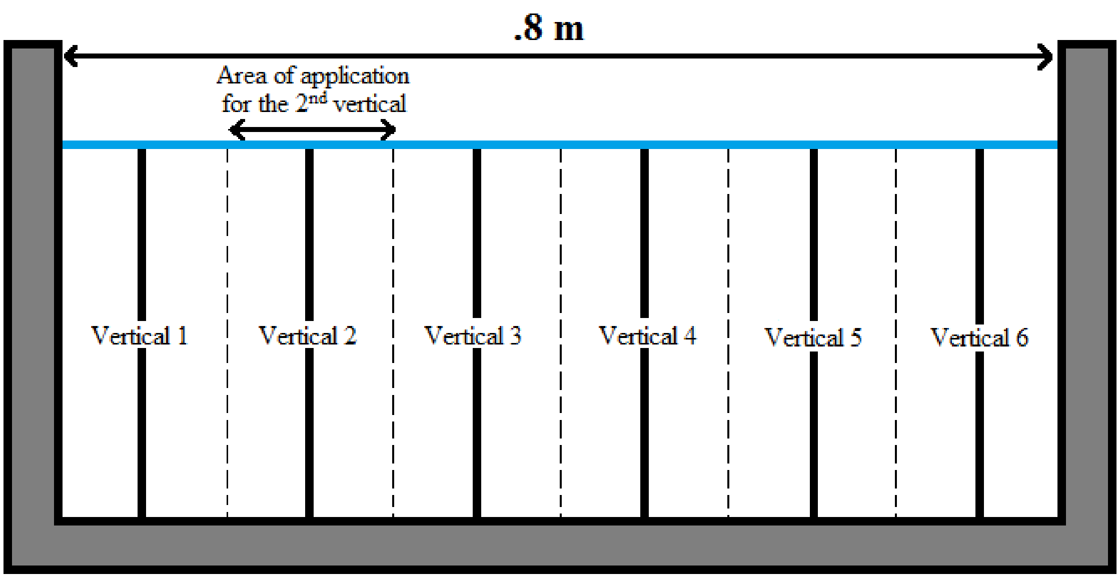


Figure 95: Illustration of the area of application of six verticals in a free surfacechannel with no bed irregularities.

Per ISO 748:2007, the minimum number (n) of verticals required for a measuring section depends on the width of the section:

- Width of the measuring section < .5 m — n = 5 or 6
- Width of the measuring section ≥ .5 m and < 1 m — n = 6 or 7
- Width of the measuring section > 1 m and < 3 m — n = 7 to 12
- Width of the measuring section > 3 m and < 5 m — n = 13 to 16

For measuring section widths ≥ 5 m, the number of verticals must be selected so that the streamflow in each area of application will be, as much as possible, less than 5% of the total streamflow and never exceed 10%. Here is an example:

Total streamflow of the measuring section = 200 m^3/s

20 sections → streamflow of each area of application ≈ 10 m^3/s

$$\frac{10\ m^3/s}{200\ m^3/s} = 5\%$$

7.7 DURATION AND FREQUENCY OF VELOCITY MEASUREMENT AND NUMBER OF TRIALS

Each measurement of velocity must last for 30 or more seconds and be repeated consecutively at least three times per vertical in the same trial (ideally five times). The exposure time may differ among electromagnetic and acoustic current meters. It is important to abide by the exposure time set out in the manufacturer's documentation if it exceeds 30 seconds.

The measuring instrument must be aligned with the direction of the discharge (usually perpendicular) to the measuring section. If the discharge is not perpendicular, the current meter must be left to self-align then measure its angle (θ) to the perpendicular of the section and apply the appropriate corrections to the measured velocity:

$$V_{corrigée}: V_{mesurée} \cos\theta \qquad (28)$$

Some current meters can directly measure the normal velocity component when maintained perpendicular to the measuring section in oblique discharge. In such cases, no correction will be required. However, when using this type of current meter, the maximum angle prescribed by the manufacturer must not be exceeded.

A series of current meters can be installed on the same rod to collect velocity data faster in the same vertical. In such cases, the user must ensure that there is no interference between the current meters.

Three consecutive velocity measurements are carried out on each vertical. For example, if three trials are conducted, the process will be as follows:

Trial 1:
- 3, 30-second measurements of velocity on vertical 1
- 3, 30-second measurements of velocity on vertical 2
- 3, 30-second measurements of velocity on vertical 3
- Etc. for each additional vertical

Trial 2:
- 3, 30-second measurements of velocity on vertical 1
- 3, 30-second measurements of velocity on vertical 2
- 3, 30-second measurements of velocity on vertical 3
- Etc. for each additional vertical

Trial 3:
- 3, 30-second measurements of velocity on vertical 1
- 3, 30-second measurements of velocity on vertical 2
- 3, 30-second measurements of velocity on vertical 3
- Etc. for each additional vertical

In some cases, for example in natural settings, whenever the water level is variable, several verticals are required, and velocity measurements must last at least 60 seconds. It may prove difficult to conduct three consecutive measurements of velocity on each vertical while meeting all of the method's criteria, particularly in regard to a maximum 5% variance between the shallowest and deepest water compared to the maximum depth during the trial.

In fact, in such conditions, the duration of the trial can be considerably greater and involve the potential risk of water level variance. To remedy the situation, the same number of velocity measurements for each vertical can be maintained while being not necessarily consecutive. The 5% variance criterion will, in this case, be calculated for each series of verticals. For example, if there are three trials:

Trial 1: 1st 60-second measurement of velocity for verticals 1-20 → $\Delta h \leq 5\%$
2nd 60-second measurement of velocity for verticals 1-20 → $\Delta h \leq 5\%$
3rd 60-second measurement of velocity for verticals 1-20 → $\Delta h \leq 5\%$

Trial 2: 1st 60-second measurement of velocity for verticals 1-20 → $\Delta h \leq 5\%$
2nd 60-second measurement of velocity for verticals 1-20 → $\Delta h \leq 5\%$
3rd 60-second measurement of velocity for verticals 1-20 → $\Delta h \leq 5\%$

Trial 3: 1st 60-second measurement of velocity for verticals 1-20 → $\Delta h \leq 5\%$
2nd 60-second measurement of velocity for verticals 1-20 → $\Delta h \leq 5\%$
3rd 60-second measurement of velocity for verticals 1-20 → $\Delta h \leq 5\%$

This is an exceptional situation, so the report must describe the context and state why the method was adapted.

Theoretically, velocity can even be measured at a single point (e.g., .6H) on each vertical whose size should be of the same order of magnitude. It is still recommended to comply with the maximum variance of 5% between the lowest and highest velocities compared to the highest velocity measured for each vertical.

Whenever the velocity-area method is used to check the accuracy of an installed primary instrument, at least three trials are required, all of which must meet the method’s applicable criteria. It is also recommended to conduct trials at three streamflow levels (min – avg. – max) to check the *in situ* streamflow measuring system.

If these criteria are not met during a trial (e.g., the variation of water level during the trial >5% or variation of velocity for a vertical >5%, etc.), the cause must be found and its impact on streamflow assessed to evaluate whether a different reference method is warranted.

If the velocity-area method remains the best option, three full trials must be conducted at the problem streamflow. Maximum permissible velocity variance must in such cases be met at each of the trials and not for the average of the three, and the individual raw data for each trial must be shown in the audit report.

7.8 DETERMINATION OF THE AVERAGE VELOCITY IN A VERTICAL

The discharge velocity varies in accordance with the depth at which measurement occurs. The curve in Figure 96 shows the relationship between depth and discharge velocity along a vertical in a channel or pipe.

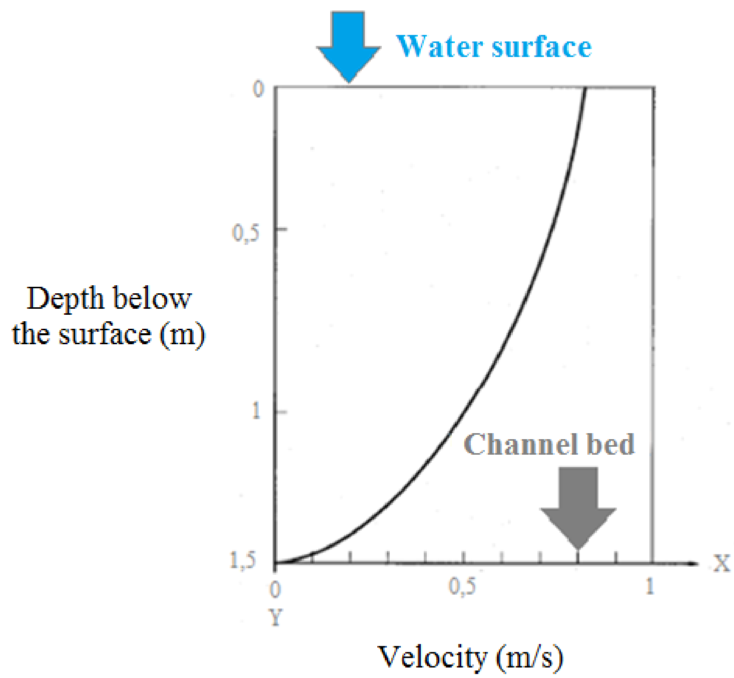


Figure 96: Sample laminar discharge velocity curve in a vertical.

Various methods exist for determining velocity on the basis of available trial time or discharge conditions, characteristics of the measuring section and desired degree of accuracy. Any of the following methods can be selected.

Velocity distribution method

The velocity values are obtained by readings taken at a predetermined number of points along each vertical, from the water surface to the bed. The number of points and their spacing must be such that differences between two adjacent points do not exceed 20% of the greatest velocity.

This method provides superior accuracy, given the number of velocity measurements for each vertical. However, the advantage may also become a source of errors, since a longer length of time is required to conduct the measurements, during which discharge conditions may change.

ISO 748 lists the velocity calculations to be used.

Methods using a reduced number of points (also called the velocity points method)

If, for a given channel, one can presume that the velocities measured at various points may be considered to be representative of the discharge over the entire vertical, then either of the below-mentioned methods that use a reduced number of points can be envisaged.

The methods that use a reduced number of points are simplified versions of the velocity distribution method and may be used subject to certain conditions related to water level and measuring instrument. They are able to assess streamflow faster, making them attractive, particularly when accuracy checking streamflow measuring systems. When using these methods, the measuring points can be located at various heights, depending on the situation (Figure 97 and Figure 98):

Single-point method:

- o Velocity readings are conducted at a single point for each vertical (.6 times the water level) and measured below the discharge surface.
- o Can be used for water levels equal to or less than .76 m.

Two-point method:

- o Velocity readings are conducted at two points for each vertical (.2 and .8 times the water level) and measured below the discharge surface. Average discharge velocity is the arithmetic average of the readings.
- o Superior accuracy compared to the single point method, particularly when the level of the water is greater, since the effects of variations in discharge at the surface and the bed become more significant.
- o Can be used for water levels greater than .76 m with a laminar discharge profile.

Three-point method:

- o Velocity readings are conducted at three points for each vertical (.2, .6 and .8 times the water level) and measured below the discharge surface. Average discharge velocity is calculated using equation 30.
- o Can be used for water levels greater than .76 m with abnormal velocity distribution, such as turbulent discharge.

Methods involving five or six points may also be used (see ISO 748).

Where doubt persists or when using a new measuring section, the accuracy of the reduced point methods must be evaluated prior to use. Here, preliminary measurements taken with reduced point methods must be compared with results from the velocity distribution method.

If the physical characteristics of the measuring section and the discharge conditions are well-known (e.g., the measuring device installation is perfect, the flume is well-maintained and not warped), the reduced point methods can be used, presuming that the theoretical velocity profiles for a given vertical correspond to a standard distribution curve.

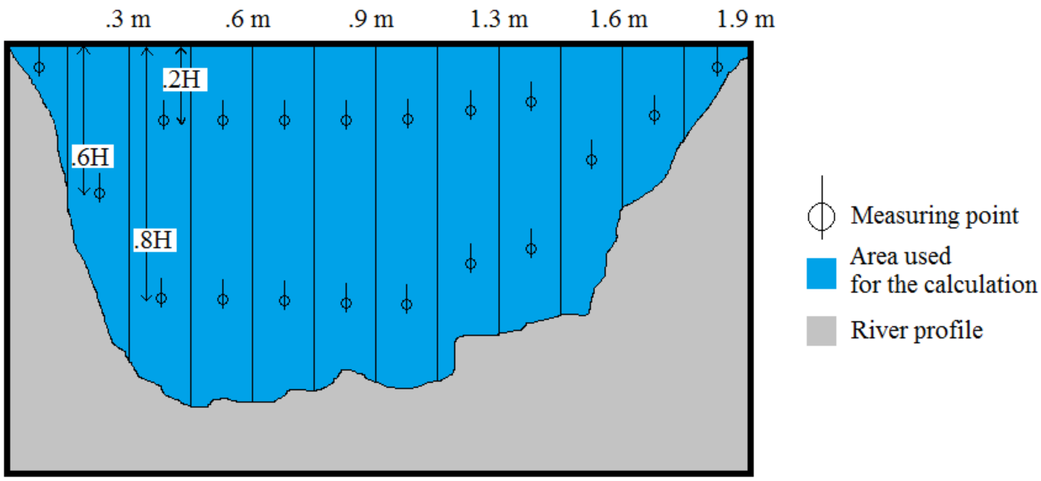


Figure 97: Location of measuring points in a natural watercourse using the reduced points method.

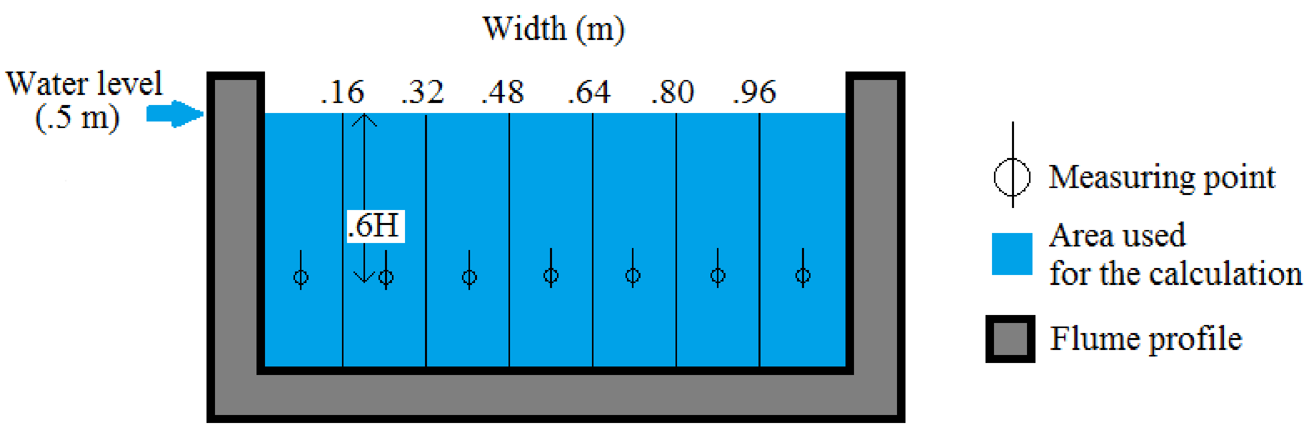


Figure 98: Location of measuring points in an artificial rectangular channel using the reduced points method

The average velocity unit used for calculations in the reduced number of points method is as follows:

- Single-point method: The measured value is taken to be the average velocity for the vertical
- Two-point method: The arithmetic average of two values is taken to be the average velocity for the vertical
- Three-point method: The .6 value is weighted and average velocity is calculated by the following equation:

$$\bar{v} = .25\,(v.2 + 2v.6 + v.8) \qquad (29)$$

See ISO 748 for more details on the five- and six-point methods.

Velocity integration method

With this method, a current meter is placed over the verticals to measure velocities from top to bottom and bottom to top over the entire depth. This technique quickly determines the average velocity for a given vertical (see ISO 748 for more details).

7.9 SOURCES OF ERRORS IN THE VELOCITY-AREA METHOD

Some manufacturers cite a level of measuring errors (often described as the instrument's accuracy) of around 1%, which can be seen as a theoretical reference number. Accuracy can vary greatly by effluent type and installation conditions.

Using this method in a natural channel such as a river where operating conditions are not met can lead to measurement errors as great as 10 to 15% in some cases. However, in manufactured channels such as Parshall flumes, errors produced by this method in optimal conditions and where all precautions are taken drop to the 5 to 10% range.

Where a high level of variance between the *in situ* streamflow and the trial streamflow resulting from the application of this method is observed, it is first recommended to validate the implementation of the method before concluding non-compliance and taking corrective measures.

When applicable, the calculation of uncertainty[28] must consider all possible sources of measuring errors, including systematic and random. These can vary depending on the equipment used and, for example, can stem from the following:

- The choice of equipment.
- The limited number of verticals.
- The limited number of measuring points along the vertical.
- The technical limitations of the instrument (width, height, velocity).
- Condition, maintenance and calibration errors.
- Errors related to the measurement of the width of the verticals and the area of the wetted section.
- Errors ascribable to the limited time of measurement and the instrument's exposure to the velocity at a given point.
- The instrument measures liquids whose physical characteristics are dissimilar to the liquids used for calibration.
- The choice of the streamflow calculation method.
- The instrument was used beyond the measuring interval velocities for which it was calibrated.

[28] ISO 748:2007 contains tables of uncertainty values which can aid in calculating overall uncertainty. The calculation method is included in section 9 of the ISO standards. An equivalent method may also be employed.

- The apparatus used for measuring (rod, suspension cable, etc.), was not the same as the one used for calibrating the current meter, leading to systematic errors.
- The instrument was inappropriately handled or did not remain in the correct position during measurements (e.g., boat drift).

If measurements were not taken in optimal discharge conditions, the following potential sources of errors should also be considered:

- Instrument functionality disturbance by particulates such as debris or algae.
- Ice in the discharge.
- Oblique discharge whose appropriate corrective factors were not accurately known.
- Discharge instability or disturbance.
- Water surface disturbance by wind.

7.10 Utilization of the velocity-area method when discharge is iced over

If the streamflow has to be measured in winter and the channel is wholly or partially iced over, the velocity-area method may be used, as long as specific conditions are met. For more information, see ISO 9196.

7.11 Velocity-area as a reference method

For checking the accuracy of an *in situ* streamflow measuring system, the velocity-area method may also be used as a reference method. Various methods for determining average velocity in a vertical are acceptable and the methods that use a reduced number of points are often preferred.

The value of the measured streamflow will, in this case, be compared with the simultaneous measurement of the streamflow *in situ* by the measuring system being checked for potential variance. This makes it possible to gauge whether maximum permissible regulatory variance is met. To appropriately conduct accuracy checking here, the user must apply the factors described in section 6. In addition, section 12 describes the details required to produce a full report.

Velocity-area...

A reference method for deducing discharge based on the area of the wetted section and the velocity of the flow in the cross-section.

The method measures the velocity in verticals or using a wetted section algorithm that varies by make and model (rotating/mechanical or electromagnetic current meter; Acoustic Doppler Velocimeter/acoustic current meter; area-velocity Doppler flowmeter; non-contact radar area-velocity flowmeter).

This method requires annual calibration or checks on a comparative test bed. The velocity measuring section must display optimal discharge conditions for proper results, given the operational specifications of the device used.

Schedule 5 provides a field checklist for checking the accuracy of a discharge measuring system by this method.

8 TRACER DILUTION METHOD

A variety of techniques can be used to measure flow with tracers. In this publication, we cover the methods shown in Figure 99.

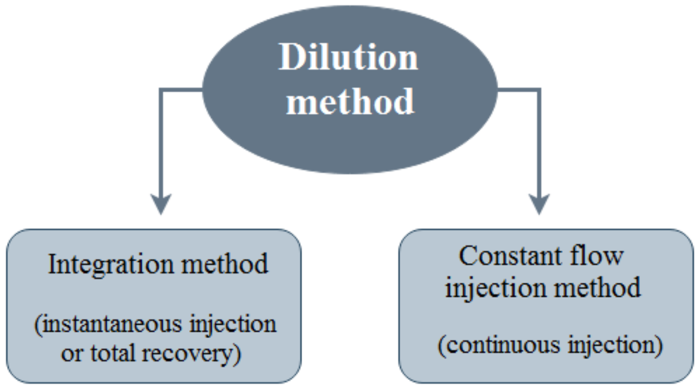


Figure 99: Methods used to measure flow with tracers.

The dilution method enables the flow to be determined independently of the *in situ* measuring system so that it can be used as a reference method for checking the accuracy of a flow measuring system.

8.1 OVERVIEW

The basic principles of the dilution method for measuring flow rely on:

- The variation of tracer concentration between the injection location and the sampling section withdrawal point.
- The conservation of the tracer mass between these two points.

This measuring method consists of injecting a tracer of known concentration at a given point in the channel (injection point) and monitoring the progression of the concentration level at a sampling point downstream. For example, for a given quantity of injected tracer, the higher the discharge rate, the more the tracer will be diluted in the sampling section.

The distance between the injection point and the selected downstream section must be sufficient to ensure that the tracer/water mix is fully dispersed both vertically and laterally. The length of the stretch between the two cross-sections is called the reach. The dispersion of the tracer is generally slower along the walls of the channel than in the centre (Figure 100). If the measuring reach is too short in length, the tracer concentration will be much higher at the centre of the channel (Figure 100, point b) than near the walls (Figure 100, points a and c). Measurement accuracy then becomes difficult to achieve.

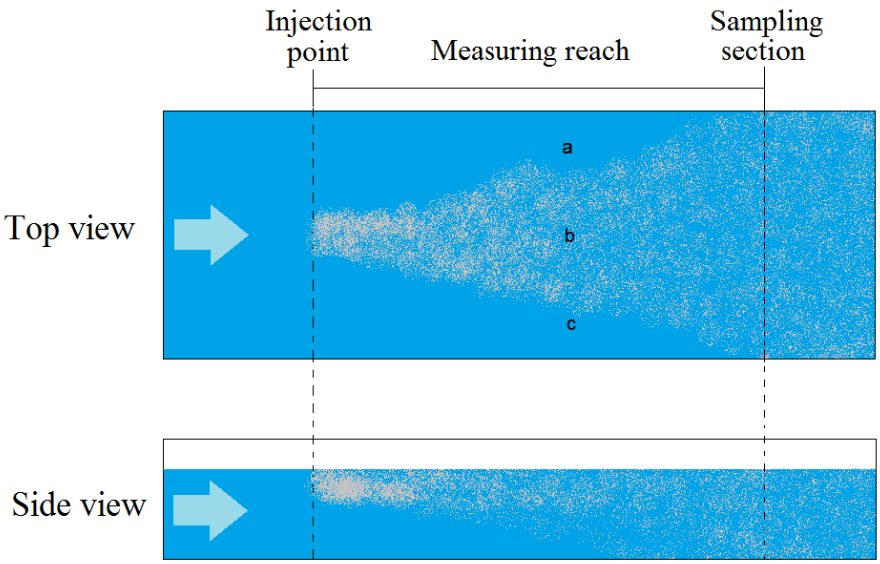


Figure 100: Lateral and vertical tracer dispersion in the measuring reach.

The length of the measuring reach is optimal when the tracer measuring time (T_D) is not excessive and sampling can therefore be conducted at several lateral points. If the length of the measuring reach is excessive, mixing will be almost perfect (Figure 101) but the time needed to measure the tracer will be lengthy, and problems in measuring weak concentrations at the extremities of the curve may arise. An overly lengthy measuring reach can also lead to loss of tracer.

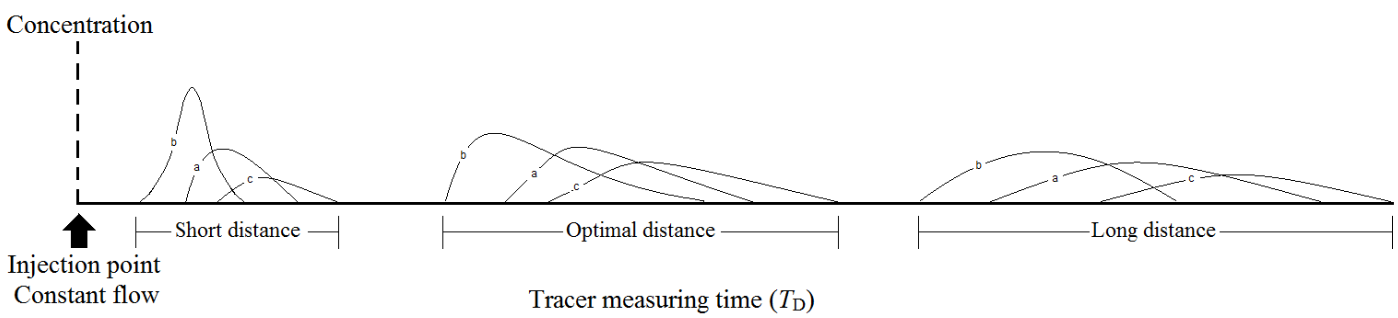


Figure 101: Typical response curves at several lateral points following the instantaneous injection of tracer at the centre of a channel.

In practice, dilution methods should only be used for small channels due to the length of the measuring reach required by larger channels. A rough estimate of the measuring reach is around 25 times the width of the channel. More details on estimating the measuring reach can be found in section 8.5.1.

8.2 Application Conditions

The dilution gauging method requires that a number of conditions are met:

- The selected tracer is appropriate.
- The flow of the discharge (Q) remains constant for the full duration of the trial (flow variation less than 5% between minimum and maximum values).
- The downstream sampling section is sufficiently distant from the injection point for the injected solution to be uniformly mixed throughout the width of the channel.
- There are no dead water zones.
- No water is lost in or added to the selected section.
- All of the tracer flows through the sampling section.

The dilution gauging method can be used for all flows but is particularly efficient in high water turbulent flow. The dilution method is especially useful in the following conditions:

- The use of a flowmeter is problematic due to fast, turbulent discharge.
- The measuring reach contains debris, deposits or heavy vegetation (this will also affect the choice of tracer).
- The measuring reach is difficult to access or has an irregular shape.
- The transverse measuring area cannot be accurately measured or varies during the trial.
- Discharge is turbulent with high gradients, and measurement using the velocity-area method is impractical.

Table 36 shows the advantages and drawbacks of the dilution method.

Table 36: Advantages and drawbacks of the dilution method

Advantages	Drawbacks
▪ Enables the flow to be measured when other methods do not work. ▪ Enables heavy flow to be measured. ▪ Makes it possible to counter-check measuring and liquid transportation equipment on-site. ▪ Does not require establishing the dimensions of the discharge area. ▪ Measures flow in remote areas that are difficult to access. ▪ Measures flow in both closed conduits and open channels.	▪ Tracers can be expensive. ▪ In general, only provides instantaneous flow values. ▪ The procedure requires, usually at least three, trained and experienced staff members. ▪ The procedure is time-consuming. ▪ Parameters that could cause interference must be considered in the choice of the tracer and measured during its use. ▪ The flow value is not always immediately available.

8.3 DESCRIPTION OF THE DILUTION BY INTEGRATION METHOD (INSTANTANEOUS INJECTION)

In this method, a known volume of tracer (V) with initial concentration (C_1) is quickly injected into a section of the discharge channel. The diluted concentration of the tracer (C_2) is then measured after a sufficient time has passed for the tracer to completely transit the section (Figure 102).

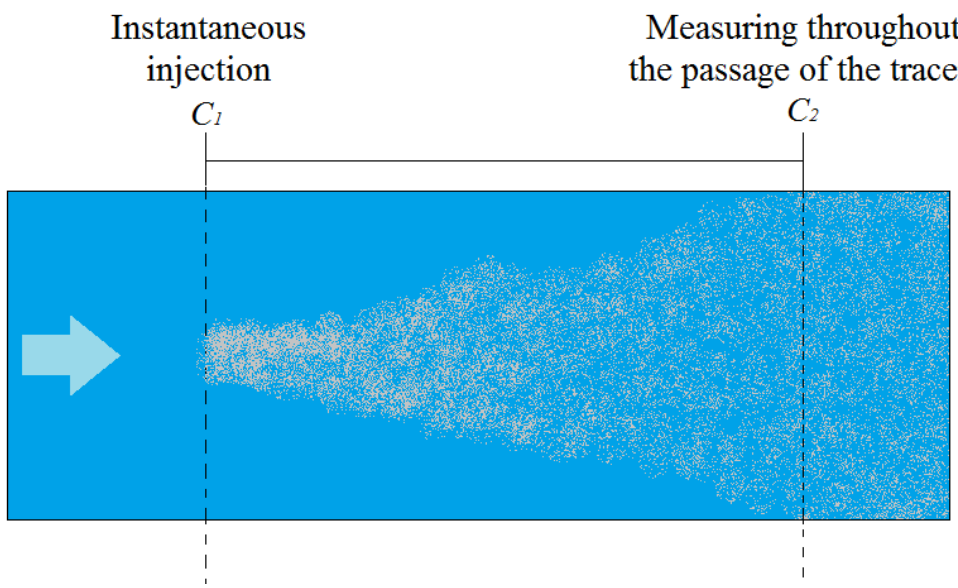


Figure 102: Illustration of the dilution method by integration.

Figure 103 shows the proper shape of the recovery curve of the tracer in a channel based on data collected by a measuring instrument.

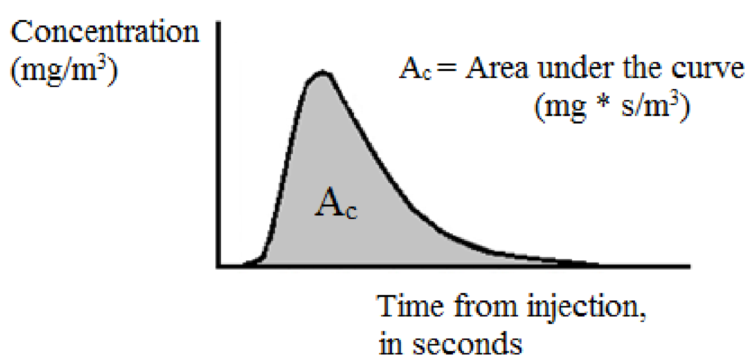


Figure 103: Theoretical typical recovery curve of concentration over time.

Several factors may lead to a curve that differs from the theoretical one, particularly when an injection is not instantaneous or there are pools of stagnant water. In such situations, it is necessary to ensure that the tracer has completely passed through and that the recovery percentage is sufficient.

The principle of mass conservation can determine the flow by the following formula:

$$\boldsymbol{Q = \frac{M}{Ac}} \qquad (30)$$

Where	Q	Flow of the discharge, in m^3/s
	M	Mass of injected tracer, in mg
	A_c	Area under the curve after an appropriate mix of tracer ($mg*s/m^3$)

In practice, samples are taken in constant time conditions and flow is determined by the following equation:

$$\boldsymbol{Q = \frac{V\,C_1}{\Delta t \sum(C_2 - C_{bf})}} \qquad (31)$$

Where	Q	Flow of the discharge, in m^3/s
	V	Volume of the injected solution, in m^3
	C_1	Concentration of tracer in the injected solution, in mg/l
	Δt	Interval of time between the beginning and the end of sampling, in seconds
	C_2	Concentration of the diluted tracer in the sample, in mg/l
	C_{bf}	Background noise concentration, in mg/l

It is also possible to use an average sample value when time intervals or flow are for all samples. The following equation then gives the flow:

$$\boldsymbol{Q = \frac{V\,C_1}{t_p\,(\bar{C}_2 - C_{bf})}} \qquad (32)$$

Where	Q	Flow of the discharge, in m^3/s
	V	Volume of the injected solution, in m^3
	C_1	Concentration of tracer in the injected solution, in mg/l
	t_p	Time interval for the tracer cloud to pass through the sampling section, in seconds
	$\bar{C}_2$	Average concentration of diluted tracer in the sample, in mg/l
	C_{bf}	Background noise concentration in mg/l

Table 37 shows the advantages and drawbacks of the integration method.

Table 37: Advantages and drawbacks of the integration method

Advantages	Drawbacks
▪ No sophisticated instrument is required for tracer injection. ▪ The quantity of tracer required is less than with constant-rate injection. Three to five times less tracer is required to measure low flows than with constant-rate injection. However, in high flows, the difference is minimal. ▪ The only method that can be used with radioactive tracers.	▪ The entire sequence must be sampled. ▪ This method requires a minimum of 30 samples to draw a curve. ▪ Utilization is restricted to measuring where the flow is stable (variation less than 5%). ▪ The successful application of this method relies on the recovery of the full mass of the tracer injected at the control point and requires great accuracy in measuring the area under the recovery curve.

8.4 DESCRIPTION OF THE DILUTION METHOD BY INJECTION AT A CONSTANT (CONTINUOUS) FLOW

In this method, tracer with initial concentration (C_1) is injected into a section of a watercourse or pipe whose constant flow is known (q). In the second section, the concentration of the diluted tracer (C_2) is measured over a length of time that is sufficient to check that a good mix has been achieved and that the concentration of tracer has reached a plateau (constant value).

Under constant flow, the constant-rate injection of a series of tracers with similar concentration at similar intervals of time will produce similar curves. Figure 104 shows the superposition of several concentration/time curves.

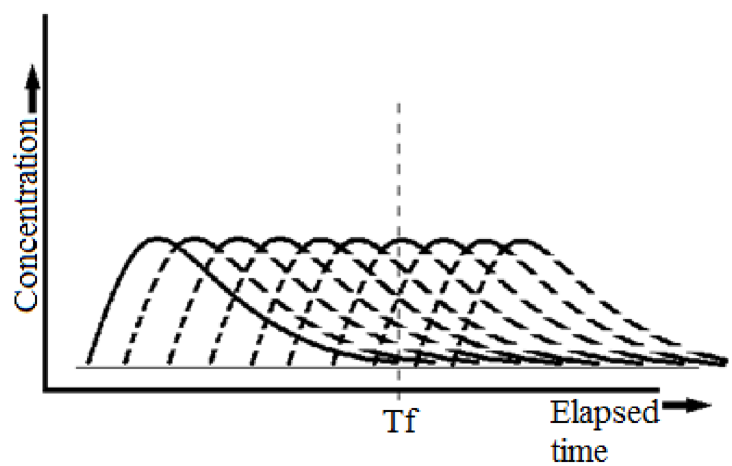


Figure 104: Superposition of concentration/time curves following the instantaneous injection of a tracer.

The individual curves will eventually be superimposed and become indistinct. Equilibrium will be reached at the time corresponding to the final extremity of the first injection (Tf), generating a plateau of constant concentration. Figure 105 illustrates this situation with the plateau at Tf.

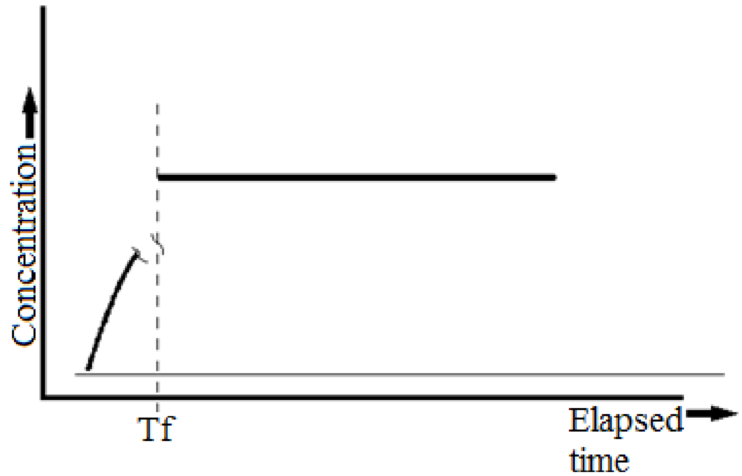


Figure 105: Illustration of the plateau reached at time Tf.

The first advantage of the constant flow injection method is that measuring the totality of the curve is not required. When equilibrium has been reached, the principle of mass conservation applies and the flow can be determined by the following equation:

$$\boldsymbol{Q = q\left(\frac{C_1 - C_2}{C_2 - C_{bf}}\right)} \qquad (33)$$

Where
- Q Flow of the discharge to be measured, in m^3/s
- q Tracer injection flow, in m^3/s
- C_{bf} Natural concentration of the tracer in the discharge, in mg/l
- C_1 Tracer injection concentration, in mg/l
- C_2 Concentration of tracer in the sampling section, in mg/l

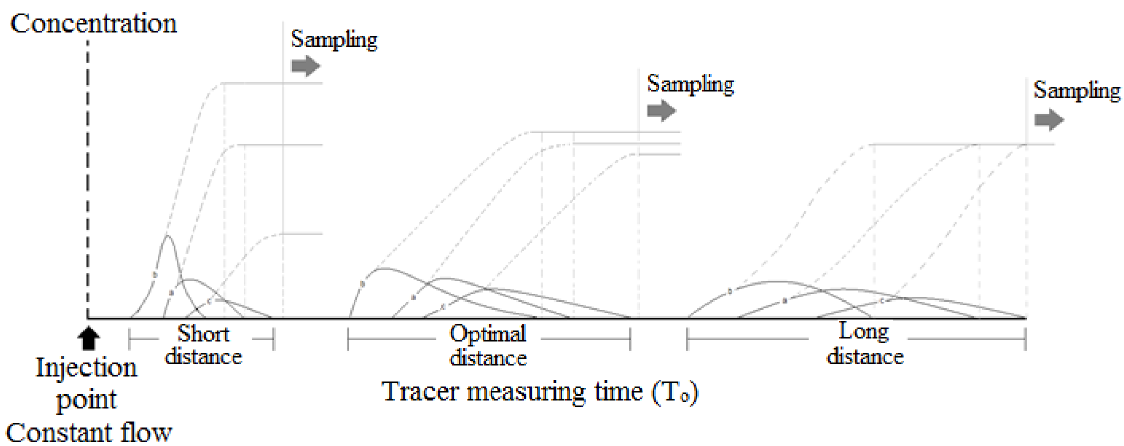
However, since C_1 is usually considered as much greater than C_2 and *Cbf* is often equal to 0, it is customary to simplify the equation, as follows:

$$\boldsymbol{Q = q\,\frac{C_1}{C_2}} \qquad (34)$$

The method relies on the ratio between the concentration of the injected solution (C_1) and the concentration in the discharge at the sampling section (C_2). The same solution must be used for standards and injection purposes.

When samples are withdrawn at three points, such as in large channels, the impact of the length of the reach on the measurements obtained using the constant flow injection method can be visualized as shown in Figure 106.

When the distance is insufficient, three plateaux of different concentrations will be engendered. When the distance is optimal, three plateaux of similar concentrations will result in a reasonable lapse of time (T_D). Finally, while three plateaux of identical concentration will result from the use of a long reach, the duration of injection and time (T_D) required to obtain this is very extensive.



Reach length	Short distance	Optimal distance	Long distance
Impact	Areas under the curves are not identical. Equilibrium quickly reached. Different levels of concentration. Incomplete lateral mixing.	Areas under the curves are similar. Equilibrium reached fairly quickly. Similar levels of concentration. Adequate mixing.	Areas under the curves are identical. Equilibrium reached slowly. Identical levels of concentration. Perfect mixing.

Figure 106: Impact of the length of the reach on the measurements obtained with the constant flow injection method.

Table 38 shows the advantages and drawbacks of the constant flow injection method.

Table 38: Advantages and drawbacks of the constant flow injection method

Advantages	Drawbacks
▪ The number of samples withdrawn and analyzed is less than with the instantaneous injection method. ▪ Can be used for measuring reaches where flow is not constant, on condition that the time of injection is extended and the interval of time between samplings is reduced. ▪ Accuracy is greater than with the instantaneous injection method.	▪ Tracer injection requires constant attention and the use of an injection device whose flow can be regulated and controlled with precision. ▪ The required quantity of tracer for measuring low flow can be three to five times greater than with the instantaneous injection method. For high flows, the difference is minimal.

8.5 USING THE DILUTION METHODS (INTEGRATION AND CONSTANT FLOW)

The procedural steps listed below should be followed when using either of the dilution methods.

8.5.1 Selection of the measuring reach

8.5.1.1 Overview

The measuring reach corresponds to the stretch between the two measuring cross-sections. It must be as short as possible while sufficiently long to enable a uniform mix of the injected solution over the entire width of the stretch. Since lateral mixing is the most difficult to achieve, narrow turbulent stretches are preferred.

There can be no loss or gain in tracer disturbance in the reach. Grassy areas or junctions should be avoided.

In order to minimize the risk of measuring errors, drifts, inflows, leaks, backflows or dead water zones in the reach should be avoided.

Ideally, the injection point should be located upstream of a constriction.

8.5.1.2 Estimating the length of a measuring reach

According to the rule of thumb, the length of a measuring reach should be 25 times the width of the channel. However, perfect mixing conditions may sometimes require a shorter distance.

The optimal length of the reach can also be estimated. The time needed for the maximum concentration of the tracer to pass through the sampling section can be evaluated by means of a colorant for a preliminary trial and measuring the transit time of the mix visually. If the tracer is invisible, a colorant can be added to the stock solution to dispense with a preliminary trial. The total transit time is around four times longer than the time required for maximum concentration to be reached.

Numerous empirical equations are available to estimate the length of time needed for a good mix. Based on information about the reach, the following equation can be used for alluvial watercourses or channels:

$$L = \frac{K\,v\,b^2}{0{,}63\,S^{1/2}d^{3/2}} \qquad (35)$$

Where	*L*	Mixing length, in m
	K	Constant, equal to .1 for injection into the centre of the current and .4 for lateral injection
	v	Average velocity of the discharge, in m/s
	b	Average width of the discharge, in m
	S	Slope of the discharge surface, in m/m
	d	Average depth of the discharge, in m

A minimum length for artificial channel discharge should be at least 20 times the diameter of the conduit because the preceding equation undervalues results for small-width channels (< .6 m).

An equation can only produce rough estimates of the mixing distance, so complementary field trials are usually needed. More information about equations is available in ISO 9555-1:1994.

8.5.1.3 Characteristic of injection point and the sampling section

The injection point must be selected to ensure access, and located in turbulent discharge that can be induced at will. Access at the injection point must be safe and sufficient in size to enable the injection equipment to be set up.

The sampling section must be selected on the basis of access and safety criteria. Turbulence is not a consideration here.

This section must be sufficient in size to enable the sampling equipment to be set up.

8.5.2 Choice of tracer

The selected tracer cannot be blocked by dead zones, measuring sensors, grassy plants or suspended matter at levels that could affect the accuracy of measurement.

8.5.2.1 Overview

In general, the tracer should be water-soluble, detectable and measurable in a variety of concentrations.

However, for the purposes of this publication, the tracer should not endanger the natural environment or pose risks to human health and should be no more than slightly present in the discharge. It should mix easily in water, be stable over time, affordable and easy to dose.

8.5.2.2 Types of tracers

The categories of tracers generally used and the types detailed herein are shown in Figure 107.

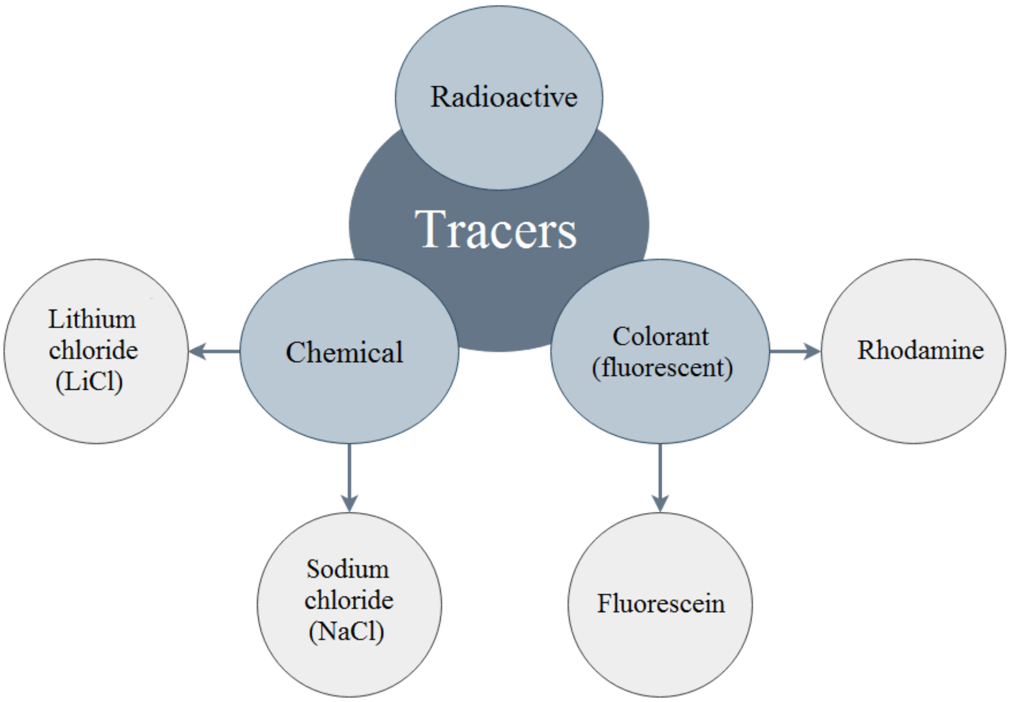


Figure 107: Tracer categories and types.

8.5.2.3 Chemical tracers

The salts generally used are sodium chloride (NaCl) and lithium chloride (LiCl).

The manipulation of chemical tracers must comply with standard laboratory practices. They can be easily purchased and are photochemically stable.

However, the detection limit for chemical tracers is relatively higher than for other types of tracers. In certain cases, the analytical method dosing range can be restrictive, which limits their use in the constant flow injection method. The characteristics of two tracer chemicals are shown in Table 39.

Table 39: Characteristics of chemical tracers

	Lithium chloride (LiCl)	Sodium chloride (NaCl)
Solubility in water (at 25 °C)	~ 800 g/l	~ 350 g/l

Usual concentration of stock solution	300 g/l	300 g/l
Usual concentration in the sampling section	2-500 µg/l of lithium (preferable to remain below 440 µg/l)	50 mg/l (preferable to remain below 230 mg/l of chlorine)
Analytical method	Mass spectrometry using argon plasma as the ionizing source	Continuous conductimetry
Detection limit	1 µg/l	N.A. (measurement of conductivity)
Application range	1 µg/l-5 mg/l	2 mg/l-5.8 g/l
Various	▪ Habitually low background noise (< 0.1 µg/l) but may reach 10 mg/l near industrial or mine effluent ▪ Exothermal preparation of the solution ▪ Concentrated solutions are acidic ▪ Possibility of adsorption over suspended matter ▪ No method for analysis *in situ*	▪ Easily available and inexpensive ▪ Easy to use ▪ Background noise may be elevated (50-1,000 mg/l) ▪ May necessitate large quantities ▪ May be absorbed by vegetation and the channel bed ▪ Analysis feasible *in situ*

Chemical tracers induce environmental disturbances. According to the literature, if they are used in accordance with suggested dosages, the disturbances will be weak and of short duration, with no long-term impact. Measures must be put in place to ensure that acceptable limits are not exceeded.

8.5.2.4 Colorants/fluorescents tracers

A certain number of colorants may be used as tracers for measuring flow. Rhodamine WT and fluorescein are described in this publication because they are the most frequently used.

Tracer colorants may be used alone or in conjunction with a chemical tracer to facilitate monitoring.

Several factors can affect tracer colorants, including temperature, pH, turbidity, salinity and background fluorescence.

Background fluorescence particularly affects fluorescein, so this colorant is no longer recommended for measuring flow in free-surface channels. However, this can be remedied by measuring background fluorescence several times during sampling. It should not be presumed that background noise is nil or constant.

With regard to temperature, a fluorimeter must be calibrated with standard solutions whose temperature is similar to that of the samples to be analyzed.

As well, one of the main drawbacks of tracer colorants is that they may easily become attached to suspended matter and colloids by adsorption, which can significantly impair the accuracy of measurement. The interior surface of many types of channels can be covered with clay, ferrous oxide or a biofilm that can interact with the colorant.

As rhodamine WT is likely to react with chlorine, tap water should not be used in preparing standard solutions.

Finally, tracer colorants can also be photochemically degraded. To reduce the repercussions, the fluorimeter and samples must be protected from sunlight.

The characteristics of two tracer colorants are shown in Table 40.

When used in habitually prescribed concentrations, fluorescein and rhodamine WT are unlikely to present a toxic risk to human life and/or common aquatic organisms. According to the USEPA[29], this statement is reliable if concentration remains at 1-2 mg/l in the measuring section for 24 hours.

Table 40: Characteristics of colorants/fluorescent tracers

	Fluorescein (uranin in Europe)	Rhodamine WT
Solubility in water (at 25 °C)	~ 250 g/l	~ 200 g/l
Usual concentration in the sampling section	5 µg/l	1-10 µg/l
Application range	.01-500 µg/l	.01-500 µg/l
Analytical method	Fluorimetry	Fluorimetry
Detection limit	.01 µg/l	.01 µg/l
	Fluorescein (uranin in Europe)	**Rhodamine WT**
Colour	Yellow-green	Red
Maximum concentration in the measuring section	----	10 µg/l

[29] United States Environmental Protection Agency.

8.5.2.5 Radioactive tracers

Due to particular specifications for the use of radioactive tracers, they are not addressed in this publication. Further information about this type of tracer can be found in ISO-9555-2.

8.5.2.6 Tracer preparation

As a general rule, the tracer container should be thoroughly shaken before withdrawing any quantity, in order to eliminate deposits and procure a homogeneous solution.

Preparing a stock solution of chemical tracer (lithium chloride)

The method used to prepare a stock solution of lithium chloride may be adapted to other chemical tracers. The following equation may be used to prepare a solution of lithium chloride with a given tracer concentration:

$$M_{salt} = C_{tracer}\ x\ V\ x\ \frac{MM_{salt}}{MM_{tracer}} \qquad (36)$$

Where	M_{salt}	Mass of the salt to be weighed (g/mol)
	C_{tracer}	Concentration of the tracer (mg/l)
	V	Required volume of solution (l)
	MM_{salt}	Molecular mass of the salt (g/mol)
	MM_{tracer}	Molecular mass of the tracer (g/mol)

Therefore, to prepare 10 litres of a solution of 10,000 mg/l of lithium and take account of the fact that the molecular mass of the tracer (LiCl) is 42.392 g/mol and the molecular mass of the salt (LiCl) is 6.939 g/mol, the known values are subbed into the equation to determine the quantity of LiCl required to prepare the solution. The equation then becomes:

$$M_{salt} = \frac{10000\ mg/l}{1000\ mg/l}\ X\ 10\ l\ x\ \frac{42.392\ g/mol}{6.939\ g/mol} = 610.9\ g \qquad (37)$$

Preparation of a stock solution and a standard solution of rhodamine WT

The method of preparing a solution of rhodamine WT may be adapted for the preparation of any tracer colorant.
Rhodamine WT is usually available in a 20% aqueous solution. This means that 1 microgram of the 20% solution diluted in 1 litre of water will contain 0.2 micrograms of the active ingredient. The relationship between the reading from a standard fluorimeter and the concentration of rhodamine WT is linear between 0 and 500 ppb. The linearity of the active ingredient falls between 0 and 100 ppb. This information is crucial in determining the peak intensity of the desired tracer. Consequently, to avoid confusion, it is of prime importance to identify the stock and standard solutions in terms of the solution tracer and/or active ingredient.

The standard solution is prepared three times. A predetermined quantity of tracer at a set concentration can be prepared by the following procedure:

1. Preparation of the stock solution in a laboratory
   Preparation of a 10,000-ppm solution of the tracer solution:
   With a laboratory scale, weigh 1 g of the rhodamine WT 20% solution in a 100-ml volumetric flask and dilute it with distilled water to the mark. This solution has a specific gravity of 1.002 g/ml allowing the following dilutions to continue per mass or volume.

2. Dilution of the stock solution in a laboratory
   Preparation of a 100-ppm solution of the tracer solution:

   Pipette 1 ml of solution 1 into a 100-ml volumetric flask and dilute it to the mark with distilled water.

3. Dilution of the stock solution with discharge water
   Preparation of a 500-ppb solution of the tracer solution:

   Pipette 5 ml of solution 2 into a 1,000-ml volumetric flask and dilute it to the mark with discharge water. The obtained solution is equivalent to 500 ppb of rhodamine WT 20% or 100 ppb of the active ingredient.

Using laboratory equipment such as a pipette, volumetric balloon or fluorimeter requires training, and a laboratory must be consulted before work can begin. The elevated viscosity of rhodamine WT complicates the use of pipettes.

Since this colorant is quite viscous and adheres to walls, it is preferable to dilute it with a good amount of distilled or demineralized water, so as to ensure that the injection is of a precise quantity.

8.5.3 Determination of tracer quantity

8.5.3.1 Parameters required for determining tracer quantity

The following four parameters need to be defined in order to perform the work correctly:

- Concentration of the tracer upon injection (C_1).
- Concentration of the diluted tracer (withdrawn in the sampling section [C_2]).
- Estimated effluent flow to be measured (Q').
- Estimated time for the tracer to transit the sampling section ($t_f - t_i$).

When using the constant flow method, the following must be known:

- The duration of injection once the plateau has been reached (t_p).

When the flow is unknown, various options can be envisaged to estimate it, such as:

- Estimate the average velocity in the wetted section using a float.

- Use data from an adjacent hydraulic structure.
- Consult the calibration curve of an adjacent gauging station.

It is also current practice to use a colorant for a preliminary trial and measure the transit time based on the visual effect of the mix. When a chemical tracer is used, adding a colorant makes it possible to visualize the passage of the tracer as long as it causes no interference.

Table 41 shows other parameters to be considered in determining the quantity of tracer based on the implemented dilution method (integration or constant flow).

Table 41: Parameters to be considered when determining tracer quantity

Integration method (instantaneous injection)	Constant flow method (constant-rate injection)
The expected concentration of the tracer after mixing with discharge (C_2) must produce an easily measurable signal. A concentration greater than two to five times the natural concentration in the discharge is sought. Also, the maximum permissible level of tracer in the receiving environment must be met[30]. When the background noise is high, a ratio of less than half the background noise may be acceptable as long as the impact on the accuracy of results is not marked. As a general rule, the tracer recovery percentage varies directly with the quantity of injected tracer. The greater the concentration of the tracer in the sampling section compared to the background noise, the greater will be the quality of the measurement.	It is recommended to always prepare a quantity of tracer slightly greater (5%) than the quantity needed to carry out the work, to prepare for any eventuality. It is important that the tracer concentrations reach a stable plateau. As well, a high ratio of the plateau-to-background noise signal is required. However, when estimating this ratio, acceptable limits of tracer levels in the receiving environment should be taken into account[30].

8.5.3.2 Equation used to determine tracer quantity

Once the parameter values are known, the required tracer quantity can be calculated using the equations shown in Table 42.

[30] Surface water criteria

Table 42: Equations for determining tracer quantity

Integration method (instantaneous injection)	Constant flow method (constant-rate injection)
$$V = [\frac{C_2}{C_1} Q^{\mid} (t_f - t_i)]\ 1000$$ Where	$$V = (t_f - t_i + t_p)\ \frac{Q^{\mid} C_2}{C_1}$$ Where
V Required quantity of tracer, in ml	V Required quantity of tracer, in l
C_1 Concentration of the tracer upon injection, in mg/l	C_1 Concentration of the tracer upon injection, in mg/l
C_2 Concentration of the tracer after mixing with the discharge, in mg/l	C_2 Concentration of the tracer after mixing with discharge, in mg/l
$Q^{\mid}$ Estimated flow (e.g., l/min)	$Q^{\mid}$ Estimated flow (e.g., l/min)
t_f End tracer transit time in the sampling section, in min	t_f End tracer transit time in the sampling section, in min
t_i Start tracer transit time in the sampling section, in min	t_i Start tracer transit time in the sampling section, in min
	t_p Time of injection after the plateau has been reached, in min

The tracer is then prepared using the methods described in section 8.5.2.6.

8.5.4 Equipment required for fieldwork

The following equipment is required for fieldwork for the two methods:

- 1 one-litre volumetric flask to measure water in the channel.
- 1 measuring cup to withdraw water from the channel.
- 1 wash bottle to adjust the water level in the flask.
- 2-, 5- and 10-ml pipettes to measure the volumes of the secondary solution.
- 1 pipette pear.
- 1 pail to calibrate the measuring instrument.
- 1 wide-neck 1-2-litre bottle to mix the secondary solution.
- 1 stirring rod.
- 1 chronometer.
- Tracer measurement and data acquisition equipment, if required.
- At least 30 sampling bottles.

The following should also be at hand when using the constant flow method:

- Constant flow injection equipment (float siphon, dosing pump, Mariotte's bottle, constant level bottle).
- 1 100-ml graduated cylinder to measure flow injection.

8.5.5 Injection of the tracer

When injecting the tracer, users must ensure that no quantity is lost by splashing or otherwise, by placing the tracer in the discharge at a minimum distance from the surface (5 to 8 cm), especially when the injection is carried out in relatively confined areas, such as sewer manholes.

Table 43 shows other recommendations to be implemented when injecting a tracer using the applied dilution method.

Table 43: Recommendations to be implemented when injecting a tracer

Integration method (instantaneous injection)	Constant flow method (constant-rate injection)
Injection of the total quantity of prepared tracer is instantaneous at the injection point in the measuring reach, at the centre of the discharge. The injection is usually performed with a wide-neck receptacle to enable the entire solution to be poured quickly. The timing must begin and the staff in the sampling section must be advised that the tracer has been injected. When the flow is not continuously measured, it is recommended that the water level in the measuring reach be measured and recorded to ensure the consistency of flow.	Injection in falls is proscribed. Injection of the tracer is made continuously at a known flow and concentration using equipment that allows the flow to be adjusted and controlled. The injection tube must not touch the surface of the water; thus avoiding the tracer being carried by the current and creating injection flow errors. The injection flow must be checked before and after the use of a device to confirm that the flow is constant. The injection flow is established on the basis of the average of three volumetric measurements. There can be no air bubbles in the injection system so that the tracer solution remains ongoing in the tube. The tracer must be placed in a graduated receptacle, with the level of the solution noted at .2, .4, .6 and .8 of the total duration of the injection. This observation makes it possible to counter-check the consistency of the injection flow. The injection rate is one of the crucial variables needed to calculate flow. It is important to quantify it and minimize variance.

8.5.6 Withdrawal of samples

Samples are of two types: control and measurement.

8.5.6.1 Control sample

Control samples are used for the following:

- Checking and quantifying the natural level of tracer in the discharge (background noise).

- Checking the consistency or variations in the natural concentration of the tracer in the discharge.
- Checking the concentration of the injected tracer.

When using the integration method of dilution, samples also serve to determine the tracer recovery rate.

Background noise

At least three series of three samples of water in the discharge are withdrawn from the measuring reach to determine the natural concentration of the tracer and check that there are no variations.

Withdrawals are taken:

- Before starting to manipulate the tracer.
- During the trial.
- At the end of the injection.

The samples must be withdrawn at a location that is representative of the discharge quality without risk of contamination by the tracer, such as upstream of the measuring reach.

Concentration of the injected tracer (C_1)

The specifications for determining the concentration of injected tracer are shown in Table 44.

Table 44: Determining the concentration of injected tracer (C_1)

Integration method (instantaneous injection)	Constant flow method (constant-rate injection)
Three injection solution samples of around 50 ml must be withdrawn before the trial to check concentration and prepare benchmarks. C_1 corresponds to the average of the three samples. The certificates of analysis of all appropriately identified samples must be appended to the report.	Three injection solution samples must be withdrawn at the beginning of the trial, and three others at its conclusion for the purpose of checking concentration. The average result of the six measurements will then be deemed the concentration of the injected tracer. For the trial to be valid, the difference between each of the six measurements must be less than 5%. The certificates of analysis of the six measurements must be appended to the report.

8.5.6.2 Measurement samples

The following needs to be applied when withdrawing samples (Table 45):

Table 45: Description of sampling methods

Integration method (instantaneous injection)	Constant flow method (constant-rate injection)
The measurement samples are withdrawn at the sampling section after the tracer is injected. They are used to determine the concentration of the tracer after mixing (C_2) and to determine the value of the flow (Q) in the measuring reach. Sampling must last for the duration of the tracer transit, starting before the tracer arrives in the sampling section and continuing as long as any tracer is detected. At least 30 samples are required to check that the tracer has completely exited the section. Sampling must continue even after the estimated time when the tracer should have exited. It must last at least three to four times the time needed for the maximum concentration of the tracer to enter the sampling section.	The samples, which are used to determine the concentration of the tracer, are withdrawn in the sampling section after the tracer has been injected. The number of samples must be sufficient to draw a tracer response curve with a minimum number of points, i.e., three points for the ascending part of the curve and nine for the plateau. Sampling must commence before the tracer arrives at the sampling section and continue after the plateau is reached. If a continuous analyzer is used, it will be possible to check whether the plateau has been reached over the entire width of the channel. A variation of the signal along the width of the channel is an indication that a good mix has not been achieved. If this is the case, the measuring equipment should be moved upstream.
For example, if it is estimated that the maximum concentration will reach the sampling section 10 minutes after injection, sampling must continue after the 10 minutes for at least 30 minutes–and ideally 40 minutes. The measurement samples must be withdrawn at very short intervals–no more than one minute–and the exact time of withdrawal must be recorded for each. When the flow is fast and the tracer transit time is short, the frequency of withdrawals must be very short (i.e., every 10 seconds).	The samples must be withdrawn over a short period of time–no more than five minutes after injection in all–including once a minute after the plateau has been reached. The exact time of each withdrawal must be recorded for each sample.

For wide channels, samples must be simultaneously withdrawn at three points (1/6, 3/6 and 5/6 of the width), when the following is true:

- The channel width exceeds 2.4 m (8 ft) and has uniform, homogenous walls–as in a concrete pipe.

- The channel width exceeds 1.8 m (6 ft) and has uniform but not homogenous walls– as in a ditch.

Each sample must be identified and immediately prepared for shipment to the laboratory. The samples must be kept out of direct sunlight. This is especially the case for photosensitive tracers such as colorants.

The certificates of analysis of all samples must be appended to the report.

8.5.7 Analysis of the results

The concentration of the samples is usually determined in a laboratory. It may be practical (but not mandatory) to do this on-site for colorants or salts. If this method is chosen, the samples should be kept for future counter-checking reference purposes.

8.5.8 Interpretation of results

A sample may be rejected only if a statistical justification is provided or if systematic errors have been found. In such cases, the required justification must be attached to the report. Table 46 lists the factors to be considered when interpreting results.

Table 46: Interpreting results

Integration method (instantaneous injection)	Constant flow method (constant-rate injection)
When samples are withdrawn at three points, for example, in wide channels, a concentration/time curve must be drawn for each withdrawal point and the area under the curves must be measured. The mix is considered as uniform when the areas under the curves are similar. An average curve is then drawn from the three individual curves. When the samples are withdrawn at a single point, a concentration/time curve is also drawn but only one plateau will be used to calculate the flow.	When the samples are withdrawn at three points, for example, in wide channels, a concentration/time line must be drawn for each withdrawal point. An identical plateau for the three lines indicates that the mix is uniform and the duration of injection is sufficient. The tracer injection period must be sufficient to enable the superposition of the three lines, and only the concentrations above the plateau should be used to calculate the flow. Figure 106 illustrates the effect of the duration of the injection time. Equilibrium (the plateau) among the three points is rarely achieved even when withdrawals are simultaneous since the transverse velocity of the discharge varies from one point to the next. Figure 104 shows the curve for samples withdrawn at a single point.

8.5.9 Recovery percentage

This criterion applies only to the integration method.

In order for an instantaneous injection method trial to be deemed valid, 95% of the mass of the injected tracer must be recovered.

For wide channels requiring three curves, the recovery rate must be individually verified for each.

The tracer recovery percentage is determined by multiplying the area below the recovery curve (concentration/transit time) by the flow of the discharge, per the following equation:

$$\% P_{rec.} = \frac{M_{rec.}}{M_{inj.}} X\ 100 \qquad (38)$$

Where	$\% P_{rec.}$	Recovery percentage
	$M_{rec.}$	Mass of recovered tracer
	$M_{inj.}$	Mass of injected tracer

8.6 How to conduct a dilution trial (by the integration or constant flow method) using a chemical tracer and continuous measurement of conductivity

This section describes the basic principles used to conduct a trial with a NaCl chemical tracer injected instantaneously (8.6.1) or continuously (8.6.2) and using a sensor that measures conductivity continuously.

Both procedures assume that at low concentrations, electrical conductivity will vary linearly as a function of the salt concentration. The precision of results is based on the assumption that all of the salt used is completely dissolved.

Since conductivity varies with temperature, it is essential that the conductivity sensor is used in conjunction with a temperature sensor to compensate for this effect.

8.6.1 Integration method (instantaneous injection)

The pertinent factors are as follows:

- The NaCl chemical tracer is injected instantaneously.
- A continuous conductivity sensor is used in conjunction with a temperature sensor.

The process involves the following steps:

1. Prepare the injection solution.

The estimated kg/l quantity of NaCl that can be easily dissolved in water has a ratio of 1/5. The solution must not be prepared with discharge water and can be premixed in a laboratory. Advanced preparation of the solution will ensure optimal dissolution of the salt.

2. Select the injection point and the measuring reach.

3. Withdraw a known volume of the injection solution (X) and mix it with a known volume of the discharge water (V_0). This will be the secondary solution.

   The relative concentration of this solution will be:

$$\boldsymbol{CR_{sec}} = \frac{\boldsymbol{X}}{\boldsymbol{V_o+X}} \qquad \textbf{(39)}$$

4. Take an instantaneous measurement and record the electrical conductivity (CE_{bf}) upstream of the injection point and downstream of the sampling section.

5. Install the continuous conductivity measurement sensor and begin to record the measured values.

6. Inject a known volume (*V*) of the solution prepared for instantaneous measurement at the injection point. The injected quantity can be estimated by the equation shown in section 8.5.3.2 (integration method).

7. Record the sensor's conductivity values (CE_t) over time and with regular intervals until they return to the level measured in step 4. If the values do not return to the level measured in step 4, the conductivity upstream from the injection point must be measured again for any fluctuations.

8. Withdraw a known volume (V_c) of discharge water and pour it into a tank. Install the tank in the discharge so that the temperature of the tank water is as close as possible to the temperature of the water in the channel. Measure the conductivity of this volume (CE_0), which will correspond to CR=0 (the 0 will serve to determine K).

9. Determiner the calibration constant K.

   The value of K is determined by drawing a relative concentration curve (CR) as a function of the electrical conductivity (CE).

   Using a pipette, add a known volume of the secondary solution prepared in step 3 to the tank and measure the electrical conductivity (CE). Repeat this step at a minimum of 3 points until the electrical conductivity exceeds the expected maximum detection level. The relative conductivity at each point is determined by the following equation:

$$CR = \frac{CR_{sec} \sum y}{(V_c + \sum y)} \qquad (40)$$

Where $\sum y$ Total quantity of the secondary solution added to the tank, in ml.

Determine K corresponding to the slope of the relative concentration graph CR as a function of the electrical conductivity CE.

10. Calculate the flow with the following equation:

$$Q = \frac{V}{K\,\Delta t\, \sum[\,CE(t) - CE_{bf}\,]} \qquad (41)$$

Where
V Volume of the injection solution, in m^3
K Calibration constant (cm/µS)
Δt Interval of time between each measurement, in seconds
CE_t Electrical conductivity of the progression of the tracer (µS/cm)
CE_{bf} Electrical conductivity of the background noise (µS/cm)

11. Check the tracer recovery rate.

8.6.2 Constant-rate injection

This procedure can also be adapted for use with fluorescent tracers.

The following is required:

- Continuous injection of the NaCl chemical tracer.
- A continuous conductivity measuring sensor in conjunction with a temperature sensor.

The steps in the trial are as follows:

1. Prepare the injection solution.

   The estimated kg/l quantity of NaCl that can be easily dissolved in water has a ratio of 1/5. The solution must not be prepared with discharge water and can be premixed in a laboratory. Advanced preparation of the solution will ensure optimal dissolution of the salt. In this step, the concentration of salt need not be measured with great precision since the result of the trial will be expressed in tracer volume, not mass.

2. Select the injection point and the measuring reach.

3. Withdraw a known volume of the injection solution (X) and mix it with a known volume of the channel water (V_0). This will be the secondary solution.

The relative concentration of this solution will be:

$$CR_{sec} = \frac{X}{V_o + X} \quad \textbf{(42)}$$

4. Take an instantaneous measurement and record the electrical conductivity (CE_{bf}) upstream of the injection point and downstream of the sampling section.

5. Install the continuous conductivity measurement sensor and begin to record the measured values.

6. Install the constant-rate injection equipment. Begin injecting the solution. The injected quantity can be estimated by the equation shown in section 8.5.3.2 (constant flow method).

   Simultaneously with injection, commence the measurements in the sampling section. When electrical conductivity (CE_s) stabilizes, check whether conductivity is the same at two other points in the width of the channel. If this is not the case, move the sampling section further downstream to obtain a better mixing zone.

7. Measure the injection rate at least three times during the procedure. Withdraw a portion of the injection solution.
8. Withdraw a known volume (V_c) of discharge water and pour it into a tank. Install the tank in the discharge so that the temperature of the tank water is as close as possible to the temperature of the water in the channel. Measure the conductivity of this volume (CE_0), which will correspond to CR=0 (the 0 will serve to determine K).

12. Determiner the calibration constant K.

    The value of K is determined by drawing a relative concentration curve (CR) as a function of the electrical conductivity (CE).

    Using a pipette, add a known volume (in this case, 2 ml) of the secondary solution prepared in step 3 to the tank and measure the electrical conductivity (CE). Repeat this step at a minimum of three points until the electrical conductivity exceeds the maximum expected detection level.

    The relative conductivity at each point is determined by the following equation:

$$CR = \frac{CR_{sec} \sum y}{(V_c + \sum y)} \quad \textbf{(43)}$$

Where $\sum y$ Total quantity of the secondary solution added to the tank in ml

Determine k corresponding to the slope of the relative concentration graph CR as a function of the electrical conductivity CE.

9. Calculate the flow with the following equation:

$$Q = \frac{q}{K\,(CE_s - CE_{bf})} \qquad (44)$$

Where		
	Q	Flow of the discharge to be measured
	q	Injection rate of the tracer, in l/s
	K	Calibration constant (cm/µS)
	CE_s	Stable electrical conductivity (µS/cm)
	CE_{bf}	Background noise electrical conductivity (µS/cm).

8.7 EXAMPLES (FOR BOTH METHODS)

Refer to the article entitled "Introduction to salt dilution gauging for streamflow measurement" by Dan Moore in *Watershed Management Bulletin*.

8.8 SOURCES OF ERRORS IN THE TRACER DILUTION METHOD

As described in ISO 9555-1:1994, flow is calculated from the dilution of a given quantity of tracer, and measurement uncertainty is the range in which the exact flow is found, with 95% probability.

In normal conditions, measurement errors with the dilution method are ± 2-10%.

The sources of systematic errors with the integration and constant-rate dilution methods likely originate from:

- The tracer.
- The duration of the trial.
- Poor mix in the measuring reach.
- Water volume variance in the reach.
- Sampling and sample analysis.

While this is not always the case, systematic errors tend to overestimate the flow. Since reducing systematic errors is much more difficult than reducing random errors, readers may wish to refer to ISO 9555-1:1994 for error distribution hypotheses.

The following sections summarize the points to check in order to minimize manipulation errors involved in each method.

Dilution integration method (instantaneous injection)

- Concentration of the stock solution.
- Fast injection of the tracer.
- Quantity of tracer injected.
- Tracer loss from splashing.
- Tracer solution deterioration.
- Lack of homogeneity of the tracer solution prior to injection.
- Contamination of the sampling receptacles.
- Flow variations during the measurement process.

Errors may arise during withdrawals needed to prepare the injection and standard solutions. These types of errors can be minimized by using volumetric flasks and glass pipettes, whose capacity should be as close as possible to the desired volume.

The accuracy of the flow calculation is directly linked to the accuracy of the injected tracer volume. Particular attention is required when measuring this volume.

A second uncertainty usually originates in the time-measuring instrument. However, if a digital chronometer is correctly used, the uncertainty level should be very low compared to other sources.
The difference between the measurement of the concentration of the injected tracer and the concentration measured in the sample is often another source of inaccuracy. Uncertainty ascribable to a measuring instrument used in low variance conditions between these two values will generate an elevated uncertainty percentage. Such errors can be minimized by injecting a more concentrated solution and using the standard dilution method.

ISO 9555-1:1994 describes the statistical method for estimating random errors ascribable to the instantaneous injection method. The calculation of flow uncertainty necessitates knowledge of uncertainty in volume (V), transit time (T_p), and dilution ($C_1/\bar{C}_2 = D_i$).

$$\partial(Q) = \sqrt{\partial(V)^2\left(\frac{\partial Q}{\partial V}\right)^2 + \partial(T_p)^2\left(\frac{\partial Q}{\partial T_p}\right)^2 + \partial(D_i)^2\left(\frac{\partial Q}{\partial D_i}\right)^2} \qquad (45)$$

Dilution uncertainty may be resolved by using the standard dilution method. This method is not addressed herein and readers are encouraged to consult section 6.3 of ISO 9555-1:1994 to familiarize themselves with it.

Constant-rate dilution

- Concentration of the stock solution.
- Appropriate mixture of the tracer solution and effluent.

- Deterioration of the tracer solution as it is injected.
- Deterioration of the tracer solution as it comes into contact with the discharge.
- Unstable injection rate.
- Loss of tracer solution at the injection point.
- High variance among concentrations above the plateau of the curve.

Errors may arise during the withdrawals needed to prepare the injection and standard solutions but can be minimized by using appropriate glass volumetric flasks and pipettes. The capacity of the pipettes should be as close as possible to the desired volume.

Accuracy of the flow calculation is directly linked to the precision of injection. Particular attention should be given to this factor.

Another source of possible error is the difference between the measurement of the background noise and the plateau. Uncertainty ascribable to a measuring instrument used in low variance conditions between these two values will generate an elevated uncertainty percentage. Such errors can be minimized by injecting a more concentrated solution while minimizing any environmental impact.

ISO 9555-1:1994 describes the statistical method for estimating random errors ascribable to the constant-rate injection method. The calculation of flow uncertainty necessitates knowledge of uncertainty in the injection rate (q) and the dilution ($C_1/C_2 = D_i$). The dilution uncertainty can be resolved by the standard dilution method. This method is outside the framework of this publication, so readers are encouraged to familiarize themselves with section 6.3 of ISO 9555-1:1994.

$$\partial(Q) = \sqrt{\partial(q)^2 \left(\frac{\partial Q}{\partial q}\right)^2 + \partial(D_i)^2 \left(\frac{\partial Q}{\partial D_i}\right)^2} \qquad (46)$$

8.9 USING TRACER DILUTION AS A REFERENCE METHOD

When checking the accuracy of an *in situ* flow measuring system, the tracer dilution method can be used as a reference method. The flow value measured with this method will then be compared with the simultaneous measurement of the *in situ* flow by the measuring system being checked to calculate the variance between the two values and confirm whether or not maximum permissible variance (e.g., regulatory) is being met.

Three trials are required and maximum permissible variance must be met for each trial, not the average of the trials. If trials can be conducted at three flows (min – avg. – max) by the *in situ* measuring system, a single trial is acceptable for each flow as long as all operational conditions of the method are complied with. Otherwise, three trials may be required for each flow in order to validate the obtained result.

Appropriate accuracy checking requires the application of all elements described in section 6. In addition, section 12 describes the details that are required in the report for it to be complete.

Tracer dilution…

…a reference method, whose principle is based on the variance of tracer concentration between its injection and sampling points and the conservation of tracer mass between the two.

Tracers come in three categories: chemical, fluorescent/colorant and radioactive.

The length and characteristics of the measuring reach are of prime importance for obtaining representative measurements.

Two types of samples must be withdrawn: control and measurement.

Appendix 5 provides a sample field grid for checking the accuracy of a flow measuring system with this method.

9 VOLUMETRIC METHOD

The volumetric (or gravimetric) method can be used by weighing a quantity of liquid collected in a given lapse of time or by measuring the volume of liquid flow in a predetermined time frame (also called the capacity, measured capacity, capacitive, potting, pail or timed volume method). Two principles are used to measure the quantity of liquid collected in a receptacle: mass and volume.

When operational conditions permit, the volumetric method should be preferred due to its simplicity, rapidity, low cost and accuracy. It can be applied to the instantaneous measurement of water flow or volume in open channels or closed conduits and can be used to measure flow or to check the accuracy of a flow measuring system.

Given logistical constraints (capacity of the receptacle), this method is best adapted to the measurement of low flow.

This method can determine flow independently and therefore can be used as a reference method to check another flow measuring system.

9.1 FUNCTIONAL PRINCIPLE

Different procedures may be used in implementing the volumetric method. These include:

- Calculating the time required to fill a selected receptacle, such as a pail or plastic bag, and evaluating the amount of liquid recovered by measuring its volume with a volumetric flask or weighing its mass with a scale.
- Calculating the time required to fill a receptacle whose volume is accurately known, such as a 20-litre receptacle.
- In the case of higher flows, using a regularly-shaped receptacle whose dimensions are known to determine the volume at all rates during emptying (sequential aeration tank, pumping station) or filling (tank). A chronometer is then used to measure the change in water level over time between the initial and final levels.

The following equation expresses the relationship between flow, volume and time:

$$\boldsymbol{Q = \frac{V}{t}} \qquad (47)$$

Where
- Q Flow in m^3/s or l/s
- V Volume in m^3 or l
- t Emptying or filling time, in seconds

9.2 FILLING AND EMPTYING THE RECEPTACLE

The most common procedure used to fill a receptacle is to place it under free flow water, for example, at the outlet of a pipe, culvert or weir.

The total discharge to be measured must be collected in the receptacle. If there are no falls or the flow is too extensive, the measuring site must be modified (Figure 108) so that the guiding device does not influence the primary structure (particularly by inducing backflow upstream).

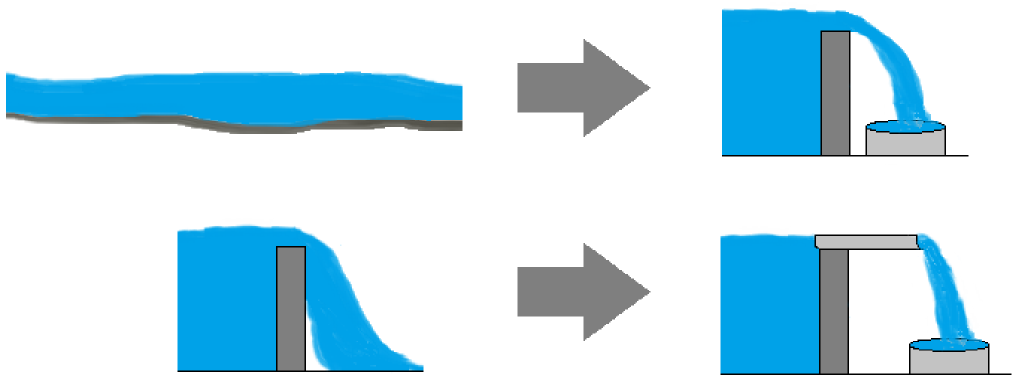


Figure 108: Examples of modifying the measuring section to limit extensive flow (above) and the guiding device (below).

While it is more common to use the volumetric method by filling a receptacle, it is also possible to use it by emptying a receptacle into a sequential aeration tank or pumping station. However, the same method (filling or emptying) must be used for all the trials. As such, alternating filling and emptying is not appropriate.

The receptacle must be completely emptied and drip-dried between each filling.

This method can be used for a pressurized closed pipe, for example, by filling a water truck (weight) or using a tank (volume or weight). For more details about its application in closed pipes, readers should refer to ISO 4185 (Measurement of liquid flow in closed conduits — Weighing method) and ISO 8316 (Method by collection of the liquid in a volumetric tank).

9.3 DETERMINATION OF WATER VOLUME

The volumetric method enables the average flow value to be measured for the duration of a trial. In the case of accuracy checking, comparison should be made between the volume measured by the volumetric method and the total volume calculated by the *in situ* measuring equipment during the trial, such as a flowmeter installed over a primary structure, as shown in the example in Table 47.

Table 47: Example and comparison of total volumes for three trials by the volumetric method and the *in situ* measuring system

Trial	Trial duration (minutes)	Totalized volume (m^3)		Variance (%)
		Volumetric method	*In situ* measuring system (flowmeter and Parshall flume)	
1	5	50	48	4.0
2	5	51	48	5.6
3	5	50	49	2.0

If no totalizer is available, the *in situ* measuring system volume can be obtained by averaging instantaneous flow during the trial. A variable discharge would imply that a greater number of instantaneous measurements are needed to raise the level of accuracy.

The example in Table 48 shows that variance between the volumetric trial and the *in situ* system is greater (5.6%) when the average *in situ* flow is comprised of readings taken every minute as compared to the example in Table 49, where flow is measured every 15 seconds (1.4%).

A greater number of instantaneous measurements will make the average more representative of variations in the discharge present during the trial and be closer to the value obtained by the volumetric trial. This is as true for accuracy checking as it is for the instantaneous measurement of effluent flow.

Table 48: Example and comparison of volume totalized by the volumetric method with the average of instantaneous measurements of flow (1/minute) over five minutes

Trial	Time (H:M:S)	*In situ* measuring system			Volumetric method	Variance (%)
		Instantaneous flow (m^3/min)	Average flow (m^3/min)	Totalized volume (m^3)	Totalized volume (m^3)	
1	09:00:00	110	111.3	111.3 m^3/min x 5 min = 556.7	590	5.6
	09:01:00	111				
	09:02:00	112				
	09:03:00	112				
	09:04:00	112				
	09:05:00	111				

Table 49: Example and comparison of volume totalized by the volumetric method with the average instantaneous flow (1/15 seconds) over five minutes

Trial	Time (H:M:S)	*In situ* measuring system			Volumetric method	Variance (%)
		Instantaneous flow (m^3/min)	Average flow (m^3/min)	Totalized volume (m^3)	Totalized volume (m^3)	
1	09:00:00	110	119.7	119.7 m^3/min x 5 min = 598.3	590	1.4
	09:00:15	145				
	09:00:30	110				
	09:00:45	125				
	09:01:00	111				
	09:01:15	130				
	09:01:30	118				
	09:01:45	110				
	09:02:00	112				
	09:02:15	155				
	09:02:30	125				
	09:02:45	129				
	09:03:00	112				
	09:03:15	117				
	09:03:30	112				
	09:03:45	134				
	09:04:00	112				
	09:04:15	115				
	09:04:30	112				
	09:04:45	108				
	09:05:00	111				

9.4 Duration of the Trials

The volumetric method involves measuring cumulative volume in a predetermined lapse of time or recording the time required to collect a predetermined volume, for example:

- Fill a graduated receptacle for two minutes and record the totalized volume.
- Record the time required to fill a 20-litre receptacle.

In all cases, time is calculated using a chronometer capable of reading at least 1/100 seconds (.01%).

The duration of trials depends on the discharge flow to be measured. For very low rates (≤ 2 l/s), the minimum duration is 10 seconds (ideally 20 seconds) using a 20-40-litre receptacle.

For heavy flow measured by filling or emptying a tank, a minimum 150-mm difference in water level is required.

For intermediate flow, the duration of the trials must lead to negligible errors of measurement. A minimum duration of 5 minutes is recommended.

The gravimetric method (weighing the liquid) usually involves more flow trials, each lasting less than five minutes.

Starting and stopping the chronometer must accurately correspond with starting and stopping the collection of the water.

9.5 NUMBER OF TRIALS

The greater the number of trials, the greater the statistical weight of the reference value and its relevance.

In all cases, this method requires at least three trials. Additionally, accuracy checking an *in situ* flow measuring system involves meeting maximum permissible variance for each of the trials.

Table 50 illustrates accuracy checking where the third trial shows variance above the maximum permissible variance of 10%, necessitating a fourth trial.

Table 50: Example of a trial where variance exceeds 10% and requires an additional trial

Trial	Volumetric trial (m^3)	*In situ* volume (m^3)	Variance (%)
1	53	50	5.66
2	52	50	3.85
3	56	48	**14.29**
4	50	48	4.0

9.6 TYPE OF RECEPTACLE

The type, volume and shape of a receptacle must be adapted to the individual measuring conditions. As such, the choice can be made from a wide variety of receptacles such as pails, tubs, plastic bags, tanks, water trucks, pumping stations, processing units like sequential aeration tanks, primary clarifiers, etc. The selected receptacle must, however, possess certain properties:

- Dimensions known with precision, ideally a standard calibrated receptacle.
- Warp-resistant.
- Enables filling without air pockets.
- Fosters complete and rapid emptying.

9.7 VOLUME OF THE RECEPTACLE

The volume of the receptacle should be based on the flow to be measured and its capacity must be determined with precision. In addition, the receptacle into which the liquid flows during the trial must have sufficient capacity to ensure that errors of time and level are negligible.

Various ways of determining the volume of a receptacle:

- Using a graduated, standard receptacle that has a calibration certificate.
- Calibrating the receptacle by weighing it yearly with a calibrated scale and securing a calibration certificate.
- Accurately measuring the dimensions of the receptacle, and reproducing them in a detailed diagram.
- For large tanks such as pumping stations or sequential aeration tanks, using a precise dimensional plan (e.g., construction plan) or accurately measuring each section with a laser during maintenance.

When the dimensions of the receptacle or tank must be measured, a large number of measurements must be taken to account for irregularities such as inclined walls, deformations, deposits on walls or at the tank bed, pumps, pipes, etc.

Any irregularities and values to be subtracted need to be considered when determining volume. As shown in Figure 109, a volume of 2 m^3 would need to be subtracted from the 12-m^3 volume of a rectangular tank, giving a true volume of 10 m^3.

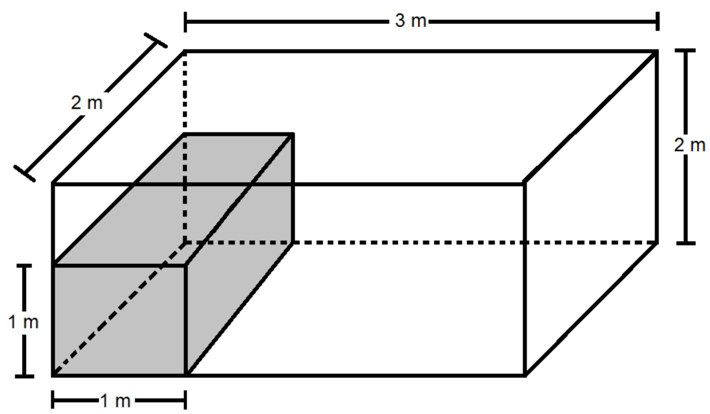


Figure 109: Example of a rectangular tank with a volume to subtract.

The capacity of a receptacle must be accurately determined prior to the trials to ensure that the original dimensions in the construction plan remain valid with respect to deformations, deposits, and added items such as pumps, pipes, metal plates, etc.

As previously stated, the material of which the tank is made must be sufficiently solid to ensure that the walls remain stable during the trials.

In general, the bigger the receptacle and the longer the duration of the trial, the more accurate is the result. For weaker flow, a receptacle of between 5 and 40 litres can be adequate, on condition that it is sufficient to enable trials of at least 10 seconds, and ideally 20 seconds. Table 51 shows several examples of receptacle volumes based on the flow of discharge for trial durations lasting 10 and 20 seconds.

Table 51: Examples of receptacle volumes for various discharge flows

Flow		Duration of trial	
		10 seconds	20 seconds
l/s	m^3/s	Minimum volume (l)	
.5	.0005	5	10
1	.001	10	20
2	.002	20	40

9.8 Measurement of the water level

Various level-identifying devices may be used on the basis of the setup or the volume to be measured, for example:

- A graduated receptacle.
- A laser range-finder or graduated ruler attached to the wall of a receptacle to measure the water level more or less from the reference level.
- A level tube with a graduated ruler to check the level using the principle of communicating vessels.
- A level gauge, such as a float.
- A level measuring sensor (ultrasound, pressure, bubble pipe, etc.).

The accuracy of water level measurement increases with the variance of water level during a trial.

9.9 Determination of the mass of the liquid

The mass of the liquid collected during a chronometer-measured lapse of time must be determined during the weighing process. The scale used must have been calibrated in the last 12 months and possess a calibration certificate.

Complete emptying of the receptacle is required after each trial. To ensure the highest level of measurement precision, the empty receptacle (such as a water tank) must also be weighed before each trial.

9.10 DETERMINATION OF LIQUID MASS VOLUME

To determine volume after weighing, the mass of the weighed liquid in kg is multiplied by its volumetric mass.

Table 52: Example of the volumetric method by weight

Information gathered during a trial	
Mass of the empty water truck	10,000 kg
Mass of the filled water truck	12,000 kg
Mass of the liquid collected during the trial	2,000 kg
Duration of water tank filling	5 minutes
Volumetric mass of the collected liquid	1,000 kg/m^3 [31]

The equation used to obtain the volume of the weighed liquid is as follows:

$$\boldsymbol{Volume = \frac{mass}{volumetric\ mass}} \qquad (48)$$

Using the example shown in Table 52, the equation thus becomes:

$$\boldsymbol{Volume = \frac{2000\ kg}{1000\ kg/m^3} = 2\ m^3} \qquad (49)$$

The conversion of this totalized volume during the flow trial is determined as follows:

$$\boldsymbol{Flow = \frac{volume}{trial\ duration} = \frac{2\ m^3}{5\ minutes} = .4\ m^3/min} \qquad (50)$$

9.11 SOURCES OF ERRORS IN THE VOLUMETRIC METHOD

Based on the context in which the volumetric method is used, measurement errors can vary between 1 and 10%. Measurement accuracy is, therefore, best when the duration of the trials is longer.

[31] Volumetric mass of water: When the characteristics of the liquid are different from water, its own volumetric mass should be used.

The sources of errors are mainly related to the precision of measurement of the volume of the receptacle, the weight of the collected liquid and the duration of the trial, which may be reduced to a negligible point by correcting the following:

- Errors due to the determination of the volume of the receptacle:
  - Errors in the dimensions of the receptacle.
  - Deformation, irregularities, deposits on the bottom and the walls.
  - Leaks, added parasitic water, liquid absorbed by the walls.
  - Elements to ignore such as pumps and pipes.
- Errors due to the measurement of the water level:
  - Inaccurate reading of the water level.
  - Incorrect measuring instrument graduation or position.
  - Level sensor drift.
- Errors due to the calculation of time:
  - Wrong chronometer reading.
  - Discrepancy between the chronometer start and stop time during filling or emptying.
- Errors due to the determination of volumetric mass.
- Errors due to the method:
  - Discharge to be measured not fully collected.
  - Incomplete emptying of the receptacle between trials.
  - Inadequate trial duration or number of trials.
  - Frequency of instantaneous flow insufficient to determine average *in situ* flow.

9.12 USING THE VOLUMETRIC METHOD AS A REFERENCE METHOD

The volumetric method can be used as a reference method when accuracy checking an *in situ* flow measuring system. The measured flow value will be simultaneously compared with the *in situ* flow measurement made by the measuring system being checked to calculate any variance between the two values. This makes it possible to confirm that permissible variance (e.g., regulatory) is met.

Three trials are required and maximum permissible variance must be met for each trial, not the average. If three trials at three flows (min – avg. – max) can be made by the *in situ* flow measuring system, a single trial may be conducted as long as all the method's operational conditions are met. Otherwise, three trials may be required to confirm the validity of the results.

To appropriately check accuracy, everything listed in section 6 must be considered. Section 12 describes the precisions needed in the report for it to be deemed complete.

Volumetric method…

…applicable for the instantaneous measurement of water flow or volume in open-surface channels or closed pipes

Various procedures are carried out based on the calculation of elapsed time:

- Fill a receptacle in which the quantity of recovered liquid is gauged by measuring its volume or weight
- Fill a receptacle whose volume is precisely known
- Water level variance during filling or emptying a regularly shaped receptacle whose dimensions are known

Duration of each of the three trials:

- Low flow : (<2 l/s) = 10-20 seconds for Q ≤2 l/s
- Intermediate flow or gravimetric method = ideally 5 minutes
- Heavy flow (tank) = 5 minutes and water Δ h of 150 mm

Appendix 5 provides a field grid for checking the accuracy of a flow measuring system using this method.

10 METHOD USING THE CAPACITY OF A PUMP AT A PUMPING STATION

10.1 Description of a pumping station

A pumping station is the physical location of pumps or backflow valves that send water to other locations or equipment.

A pumping station is not a measuring instrument, but a building whose known functional and structural data enables instantaneous flow to be indirectly determined.

This method makes it possible to determine flow independently for use as a reference method to check the accuracy of a flow measuring system if the following conditions are met:

- The capacity of the pump is known (determined by the method described in section 5).
- The pump works at constant velocity.
- The method is applied per the operating conditions described in this section.

10.2 Pumping station setup

Pumping stations can be set up in a variety of configurations, initially distinguished by their filling and emptying sequences.

A pumping station may be isolated (filling and emptying conducted separately) or non-isolated (filling and emptying are done simultaneously).

The number of pumps and their individual operational modes are other setup characteristics. Pumps may work in alternation, simultaneously or sequentially (the second pump turns on when a specific water level has been reached).

Figure 110 shows a schematic of different pumping station setups.

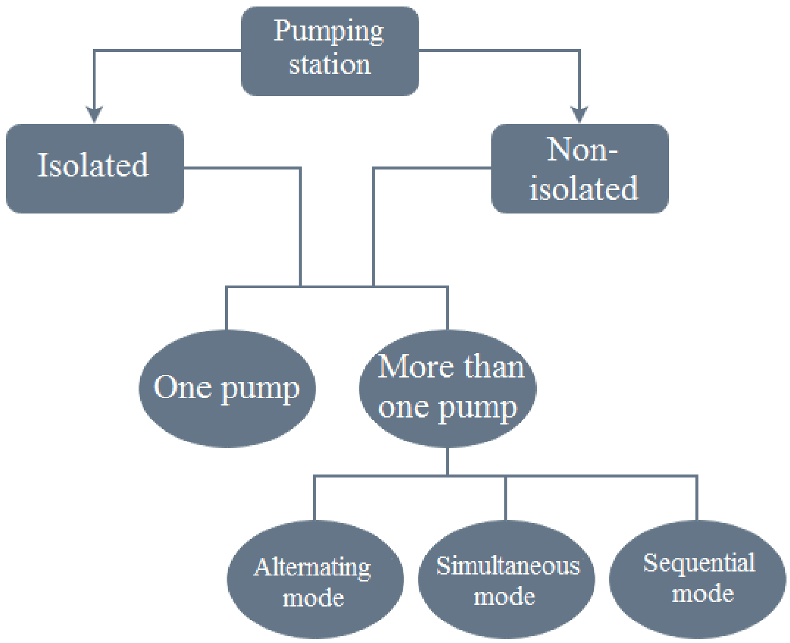


Figure 110: Different pumping station setups.

10.3 Various methods of measuring flow in a pumping station

The following two methods can be used to calculate the flow transiting a pumping station:

- The flow entering the pumping station is measured by the pump start/stop time stamps and water level is monitored by the volumetric method.
- The flow exiting the pumping station is based on the length of time the pump operates, using the pump capacity method.

This section addresses the exiting flow based on the operational pump time, not the volumetric method, including its application as described in detail in section 9.

10.4 Description of the pump capacity method

This method uses the true capacity of the pump based on its operational time to calculate the volume of water exiting a pumping station with the following equation:

$$V = Q_p\, t \qquad (51)$$

Where V Volume of water, in m^3
Q_p Pump capacity, in m^3/min
t Emptying time, in minutes

In all cases, the emptying time is determined with a chronometer capable of reading at least 1/100 seconds (.01%).

The total measured by the pump must accurately correspond to the start and stop of the chronometer when the pump is working at maximum capacity.

A sample calculation is shown in Table 53.

Table 53: Measuring the exiting volume based on pump capacity and emptying time

Pump capacity (Q_p)	150 m^3/min
Emptying time (t)	30 min
Water volume (V)	V = 150 m^3/min x 30 min V = 4,500 m^3

10.5 APPLICATION CONDITIONS OF THE PUMP CAPACITY METHOD

10.5.1 Information about the pumping station

When the capacity of a pump is used to determine instantaneous flow or as a reference method for checking the accuracy of a flow measuring system, the following information must be verified and recorded:

- The type of pumping station (wet/dry, isolated/non-isolated).
- The number of pumps and their operational mode (alternating, sequential, simultaneous).
- The location of the pumps (inside or outside the pumping station).
- The serial numbers of the pumps.
- The theoretic technical specifications of the pumps (original capacity).
- The true capacity of the pumps per the mode used (isolated/combined) and the method used to determine this (description of the method and raw data).
- The normal position of high-level and low-level alarms, if any.
- Whether or not an overflow device is used, and its location in the pumping station.
- Whether or not there are any submerged pipes supplying the pumping station.
- Whether or not there are backflow valves, and their condition.

10.5.2 Determining pump capacity (Q_p)

Prior to conducting trials, the true capacity of pumps (Q_p) must be determined on the basis of the method used and the conditions described in section 5.

10.5.3 Duration of the trials

The accuracy of a trial increases with its duration. Ideally, trials should be as long as possible, based on the characteristics of the pumping station. The duration of trials can vary greatly from one pumping station to another. The minimum duration of a trial is 5 minutes. In all cases, the minimum variation in water level between the start and stop of a pump must be 150 mm.

10.5.4 Number of trials

At least three trials are required within the shortest possible interval of time. All trials must be conducted within 48 consecutive hours. When checking the accuracy of a flow measuring system, the maximum permissible variance compared to values reported *in situ* must be met for each trial. Otherwise, a new trial is required.

10.6 Evaluation of the *in situ* flow measuring system

In the case of checking the accuracy of an *in situ* flow measuring system, the following variables are required:

- Totalized volume of water during the trial conducted with the *in situ* system.
- Totalized volume of water during the trial period with the pump capacity method at a pumping station.

Table 54 shows an example of raw data collected from checking the accuracy of an isolated one-pump pumping station with the pump capacity method.

Table 54: Accuracy checking an *in situ* flow measuring system

Trial	Pump capacity (m^3/s)	Trial duration (seconds)	Volumetric trial (m^3)	*In situ* volume (m^3)	Variance (%)
1	.35	540	189.0	192.3	1.74
2		530	185.5	190.7	2.80
3		560	196.0	199.2	1.63

If the variance for each trial is less than the maximum permissible variance, the accuracy of the *in situ* measuring system is in compliance.

10.7 Sources of errors in the pumping station pump capacity method

The sources of errors are mainly related to the following:

- Errors due to the determination of pump capacity.
- Errors due to the calculation of emptying time:
    - Inadequate reading of the chronometer.

- Discrepancy between the start and stop of the chronometer during emptying.
  - Discrepancy between the time stamp and the water level measurements.
- Errors due to the method:
  - Inadequate duration or number of trials.
  - Speed of the pump not constant during the trial.
  - Pump not working at maximum capacity.
  - Characteristics of the pumping station not considered (e.g., number of pumps and their operating modes).

10.8 Using the method based on the capacity of a pumping station pump as a reference method

The pumping station pump capacity method for accuracy checking an *in situ* flow measuring system can be used as a reference method. The flow value measured in this way along with the simultaneous *in situ* measurement of flow (by the measuring system being checked) can be used to calculate the variance between these two values and ensure that maximum permissible variance is met (e.g., regulatory).

Three trials are required and the maximum permissible variance must be met for each trial and not for the average of the trials. If conducting trials at three flows (min – avg. – max) by the *in situ* measuring system is feasible, a single trial for each flow may be made as long as all the conditions that apply to the method are met. Otherwise, three trials at different flows are required to validate the results.

To appropriately check accuracy, what is described in section 6 of this publication must be accomplished. Section 12 describes details on the required contents of the report so that it is complete.

The capacity of a pumping station pump……

… can be used as a reference method if:
- The capacity of the pump is known (see section 5).
- The pump works at constant speed.

A pumping station is defined by the following:
- Its type: isolated or non-isolated
- The number of pumps: one or more
- The operating mode: alternating, simultaneous or sequential

The applicable method for measuring the discharge exiting the pumping station.

The three trials must last as long as possible (<5 minutes with a minimum Δ water level of 150 mm) within 48 consecutive hours.

Appendix 5 provides a sample field grid for checking the accuracy of a discharge measuring system with this method.

11 REFERENCE INSTRUMENT METHOD

This method makes it possible to obtain the instantaneous measurement of water flow or volume using a reference instrument that measures velocity, pressure, electrical current or any other parameter with variance that can be directly correlated to the flow of discharge.

This method can thus make it possible to determine flow independently when used as a reference method in accuracy checking a flow measuring system.

This method applies to closed pipe discharge.

11.1 Types of reference instruments

A reference instrument can produce flow values that are as close as possible to true values.

They can be ultrasound flowmeters installed outside of pipes, as is the case for clamp-on transit time and Doppler flowmeters. The description and the operating conditions of this type of equipment are described in section 4.4.3.

11.2 Application conditions for reference instruments

The use of reference instruments involves the following conditions:

- Reference instrument measuring errors must be equal to or less than 2.5% (generally referring to the notion of "precision" as described by the manufacturer).
- Reference instrument must be used in operating conditions prescribed by the manufacturer. The parameters to consider vary by the type of measuring instrument, but are generally related to the following:
    - The interior diameter of the conduit.
    - The interval of velocity measurements.
    - The pressure.
    - The upstream and downstream lengths without disturbances (elbow, valve, etc.).
    - The properties of the water (turbidity, conductivity, temperature, etc.).
    - The discharge conditions.
    - The material, condition and thickness of the conduit.

  The applicable parameters must be checked at the start of a trial to be compared with the operating conditions prescribed by the manufacturer.

  The choice of reference instrument must always bear on the fact that measurements are affected by the lesser of the possible parameters or the most negligible of the effects of the parameters.
- Reference instrument must be calibrated annually or at shorter intervals whenever malfunction is suspected. Calibration must be conducted at several points in the velocity range.

Calibration of reference instruments must comply with recognized procedures such as those described in ISO 4185 (weight) and ISO 8316 (volumetric tank) or test bed calibration including a traceable standard and a calibration certificate.

The technical specifications and errors of measurement of a reference instrument must be listed in the calibration certificate.

- The body that calibrates a reference instrument must be accredited, certified to a national or international reference such as ISO 17025 or BNQ.
- Ideally, reference instrument should be installed over the same conduit as the one with equipment to be checked or on a drift, following manufacturer's recommendations.

The non-respect of operating conditions of a reference instrument, such as non-respect of the upstream and downstream lengths without disturbances, may cause measurement errors. These errors and the required justifications (such as for corrective factors) must be included in the report.

11.3 *IN SITU* CONDITIONS TO BE MET PRIOR TO THE TRIALS

All trials must proceed in stable discharge or permanent regime conditions. The conduit must always run full and be without air or gas bubbles. There must be no fluctuation in pressure or pulses that could affect measurements. Prior to commencing a trial, it is also recommended to reach measurement stability (such as 15 minutes in stable environments).

Ideally, the instrument's zero must be checked. To accomplish this, discharge must be stopped and the conduit filled with water.

11.4 DETERMINATION OF WATER VOLUME AND FLOW

Instantaneous flow (minimally 1/minute) and volume must be recorded during the trial period so that the data obtained can be representative of the prevailing discharge conditions. If a device does not include a volume totalizer, the displayed volumes must be noted at least every minute in order to determine the discharge variance.

11.5 DURATION AND NUMBER OF TRIALS

When flow is variable, such as day/night differences at a municipal station or for surface runoff, a 30-minute trial at three flows (30 minutes per rate) is ideal, corresponding to the habitual *in situ* discharge range. The three flow rates are needed to determine the instantaneous measurement of minimum (no less than 10% of the maximum), average and maximum flow.

When measuring regular discharge flow such as at the outlet of a retention basin, three trials of at least 30 minutes are required. The three trials enable instantaneous flow to be determined for the flow interval during the trials.

11.6 Sources of errors in the reference instrument method

Sources of errors are mainly related to the following:

- Errors due to the reference instrument:
    - Errors of measurement > 2.5%.
    - Measuring drift in the reference instrument.

- Errors due to *in situ* conditions:
    - Non-compliance with manufacturer's recommendations.
    - Inappropriate discharge conditions such as air bubbles, pressure fluctuations, etc.

- Errors due to the method:
    - Time interval too short to enable stabilization of the instrument.
    - Insufficient frequency of measurement.
    - Inappropriate trial duration or number of trials.

11.7 Using the reference instrument as a reference method

In accuracy checking an *in situ* measuring system, the reference instrument method can be used as a reference method. The measured flow is compared with the simultaneous measurement of the *in situ* flow (by the measuring system being checked) to calculate the variance between these two flow values. This ensures that the (regulatory) validity of the maximum permissible variance is properly met.

Three trials are required and maximum permissible variance must be met for each trial, not the average. If conducting trials at three flows is feasible *in situ*, a single trial may be performed if all conditions of the method are met. Otherwise, three trials at each flow may be required to validate the results.

To appropriately check accuracy, what is described in section 6 of this publication must be accomplished. Section 12 describes details on the required contents of the report so that it is complete.

Reference instrument…

An instrument that measures velocity, pressure, electrical current strength, etc. where variance can be directly correlated to the discharge flow

A reference method that can be used with closed conduits whose use involves the following:

- A full pipe, stable flow or permanent regime
- Measuring errors ≤ 2.5%
- Utilization in manufacturer-prescribed conditions
- Annual calibration by a body that is accredited with a national or international standard
- Ideally installed on the same conduit as the equipment being verified
- Three trials of a minimum of 30 minutes each

Appendix 5 provides a sample field grid for checking the accuracy of a flow discharge measuring system using this method.

12 DETAILS OF THE REPORT

12.1 CONTENTS OF THE REPORT

The report is the main official documentation in checking the accuracy of a system for measuring water flow or volume.

The information in the report has to make it possible to confirm the reliability of the results obtained during the verification process.

The report must include the date of the trials, as well as the name, position and signature of the inspector and the representative of the firm (hydrologist or hydraulics engineer) that validated the results of the check and approved its recommendations. It must be written in French and all relevant data in the report or appendices must be in the metric system, accompanied by their measurement units.

Also, at a minimum, the report must include the following information to the extent that it applies to the verification method that was used:

1- Summary (desirable).
2- Context:
   a. Date of the verification.
   b. Location of the site (name of company or municipality).
   c. Effluent designation (EFF-1 – Final effluent n°1, etc.).
   d. Type of effluent, such as drinking water, municipal or industrial wastewater.
   e. Reference for the specifications (regulatory, authorization, guideline).
   f. Description of the flow monitoring specifications, such as weekly or continuous
   g. Maximum permissible variance, such as 10%.
3- Description of the discharge setup and the *in situ* measuring system (primary and secondary structures):
   a. Photos and diagrams.
   b. Equipment types, makes and models.
   c. Description of the technical characteristics of the device, including the manufacturer's technical specifications, such as the interval and frequency of measurement, units, device measuring errors and recording method.
   d. Dimensions of the channel or the pipe.
   e. Overall condition (clogging, warping, fissures, etc.).
   f. Discharge conditions at the upstream and downstream measuring instrument location.
   g. Typical daily intervals of measurement: minimum, maximum and average.

h. Description and compliance of the installation with respect to the manufacturer's recommendations (materials, direction of the discharge, disturbance elements, upstream and downstream lengths without disturbances).

4- Description of the data transmission system (reference and *in situ* systems), as the case may be.

5- Description of the method used to check the *in situ* measuring system:

a. Details of how the method was used (diagrams, photos, etc.).

b. Description of the instruments used in the checking process: type, make, model, serial number, functional principle, measurement errors, dimensions, measurement interval and correspondence with *in situ* conditions, if applicable (e.g., reference instrument).

c. Date of calibration of the instrument (if applicable), including the calibration certificate issued by an accredited body.

d. Description of the characteristics and location of the measuring section selected for accuracy checking (distance from the *in situ* measuring system, installation over a by-pass, etc.).

6- Description of the method of checking the data transmission system, if applicable.

7- Presentation of the results:

a. Presentation of the raw data and any calculations that were made.

b. Values (flow or volume) ascertained by the *in situ* measuring system and the reference method, as well as the calculated variance for each of the trials with the method described in section 6.

8- Interpretation of the results.

9- Conclusion concerning the compliance of the facility and its capacity to produce reliable measurements, as well as any recommendations, when required.

10- Appendices:

a. Summary of the last accuracy checking report on the measuring system (conclusions, recommendations and any performed corrective measures).

b. Copy of the most recent calibration certificate of the device used in the checking process, if applicable.

c. A detailed report of the checks and corrective measures for the discharge facility, the *in situ* measuring system and the data transmission system, if applicable.

d. Raw data from the accuracy checking trials (as applicable, provide the data that was recorded by means of graph paper or compiled with software) and other relevant parameters such as temperature, pressure, etc. that were measured during the trials.

e. Curves and tables used to determine flow.

f. Certificates of analysis (tracer dilution method).

12.2 RETENTION OF THE REPORT

The report must be kept on-site for the minimum regulatory period specified in the applicable regulation or other legal text or document from the date it was produced, and remain available at all times for consultation by an Ministère representative.

Verification report…

Documentation of the accuracy checking of systems that measure water discharge or volume

To be accepted, a report must include all required information, including raw data, calculations, interpretation of results, conclusion and any required recommendations.

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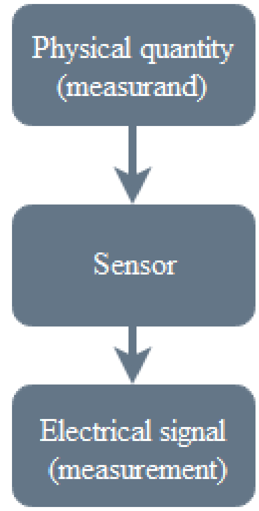
APPENDIX 1: METROLOGY[33] ADAPTED TO HYDROLOGY

In the field of metrology, **measurement** is the consistent process used to obtain one or more values that may reasonably be ascribed to **a quantity**.



Measurement process: Action of measuring or full range of operations used to **measure** a **quantity**.

Measurand: Particular **quantity** intended to be measured.

Measurement result: Value of a measured quantity.

Quantity: Property of a phenomenon, body or substance, which has a magnitude that can be expressed as a number and a reference.

The properties may be fundamental (e.g., length, mass, time, etc.) or derived from fundamental quantities (e.g., surface, velocity, etc.).

Example: Measuring a physical quantity such as length consists of allocating a quantitative value to it based on size (e.g., a metre).

Measurement is made with an **instrument** that consists of a device used by itself or in conjunction with others, the whole constituting a **measuring system**.

> The metrological qualities of a **measuring instrument** are based on **range**, **resolution**, **sensitivity**, **accuracy, trueness** and **reliability**.

Range: Absolute value of the difference between the extreme quantity values of a nominal indication interval.

Example: 20 V.

Not to be confused with **measuring interval**, which consists of a set of values of quantities that can be measured by a **measuring system** and that has specified

[33] Definitions based on terms used by the International Organization of Legal Metrology (IOLM), the International Organization for Standardization (ISO) and the *International vocabulary of metrology – Basic and general concepts and associated terms* (VIM).

instrumental measurement **uncertainty,** under defined conditions.

Example: -10 V to +10 V.

Resolution

The smallest change in a quantity being measured that produces a value can be displayed by the instrument.

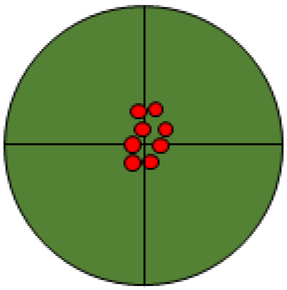
Example**:** In a water level measuring apparatus with a resolution of .001 m, the change in measured value will be displayed as soon as there is a perceived difference of 1 mm in the level of the water.

Sensitivity

Output signal variation compared to input signal variation.

Example: The fluctuations of the output signal of a measuring instrument correctly reproduce the fluctuations of the input signal.

Accuracy

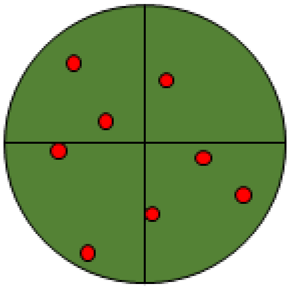


Qualitative expression of the degree of closeness between a measured value and its **true value** (illustrated by the intersection of the lines at the centre of the circle). It is sometimes characterized by the difference between the average (and therefore **trueness**) and the dispersion (**precision**) of measurements.

The quantitative expression of accuracy corresponds to **uncertainty**.

Accuracy should not be confused with **precision,** which, while commonly used as a synonym, **does not officially exist** in metrology.

Trueness

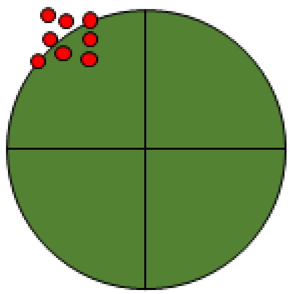


The ability to provide values that are equal to the measured **quantity**.

A sensor is deemed **true** if the variance between the average and the **true value** of the results (illustrated by the intersection of the lines at the centre of the circle) is low, even if the **standard deviation** is high.

Reliability

The **standard deviation** is a measure of the dispersion of data around the average. For example, the greater the standard deviation, the more distant are data from each side of the average.



The capacity of providing reliable neighbouring values of a measured quantity.

It defines the dispersion of results. A reliable instrument will repeatedly report similar measurement values around their average, even if the average is not necessarily close to the **true value** (illustrated by the intersection of the lines in the centre of the circle).

A sensor is deemed reliable if it produces the same **standard deviation** even when values are low.

All devices, procedures and, therefore, measurements include of necessity some degree of **error** (or **uncertainty**).

Error

The difference between a **measured value** and the **true value**. It is expressed as a unit of quantity (e.g., an absolute error of 20 ± .5 cm) or as a percentage (relative errors that express the relationship between absolute uncertainty and the measured value [e.g., 20 cm ± 2.5%]).

There are two types of errors: **random** and **systematic**.

Random errors in the field of interest to us are related to the variable reaction time of an experimenter between starting and stopping a chronometer, which can be overestimated or underestimated. Random errors can be reduced by repetitive measurement.

Systematic errors are replicated at each measurement (bias). For example, this would be the case if a ruler missing the first centimetre was used.

True value

A value obtained by a perfect measurement. In practice, the true value cannot be measured, since the result of measurement always includes some degree of error. However, the **measurement uncertainty** that is associated with random and systematic **errors** can be evaluated.

The important notion in metrology is not to ascertain whether a measurement is true or false but to estimate its level of **uncertainty**.

Measurement uncertainty corresponds to the fact that the result of a given measurement is not just one value, but rather, an infinite number of values dispersed around the result.

> **Uncertainty** = estimate of **random error** during a **measurement.**
>
> **Uncertainty** is the interval around the **measured value** in which the **true value** can be found**.**

In other words, **uncertainty** is the probability of **measurement errors**, expressing the "inaccuracy quantity." It corresponds to the quantitative expression of **accuracy** and enables the level of confidence of a measurement to be determined.

Depending on equipment specifications or current regulations, a **maximum error** level can be set for a given instrument or measuring system.

The **maximum** permissible **error (error limit, maximum acceptable error, etc.)** corresponds to the extreme value of **measurement errors** compared to a known **reference value** that can be tolerated by the equipment specifications or regulations for a **measurement**, **measuring instrument** or **measuring system**.

Reference value	The value of a **quantity** used for comparison purposes.

Verification is used to confirm whether or not a **measurement**, **measuring instrument** or **measuring system** falls within the **maximum** permissible **error**.

Verification	Provides tangible proof that a given entity meets specifications. Not to be confused with **calibration**. Example: Confirmation that a flow **measuring system** complies with a regulatory **maximum** permissible **error**.

In **accuracy checking**, the *in situ* flow measuring system is compared to the calculation of **variance** between two simultaneous measurements of flow using a **reference method**. This makes it possible to confirm whether **maximum** permissible **variance** is met (e.g., 10% variance between the two).

For the requirements of **accuracy checking**, the value obtained by the reference method is deemed the **reference value**.

Variance	Difference between the value of a **quantity** and a **reference value**, the latter being established by a reference method or **reference instrument**. Example: A variance of 5% is calculated by comparing the flow measured by an *in situ* **measuring system** with the flow

	simultaneously obtained by a different method (such a volumetric) deemed the **reference value**.
Max. permissible variance	For the needs of this publication, the maximum permissible difference between the value obtained by the *in situ* measuring instrument and the one obtained by the **reference method**.

Error = comparison to the true value or benchmark (expresses uncertainty).

Variation = comparison to a reference value obtained by a recognized reference method.

Reference instrument	**Device that measures** the velocity, pressure or strength of an electric current or any other parameter whose variation can be directly correlated with water discharge flow. The instrument must be **calibrated** on a test bed by an **accredited body** annually or whenever a dysfunction is suspected. It confers a **reference value** to the instrument that can be compared with the **value measured** by the *in situ* **measuring system** to check whether variance falls below the permissible **maximum**.
Reference method	Method of measuring the instantaneous flow of the discharge, independent of a hydraulic structure.The following accuracy checking reference methods are recognized by the Ministère: velocity-area, tracer dilution, volumetric, pump capacity, reference instrument.
Measured value	Value of a quantity that represents the result of a measurement.

In the **accuracy checking** process, **trials** make it possible to determine the **trial flow**, which is then used as the **reference value**.

Trial	A series of operations used in **accuracy checking** to obtain a **reference value**. **Accuracy checking** usually involves more than just one trial.
Flow trial	Average flow obtained during a **trial** from the **reference method**.

Prior to use or if disruption is presumed, a **measuring** or **reference instrument** may require adjustment or calibration.

Adjustment

Change to a measuring **instrument** or **system** to enable it to provide prescribed indications that correspond to the data values of the quantities to be measured. Not to be confused with **calibration**. Examples of adjustments to a **measuring system**: resetting the zero, adjusting the offset or adjusting the span.

Calibration

Process consisting of comparing and correcting the response of a measuring instrument using a measuring caliber or **benchmark** over the full **measurement range**. The results can be expressed as a statement or as a calibration function, diagram, curve or table. While a calibrated instrument is not necessarily true, calibration can determine the device's **error rate** and compensate for it.

Not to be confused with the adjustment of a measuring system.
Example 1: A rotating current meter is calibrated by the National Calibration Service to determine the uncertainty of the propeller and the equation for measuring velocity. Example 2: A flume is calibrated by drawing a stage-discharge curve for its full **measurement range**. To be representative, the curve should theoretically be drawn for each water level used by the instrument.

Benchmark

Defining a given **quantity**, with a specified associated value and **uncertainty** level; used as a reference. The defined quantity may be provided by a measuring system, material measure or reference material.

Example: a 1-kg mass benchmark with a level of uncertainty associated with .0000003 kg.

Primary benchmarks are determined by a primary measuring procedure or created by convention. They possess the highest level of metrology quality and are accepted without reference to other benchmarks of the same quantity in a specified context.

Example: A recognized test bed used by one of the bodies accredited by the Standards Council of Canada (SCC), such as the Canadian Standards Association (CSA) or the Bureau de normalisation du Québec (BNQ).

Secondary benchmarks are established by a **comparative**

quantity and type **calibration process** to the **primary benchmark**.

Example: the propeller of a current meter. Not to be confused with checking the response of a reference instrument on a test bed. Given that it does not involve correcting the measurement errors of a device, it is not deemed calibration.

Accredited body Associated to a national or international reference (ISO, BNQ, etc.).

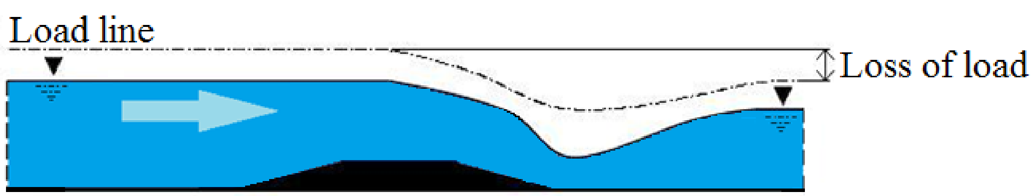
APPENDIX 2: PARTIAL AND TOTAL LOAD

The total load of a discharge can be defined as its capacity to circulate more or less easily or freely in a open channel or closed conduit.

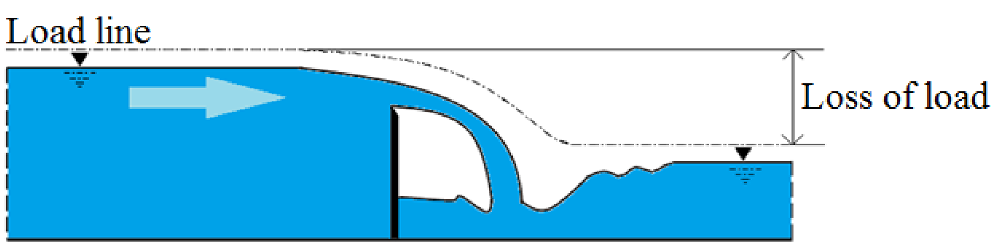
This capacity to circulate in a open channel is the product of the water level and the velocity of the discharge. In a closed conduit, it is measured by the discharge pressure and velocity.

Optimal total load exists when the discharge is not subject to any physical constraints. The physical characteristics of the discharge remain more or less identical in both the upstream and downstream sections of the channel. This situation determines the reference conditions, meaning that whenever the discharge changes or is disturbed, the total load in the channel also changes, and the difference between the two situations indicates that loss of load has occurred.

For example, installing a triangular weir in a open channel raises the water level and slows the velocity of discharge upstream of the weir. In such cases, load loss corresponds to the difference in water level between the upstream and downstream sections of the weir. For flumes, maximum load loss is the same as maximum depth, i.e., maximum flow. The graphic representation of the total load curve as a function of the horizontal distance measured in the direction of the discharge makes it possible to visualize the load line. The following illustrations clarify the concept:



Gauging flume



Weir

APPENDIX 3: SAMPLE INSPECTION CHECKLISTS FOR PRIMARY AND SECONDARY STRUCTURES/DEVICES

3.1 Inspection checklist for a Parshall flume.

3.2 Inspection checklist for a Palmer-Bowlus flume.

3.3 Inspection checklist for an H flume.

3.4 Inspection checklist for a thin-plate weir.

3.5 Inspection checklist for a broad-crested weir.

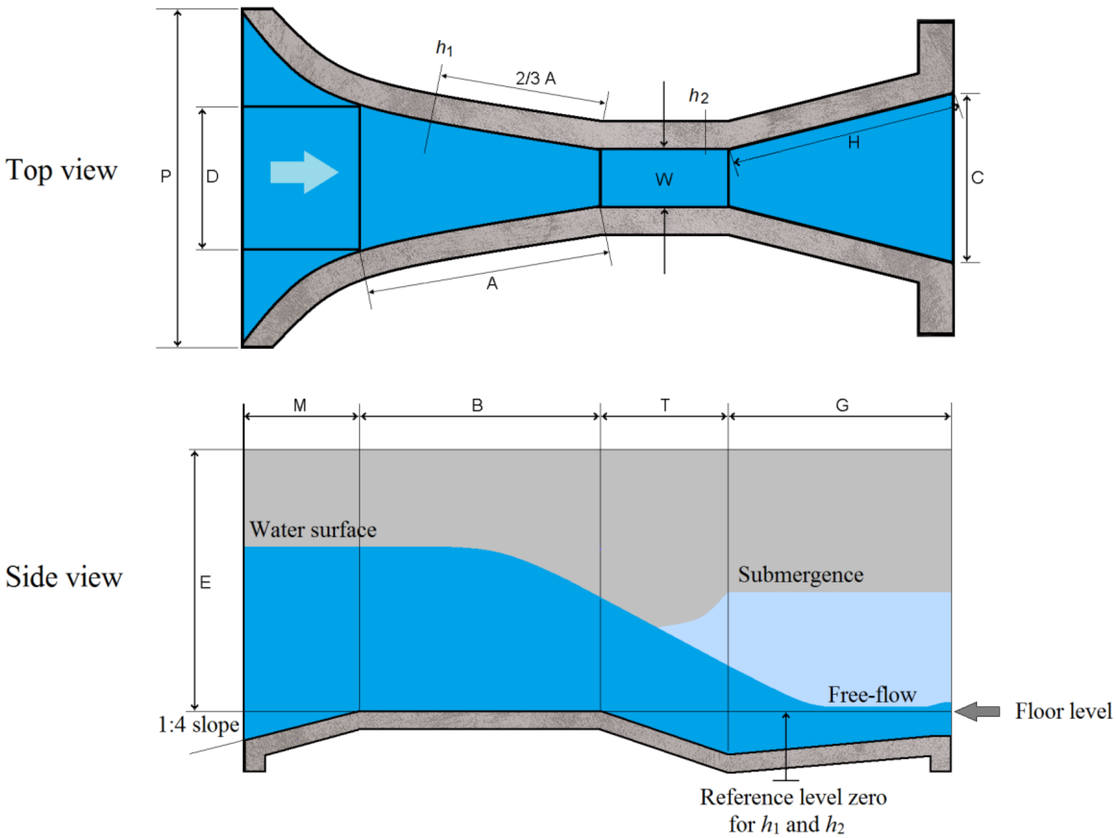
3.6 Inspection checklist for a secondary device.

3.7 Inspection checklist for a closed pipe measuring system.

Appendix 3.1 – Inspection checklist for a Parshall flume

Criteria	Compliance	Non-compliance
Dimensions of the flume		
Ease of access (avoid covering with a concrete plate, etc.)	☐	☐
Stage-discharge table and equation appropriate for the flume	☐	☐
Interval of flow usually measured (20-80% of capacity)	☐	☐
Standard dimensions (see diagram on next page)	☐	☐
Position of the Parshall flume to the channel (ideally centred)	☐	☐
Installation complies with manufacturer's standards and specifications	☐	☐
Level cross-section, length and/or walls	☐	☐
Impermeable (Parshall flume and approach channel)	☐	☐
Condition of the flume (no warping of bed or walls)	☐	☐
Cleanliness of the walls, bed and throat (no accumulated deposits, etc.)	☐	☐
Location of the measuring point (2/3A) and position relative to the flume (centred, next to a wall, etc.)	☐	☐
Stage gauge at the measuring point in compliance with requirements	☐	☐
Description of the discharge at the measuring point (in a stilling well, directly in the channel, variable water level difficult to read, etc.)	☐	☐
No foam or vapour	☐	☐
Length of the approach channel (5-10D recommended) and description (elbow 10 m upstream, inflow pipe, measuring probes, slope inducing hydraulic jump or excessive velocity, etc.)	☐	☐
Description of the upstream discharge (laminar, calm, turbulent, waves, preferential)	☐	☐
Description and length of the outlet channel (elbow 1 m upstream, measuring probes, slope enabling the rapid evacuation of water, vegetation, etc.)	☐	☐
Description of the downstream discharge (free flow, falls, submerged)	☐	☐
Submergence ratio h_2/h_1	☐	☐
Frequency of inspection and maintenance (required, recommended, monthly or +)	☐	☐
Registration and duration of information conservation (regulatory)	☐	☐
Date of the most recent accuracy check of the primary structure using a reference method. Meets inspection frequency based on specifications, such as yearly.	☐	☐
Method recognized by the Ministère used for accuracy checking: tracer dilution, velocity-area, volumetric, pump capacity, reference instrument	☐	☐
Results of accuracy checking and compliance with maximum permissible variance, such as 10%	☐	☐

Parshall flume diagram



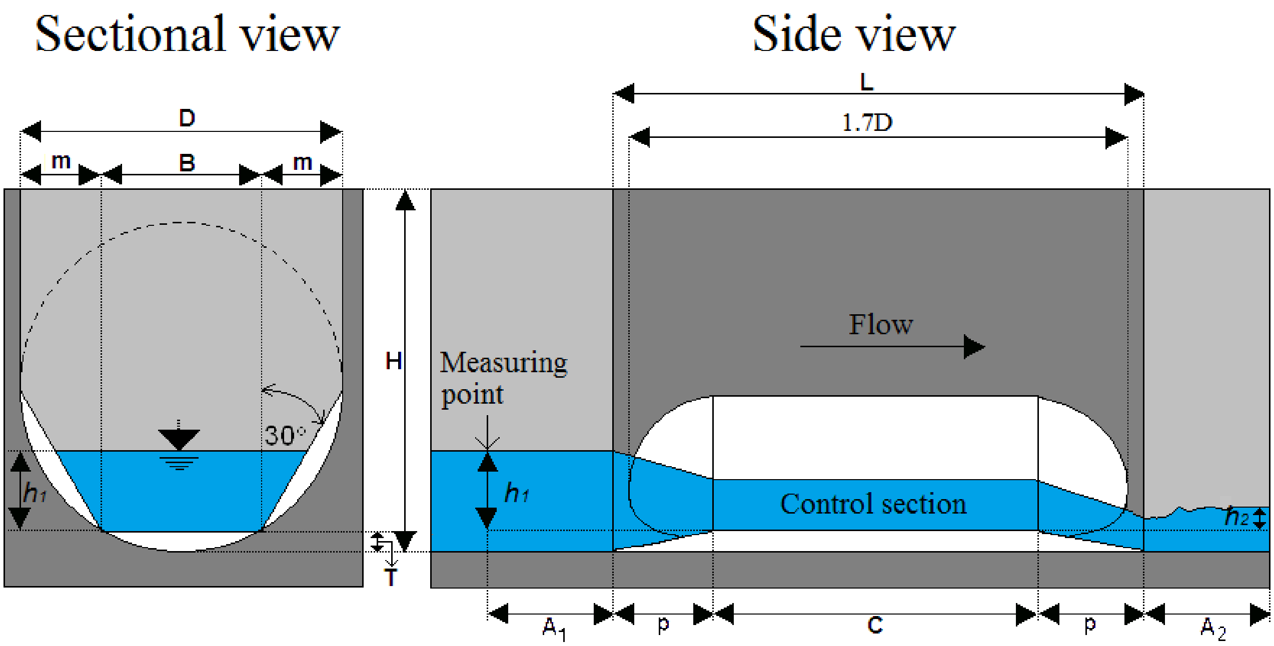
Key		
Approach channel	M P	Length of the slope at the Parshall flume inlet Width of the approach channel
Convergent section	D E A 2/3A h_1 B	Width at the inlet of the convergent section Depth of the convergent section channel Length of the convergent section wall Length measured from the constriction Water level upstream Length of the convergent section
Control section	T W h_2	Length of the control section Width of the control section (dimensions of the channel) Water level downstream
Drift section	C G H	Width of the drift section outlet Length of the drift section Length of the drift section wall

Dimensions (m)	Approach channel		Convergent section					Control section		Drift section		
	M	P	A	2/3A	B	D	E	T	W	C	G	H
Standard												
Measured												

Appendix 3.2 – Inspection checklist for a Palmer-Bowlus flume

Criteria	Compliance	Non-compliance
Dimensions of the flume		
Ease of access (avoid covering with a concrete plate, etc.)	☐	☐
Stage-discharge table and equation appropriate for the flume	☐	☐
Interval of flow usually measured (70% of capacity)	☐	☐
Standard dimensions (see diagram on next page)	☐	☐
Position of the Palmer-Bowlus flume to the channel (ideally centred)	☐	☐
Installation complies with manufacturer's standards and specifications	☐	☐
Level cross-section, length and/or walls	☐	☐
Waterproof (Palmer-Bowlus flume and approach channel)	☐	☐
Condition of the flume (warping of bed or walls)	☐	☐
Cleanliness of the walls, bed and throat (no accumulated deposits, etc.)	☐	☐
Location of the measuring point (D/2 upstream and D/6 compared to bed) and position relative to the flume (centred, next to a wall, etc.)	☐	☐
Stage gauge at the measuring point in compliance with requirements	☐	☐
Description of the discharge at the measuring point (in a stilling well, directly in the channel, variable water level difficult to read, etc.)	☐	☐
No foam or vapour	☐	☐
Length of the approach channel (25D recommended) and description (elbow 10 m upstream, inflow pipe, measuring probes, slope inducing hydraulic jump or excessive velocity, etc.)	☐	☐
Description of the upstream discharge (laminar, calm, turbulent, waves, preferential)	☐	☐
Length of the outlet channel (5-20D recommended) and description (elbow 1 m upstream, measuring sensors, slope enabling the rapid evacuation of water, vegetation, etc.)	☐	☐
Description of the downstream discharge (free flow, falls, submerged)	☐	☐
Submergence ratio h_2/h_1 (< 85%)	☐	☐
Frequency of inspection and maintenance (required, recommended, monthly or +)	☐	☐
Registration and duration of information conservation (regulatory)	☐	☐
Date of the most recent accuracy check of the primary structure using a reference method. Meets inspection frequency based on specifications, such as yearly.	☐	☐
Method recognized by the Ministère used for accuracy checking: tracer dilution, velocity-area, volumetric, pump capacity, reference instrument	☐	☐
Results of accuracy checking and compliance with maximum permissible variance, such as 10%	☐	☐

Palmer-Bowlus flume diagram



Key	
A_1	Length enabling h_1 measuring point to be located (D/2)
A_2	Length enabling h_2 measuring point to be located (D/2)
B	Width at the base of the control section of the flume (D/2)
C	Length of the control section of the flume (throat) (corresponds to the width of the pipe)
D	Width of the flume (corresponds to the diameter of the pipe)
H	Height of the flume (D + approximately .0508 m or 2 in)
L	Total length of the base of the flume (2D + approximately .0508 m or 2 in)
m	Distance between the base and the sides (D/4)
p	Length of the entry and exit sections (D/2)
T	Difference in water level between the base of the control section of the flume and the invert (D/6) (corresponds to the h_1 and h_2 zero)

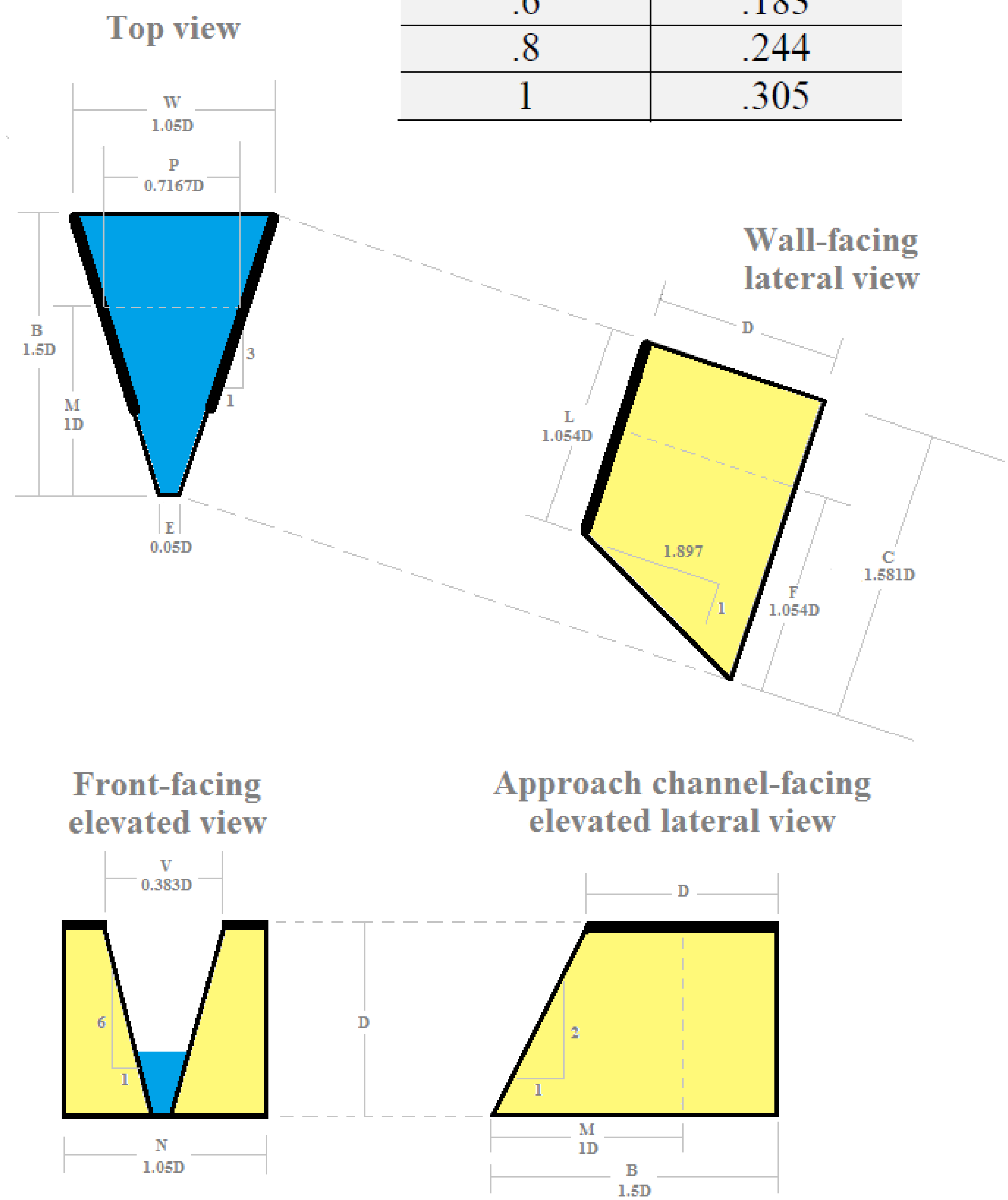
Dimensions (m)	A_1	A_2	B	C	D	H	L	m	p	T
Standard										
Measured										

Appendix 3.3 – Inspection checklist for an H flume

Criteria	Compliance	Non-compliance
Dimensions of the flume		
Ease of access (avoid covering with a concrete plate, etc.)	☐	☐
Stage-discharge table and equation appropriate for the flume	☐	☐
Interval of flow usually measured (70-100% of capacity)	☐	☐
Type (HS, H, HL) and standard dimensions (see diagram on next page)	☐	☐
Position of the H flume to the channel (ideally centred)	☐	☐
Installation complies with manufacturer standards and specifications	☐	☐
Level cross-section, length and/or walls	☐	☐
Waterproof (H flume and approach channel)	☐	☐
Condition of the flume (no warping of bed or walls)	☐	☐
Cleanliness of the walls, bed and throat (no accumulated deposits, etc.)	☐	☐
Location of the measuring point (h_1) and position relative to the flume (centred, next to a wall, etc.)	☐	☐
Stage gauge at the measuring point in compliance with requirements	☐	☐
Description of the discharge at the measuring point (in a stilling well, directly in the channel, variable water level difficult to read, etc.)	☐	☐
No foam or vapour	☐	☐
Length of the approach channel (3-5D recommended) and description (elbow 10 m upstream, inflow pipe, measuring probes, slope inducing hydraulic jump or excessive velocity, etc.)	☐	☐
Description of the upstream discharge (laminar, calm, turbulent, waves, preferential)	☐	☐
Length of the outlet channel and description (elbow 1 m upstream, measuring probes, slope enabling the rapid evacuation of water, vegetation, etc.)	☐	☐
Description of the downstream discharge (free flow, falls, submerged)	☐	☐
Submergence ratio h_2/h_1	☐	☐
Frequency of inspection and maintenance (required, recommended, monthly or +)	☐	☐
Registration and duration of information conservation (regulatory)	☐	☐
Date of the most recent accuracy check of the primary structure using a reference method. Meets inspection frequency based on specifications, such as yearly.	☐	☐
Method recognized by the Ministère used for accuracy checking: tracer dilution, velocity-area, volumetric, pump capacity, reference instrument	☐	☐
Results of accuracy checking and compliance with maximum permissible variance, such as 10%	☐	☐

HS flume

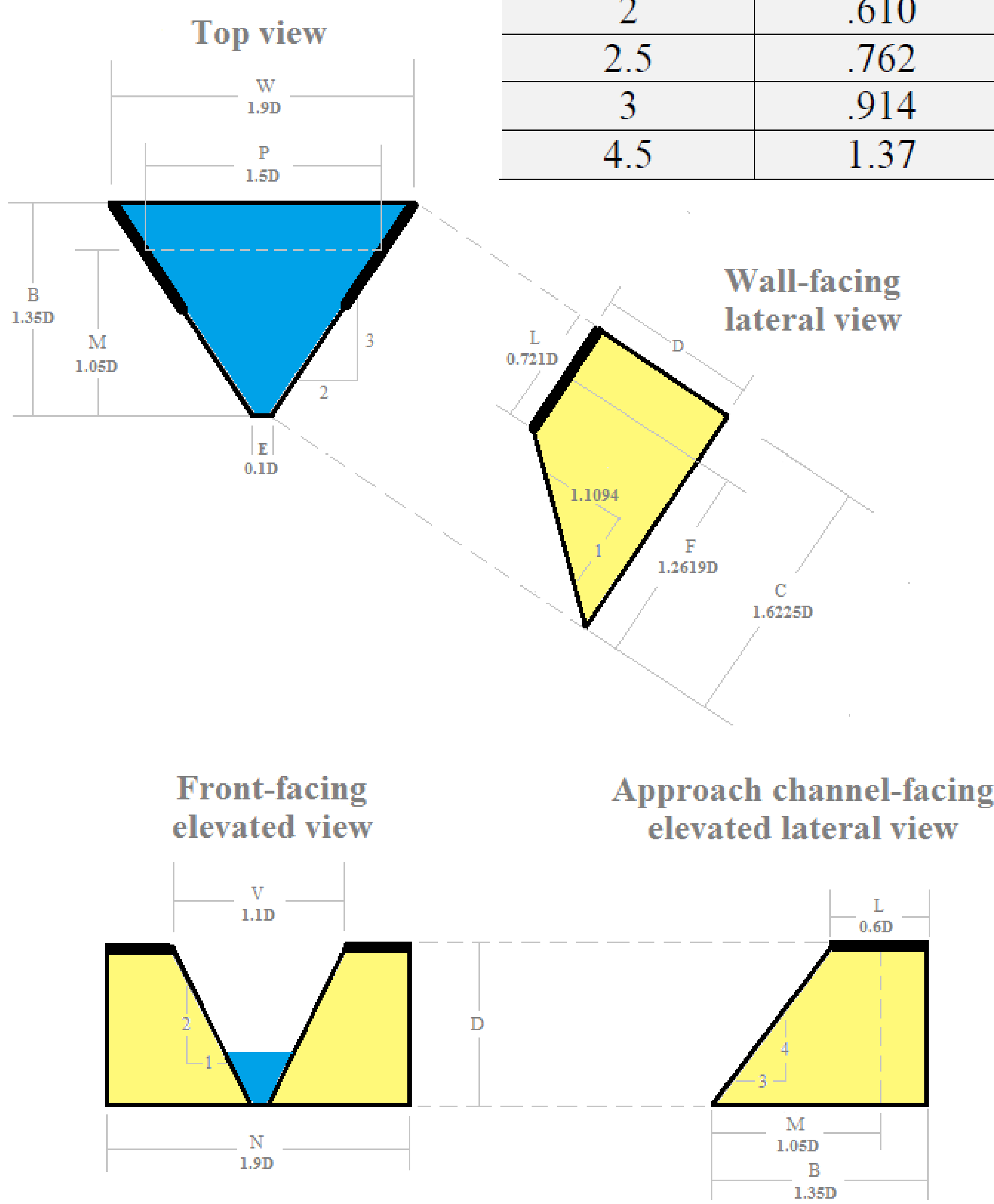
HS flume height (D)	
ft	m
.4	.122
.6	.183
.8	.244
1	.305



Identification and description of the flume sections		Standard dimensions	Measured dimensions
A	Length of the approach channel		
B	Length of the base of the flume (in the axis of the flume)		
C	Length of the base of the flume (compared to the wall)		
D	Flume height (corresponds to the flume dimensions)		
E	Width of the base of the control section, at the outlet of the flume		
F	Position of the measuring point (compared to the wall)		
L	Length of the wall at its summit		
M	Position of the measuring point (in the axis of the flume)		
N	Total width of the flume (in the axis of the flume)		
P	Width of the base at the measuring point		
V	Width of the control section at its summit		
W	Width of the approach channel		

H flume

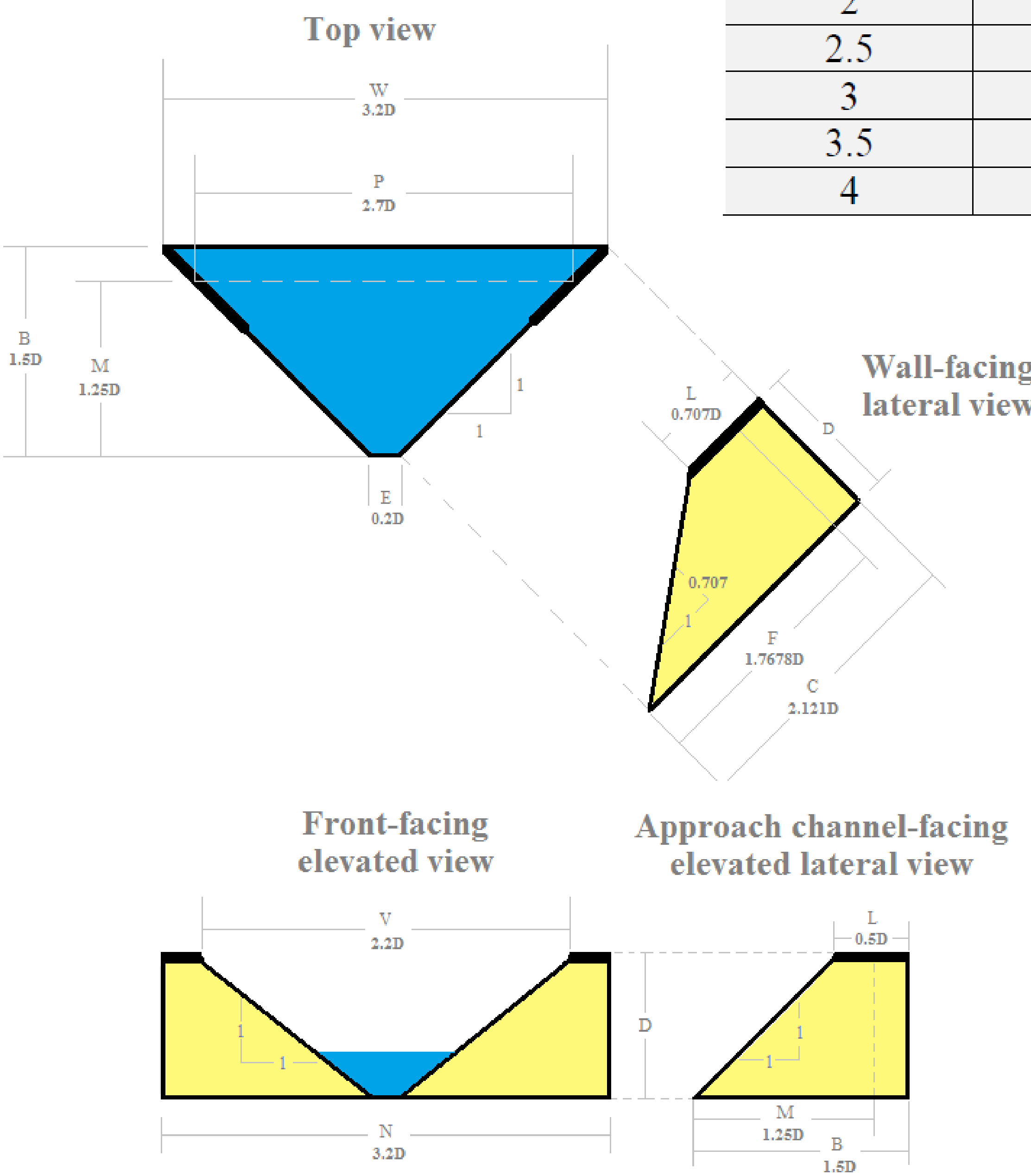
H flume height (D)	
ft	m
.5	.152
.75	.229
1	.305
1.5	.457
2	.610
2.5	.762
3	.914
4.5	1.37



Identification and description of the flume sections		Standard dimensions	Measured dimensions
A	Length of the approach channel		
B	Length of the base of the flume (in the axis of the flume)		
C	Length of the base of the flume (compared to the wall)		
D	Flume height (corresponds to the flume dimensions)		
E	Width of the base of the control section, at the outlet of the flume		
F	Position of the measuring point (compared to the wall)		
L	Length of the wall at its summit		
M	Position of the measuring point (in the axis of the flume)		
N	Total width of the flume (in the axis of the flume)		
P	Width of the base at the measuring point		
V	Width of the control section at its summit		
W	Width of the approach channel		

HL Flume

HL flume height (D)	
ft	m
2	.610
2.5	.762
3	.914
3.5	1.07
4	1.219



Identification and description of the flume sections		Standard dimensions	Measured dimensions
A	Length of the approach channel		
B	Length of the base of the flume (in the axis of the flume)		
C	Length of the base of the flume (compared to the wall)		
D	Flume height (corresponds to the flume dimensions)		
E	Width of the base of the control section, at the outlet of the flume		
F	Position of the measuring point (compared to the wall)		
L	Length of the wall at its summit		
M	Position of the measuring point (in the axis of the flume)		
N	Total width of the flume (in the axis of the flume)		
P	Width of the base at the measuring point		
V	Width of the control section at its summit		
W	Width of the approach channel		

Appendix 3.4 – Inspection checklist for a thin-plate weir

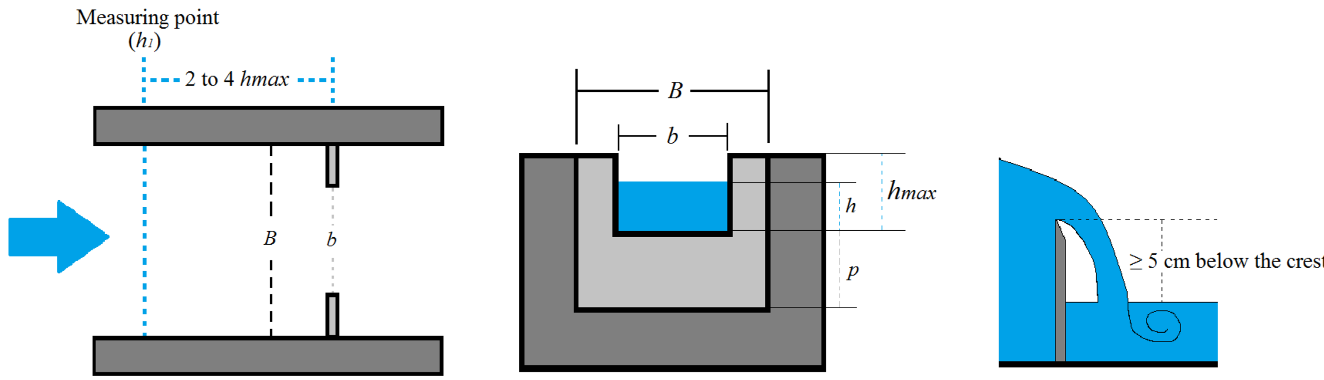
Criteria	Compliance	Non-compliance
Ease of access (avoid covering with a concrete plate, etc.)	☐	☐
Type (rectangular, triangular, without contraction, etc.) and standard dimensions (see diagram on next page)	☐	☐
Stage-discharge table and equation appropriate for the weir (complies with operational limits)	☐	☐
Interval of flow usually measured (max. ≤ 70-100% of capacity)	☐	☐
Minimum (h_{min}) and maximum (h_{max}) water levels	☐	☐
Position of the weir perpendicular to the walls of the channel and the discharge	☐	☐
Compliance of the outlet plate (rigid, no corrosion, thickness 1-2 mm or notched edge of 45° minimum angle on the downstream side)	☐	☐
Compliance of the crest (level over entire length, smooth, straight at intersection with the upstream face of the weir plate)	☐	☐
Condition of the weir (no bed or wall warping, smooth plate with no irregularities)	☐	☐
Position of the notch (symmetrical and equidistant from the sides of the discharge channel)	☐	☐
Installation complies with manufacturer's standards and specifications	☐	☐
Level transversally, longitudinally and vertically	☐	☐
Impermeable (weir and approach channel)	☐	☐
Cleanliness of the weir and notch (no accumulation of deposits, etc.)	☐	☐
Location of the measuring point (2 to 4 h_{max}) and position with respect to the approach channel (centred, next to wall, etc.)	☐	☐
Stage gauge at the measuring point in compliance with requirements	☐	☐
Description of the discharge at the measuring point (in a stilling well, directly in the channel, variable water level difficult to read, etc.)	☐	☐
No foam or vapour	☐	☐
Ventilation under the nappe and water level downstream ≥ 5 cm below the crest	☐	☐
Length of the approach channel (5x the width of the nappe) and description (no obstruction, elbow 1 m upstream, measuring probes, slope inducing excessive velocity, etc.)	☐	☐
Description of the upstream discharge (laminar, calm, turbulent, waves, preferential)	☐	☐
Description and length of the downstream section (elbow 1 m upstream, measuring probes, slope enabling the rapid evacuation of water, vegetation, etc.)	☐	☐
Description of the downstream discharge (free flow, falls, submerged)	☐	☐
Frequency of inspection and maintenance (required, recommended, monthly or +)	☐	☐
Registration and duration of information conservation (regulatory)	☐	☐
Date of the most recent accuracy check of the primary structure using a reference method. Meets inspection frequency based on specifications, such as yearly.	☐	☐

Criteria	Compliance	Non-compliance
Method recognized by the Ministère used for accuracy checking: tracer dilution, velocity-area, volumetric, pump capacity, reference instrument	☐	☐
Results of accuracy checking and compliance with maximum permissible variance, such as 10%	☐	☐

Appendix 3.5 – Inspection checklist for a broad-crested weir

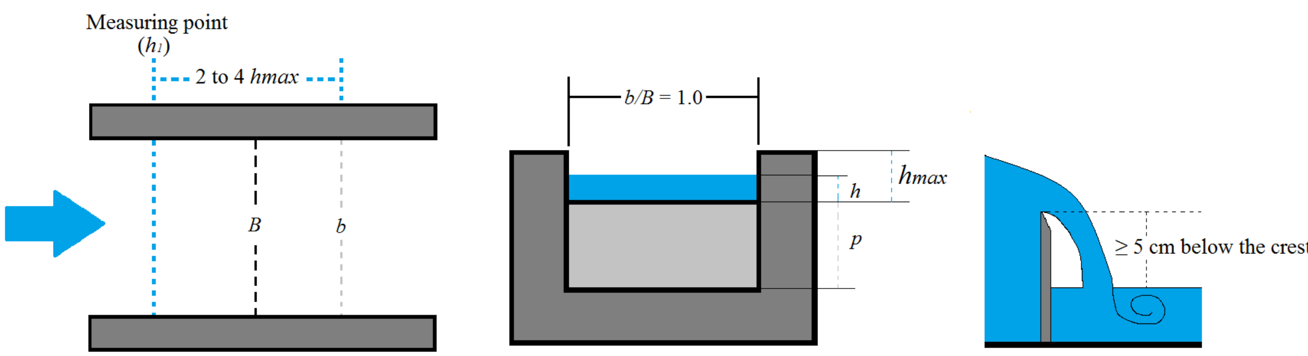
Criteria	Compliance	Non-compliance
Ease of access (avoid covering with a concrete plate, etc.)	☐	☐
Type (rectangular) and standard dimensions (see diagram on next page) *(For other shapes, refer to ISO to complete the field inspection checklist)*	☐	☐
Stage-discharge table and equation appropriate for the weir (complies with operational limits)	☐	☐
Interval of flow usually measured	☐	☐
Minimum (h_{min}) and maximum (h_{max}) water level	☐	☐
Position of the weir perpendicular to the walls of the channel and the discharge	☐	☐
Condition of the weir (no warping of bed or walls)	☐	☐
Compliance of the crest (surface level, no warping, upstream face forms a right-angle at its intersection with the plane of the crest)	☐	☐
Position of the notch (symmetrical and equidistant from the sides of the discharge channel)	☐	☐
Installation complies with manufacturer's standards and specifications	☐	☐
Level transversally, longitudinally and vertically	☐	☐
Waterproof (weir and approach channel)	☐	☐
Cleanliness of the weir and notch (no accumulation of deposits, etc.)	☐	☐
Location of the measuring point (3 to 4 h_{max}) and position with respect to the approach channel (centred, next to wall, etc.)	☐	☐
Stage gauge at the measuring point in compliance with requirements	☐	☐
Description of the discharge at the measuring point (in a stilling well, directly in the channel, variable water level difficult to read, etc.)	☐	☐
No foam or vapour	☐	☐
Ventilation under the nappe or rectangular flume downstream = weir width	☐	☐
Length of the approach channel (5x the width of the nappe) and description (no obstruction, elbow 1 m upstream, measuring probes, slope inducing excessive velocity, etc.)	☐	☐
Description of the upstream discharge (laminar, calm, turbulent, waves, preferential)	☐	☐
Description and length of the downstream section (elbow 1 m upstream, measuring probes, slope enabling the rapid evacuation of water, vegetation, etc.)	☐	☐
Description of the downstream discharge (free flow, falls, submerged)	☐	☐
Frequency of inspection and maintenance (required, recommended, monthly or +)	☐	☐
Registration and duration of information conservation (regulatory)	☐	☐
Date of the most recent accuracy check of the primary structure using a reference method. Meets inspection frequency based on specifications, such as yearly.	☐	☐
Method recognized by the Ministère used for accuracy checking: tracer dilution, velocity-area, volumetric, pump capacity, reference instrument	☐	☐

Criteria	Compliance	Non-compliance
Results of accuracy checking and compliance with maximum permissible variance, such as 10%	☐	☐



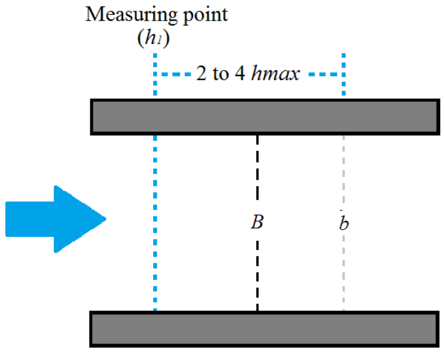
Top view **Front view**

Rectangular weir						
Dimensions (m)	***B***	***b***	***p***	h_{max}	h_1	**h below crest**
Standard						
Measured						

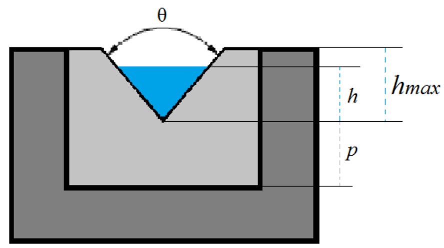


Top view **Front view**

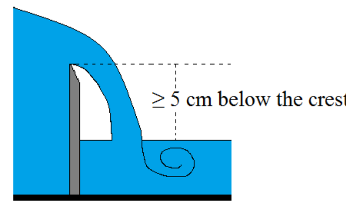
Weir without lateral contraction						
Dimensions (m)	***B***	***b***	***p***	h_{max}	h_1	**h below crest**
Standard						
Measured						



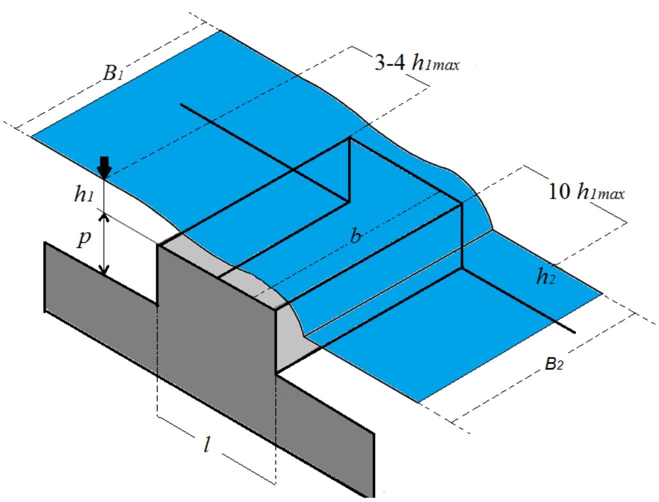
Top view



Front view



Triangular weir							
Dimensions (m)	***B***	***b***	***p***	h_{max}	h_1	**h below crest**	**Angle**
Standard							
Measured							



Key

- B_1 Width of the approach channel (m)
- B_2 Width of the outlet channel (m)
- b Width of the weir crest perpendicular to the direction of the flow (m)
- h_1 Upstream water level measurement point (m)
- h_2 Downstream water level measurement point (m)
- l Length of the weir in the direction of the flow (m)
- p Weir height (difference between the level of the channel bed and of the crest)

Rectangular broad-crested weir								
Dimensions (m)	B_1	B_2	***b***	***l***	***p***	h_{max}	h_1	h_2
Standard								
Measured								

Appendix 3.6 – Inspection checklist for a secondary device

Criteria	Compliance	Non-compliance
Ease of access	☐	☐
Type of secondary device (bubble pipe, ultrasonic, pressure, etc.)		
Make and model of device		
Pre-programmed conversion formula in the device (stage-discharge relation)	☐	☐
Pre-programmed measurement range in the device (min. and max.), corresponding with measurement range of the primary structure	☐	☐
Local display (units)	☐	☐
Frequency of measurement (weekly, continuous 1 measurement/minute, etc.), corresponding with monitoring specifications	☐	☐
Methods of recording the flow (e.g., graph, transmission to a computer, local with memory card, etc.)	☐	☐
Flow recording time frame, if applicable (8 a.m.-8 a.m., 12 a.m.-12 a.m., etc.)	☐	☐
Frequency of inspection and measurement accuracy checking of the device (required, recommended weekly or +) and data transmission (if applicable)	☐	☐
Procedure for accuracy checking the measuring device	☐	☐
Procedure for accuracy checking data transmission	☐	☐
Variance check set to device calibration (required, nearest possible to 0% and always ≤ 5% over the flow)	☐	☐
Variance check set to data transmission calibration (required, nearest possible to 0%)	☐	☐
Registration and duration of information conservation (regulatory)	☐	☐
Accuracy checking of the secondary device during the control process (raw data available in the following table)	☐	☐

<table>
<tr><th colspan="8">Accuracy checking during the control process</th></tr>
<tr><th rowspan="2">Time</th><th colspan="3">In situ device</th><th colspan="2">Manual measurement</th><th colspan="2">Variance (%)</th></tr>
<tr><th>Level (unit)</th><th>Flow (unit)</th><th>Computer system (unit)</th><th>Level (unit)</th><th>Flow (unit)</th><th>Flow (manual/ device) (≤ 5%) (unit)</th><th>Data transmission (device/ computer system) (as close as possible to 0%) (unit)</th></tr>
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</table>

Appendix 3.7 – Inspection checklist for a closed conduit measuring system

Criteria	Compliance	Non-compliance
Ease of access	☐	☐
Type (electromagnetic, ultrasound, diaphragm, insertion, external, etc.)		
Make and model		
Pre-programmed measurement range (min. and max.)	☐	☐
Display (unit)	☐	☐
Frequency of measurement (weekly, continuous 1 measurement/minute, etc.), corresponding with monitoring specifications	☐	☐
Methods of recording the flow (ex.: graph, transmission to a computer, local with memory card, etc.)	☐	☐
Flow recording time frame, if applicable (8 a.m.-8 a.m., 12 a.m.-12 a.m., etc.)	☐	☐
Nominal diameter (DN) of the flowmeter and the conduit	☐	☐
Conduit material	☐	☐
Position of the flowmeter (required): horizontal ☐ vertical ☐	☐	☐
Direction of the discharge (required): ascending ☐ descending ☐	☐	☐
Capacity of the conduit: full ☐ not full ☐	☐	☐
Condition of the conduit and flowmeter (no visible rust, good condition, etc.)	☐	☐
Installation compliance with manufacturer's standards and recommendations (include technical specs for conductivity, no excessive vibration, etc.)	☐	☐
Length upstream of the flowmeter without disturbances, type of disturbance element (elbow, valve, etc.) and comparison with manufacturer's specifications	☐	☐
Length downstream of the flowmeter without disturbances, type of disturbance element (elbow, valve, etc.) and comparison with manufacturer's specifications	☐	☐
Frequency of inspections and accuracy checks of the measuring device (required, recommended monthly or +) and data transmission (if applicable)	☐	☐
Procedure for accuracy checking the measuring device	☐	☐
Procedure for accuracy checking data transmission	☐	☐
Variance check set to data transmission calibration (required, nearest possible to 0%)	☐	☐
Registration and duration of information conservation (regulatory)	☐	☐
Date of the most recent accuracy check using a reference method. Meets inspection frequency based on specifications, such as yearly	☐	☐
Method recognized by the Ministère used for accuracy checking: tracer dilution, velocity-area, volumetric, pump capacity, reference instrument	☐	☐
Results of accuracy checking and compliance with maximum permissible variance such as 10%	☐	☐

NB Attach a diagram or annotated photographs of the installation.

APPENDIX 4: SAMPLE FIELD CHECKLISTS for DETERMINing pump CAPACITY

Criteria	Details
Overview	
Date of verification	
Name and position title of the auditor	
Location of the site (Business or municipality, etc.)	
Effluent designation (e.g., EFF-1- Effluent final n° 1)	
Type of effluent (Drinking water, municipal wastewater, industrial wastewater, etc.)	
Description of monitoring specifications (weekly, continuous, etc.), maximum permissible variance (e.g., 10%) and reference (regulation, authorization, guideline)	
Theoretical pump capacity	
Date of the last determination of pump capacity and calculated capacity	
Description of the *in situ* measurement facility	
Description of the characteristics of the facility Pumping station, basin, etc. Isolated or non-isolated Wet or dry Number of pumps Serial numbers of the pump(s) Operation (alternating, simultaneous, sequential) Pump speed (constant or other) Pump location (inside or outside the pumping station) Backflow valve installed and condition Water level measuring sensor and accuracy Pipe diameter	
Description of the data transmission system (recorder, computer, system, etc.)	
Method of determining pump capacity–Overview	
Type of pumping station	☐ Isolated ☐ Non-isolated
Impermeable pump pipe backflow valves (to avoid water reflowing into pumping station)	

Criteria	Details
Calculation of the backflow (if station not isolated) (Q_r)	Backflow level (h_r): Backflow duration (t_r): Backflow volume (V_r):
Invariability of Q_r during the trials (if station not isolated)	
Trials made under a permanent regime	
Trials made under constant velocity	
Calculation method of time and resolution	
Trials made in normal operational conditions (e.g., habitual operational capacity for variable speed pumps)	
Trials conducted during emptying of the station, not filling	
Number of trials (≥ 3) per operational mode (individual, combined, variable speed)	
Raw data shown	
Volumetric method for determining pump capacity	
Surface of the pumping station (A), including dimensions and diagram	
Description and accounting of subtracted values	
Height of water (h) pumped between the beginning (h_d) and the end (h_f) of each trial	
Pumping volume (V) for each trial	
Pumping time (t_p) for each trial	
Reference instrument method for determining pump capacity	
Type, make and model	
Measurement errors (precision) (≤ 2.5%)	
Interval of measurement and correspondence with *in situ* conditions (temperature, pressure, speed, conductivity, etc.)	
Date of calibration (annual) and calibration certificate issued by an accredited body that includes the measuring error rate	

Criteria	Details
Correspondence between the utilization criteria of the device and the *in situ* conditions, for example: Interior diameter and type of conduit Speed measurement interval Pressure Upstream and downstream lengths without disturbance and type of disturbance (elbow, valve, pump, etc.) Water properties (turbidity, conductivity, temperature, etc.) Discharge conditions Conduit material, condition, thickness	
Temporary installation of the reference instrument: Distance from the *in situ* instrument Installation in a bypass conduit Horizontal/vertical position	
Functional check of the *in situ* device before the trial (checking the zero, etc.)	
Stabilization of the reference instrument before the trial	
Pumping volume (V) for each trial	
Pumping time (t_p) for each trial	
Calculations	
Calculation of the true capacity of the pump (Q_p) for each trial	
Variance between the minimum and maximum values during all three trials < 10%, otherwise, trial repeated	
Average of selected trials used to determine pump capacity	
Conclusion	
Conclusion of verification	
Any applicable uncertainty about the method and correction factors	
Representativeness of trial results compared to normal discharge conditions (low/peak flow)	
Corrective measures required to be applied to the pumping system, including schedule	

APPENDIX 5: SAMPLE field Checklists for ACCURACY CHECKING A flow MEASURING SYSTEM

5.1 Overview.

5.2 Velocity-area.

5.3 Tracer dilution.

5.4 Volumetric.

5.5 Pump capacity.

5.6 Reference instrument.

5.1 Overview field checklist

Criteria		Details
Overview		
Date of verification		
Name and position title of the agent		
Location of the site (name of business or municipality, etc.)		
Effluent designation (e.g., EFF-1- Final effluent n° 1)		
Type of effluent (Drinking water, municipal wastewater, industrial wastewater, etc.)		
Flow (volume) intervals of *in situ* measurement: usual daily minimum, maximum and average		
Description of monitoring specifications (weekly, continuous, etc.), maximum permissible variance (10%, etc.) and reference (regulatory, authorization, guideline)		
Date of last accuracy check and observed variance (%)		
Description of the *in situ* measuring system		
Closed conduit[34]	Description of the conduit and installation (include photos, diagrams, plans, dimensions, etc.), for example: Interior diameter Material Condition of the conduit (interior clogging, exterior rust) Horizontal or vertical position Direction of the discharge (ascending/descending) Upstream and downstream disturbance elements: elbow, valve, pump, etc. Upstream and downstream lengths without disturbance	
	Description of the *in situ* device, for example: Type, make, model Interval of measurement (e.g., 0-1,000 m^3/min, 0-50 °C) Displayed units (m^3/min, m^3) Frequency of measurements (e.g., 1/min) Method of recording (recorder, computer system, memory card) Manufacturer’s technical sheet Errors of measurement of the device (precision)	

[34] Appendix 3.7 provides a sample closed conduit inspection grid.

Criteria		Details
Open channel[35]	Description of the primary structure (including photos, diagrams, plans, dimensions, etc.), for example: Type (weir, Parshall flume, etc.) Dimensions Natural, artificial, river channel Rectangular or circular weir Regular or irregular shape Material Location of the measuring point Cleanliness, condition, etc. Level transversally, longitudinally, vertically Discharge upstream (turbulence, preferential current, etc.) Discharge downstream (free flow or submerged, submergence ratio) Upstream and downstream disturbance elements	
	Description of the secondary device, for example: Type (bubble pipe, ultrasound sensor) Make and model Interval of measurement (e.g., 0-1,000 m^3/min) Stage-discharge relation Units displayed (m^3/min, m^3) Frequency of measurements (e.g., 1 /min) Method of recording (recorder, computer system, memory card) Manufacturer's technical sheet Errors of measurement of the device (precision)	
Description of the data transmission system		

[35] Appendices 3.1 to 3.5 provide sample open channel primary structure inspection checklists. Appendix 3.6 provides a secondary device inspection checklist.

5.2 Velocity-area

Criteria	Details
Characteristics of the measuring section	
Width of the measuring section	
Description of the velocity measurement location including diagram and photos, for example: Materials, slope, condition and cleanliness No accumulated sedimentation Regular channel bed No turbulence and good distribution of the discharge Upstream and downstream disturbance elements: elbow, valve, pump, material that could affect acoustic readouts, etc. Upstream and downstream lengths free of obstruction: minimum 10 and 5 times the width of the channel Location with respect to the *in situ* measuring system	
Characteristics of the device used	
Type (rotating current meter, Doppler acoustic velocimeter, velocity-area Doppler flowmeter, etc.)	
Make and model (include the manufacturer's technical sheet)	
Errors of measurement (precision)	
Mounting, for example: On a rod Laterally on the side of the flume At the bed of the flume	
Interval of measurement of the device and correspondence with *in situ* conditions (temperature, pressure, velocity, conductivity, height, ice, foam, suspended matter, floating debris, etc.)	
Diameter of the propeller or sensor and compliance with water level during trial	
Meets special operating conditions (e.g., dead zone)	
Meets maintenance specifications (e.g., conservation of a maintenance and checking sheet)	

Criteria	Details
Date of calibration or verification, including the calibration or compliance certificate from an accredited body, the propeller equation or calibration table, errors of measurement and the correction factor: Rotating current meter: calibration required at lesser of annually or after 300 hours of operation Electromagnetic current meter: annual calibration Doppler acoustic velocimeter: annual calibration or verification Area-velocity Doppler flowmeter and non-contact radar: annual verification, validating the device's calculations	
Verification process	
Verification of the *in situ* secondary device prior to a trial (variance ≤ 5%) (required whenever the secondary device is used to determine the *in situ* flow that will be compared to the trial flow)	
Verification of the *in situ* data transmission system prior to a trial	
Device synchronization before the trial (time, frequency of measurements, transmission delays)	
Precautions needed prior to a trial, for example: Propeller rotation trial, check counter rotation recording Device submerged in the discharge for 10 minutes before a trial Clean sensors Update acquisition software and firmware, etc.	
Orientation of the propeller or sensor, for example: Propeller self-adjustment Parallel, perpendicular, against the discharge Position of the sensor (e.g., in the centre of the channel) Angle of the beam (20°, 45°, etc.)	
Number of trials (1 trial if all conditions are met the first time, otherwise 3 trials)	
Measurement of water level	
Method and frequency of measurements during the trial, for example: Make and model of the device Above-surface or submerged measurement Pressure, ultrasound, radar sensor Sensor incorporated into or external to the instrument Sensor submerged or non-contact	

Criteria	Details
Water level sufficient to use the selected device, for example: Rotating current meter = h ≥ 4x the diameter of the propeller Electromagnetic current meter = h ≥ 3x the vertical dimension of the sensor Acoustic Doppler Velocimeter (ADV) = h ≥ 3x the vertical dimension of the sensor Area-velocity Doppler flowmeter = per manufacturer's recommendations	
Variance between lowest and highest water level for the duration of the trial ≤ 5%. If the flow cannot be stabilized and this method is nonetheless used, 3 full trials are required.	
Raw data of measured water level	
Measurement of velocity	
Method of measurement during a trial, for example: Mechanical, acoustic, electromagnetic Stationary deployment or over floatation equipment Point-by-point exploration using verticals Measurement of the average velocity in a beam Modeling based on sampling area, etc.	
Position of the device during the trial (level to the surface, parallel to the direction of the discharge, centered over the measuring section)	
Sampling area size	
Number of acoustic sensors	
Angle of the beam	
Number of verticals based on the width of the measuring section and position of each vertical in the channel	
Methods for determining average velocity for each vertical, for example: Velocity distribution Reduced number of points (single-point: .6H; two-point: .2 and .8H, etc.) Velocity integration	

Criteria	Details
Number of measurements of velocity and their duration in the trial. For example: Current meter: 3 or ideally 5 consecutive measurements of velocity, each lasting ≥ 30 seconds Area-velocity Doppler flowmeter and radar: continuous measurement, minimum at 30-second intervals for 30 minutes	
Variance between the lowest and highest velocity measured for each vertical in each trial (ideally ≤ 5%)	
Propeller equation	
Raw measured velocity data	
Calculations	
Calculation of the area of the wetted section	
Trial flow and volume (including calculation details and all raw data)	
In situ flow and volume (including calculation details and all raw data)	
Variance obtained (%) for each trial and the equation used	
Conclusion	
Conclusions	
Uncertainty of the method and any applicable corrective factors	
Representativeness of results with respect to normal discharge conditions (trial conducted at low or peak flow, etc.)	
Specifications met during each of the three trials (maximum permissible variance 10%, etc.)	
Any required flow measuring system corrective measures, including schedule	

Sample compilation of trial raw data for measuring a vertical with a reduced number of points

Date:		Site:			Effluent designation:			Width of the measuring section (m):			
Trial n°:		Trial start time: Height (m):			Trial end time: Height (m):			Duration in seconds of velocity measurements:			
Vertical number:		1	2	3	4	5	6	7	8	9	10
Distance to the edge of the channel (m):											
Measurement of height (m)	H n°1										
	H n°2										
	H n°3										
	H n°4										
	H n°5										
	$H_{avg.}$ (m)										
	H_{min} (m):			H_{max} (m):				Variance (≤ 5%):			
Measurement of velocity (m/s) .2H	*v* n°1										
	v n°2										
	v n°3										
	v n°4										
	v n°5										
	$v_{avg.}$ (m/s)										
	Variance *v* min./max. (%)										
Measurement of velocity (m/s) .6H	*v* n°1										
	v n°2										
	v n°3										
	v n°4										
	v n°5										
	$v_{avg.}$ (m/s)										
	Variance *v* min./max. (%)										
Measurement of velocity (m/s) .8H	*v* n°1										
	v n°2										
	v n°3										
	v n°4										
	v n°5										
	v_{moy} (m/s)										
	Variance *v* min./max. (%)										

Sample trial raw data compilation –
Measurement of the entire wetted section

Date:	Site:	Effluent designation:
Trial n°:	Trial start time:	Trial end time:
Measurement (1/minute)	Velocity	Height
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
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25		
26		
27		
28		
29		
30		
Min.		
Max.		
Variance (%)		

5.3 Tracer dilution field checklist

Criteria	Details
Characteristics of the measuring reach	
Nothing to block the tracer Measuring probe, grassy plants, suspended matter, etc.	
No tank, dead zones, added water or leakage	
Description of the measuring reach: Injection point in turbulent discharge, sampling point	
Number of sampling points based on the width of the channel	
Method used to determine the length required for proper mixing (equation, colorant, etc.)	
Length of the reach Must enable vertical and lateral dispersion of the tracer (around 20x the width of an artificial channel and 25x for a natural channel, possibly less depending on the characteristics of the discharge).	
Transverse sampling points ☐ 1 point ☐ 3 points, at 1/6, 3/6 and 5/6 of the cross-section of the conduit If width >2.4 m and walls are homogenous (concrete conduits) or If width > 1.8 m and walls non-homogenous (ditches)	
Stability of the discharge (variation < 5% between minimum and maximum flow) Required for the integration method. Requires constant flow if the time of injection is extended and the interval of time between withdrawing samples is reduced to one minute.	
Conservation of samples by type of tracer	
General characteristics of the method	
Dilution method: ☐ Integration (instantaneous injection) ☐ Constant flow injection (continuous injection)	
Type of tracer: ☐ Chemical (LiCl, NaCl, etc.) ☐ Colorant (fluorescein, rhodamine WT, etc.) ☐ Radioactive	

Criteria	Details
Tracer detection limit	
Continuous temperature measurement (if measuring conductivity)	
Description and compliance of the tracer preparation method	
Determination of the quantity of tracer and equation used (Section 8.5.3.2): Integration method: $$V = [\frac{C_2}{C_1} Q^{\vert} (t_f - t_i)] \, 1000$$ Constant flow method: $$V = (t_f - t_i + t_p) \frac{Q^{\vert} C_2}{C_1}$$	
Concentration of the stock solution	
Description of the method used to analyze the samples Laboratory, on-site, etc.	
Background tracer concentration in the effluent (C_{bf}) Withdraw three samples of the discharge water at a location that is representative of the quality of the discharge and without any tracer contamination risk: prior to the manipulation of the tracer, during the trial and at the end of the injection.	
Method of dilution by integration (instantaneous injection)	
Tracer injection mode Injection of total tracer quantity instantaneously using a wide-mouth receptacle; no loss of tracer during injection; at the centre of the discharge.	
Determination of the C_1 tracer concentration Average of three 50-ml samples of the injection solution Analysis certificates attached to the report	
Sampling period for measuring C_2 Continuously until all tracer has passed the measuring point. Should continue even after the estimated time of tracer passage has been reached. Should extend to at least 3 to 4 times the required time so that the maximum concentration of the tracer occurs within the sampling section.	
Sampling withdrawal frequency (< 1 minute) The exact withdrawal time of each sample must be recorded.	

Criteria	Details
Concentration of the C_2 diluted tracer Usually 2 to 5 times the natural concentration in the discharge (must meet surface water criteria). When the background noise level is high and the accuracy of results not skewed, ½ the background noise level is acceptable.	
Number of samples At least 30 samples are required to draw the curve and check that the tracer has completely passed.	
Concentration recovery curve per time (Figure 103) Recovery of the total mass of the tracer injected at the sampling point.	
Recovery percentage > 95% and compliance of the calculation method For a trial using the instantaneous injection method to be deemed valid, 95% of the mass of the injected tracer must be recovered. The following equation is used: $$\%\ \boldsymbol{P_{rec.}} = \frac{\boldsymbol{M_{rec.}}}{\boldsymbol{M_{inj.}}}\ \boldsymbol{X\ 100}$$ For wide channels where three curves are required, the recovery rate must be individually checked for each curve.	
Interpretation of results Single-point samples: A time-sensitive concentration curve is drawn, but only one plateau is used for calculating the flow. Three-point samples (for wide channels, etc.): A time-sensitive concentration curve is drawn for each sampling point and the area under each curve is measured. The tracer mix is deemed uniform if the areas under the curves are similar. An average curve is then drawn from the three curves. Rejecting a given value requires justification, such as statistical or systematic errors.	
Calculation of the trial flow, including the equation and the raw data $$\boldsymbol{Q = \frac{V\ C_1}{\Delta t \sum(C_2 - C_{bf})}}$$ or $$\boldsymbol{Q = \frac{V\ C_1}{t_p\ (\bar{C}_2 - C_{bf})}}$$	
Error sources and statistical estimates	

Criteria	Details
Method of dilution by injection at a constant flow (continuous injection)	
Tracer injection mode Injection using a device that can adjust and control the injection. Avoid the injection tube touching the surface of the water and injection in falls.	
Tracer injection flow (*q*) Average of three volumetric measurements before and after the trial. Cross-check injection consistency: Tracer solution must be placed in a graduated receptacle, and the solution level noted at .2, .4 .6 and .8 of the total duration time of injection.	
Determination of the C_1 concentration Determination of the C_1 tracer concentration (average of samples of the injection solution withdrawn at both the start and the end of the trial. The difference between each of the six measurements must be less than 5%. The certificates of analysis must be attached to the report.	
Sampling period for the measurement of C_2 Sufficient time is needed to enable checking proper mixing and that tracer concentration has reached a plateau (constant value). Must commence before the tracer reaches the sampling section and continue after the plateau has been reached.	
Frequency of sampling Withdrawals to start no more than five minutes after injection. Once the plateau has been reached, every minute. The exact withdrawal time must be noted for each sample.	
Concentration of the diluted C_2 tracer Must reach a stable plateau rather than a high plateau/background signal ratio with respect to the receiving environment.	
Number of samples Must be sufficient to trace a minimum of three points in the ascending part of the response curve and nine in the plateau.	

Criteria	Details
Interpretation of results Single-point sampling: A single plateau reached indicates equilibrium. Three-point sampling (large channels): Concentration/time line must be drawn for each sampling point. When the plateau is the same for the three lines, the mix is uniform and the injection duration is sufficient. Only those concentrations above the plateau need be used to calculate the flow. The equilibrium (plateau) between the three points is rarely reached at the same moment, since the transverse velocities of discharge differ from one point to another. Rejecting a given value requires justification, such as statistical or systematic errors.	
Calculation of the trial flow, including the equation and raw data $\boldsymbol{Q = q\left(\frac{C_1 - C_2}{C_2 - C_{bf}}\right)}$ ou $\boldsymbol{Q = q\,\frac{C_1}{C_2}}$	
Sources and statistical estimate of errors	
Conclusion	
Conclusions	
Uncertainty of the method and any applicable corrective factors	
Representativeness of results compared to normal discharge conditions (trial conducted at low or peak flow)	
Specifications met during each of the three trials (maximum permissible variance 10%, etc.)	
Corrective measures required for the flow measuring system, including schedule	

5.4 Volumetric

Criteria	Details
Verification process	
Check the *in situ* secondary device prior to the trial (variance ≤5%) (required whenever the secondary device is used to determine the *in situ* flow that will be compared with the trial flow)	
Check the *in situ* data transmission system prior to the trial	
Location of the volumetric measurement (e.g., mouth of pipe, sequential biological reator, etc.)	
Trial conducted during filling or emptying	
Procedure applied (graduated receptacle, plastic bag, scale, etc.)	
Appropriate type and characteristics of the receptacle used for the volumetric trials, such as: Dimensions precisely known, ideally a calibrated receptacle Warp-resistant Enables filling without air pockets forming Enables complete, rapid emptying	
Volume of the receptacle and consideration of what to substract (photos, diagram, plan, etc.)	
Calibration of equipment used (receptacle, scale, etc.), including the calibration certificate	
Method of *in situ* volumetric measurement (permanent total, instantaneous flow, etc.) and frequency (if applicable)	
Method of water level measurement (ruler, instrument, graduated receptacle, etc.)	
Determination of the mass effluent volume	
Duration of trials adapted to the flow Weak-flow (< 2 l/s) = 10 to 20 seconds Intermediate flow = ideally 5 minutes Heavy flow (r) = min. 5 minutes and Δ water level > 150 mm Gravimetric (weighing) = 5 minutes	
Number of trials (≥ 3)	
Raw data (depth, volume, etc.)	

Criteria	Details
Calculations	
Trial volume (including the calculation details and all raw data)	
In situ volume (including the calculation details and all raw data)	
Variance (%) for each of the trials and the formula used	
Conclusion	
Conclusions	
Uncertainty of the method and any applicable corrective factors	
Representativeness of results with respect to normal discharge conditions (trial conducted at low or peak flow, etc.)	
Specifications met during each of the three trials (maximum permissible variance 10%, etc.)	
Corrective measures required for the flow measuring system, including schedule	

5.5 Pumping station pump capacity

Criteria	Details
Description of the pumping station	
Pumping station setup Isolated or non-isolated Number of pumps and operational mode (alternating, simultaneous, sequential) Location of the pumps Submerged pipes feeding the pumping station Normal positions of high and low water level alarms, if any Overflow pipe and location in the pumping station Backflow valves (Y/N) and condition	
Pump serial numbers	
Theoretical technical specifications (original capacity) of the pump	
True pump capacity (Q_p) by operational mode (isolated, combined, etc.) and method used to determine it (section 5)	
Verification process	
Check the *in situ* secondary device prior to the trial (variance ≤5%) (required whenever it is used to determine the *in situ* flow that will be compared with the trial flow)	
Check the *in situ* data transmission system prior to the trial	
Pumps operate at a constant speed (Y/N)	
Pumps operate at maximum capacity (Y/N)	
Measurement of the flow exiting the pumping station	
Method used to measure time (e.g., a chronometer) and resolution (e.g., 1/100 of a second)	
Duration of trials (≥ 5 minutes and Δ h of water ≥ 150 mm)	
Number of trials (≥ 3) and interval of time between the trials (total time ≤ 48 hours)	
Raw data (height/level, volume, etc.)	

Criteria	Details
Calculations	
Trial volume (including the calculation details and all raw data)	
In situ volume (including the calculation details and all raw data)	
Variance (%) for each of the trials and the formula used	
Conclusion	
Conclusions	
Uncertainty of the method and any applicable corrective factors	
Representativeness of results with respect to normal discharge conditions (trial conducted at low or peak flow, etc.)	
Specifications met during each of the three trials (maximum permissible variance 10%, etc.)	
Corrective measures required for the flow measuring system, including schedule	

5.6 Reference instrument

Criteria	Details
Reference instrument	
Type, make and model	
Errors of measurement (precision) (≤ 2.5%)	
Interval of measurement and correspondence with *in situ* conditions (temperature, pressure, velocity, conductivity, etc.)	
Annual calibration date (include the certificate of calibration from an accredited body and all corrective factors)	
Correspondence between the device's operational criteria and *in situ* conditions, such as: Interior diameter and nature of the conduit Interval of velocity measurements Pressure Undisturbed upstream and downstream lengths, possible disturbance element (elbow, valve, pump, etc.) Water properties (turbidity, conductivity, temperature, etc.) Discharge conditions Materials, condition, thickness of the conduit	
Temporary installation of the reference instrument, for example: Distance from the *in situ* device Installation in a drift Horizontal or vertical position	
Verification process	
Location of the reference instrument sensor (including diagram and photos)	
Characteristics of the discharge during verification: Stable, permanent regime Minimum/maximum velocities measured during the trial Pressure, temperature, conductivity, turbidity, etc.	
Check functioning of the *in situ* device prior to the trial (check the zero)	
Device synchronization (*in situ* and reference) prior to the trial (time, frequency of measurements, transmission delays)	
Stabilization of the reference and *in situ* instruments prior to the trial	
Type of measurement (instantaneous, continuous, with a volumetric totalizer)	

Criteria	Details
Frequency of measurements (velocity, flow, total) (≥ 1 /min)	
Duration of trials (≥ 30 minutes, consecutive)	
Number of trials (≥ 3) (ideally 3 flow rates: minimum [not less than 10% of the maximum flow], average and maximum)	
Calculations	
Trial flow and volume (including calculation details and all raw data)	
In situ flow and volume (including calculation details and all raw data)	
Variance (%) for each trial and equation used	
Conclusion	
Conclusions	
Uncertainty of the method and any applicable corrective factors	
Representativeness of results compared to normal discharge conditions (trial conducted at low or peak flow, etc.)	
Specifications met during each of the three trials (maximum permissible variance 10%, etc.)	
Corrective measures required for the flow measuring system, including schedule	

Sample raw data compilation for a reference instrument

Date:	**Site:** **Effluent designation:**		
Device:	**Level of flow during the trial:**		
Trial	**1**	**2**	**3**
Start time:			
End time:			
Totalizer start			
Measurement (1/minute)	**Instantaneous flow**		
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			
26			
27			
28			
29			
30			
Totalizer end			
Min.			
Max.			
Variance (%)			

APPENDIX 6: SAMPLE FLOW MEASURING SYSTEM ACCURACY CHECK REPORT[36]

Criteria	Compliance	Non-compliance	Incomplete	N/A	Comments
Date of report	☐	☐	☐	☐	
Name, position title and signature	☐	☐	☐	☐	
Site location (name of business or municipality)	☐	☐	☐	☐	
Effluent designation (e.g., EFF-1 – Final effluent n°1)	☐	☐	☐	☐	
Type of effluent (drinking water, municipal/industrial wastewater)	☐	☐	☐	☐	
Specifications reference (regulation, authorization, guideline)	☐	☐	☐	☐	
Description of flow monitoring specifications (weekly, continuous, etc.) and maximum permissible variance (10%, etc.)	☐	☐	☐	☐	
Description of the *in situ* measuring system (primary structure and secondary device)	☐	☐	☐	☐	
Photographs and diagrams	☐	☐	☐	☐	
Equipment types, makes and models	☐	☐	☐	☐	
Description of the technical characteristics of the instrument (manufacturer's technical specifications)	☐	☐	☐	☐	
Dimensions of the flume or conduit	☐	☐	☐	☐	
General condition (clogging, warping, fissuring, etc.)	☐	☐	☐	☐	
Discharge conditions in the measuring device, upstream and downstream	☐	☐	☐	☐	
Average typical daily minimum, maximum and average measurement intervals	☐	☐	☐	☐	
Curves and tables used to determine flow	☐	☐	☐	☐	

[36] Based on Section 12

Criteria	Compliance	Non-compliance	Incomplete	N/A	Comments
Installation description and compliance with manufacturer's recommendations	☐	☐	☐	☐	
Description of the data transmission system	☐	☐	☐	☐	
Description of the method for checking the *in situ* measuring system	☐	☐	☐	☐	
Details of how the method was implemented (diagrams, photos, etc.)	☐	☐	☐	☐	
Description of the instruments used for checking accuracy (type, make, model, serial number, functional principle, measurement errors, dimensions, measurement interval and correspondence with *in situ* conditions)	☐	☐	☐	☐	
Device calibration date and calibration certificate from an accredited body	☐	☐	☐	☐	
Description of the characteristics and location of the measuring section selected for the check	☐	☐	☐	☐	
Description of the method used to check the data transmission system	☐	☐	☐	☐	
Results of the checks	☐	☐	☐	☐	
Raw data and all calculations used	☐	☐	☐	☐	
Values (flow or volumetric) obtained by the *in situ* measuring system and the reference method, as well as the calculated variance for each of the trials	☐	☐	☐	☐	
Certificates of analysis (tracer method)	☐	☐	☐	☐	
Interpretation of results	☐	☐	☐	☐	
Conclusion in regard to compliance of installation and capacity to produce reliable measurements; recommendations where required	☐	☐	☐	☐	
Summary recommendations of the last accuracy check and implementation of corrective measures, when applicable	☐	☐	☐	☐	

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