Centre d’expertise en analyse environnementale du Québec

Sampling Guide for Environmental Analysis

BOOKLET 7

FLOW MEASUREMENT METHODS IN OPEN CHANNELS

English Version of
The Original Publishing

EDITION : May 2007

Québec

For additional information
Centre d’expertise en analyse environnementale du Québec
to access our documents on our Web site
at the following address: **www.ceaeq.gouv.qc.ca**

or to contact us at:

Centre d’expertise en analyse environnementale du Québec
2700, rue Einstein, bureau E.2.220
Québec (Québec) G1P 3W8

Telephone: 418 643-1301
Fax: 418 528-1091
Email: **ceaeq@mddep.gouv.qc.ca**

Bibliographic Reference:

MINISTÈRE DU DÉVELOPPEMENT DURABLE, DE L’ENVIRONNEMENT ET DES PARCS DU QUÉBEC, May 2007, *Sampling Guide for Environmental Analysis: Booklet 7 – Flow Measurement Methods in Open Channels,* Centre d’expertise en analyse environnementale du Québec, 223 p., http://www.ceaeq.gouv.qc.ca/documents/publications/guides_ech.htm

Legal Deposit – *Bibliothèque et Archives nationales du Québec*, 2009

ISBN 978-2-550-55291-8 Guide d’échantillonnage à des fins d’analyse environnementale
ISBN 978-2-550-55292-5 Guide d’échantillonnage à des fins d’analyse environnementale (English Version)

ISBN 978-2-550-54958-1 (PDF) (previously published in English by *Thompson - Groupe Modulo*)

ISBN 978-2-550-55509-4 (PDF) (French Edition: August 2008)
ISBN 978-2-550-55309-0 (previously published in French by *Les éditions le Griffon d’argile*, ISBN 2-89443-075-2, 1st Edition 1998)

FOREWORD

This Sampling Guide for Environmental Analyses details a series of good practices to plan and conduct sampling activities. The purpose of the guide is to ensure the quality of samples collected and the validity of scientific information arising from these samples.

This essentially descriptive reference guide was developed to serve as an information tool for individuals who carry out activities that are part of an environment characterization program. The program was initiated by the *Centre d'expertise en analyse environnementale du Québec* and the *ministère du Développement durable, de l'Environnement et des Parcs*, after information came to light revealing that samplers did not have the tools necessary to gain an immediate knowledge of sampling practices in Québec.

From the outset, samplers have expressed a keen interest in having this type of reference document available. Information in the guide is not all unpublished material, but we thought it of interest and useful to include a summary of information contained in technical references or information based on practical sampling experience in Québec.

The *Sampling Guide for Environmental Analyses* consists of a series of booklets that deal specifically with sampling in different environments. Booklet 1, *Généralités* (in French only), must accompany each booklet in the series. It provides a general framework for implementing a sampling program and discusses technical procedures relating to quality, legality, health and safety issues. It also recommends procedures to optimize sampling programs.

Booklet 7, entitled "Flow Measurement Methods in Open Channels", describes techniques that are used to gauge the volume of effluent released during processes that involve use of large volumes of water.

We sincerely thank those individuals who have contributed to this document.

May 2007

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

INTRODUCTION

Many industrial processes use large amounts of water as part of manufacturing and processing operations. The petrochemical, metallurgical and pulp and paper industries are examples of such types of operations. Measuring the amount of water that is used during production is often a crucial component of managing processes. In terms of the environment, measurements of the volumes of effluent that are released into the aquatic system is information that is essential to enforcing regulations. This type of assessment is particularly useful when effluent standards are expressed on the basis of the amount of product produced or on a periodic basis.

The amount of effluent is usually gauged by means of open channels that enable water flow measurements, more specifically volume per time unit. This booklet discusses the principal techniques that are used for this type of measurement. This is an essentially descriptive document and the contents centre on four main topics:

- measuring elements commonly used in Québec;
- procedures to operate and maintain instruments;
- tables and equations to calculate flow;
- a few calibration and testing procedures for measuring instruments.

This document can by used by experts and beginners in the field. It details principles for measurement methods and calculation techniques, with an emphasis on problems that are commonly encountered.

Given the costs associated with permanent installations of this type of equipment, the guidelines contained in this booklet should be followed to determine the type of device that is best suited to the needs of a company. The information provided will also guide the reader in determining which maintenance techniques should be used to maintain reliable measurements and optimal use of a measuring device.

In some instances, however, implementing these methods may require adjustments. Although the document provides notes of caution regarding a number of problems that may arise, it is impossible to address each and every one. Therefore, the design, installation and use of structures remains the entire responsibility of the operator. Furthermore, reference to trademarks or product models is not an endorsement of a particular trademark or product.

1. GENERAL

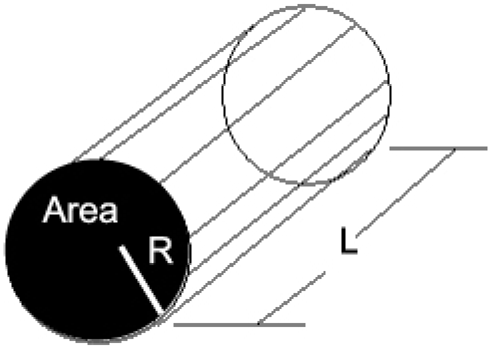
1.1. Definition of flowrate

In hydraulics, flowrate (Q) is defined as a volume (V) of liquid that flows through a given section of a flume or channel per time unit (t).

$$Q = \Delta V/\Delta t \qquad (1)$$

The above equation-solving process therefore consists of determining the volume (ΔV) on the basis of time.

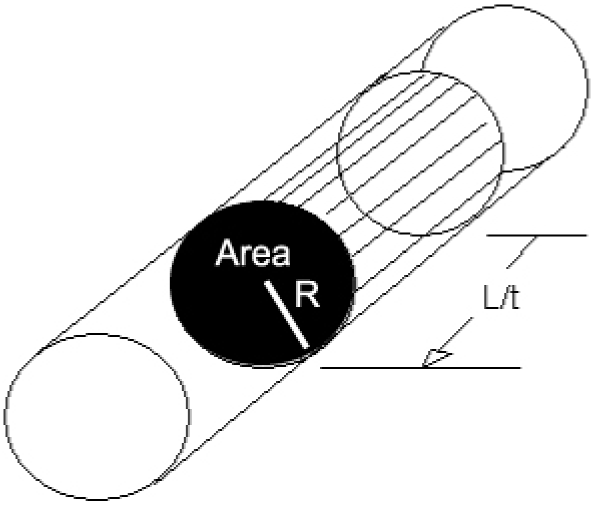
For example, in the case of a cylindrical pipe, determination of the volume of a section is obtained by multiplying the area (A) by the length (L).



$$A = \pi R^2 \qquad (2)$$
$$V = A \times L \qquad (3)$$

The volume of the cylinder is the product of the area (A) times length (L).

To express a flowrate, one of the variables has to be time dependent. Assuming that the area (A) is constant, the other variable (L) is expressed in terms of distance of movement as a function of time. The expression of the length of movement (ΔL) as a function of time (Δt) gives the speed (U).



$$U = \Delta L/\Delta t \qquad (4)$$

where:

U is the velocity of flow through the area (A).

By replacing the variable (L) in equation (3), with the value determined in equation (4), the equation becomes:

$$V = AU\Delta t \qquad (5)$$

Also, by replacing (V), in equation (1), with the value determined in equation (5), the discharge equation can be expressed as follows:

$$Q = AU \qquad (6)$$

Flowrate is usually expressed in terms of a volume unit as a function of a time unit. The unit of measurement is m^3/s or pi^3/s.

To express mass, the discharge (Q_m), equation (6) must be changed to include the density factor of the liquid being measured. The equation therefore becomes:

$$Q_m = \rho AU \qquad (7)$$

where

ρ is the density of the liquid kg/m^3;
A is the area in m^2;
U is the velocity of the liquid through the area in m/s.

Note: If effluents have different densities, this expression may result in a seriously inaccurate measurement. Expressing the flow value in volumetric units per time unit is therefore recommended.

1.2. Purpose of flow measurement

Precise and uniform methods of flow measurement are necessary to:

- determine the pollution load of urban, industrial and agricultural sources;
- determine the size of equipment for the transport and treatment of effluent and feed water;
- understand variations of flow and load in terms of time;
- measure, locate, analyze and solve problems relating to water collection and distribution networks;
- assess the performance of treatment equipment;
- determine the quality of water bodies and calculate available water resources.

These measurements are also necessary to enforce environmental laws and regulations.

1.3. Types of flow measurements

1.3.1. Point-specific flow measurement

Point-specific measurements are performed at a specific moment in time and generally cover a very brief period (a few minutes). They are therefore only representative of the moment at which they were taken.

Point-specific measurements are used primarily to:

- verify the calibration of certain hydraulic structures (ex. pumps, flumes);
- determine the flowrate of a stable discharge (ex. prolonged effluent aeration pond);
- immediately determine a flowrate;
- determine the measurements of hydraulic transport and treatment equipment.

The methods generally used to perform this type of measurement are as follows:

- volumetric method (see section 4.2);
- dilution method (see section 4.1.3);
- area/velocity method (see section 4.4);
- a point-specific reading of water depth using a portable combined insertion weir (see section 3.7).

When you are forwarding results, it is important to provide information about the location, date, time and method of measurement, to avoid confusion when results are interpreted.

1.3.2. Continuous flow measurement

Continuous flow measurements consist of a series of point-specific measurements at very close time intervals (a few seconds apart), using instruments capable of recording values during the procedure. The advantage of this type of measurement is the fact that it can extend over an extended time period (a few hours to a few days) and reveals variations in flowrate that occurs during this period. Information that is obtained is therefore more complete.

This type of measurement usually requires a temporary or permanent primary measuring device.

1.4. Discharge system

1.4.1. Closed conduits

A discharge is said to be in a closed conduit when the liquid is confined in a pipe and subjected to pressure that is greater than atmospheric pressure.

1.4.2. Open conduits

A discharge is said to be in an open conduit when the surface of the water, so-called waterline, is in contact with the air and subjected to atmospheric pressure only.

Conduits can be natural, such as streams and rivers, or artificial, such as channels for navigation, irrigation, drainage ditches, sewer networks, etc.

1.5. Flow principles in open conduits

Storm sewer and building drainage systems are open conduits. The flow area is in contact with the air and is subjected to atmospheric pressure only. Because pressure cannot be forced from one end of the flow channel to the other end, the flowrate depends on the gradient of the slope of the channel and the frictional drag along the walls. Because the flow is stable and uniform (streamlined), there is always a progressive drop in water level from the beginning to the end of the channel.

In an open channel, the total energy contained in the flow is the kinetic energy present in the form of velocity (Head Velocity) and the pressure energy due to the difference in water depth. Which produces the following equation:

$$\mathit{Total\ energy} = \frac{V^2}{2g} + d \qquad (8)$$

where

V	is the flowrate;
g	is the gravitational constant;
d	is the water depth measured from the channel bottom.

This equation shows that water depth varies when there is a variation in velocity, unlike closed conduits where changes in velocity produce changes in pressure. If flow increases and energy is converted to velocity, water depth must fall. Inversely, when velocity declines, water depth must increase. A drop in water flow area is known as “drawdown”. On the contrary, in closed conduits, changes in pressure translate into changes in flowrate, but the water level remains constant.

This flow can manifest itself in the form of three possible categories:

> **uniform flow**: the slope of the water line is parallel to the slope of the channel bottom;
>
> **gradually varying flow**: liquid experiences an acceleration or deceleration due to a moderate change in the flow section or the slope of the channel bottom;
>
> **critical flow**: this type of flow is produced by a strong contraction created by a lift in the bottom and/or a narrowing of the width of the channel or by a sudden change in the slope of the channel bottom.

A Parshall flume is an excellent example of an instrument that measures changes in liquid depth when velocity increases. When water enters the flume, it accelerates in the converging section (approach) and reaches a maximum velocity when it moves through the throat section where the bottom slopes down; causing the water level to drop significantly.

This variation in liquid depth is directly related to the amount of water flow (flowrate). Flow curves and flow tables for standard Parshall flumes are prepared on the basis of these variations.

1.6. Principles of flow measurement in open channels

A number of approaches can be used to measure the flow of liquid in an open channel:

- consider only kinetics, that is, the mechanics of movement of a liquid without the need to examine underlying forces. This is the principle of the depth/velocity method;
- basic information on known relations between gravity causing the flow and the inertial and viscosity forces that slow it down;
- quantitatively analyze changes in the physical or chemical properties of the liquid after soluble substances have been added. This is the principle of the dilution method.

Flow can be measured using a variety of methods:

- use of the flow regime variations principle, by creating a critical flow with the help of a measuring instrument known as a “weir” or “control flume”;
- measurement of the dilution rate of a tracer, the concentration of which is known at the intake point;
- the “volumetric tank” method, which consists of determining the time required to fill a container of a known volume;

- the Q = AU relation uses a wet section (A) and the average velocity (U).

Each of these methods will be discussed in detail in the sections that follow.

1.7. Primary measurement device methods

Measurements of continuous flows, in the case of an open channel flow, are performed using a hydraulic structure that establishes a unique depth-flow relationship. These hydraulic structures are called "primary measuring devices" and can be separated into two categories: control flumes and weirs.

This method, which is most common, determines flow by means of calculation, based solely on a measurement of the water depth upstream from the primary measuring device.

Choosing a primary flow measurement device must be examined and designed on the basis of the following:

- a precise knowledge of the maximum and minimum flowrates that may be channeled to the primary device. The flows must, depending on the primary device considered, be included in the limits recommended in this guide;
- fluctuations in water depth, according to minimum and maximum flows, must be the extreme limits, in order to increase measurement precision, particularly if there are small variations in flow;
- the presence of solid material and possible obstruction;
- compliance with standards governing installation, conditions for approach to the primary device and loss of pressure due to inserting the device;
- the ease of calibration and testing equipment.

Flumes are generally preferred over weirs, due to their numerous advantages, namely greater drops in pressure and their ability to self-clean.

1.7.1. Flumes

Flumes are usually prefabricated devices that are installed temporarily or permanently in a flow system.

They can be a "flat-bottom" type. In the case of a flat-bottom flume, the shape of the side walls creates a contraction of the flow of liquid (ex. cutthroat flume). They can also combine vertical and side contractions (ex. Parshall flume).

1.7.1.1 General description

A flume is essentially a specially-molded open section that creates a restriction in the flow area. Flumes work according to the Venturi principle. By reducing the flow area, velocity increases and water depth changes(1).

A flume usually has three sections: a converging section, throat section and diverging section.

Sizes vary according to the type and shape of flume. For practical purposes, to determine the absolute flow of a flume, the calibration curves supplied by the manufacturer should be used.

1.7.1.2 Advantages

- Minimal drop in pressure.
- Enables measurement in a large range of flow.
- The flowrate in flumes is usually high enough to prevent sedimentation; they are therefore self-cleaning.
- Provides a reliable measurement in free flow and submerged flow conditions.

1.7.1.3 Disadvantages

- Installation is usually expensive.
- Installation requires extremely careful work.
- Requires a secure watertight base.
- Flow at the entrance must be evenly distributed, with little turbulence, to produce accurate measurements.

1.7.2. Weirs

A weir is one of the simplest and oldest structures used to measure flow. The weir's large parts are easy to inspect, and any abnormalities can be detected or corrected immediately(2).

1.7.2.1 General description

A weir can be defined as a structure that is erected across an open channel to measure the discharge of liquid.

A thin-plated weir is a 3 to 6 mm (1/8 to 1/4 in) thick plate with a straight edge (crest), or a thick plate with a 45° angle edge that is used to reduce the thickness of the crest to the aforementioned sizes. This plate is placed across the flow and liquid is forced over the plate or into a V-notch in the weir.

The edge over which water flows is called the **crest.**

The height of the weir between the crest and the channel bottom is called the **crest height**.

The height of the discharge over the crest is called the **nappe**.

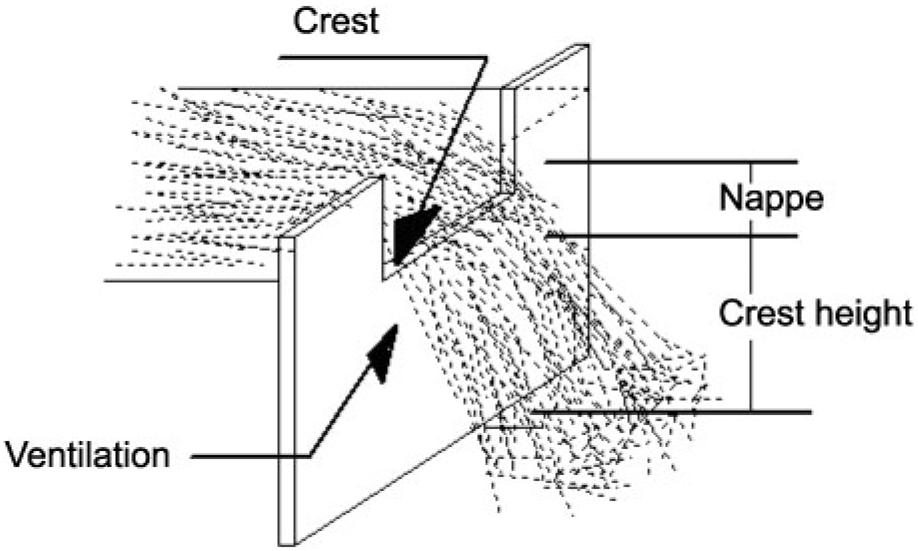
The air space under the nappe, downstream from the weir, is called the **ventilation**.

Figure 1 shows the components of a weir.

When a discharge is far enough away from the crest height to ensure that there is ventilation below the nappe, the flow is said to be free or critical. If air cannot move freely under the nappe, the flow is said to be submerged. This type of situation can create inaccurate readings because there is not enough pressure upstream from the weir. Water depth measurements are therefore too deep and the velocity too slow.

The name of a weir is usually attributed to the shape of the notch in the weir. V-notch is therefore a triangular weir, a notch in the shape of a |_| is a rectangular weir, etc.

FIGURE 1 - WEIR COMPONENTS



Flow is determined by simply measuring the vertical height, between the bottom of the notch (crest) and the surface of the water, at a determined distance upstream from the weir, and using the calculation formula or table that corresponds to the shape and size of the weir.

For each type of weir, empirical formulas and flow tables have been established for quick reference.

Weirs are reliable measuring instruments because, for a particular size and shape weir, in free flow or stable flow conditions, there is only one water depth upstream for a particular weir.

1.7.2.2 Advantages

- Is approximately 98 % precise in a laboratory. To produce this type of precision, it is important to carefully respect all of the recommended dimensions when a weir is manufactured and installed.
- Inexpensive to manufacture.
- Can be used to measure a wide range of flowrates.

1.7.2.3 Disadvantages

- Serious loss of depth and backwater effect upstream.
- Causes solids to deposit upstream.
- Requires regular maintenance and frequent inspection.

1.8. Flow metering system

A flow metering system usually consists of two components: a primary device, as defined earlier, and a secondary device (or flowmeter).

1.8.1. The secondary device

To obtain a flow measurement using the primary device, a second device called a “secondary device” must be installed. A secondary device can be simple or more sophisticated.

The simplest device is a point-specific level reading indicator, such as a float. Depth is converted to flow using the depth/flow table that corresponds to the primary device in use. More sophisticated instruments can measure depth, perform a depth/flow conversion, continuously monitor values and even transmit them over distances.

1.9. Units of measurement

The most common units of measurement are:
$\mathrm{gal}_{\mathrm{US}}/\mathrm{d}$: US gallons per day
$\mathrm{gal}_{\mathrm{US}}/\mathrm{min}$: US gallons per minute
$\mathrm{gal}_{\mathrm{UK}}/\mathrm{d}$: imperial gallons per day
$\mathrm{gal}_{\mathrm{UK}}/\mathrm{min}$: imperial gallons per minute
m^3/d : cubic meters per day
ft^3/s : cubic feet per second
l/min : liters per minute

The following units are also used occasionally:
$\mathrm{Mgal}_{\mathrm{US}}/\mathrm{d}$: millions of US gallons per day
$\mathrm{gal}_{\mathrm{US}}/\mathrm{h}$: US gallons per hour
$\mathrm{gal}_{\mathrm{US}}/\mathrm{s}$: US gallons per second
$\mathrm{Mgal}_{\mathrm{UK}}/\mathrm{d}$: millions of imperial gallons per day
$\mathrm{gal}_{\mathrm{UK}}/\mathrm{h}$: imperial gallons per hour
$\mathrm{gal}_{\mathrm{UK}}/\mathrm{s}$: imperial gallons per second
m^3/h : cubic meters per hour
$\mathrm{m}^3/\mathrm{min}$: cubic meters per minute
l/h : liters per hour
l/s : liters per second

Units/day are used occasionally to express hourly flow.

Example: The flow for an 8 to 9 hour period is 42,000 m^3/d. To obtain the absolute hourly volume, divide this figure by 24. 42,000 m^3/d therefore becomes 1,750 m^3/h.

For the purpose of this document, except in very specific instances, metric units of measurement have been used.

1.10. Reference measurement

If a measuring device is installed in an open channel, a reference measurement technique must be used. A reference measurement is usually a ruler in meters or feet, that is permanently placed at the measuring point and is used to:

- calibrate the secondary device (flowmeter);
- take a point-specific flow reading;
- quickly and easily check and compare the flowmeter value to the reference value.

The reference value is always considered the true value.

1.11. Measuring point

1.11.1. Location

The location of a measuring point to gauge the discharge of liquid must be determined on the basis of the following considerations:

- there must be a minimum number of measuring points, considering the costs to build and maintain them;
- the measuring point must allow measurement of the continuous flowrate of the total liquid discharge;
- the primary device must allow minimum, medium and maximum flows to be measured;
- no branching off should be made downstream from the measuring chamber;
- the site must be accessible all year long.

1.11.2. Measuring chamber

The physical characteristics of a chamber must enable personnel to carry out the measurements, maintenance and testing necessary to ensure the quality of measurements. The chamber must meet specific requirements:

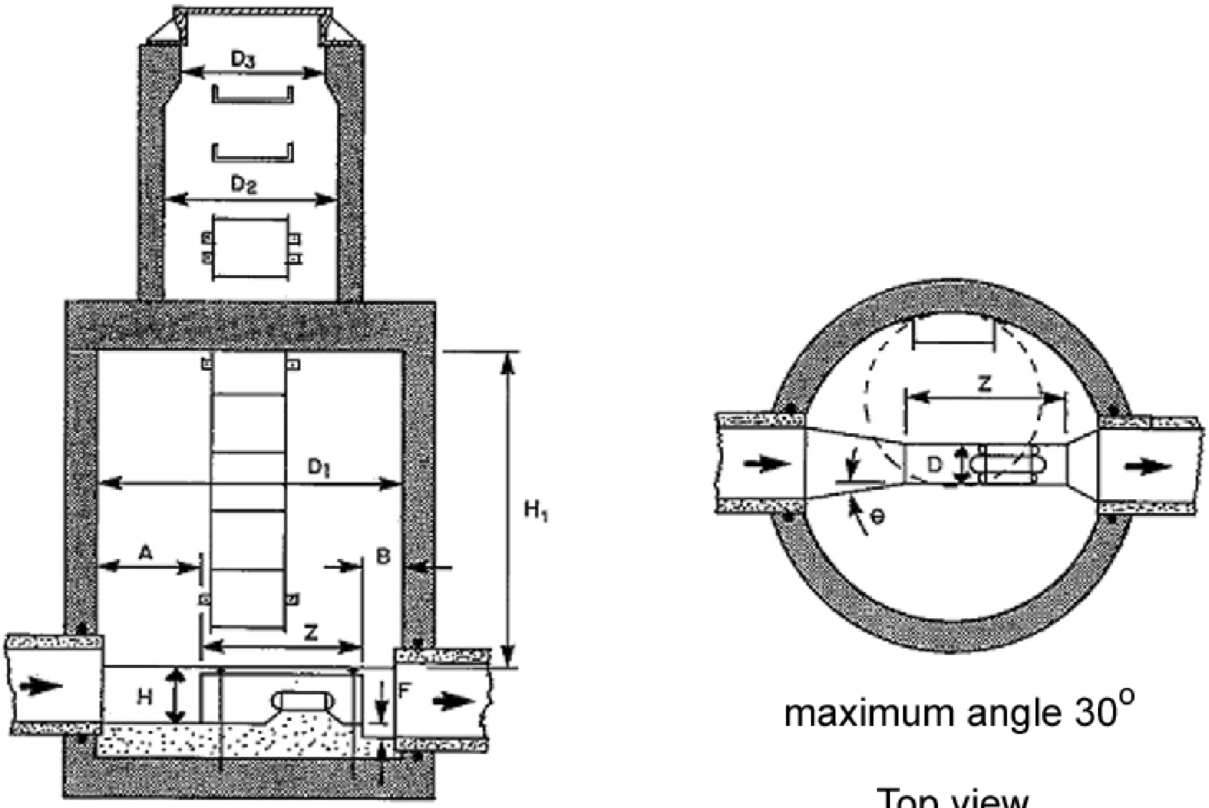
- depending on the flowrates present and the primary device installed, the chamber must be large enough to allow the primary device to be inspected and the secondary device to be inserted. There must also be enough room available to install a temporary or permanent automatic sampler;
- it must have a lighting and heating system that meet the requirements of this type of structure;
- it must have a remotely-controlled ventilation system;
- if the chamber is located deeper than 6 m, it must have a safety landing;
- the chamber's access hole must be at least 915 mm in diameter;
- the access cover must be at least 750 mm in diameter to allow access for personnel and equipment;
- a ladder must be permanently installed to provide access inside the manhole;
- safety standards governing construction and access to enclosed locations must be respected.

Figure 2 shows the main physical components and characteristics of a measuring chamber where the primary device is a Palmer-Bowlus flume. For purposes of this demonstration, pre-fabricated reinforced concrete observation wells are used. Where appropriate, a measurement chamber can be built in a square or rectangular shape.

Figure 3 shows the principal components and physical characteristics of a measuring chamber, in which the primary device is a Parshall flume.

The dimensions and physical characteristics of the measuring chambers in Tables 1 and 2 are shown for information purposes only. An assessment of flow conditions will help to determine which characteristics are required.

FIGURE 2 - PALMER-BOWLUS - FLUME CHAMBER



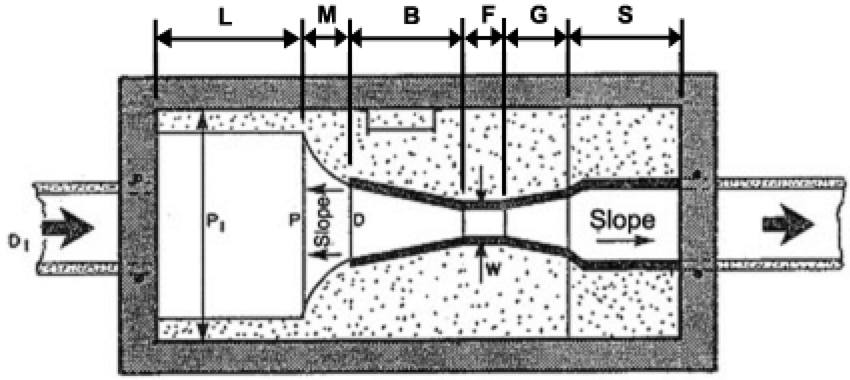
maximum angle 30°

Cross section

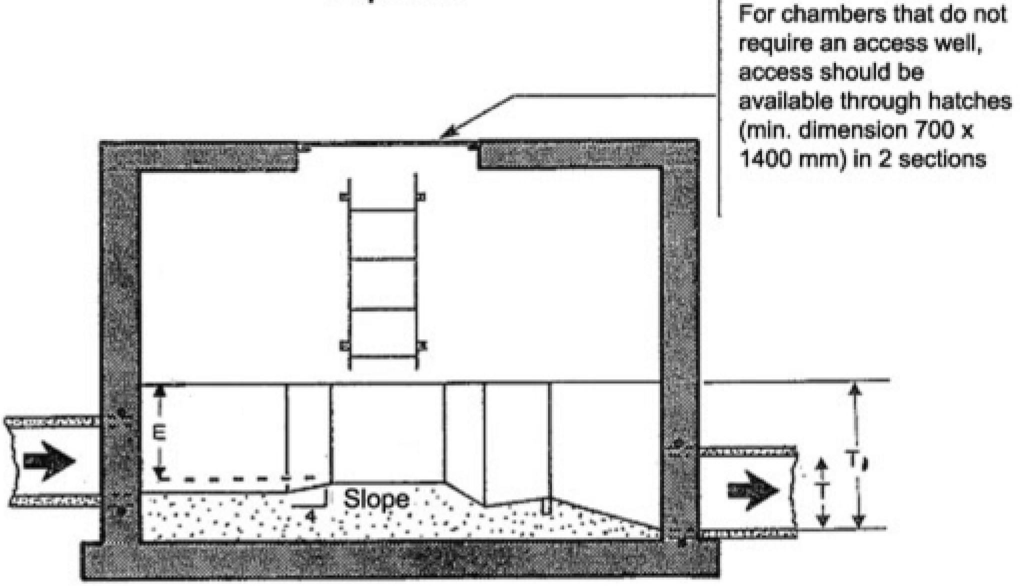
Top view

Note: The dimensions that correspond to the letters are shown in Table 1.

FIGURE 3 - PARSHALL FLUME - CHAMBER



Top view



For chambers that do not require an access well, access should be available through hatches (min. dimension 700 x 1400 mm) in 2 sections

Cross section

Notes: - See table 2 for the dimensions that correspond to letters

- D_1 = Diameter of inlet pipe

TABLE 1 - DIMENSIONS FOR PALMER-BOWLUS FLUME CHAMBER

Dimensions in millimeters and inches

Diameter (D) mm (in)	Recommended minimum dimensions								
	H	Z	B	A*	F	D1	D2	D3	H1
102 mm 4 (in)	152 6	432 17	102 4	686 27	51 2	1219 48	914 36	762 30	1219 48
152 mm 6 (in)	203 8	635 25	152 6	813 32	76 3	1600 63	914 36	762 30	1219 48
203 mm 8 (in)	254 10	839 33	203 8	813 32	76 3	1600 63	914 36	762 30	1219 48
254 mm 10 (in)	305 12	1042 41	254 10	839 33	76 3	2135 84	914 36	762 30	1524 60
305 mm 12 (in)	355 14	1244 49	305 12	889 35	76 3	2440 96	914 36	762 30	1828 72
381 mm 15 (in)	432 17	1549 61	381 15	965 38	76 3	2895 114	914 36	762 30	1828 72
457 mm 18 (in)	508 20	1854 73	457 18	1041 41	76 3	3352 132	914 36	762 30	1981 78
533 mm 21 (in)	584 23	2159 85	533 21	1117 44	76 3	3810 150	914 36	762 30	2100 84
610 mm 24 (in)	660 26	2463 97	610 24	1346 53	101 4	4419 174	914 36	762 30	2286 90
686 mm 27 (in)	736 29	2768 109	686 27	1422 56	101 4	4876 192	914 36	762 30	2591 102
762 mm 30 (in)	812 32	3099 122	762 30	1625 64	101 4	5486 216	914 36	762 30	2591 102
914 mm 36 (in)	965 38	3683 145	914 36	1955 77	101 4	6553 258	914 36	762 30	2895 114
1067 mm 42 (in)	1117 44	4292 169	1067 42	2260 89	152 6	7620 300	914 36	762 30	3048 120
1219 mm 48 (in)	1270 50	4902 193	1219 48	2565 101	152 6	8686 342	914 36	762 30	3200 126
1372 mm 54 (in)	1422 56	5511 217	1372 54	2870 113	152 6	9753 384	914 36	762 30	3352 132
1524 mm 60 (in)	1574 62	6121 241	1524 60	3175 125	152 6	10820 426	914 36	762 30	3505 138

* The minimum distance should always be twice the diameter of the inlet conduit.

TABLE 2 - DIMENSIONS FOR PARSHALL FLUME CHAMBER

Dimensions in millimeters and inches (or feet)

W	L	D	M	B	E	F	G	S	P	P1	T	T1
25 1 "	305 12 "	168 6 19/32 "	---	356 1'2"	229 9"	76 3"	203 8"	305 12"	168 6 19/32"	914 36"	248 9 3/4"	257 10 1/8"
51 2 "	457 18 "	214 8 13/32 "	---	406 1'4"	305 12"	114 4 1/2"	254 10"	457 18"	214 8 13/32"	914 36"	327 12 7/8"	348 13 11/16"
76 3 "	610 24 "	259 10 3/16 "	---	457 1'6"	610 24"	152 6"	305 1'	610 24"	259 10 3/16"	914 36"	635 25"	667 26 1/4"
152 6 "	914 36 "	397 1' 3 5/8"	305 1'	610 2'	610 24"	305 1'	610 2'	610 24"	902 2' 11 1/2"	914 36"	686 27"	724 28 1/2"
229 9 "	1372 54 "	575 1' 10 5/8"	305 1'	864 2'10"	762 30"	305 1'	457 1' 6"	762 30"	1080 3' 6 1/2"	1219 4'	838 33"	876 34 1/2"
305 12 "	1829 6’	845 2' 9 1/4"	381 1'3"	1343 4' 4 7/8"	914 3'	610 2'	914 3'	914 36"	1492 4' 10 3/4	1524 5'	991 3' 3"	1143 45 "
457 18 "	2438 8’	1026 3' 4 3/8"	381 1'3"	1419 4' 7 7/8"	914 3'	610 2'	914 3'	1067 42"	1676 5' 6"	1829 6'	991 3' 3"	1143 45 "
610 24 "	2438 8’	1207 3' 11 1/2"	381 1'3"	1495 4' 10 7/8"	914 3'	610 2'	914 3'	1067 42"	1854 6' 1"	2134 7'	991 3' 3"	1143 45"
914 3’	3048 10’	1572 5' 1 7/8"	381 1'3"	1645 5' 4 3/4"	914 3'	610 2'	914 3'	1219 4'	2223 7' 3 1/2"	2438 8'	991 3' 3"	1143 45 "
1219 4’	3658 12’	1632 6' 4 1/4"	457 1'6"	1794 5' 10 5/8"	914 3'	610 2'	914 3'	1524 5'	2712 8' 10 3/4"	2769 9'	991 3' 3"	1143 45 "
1524 5’	4572 15’	1997 7' 6 5/8"	457 1'6"	1943 6' 4 1/2"	914 3'	610 2'	914 3'	1524 5'	3080 10' 1 1/4"	3353 11'	991 3' 3"	1143 45 "
1829 6’	4572 15’	2667 8' 9"	457 1'6"	2092 6' 10 3/8"	914 3'	610 2'	914 3'	1829 6'	3442 11' 3 1/2"	3657 12'	991 3' 3"	1143 45 "
2134 7’	4877 16’	3032 9' 11 3/8"	457 1'6"	2242 7' 4 1/4"	914 3'	610 2'	914 3'	1829 6'	3810 12' 6"	3962 13'	991 3' 3"	1143 45 "
2438 8’	5486 18’	3397 11' 1 3/4"	457 1'6"	2391 7' 10 1/8"	914 3'	610 2'	914 3'	2134 7'	4172 13' 8 1/4"	4267 14'	991 3' 3"	1143 45 "
3048 10’	6401 21’	4756 15' 7 1/4"	---	4267 14'	1219 4'	914 3'	1829 6'	2134 7'	---	4877 16'	1372 4' 6"	1562 5' 1 1/2"
3658 12’	7315 24’	5607 18' 4 3/4"	---	4877 16'	1524 5'	914 3'	2438 8'	2438 8'	---	6096 20'	1676 5' 6"	1867 6' 1 1/2"
4572 15’	9144 30’	7625 25'	---	7625 25'	1829 6'	1219 4'	3048 10'	2438 8'	---	7625 25'	2057 6' 9"	2286 7' 6"
6096 20’	11582 38’	9144 30'	---	7625 25'	2134 7'	1829 6'	3658 12'	2769 9'	---	9144 30'	2438 8'	2819 9' 3"
7625 25’	13716 45’	10668 35'	---	7625 25'	2134 7'	1829 6'	3962 13'	2769 9'	---	10668 35'	2438 8'	2819 9' 3"
9144 30’	14630 48’	12312 40' 4 3/4"	---	7925 26'	2134 7'	1829 6'	4267 14'	3048 10'	---	12802 42'	2438 8'	2819 9' 3"
12192 40’	16459 54’	15481 50' 9 1/2"	---	8230 27'	2134 7'	1829 6'	4877 16'	3048 10'	---	15850 52'	2438 8'	2819 9' 3"
15240 50’	18898 62’	18529 60' 9 1/2"	---	8230 27'	2134 7'	1829 6'	6096 20'	3353 11'	---	18898 62'	2438 8'	2819 9' 3"

1.12. Choosing a measurement method

1.12.1. Selection criteria

It is important to select the right method to produce an accurate effluent flow measurement. The variety of methods available makes choosing the right one difficult. To guide you in determining which method is best, needs must be defined, the methods available must be gauged and possible compromises examined.

The following criteria must be considered(3):

- the presence of solids in water;
- the desired precision and possible precision of each method;
- the maximum flow to measure (Q_{max});
- range of measurements (Q_{max}/Q_{min});
- tolerance to fluctuations in discharge;
- width of the flume;
- the allowable and resulting maximum drop in pressure for each method;
- the repeatability and reliability required;
- the need to connect the measuring instrument to a data entry and processing system;
- the acceptable precision produced by the measuring instrument in use;
- sensitivity of the instrument to fluctuations in flow;
- installation and maintenance costs.

1.12.2. Presence of solids

Effluents contain all types of suspended solids of varying shapes and sizes. Solids tend to deposit upstream from the measuring device, stick to walls, become entangled in equipment and adhere to structures.

Upstream deposits can obstruct flow or change approach velocities, and deposits that adhere to the walls of a measuring device can distort geometry and its original dimensions. Readings using such equipment can be inaccurate. This is particularly true in the case of weirs.

Some primary measurement devices are affected little by the presence of suspended solids, particularly flumes, because they have smooth walls and a relatively flat bottom.

1.12.3. Maximum flow

Before selecting a particular measurement method, it is important to inspect the size of flow that may be measured. This information can be obtained in a several ways:

- a thorough knowledge of the facility (process, use of water, sewer network, etc.);
- a measurement of water consumption;
- the relationship between water consumption and manufacturing rates for a similar facility;
- the water supply capacity;

- a visual assessment of effluent flow by an experienced individual;
- an instant measurement of effluent flow (ex. depth/velocity);
- determination of the approximate diameter and slope of sewer pipes, indication of the network's maximum capacity.

If plant activities cause major fluctuations in flow and the only indication of flow available is an average flow value. This flow value should be increased by a factor of 2.5 to determine the maximum discharge, to reflect peak periods.

1.12.4. Tolerance of fluctuations in flow

If a measuring device has been installed correctly, it should continue to have the same precision during fluctuations in flow. It is therefore important to verify how systems react during fluctuations.

In the control section of a measuring device, a drop or increase in discharge should not cause turbulence and cause the flowrate to vary. It should instead show up essentially as a variation of water depth in the primary device.

1.12.5. Flume width

If a flow channel is too wide or too narrow, the possibility of restricting or enlarging the flow area should be examined, to allow measuring equipment to be installed and to ensure that equipment can operate correctly.

The flow channel should be at least as wide as the measuring device and no wider than the width of the measuring element plus 10 m. Figure 4 illustrates this type of setup.

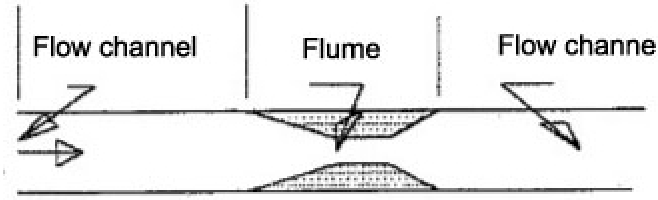
1.12.6. Loss of charge

Before installing a measuring device, it is important to verify the allowable maximum drop in charge.

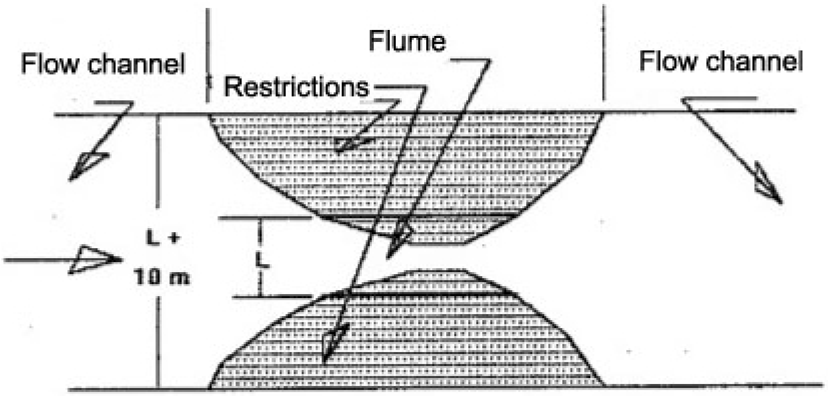
Different measurement methods create different drops in charge. For a particular measuring instrument, the maximum loss of depth corresponds to the maximum flow.

Loss of charge for flumes is generally less than that caused by weirs. The difference is approximately 30 %.

FIGURE 4 - FLUME - FLUME AND FLOW CHANNEL LAYOUT



Situation where the minimum width of the flow channel
is the same width as the flume



Situation where the maximum width of the flow channel
is the same width of the flume plus 10 meters

1.12.7. Precision

It is important not to expect to obtain a very high degree of precision. Measurements where the margin for error is less than 1 % may be unrealistic and often very expensive, whereas a margin for error of 3 % to 5 %, or 10 % is quite acceptable in most cases(3).

Under normal conditions of use, where a device has been installed according to stringent codes and by skilled individuals, most measurement methods produce a margin for error of less than 10 %.

1.12.8. Range of measurement

When selecting a method of measurement, it is important to examine the ratio between the minimum and maximum discharge, in order to select an instrument that creates an optimum water depth differential.

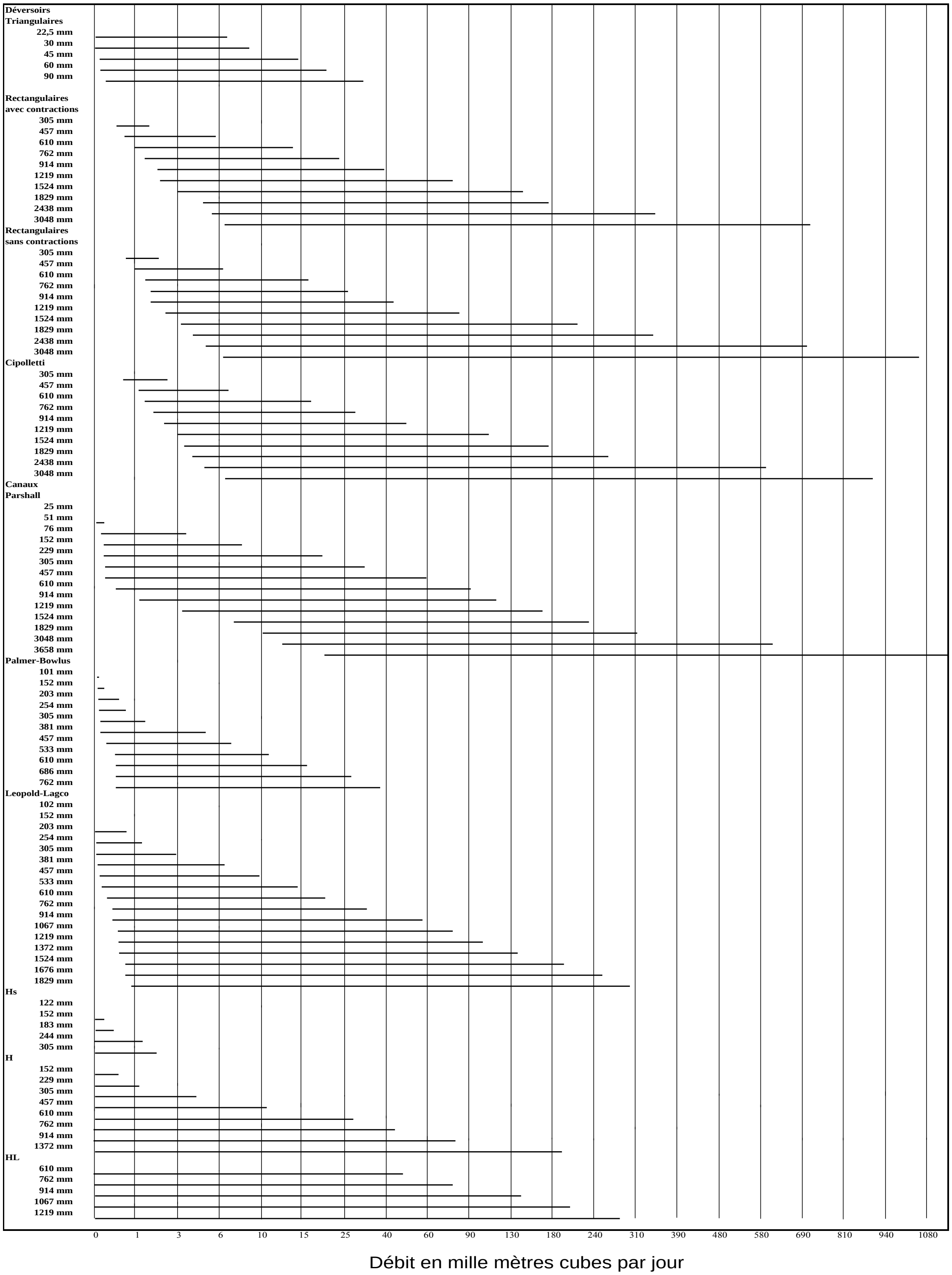
It is also important to ensure that the method chosen produces the same type of precision of measurements for the range of flow values that are likely to occur.

Table 3 shows a chart that can be used for a quick comparison of devices and to select the device best adapted to the situation. A number of publications provide these types of charts(4).

1.12.9. Important figures

Although precision is required for the compilation of data collected, precision should not be estimated with a series of figures in excess than what is allowed for the instrument with the least precision. This will result in a precision that does not exist and can cause confusion(2).

TABLE 3 - CHART FOR COMPARING THE MEASUREMENT CAPABILITIES OF PRIMARY DEVICES



Usually, in a calculation that involves multiplying or dividing with figures from observations, the result should contain the same number of figures as the value that has the least number of figures.

Application of this rule implies that the last figure does not necessarily represent a value but rather a more probable value.

1.12.10. Repeatability and reliability

Repeatability, for a measuring instrument, is the ability to always produce the same result when used under the same conditions.

Reliability is the ability of an instrument to operate without failure, under controlled conditions and for a specific period of time.

It is important to ensure that information gathered is accurate and that fluctuations in measurement are the result of an industrial process, not the instrument. This criterion is particularly important because inspection of instruments is often centralized and an operator cannot immediately determine if an instrument is operating correctly. The period between a visual inspection and the date a reading is logged often raises questions when results are interpreted.

1.12.11. Installation details

Manufacturing a layout that complies with code is recommended, rather than trying to estimate the effects of conditions that do not comply with regulations and trying to correct values obtained under these conditions.

Primary measuring devices should be located in a straight section of flow and should be perfectly aligned with the direction of flow.

Flumes and weirs must be placed level longitudinally and transversely, in other words, in the direction of flow and perpendicular to flow.

In the approach section, there should be no branch lines, curves, heads of water or abrupt changes in the channel bottom.

To avoid generating a submerged flow due to backwater, the channel should have enough capacity to allow water to discharge immediately at the highest flowrate.

Installation of primary measuring devices equipped with stilling wells is recommended. Stilling wells are connected to the measuring device through small conduits. They must be positioned in locations where water depth measurements are taken in the flume. The dimensions of wells and conduits must correspond to the standards prescribed in Table 4.
Stilling wells should be wide enough to allow a flowmeter level detector to be installed and operated and the well to be cleaned.

A staff gauge (ruler) must be permanently placed at the measuring point.

TABLE 4 - DIMENSIONS FOR STILLING WELLS

Diameter of stilling well		Diameter of conduit	
mm	in	mm	in
203	8	12.70	1/2
254	10	12.70	1/2
305	12	12.70	1/2
406	16	12.70	1/2
508	20	15.90	5/8
610	24	19.00	3/4
762	30	31.80	1 1/4

1.12.12. Maintenance

Although some types of flumes are designed to allow movement of solids, heavy debris can become deposited and cause metering errors. Periodic inspections of all primary measuring devices is recommended. The following items should be checked and the following work carried out, where necessary:

- the presence of solids or debris;
- longitudinal and transversal planes;
- the presence of cracks in the structure;
- cleaning out stilling wells and connecting conduits;
- calibration of the water level detector.

1.12.13. Calibration

A primary device may require calibration in the following instances:

- the system does not comply with standards specified in this guide;
- a serious deterioration of the system is noted.

Calibration consists of determining, for varying degrees of flow, a relationship between the flow and water depth measured in the primary device. On the basis of this, a new empirical depth/flow relationship can be established for the flow of liquid that may be measured by the device.

Even in systems have been installed under exacting standard, measuring devices produce an estimated 5 % deviation, it may be difficult to find a method that is precise and accurate enough to perform calibration. Technically, the method that is used should have no error. In practice, however, it is realistic to tolerate a 1 % to 2 % margin of error. Precision (which can improve through repeated measurements) should be approximately 95 %. Section 5 discusses the precision and accuracy of methods. It is the responsibility of the user to demonstrate that the method(s) employed complies with the aforementioned accuracy and precision objectives or other objectives prescribed by a public authority or in accordance with regulation.

Generally, the volumetric method is used only if the following conditions can be respected(5);

- A regular shape tank is available and its capacity can be measured at different levels with a precision of 99 %.
- For each test, water depth in the primary device at the measuring point is stable. The allowable deviation limits are detailed in the description of each primary device.
- It takes longer than 90 seconds to fill the measuring tank.

The dilution method, which uses salt or a chemical tracer, if:

- the primary measurement device is too large for use of the volumetric method;
- the water depth in the primary device at the measuring point is stable, for each test. The allowable deviation limits are indicated in the description of each primary device;
- a regular shape tank is unavailable, the capacity of which can be calibrated precisely at different levels.

During calibration of the primary device, information detailing its installation and status must be taken down. The calibration procedure and method of measuring water depth and flow must be described in detail. This information must be kept as a reference document, during the entire period the primary device is in use.

2. DESCRIPTION OF FLUMES

The sections that follow discuss flumes that may be present at permanent or temporary test sites.

2.1. Parshall flume

The Parshall flume was designed in the later 1920s to measure the flow of irrigation water. Today, this type of flume is often used to measure the flow of wastewater, for permanent or temporary installations(2).

2.1.1. Description

A Parshall flume consists of a converging section, a throat section and diverging section(6).

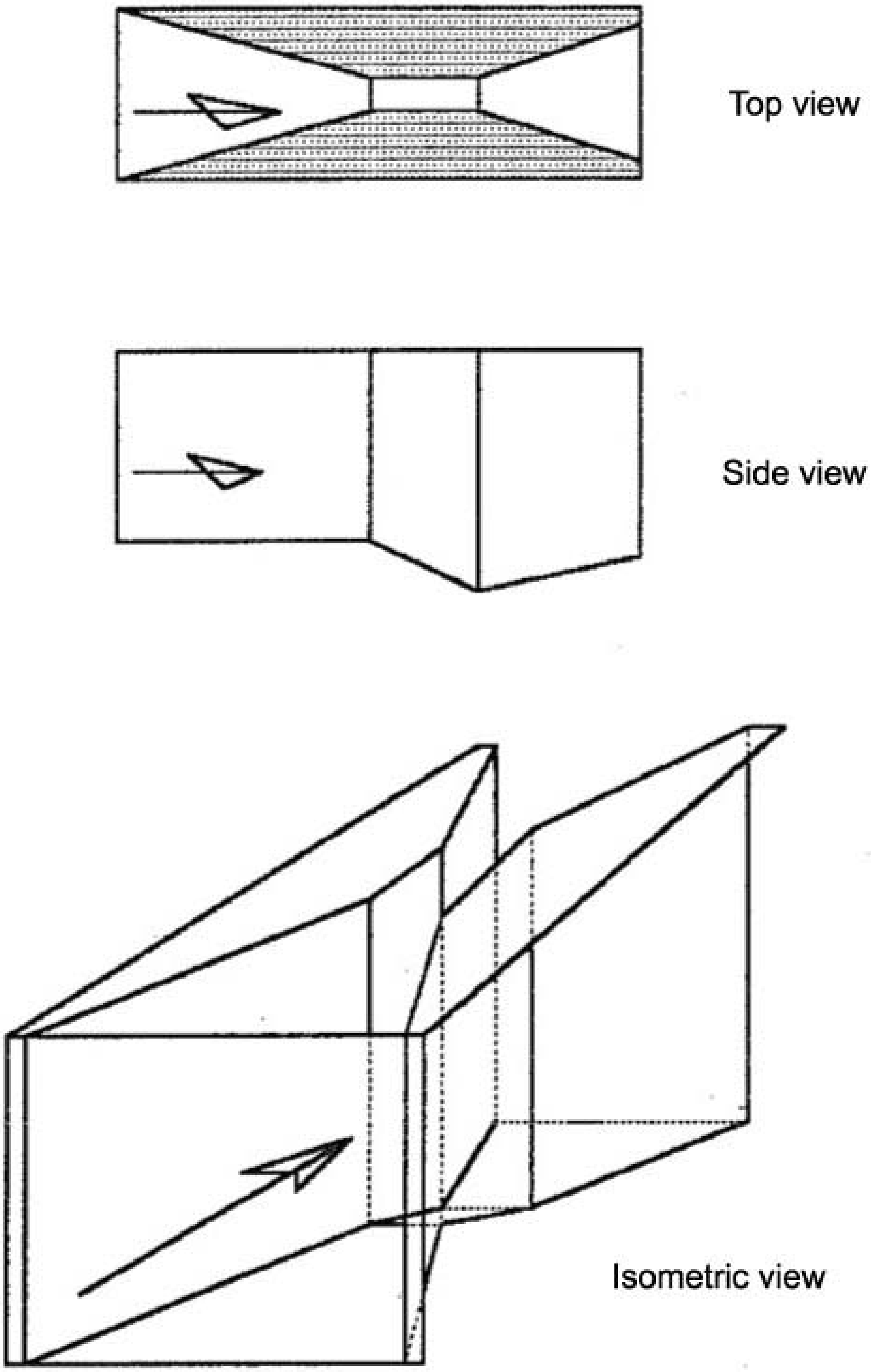
The crest of the throat section is tilted downstream. In other words, there is a sill between the horizontal crest and converging section and the crest of the throat section.

For channels smaller than 2.44 m (8 ft), the inlet of the converging section may be rounded, and larger channels may have vertical walls at a 45° angle.

To prevent erosion due to water fall, the diverging section is usually extended by means of vertical walls, and the angle of these walls will be steeper than the angle of the walls of the diverging section (see Figures 5 and 8).

These channels have been standardized for 25 mm (1 in) to 15.2 m (50 ft) widths. The standardized sizes in millimeters and inches are: 25 (1), 51 (2), 76 (3), 152 (6), 229 (9), 305 (12), 457 (18), 610 (24), 914 (36), 1219 (48), 1524 (60), 1829 (72), 2134 (84), 2438 (96), 3048 (120), 3658 (144), 4572 (180), 6096 (240), 7620 (300), 9144 (360), 12192 (480) et 15240 (600) mm (in). This type of flume is illustrated in Figure 5.

FIGURE 5 - PARSHALL FLUME - ILLUSTRATION OF FLUME



2.1.2. Operating principle

A Parshall flume operates according to the Venturi principle. Due to lateral restrictions, the flume restricts the flow area, causing the water level upstream from the throat section to rise. A sudden or steep drop in water level at the throat section creates an increase in flow velocity.

The flowrate can be obtained simply by measuring the water depth, because it has been established that depth varies proportionally with flow.

Although this flume can be used in submerged flow conditions, use in free flow conditions is recommended. In free flow conditions, only one measuring point has to be used to take a measurement, whereas in submerged conditions, the depth downstream from the throat section must also be measured.

2.1.3. Applications

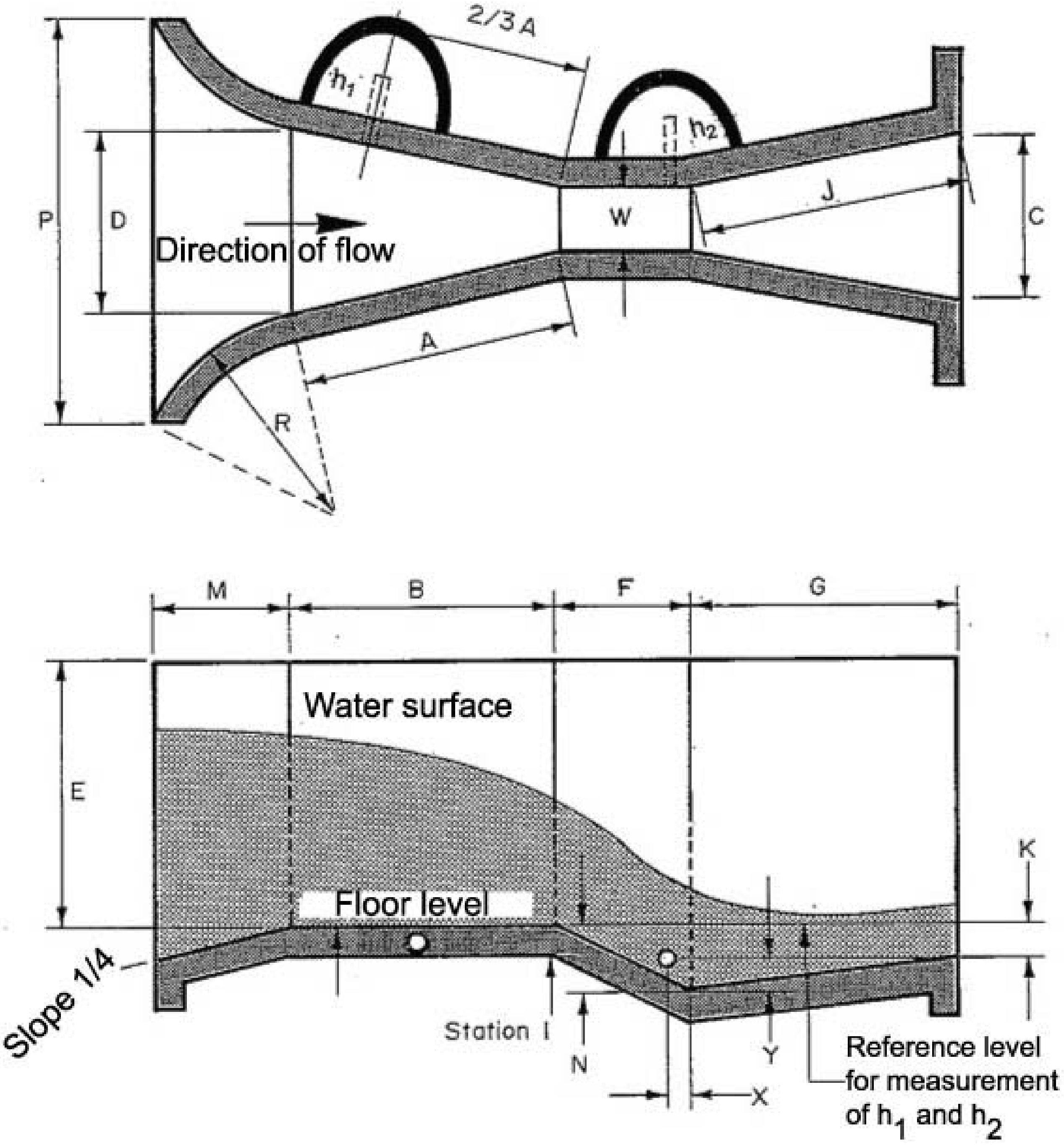
Although initially developed to measure flow in natural open channels such as rivers, streams, drainage ditches, etc., Parshall flumes are now widely used to measure flow in man-made open channels, such as storm and domestic drainage systems, sewage treatment plant inlets and outlets, etc.

Because of its geometry and operating principle, a Parshall flume is extremely effective for measuring the flow of water that contains solids. Because it creates little loss of depth, it can be easily adapted to existing sewer systems.

2.1.4. Dimensions

The dimensions of a Parshall flume are defined by the width of constriction. Figure 6 shows the physical characteristics of a Parshall flume and Table 5, its standard dimensions.

FIGURE 6 - PARSHALL FLUME - PHYSICAL AND FLOW CHARACTERISTICS



For standard dimensions, see Table 5.

TABLE 5 - PARSHALL FLUME – STANDARD DIMENSIONS

DIMENSIONS in mm et (feet and inches)

W	A	2/3A	B	C	D	E	F	G	H	K	M	N	P	R	X	Y
25 ± 0,4 1" ±1/64"	363 1' 2-9/32"	242 9-17/32 "	356 1' 2"	93 3-21/32"	168 6-19/32"	152to 229 6"to9"	76 3"	203 8"	206 8-1/8"	19 3/4"		29 1-1/8 "			8 5/16"	13 1/2"
51 ± 0,4 2"±1/64"	414 1'4-5/16"	109 10-7/8	406 1' 4"	135 5-5/16"	214 8-13/32"	152to 254 6"to10"	114 4-1/2"	254 10"	257 10-1/8"	22 7/8"		43 1-11/16 "			16 5/8"	25 1"
76 ± 0,4 3"±1/64"	467 1'6-3/8"	311 1' 1/4"	457 1' 6"	178 7"	259 10-3/16"	304,8to 457 1'to1-1/2'	152 6"	305 1'	309 1' 5/32"	25 1"		57 2-1/4 "			25 1"	38 1-1/2"
152 ± 0,8 6"±1/32"	621 2' 7/16"	414 1' 4-5/16"	610 2'	394 1' 3-1/2"	397 1' 3-5/8"	610 2'	305 1'	610 2'	----	76 3"	305 1'	114 4-1/2 "	902 2' 11-1/2"	406 1' 4"	51 2"	76 3"
229 ± 0,8 9"±1/32"	880 2' 10-5/8"	587 1' 11-1/8"	864 2' 10"	381 1' 3"	575 1' 10-5/8"	762 2' 6"	305 1'	457 1' 6"	----	76 3"	305 1'	114 4-1/2 "	1080 3' 6-1/2"	406 1' 4"	51 2"	76 3"
305 ± 0,8 12"±1/32"	1372 4' 6"	914 3’	1343 4' 4-7/8"	610 2'	845 2' 9-1/4"	914 3 '	610 2'	914 3 '	----	76 3"	381 1' 3"	229 9"	1492 4' 10-3/4"	508 1' 8"	51 2"	76 3"
457 ± 0,8 18"±1/32"	1448 4' 9"	965 3' 2"	1419 4' 7-7/8"	762 2' 6"	1026 3' 4-3/8"	914 3 '	610 2'	914 3 '	----	76 3"	381 1' 3"	229 9"	1676 5' 6"	508 1' 8"	51 2"	76 3"
610 ± 0,8 2'±1/32"	1524 5'	1016 3' 4"	1495 4' 10-7/8"	914 3 '	1207 3' 11-1/2"	914 3 '	610 2'	914 3 '	----	76 3"	381 1' 3"	229 9"	1854 6' 1"	508 1' 8"	51 2"	76 3"
914 ± 0,8 3'±1/32"	1676 5' 6"	1118 3' 8"	1645 5' 4-3/4"	1219 4'	1572 5' 1-7/8"	914 3 '	610 2'	914 3 '	----	76 3"	381 1' 3"	229 9"	2223 7' 3-1/2"	508 1' 8"	51 2"	76 3"
1219 ± 0,8 4'±1/32"	1829 6'	1219 4'	1794 5' 10-5/8"	1524 5'	1937 6' 4-1/4"	914 3 '	610 2'	914 3 '	----	76 3"	457 1' 6"	229 9"	2712 8' 10-3/4"	610 2'	51 2"	76 3"
1524 ± 0,8 5'±1/32"	1981 6' 6"	1321 4' 4"	1943 6' 4-1/2"	1829 6 '	2302 7' 6-5/8"	914 3 '	610 2'	914 3 '	----	76 3"	457 1' 6"	229 9"	3080 10' 1-1/4"	610 2'	51 2"	76 3"
1829 ± 0,8 6'±1/32"	2134 7'	1422 4'8"	2092 6' 10-3/8"	2134 7'	2667 8' 9"	914 3 '	610 2'	914 3 '	----	76 3"	457 1' 6"	229 9"	3442 11' 3-1/2"	610 2'	51 2"	76 3"
2134 ± 0,8 7'±1/32"	2286 7' 6"	1524 5'	2242 7' 4-1/4"	2438 8'	3032 9' 11-3/8"	914 3 '	610 2'	914 3 '	----	76 3"	457 1' 6"	229 9"	3810 12' 6"	610 2'	51 2"	76 3"
2438 ± 0,8 8'±1/32"	2438 8'	1626 5' 4"	2391 7' 10-1/8"	2769 9'	3397 11' 1-3/4"	914 3 '	610 2'	914 3 '	----	76 3"	457 1' 6"	229 9"	4172 13' 8-1/4"	610 2'	51 2"	76 3"
3048 ± 0,8 10'±1/32"		1829 6'	4267 14'	3658 12'	4756 15' 7-1/4"	1219 4 '	914 3 '	1829 6 '	----	152 6"		343 1' 1-1/2"			51 2"	305 1'
3658 ± 0,8 12'±1/32"		2032 6' 8"	4877 16'	4470 14' 8"	5607 18' 4-3/4"	1524 5'	914 3 '	2438 8 '	----	152 6"		343 1' 1-1/2"			229 9"	305 1'
4572 ± 0,8 15'±1/32"		2337 7' 8"	7620 25'	5588 18' 4"	7620 25'	1829 6 '	4 ' 1219	3048 10'	----	229 9"		457 1' 6"			229 9"	305 1'
6096 ± 0,8 20'±1/32"		2845 9' 4"	7620 25'	7315 24'	9144 30'	2134 7 '	1829 6 '	3658 12 '	----	305 1'		686 2' 3 "			229 9"	305 1'
7620 ± 0,8 25'±1/32"		3353 11'	7620 25'	8941 29' 4"	10668 35'	2134 7 '	1829 6 '	3962 13 '	----	305 1'		686 2' 3 "			229 9"	305 1'
9144 ± 0,8 30'±1/32"		3861 12' 8"	26' 7925	10566 34' 8"	12313 40' 4-3/4"	2134 7 '	1829 6 '	4267 14 '	----	305 1'		686 2' 3 "			229 9"	305 1'
12192±0,8 40'±1/32"		4877 16'	8230 27'	13818 45' 4"	15481 50' 9-1/2"	2134 7 '	1829 6 '	4877 16 '	----	305 1'		686 2' 3 "			229 9"	305 1'
15240±0,8 50'±1/32"		5893 19' 4"	8230 27'	17272 56' 8"	18529 60' 9-1/2"	2134 7 '	1829 6 '	6096 20 '	----	305 1'		686 2' 3 "			229 9"	305 1'

It is important to respect standard dimensions precisely if you are using established empirical tables and to obtain accurate measurements.

2.1.5. Range of measurements

Parshall flumes can measure flows varying from 70.7 m^3 per day, for a 76 mm (3 in) channel, to 8,038,656 m^3 per day, for a 15.24 m (50 ft) channel. Table 6 lists the recommended minimum and maximum flowrates for a free-flow Parshall flume for different dimensions. For the purposes of this document, only data that apply to channels with dimensions between 76 mm (3 in) and 36.57 m (12 ft), have been included.

2.1.6. Discharge equation for free flow conditions

The discharge equation resulting from the depth/flow relationship in free flow conditions, is expressed as follows(7):

$$Q = KH^n \quad (9)$$

where:

Q is the flowrate, the value of which is a function of the unit of measurement selected (Table 7);
H is the water depth measured at point h_1, in feet or meters;
K is the constant, which is a function of the dimension of the constriction and measurement unit chosen (Table 7);
n is the constant of the exponent, the value of which is a function of the dimension of the constriction, (without unit).

Table 7 shows discharge equations for free flow Parshall flumes, for values expressed in m^3 per second, in m^3 per day, in ft^3 per second and in millions of US gallons per day.

TABLE 6 - PARSHALL FLUME - RECOMMENDED MINIMUM AND MAXIMUM FLOWS IN FREE FLOW CONDITIONS

Throat width mm (in)	Minimum depth mm (in)	MINIMUM FLOWRATE		Maximum depth mm (in)	MAXIMUM FLOWRATE	
		l/s	m^3/d		l/s	m^3/d
25 1	19 0.75	0.13	11.2	184 7.25	4.38	378.2
51 2	25 1	0.4	34.3	184 7.25	8.75	756.4
76 3	31 1.25	0.82	70.7	457 18	52.56	4541.1
152 6	31 1.25	1.58	136.2	457 18	110.6	9557.7
229 9	31 1.25	2.63	227.5	610 24	251.3	21 714.1
305 12	31 1.25	3.49	301.9	762 30	456.8	39 471.2
457 18	31 1.25	5.05	436.5	762 30	695.4	60 081.6
610 24	44 1.75	11.3	974.5	762 30	937.4	80 995
914 36	44 1.75	16.4	1417.2	762 30	1426.9	123 286.5
1219 48	64 2.5	38.6	3334.7	762 30	1923.6	166 199.4
1524 60	64 2.5	47.6	4110.2	762 30	2424.4	209 470
1829 72	76 3	74.16	6407.2	762 30	2930.7	253 213
2438 96	76 3	97.2	8401.7	762 30	3950.8	341 350
3048 120	90 3.5	158.4	13 683.6	1067 42	8278.7	715 280
3658 144	101 4	226.1	19 535.9	1372 54	14522.3	1254 725

TABLE 7 - PARSHALL FLUME - DISCHARGE EQUATIONS IN FREE FLOW CONDITIONS

Flume dimensions	DISCHARGE EQUATION			
W	**m^3/s (**)**	**m^3/d (**)**	**ft^3/s (*)**	**Mgal$_{US}$/d (*)**
1"	$0.0604\ \mathbf{H}^{1.55}$	$5\,215\ \mathbf{H}^{1.55}$	$0.338\ \mathbf{H}^{1.55}$	$0.2185\mathbf{H}^{1.55}$
2"	$0.1207\ \mathbf{H}^{1.55}$	$10\,430\ \mathbf{H}^{1.55}$	$0.676\ \mathbf{H}^{1.55}$	$0.4369\mathbf{H}^{1.55}$
3"	$0.1765\ \mathbf{H}^{1.547}$	$15\,250\ \mathbf{H}^{1.547}$	$0.992\ \mathbf{H}^{1.547}$	$0.6412\mathbf{H}^{1.547}$
6"	$0.3812\ \mathbf{H}^{1.58}$	$32\,937\ \mathbf{H}^{1.58}$	$2.060\ \mathbf{H}^{1.58}$	$1.3314\mathbf{H}^{1.58}$
9"	$0.5354\ \mathbf{H}^{1.53}$	$46\,258\ \mathbf{H}^{1.53}$	$3.070\ \mathbf{H}^{1.53}$	$1.9842\mathbf{H}^{1.53}$
1'	$0.6909\ \mathbf{H}^{1.522}$	$59\,696\ \mathbf{H}^{1.522}$	$4.0\ \mathbf{H}^{1.522}$	$2.5853\mathbf{H}^{1.522}$
18"	$1.0563\ \mathbf{H}^{1.538}$	$91\,263\ \mathbf{H}^{1.538}$	$6.0\ \mathbf{H}^{1.538}$	$3.8779\mathbf{H}^{1.538}$
2'	$1.4286\ \mathbf{H}^{1.550}$	$123\,432\ \mathbf{H}^{1.550}$	$8.0\ \mathbf{H}^{1.550}$	$5.1706\mathbf{H}^{1.550}$
3'	$2.184\ \mathbf{H}^{1.566}$	$188\,701\ \mathbf{H}^{1.566}$	$12.0\ \mathbf{H}^{1.566}$	$7.7559\mathbf{H}^{1.566}$
4'	$2.9539\ \mathbf{H}^{1.578}$	$255\,214\ \mathbf{H}^{1.578}$	$16.0\ \mathbf{H}^{1.578}$	$10.341\mathbf{H}^{1.578}$
5'	$3.732\ \mathbf{H}^{1.587}$	$322\,448\ \mathbf{H}^{1.587}$	$20.0\ \mathbf{H}^{1.587}$	$12.926\mathbf{H}^{1.587}$
6'	$4.5212\ \mathbf{H}^{1.595}$	$390\,632\ \mathbf{H}^{1.595}$	$24.0\ \mathbf{H}^{1.595}$	$15.512\mathbf{H}^{1.595}$
8'	$6.1148\ \mathbf{H}^{1.607}$	$528\,322\ \mathbf{H}^{1.607}$	$32.0\ \mathbf{H}^{1.607}$	$20.682\mathbf{H}^{1.607}$
10'	$7.4628\ \mathbf{H}^{1.6}$	$644\,782\ \mathbf{H}^{1.6}$	$39.38\ \mathbf{H}^{1.6}$	$25.452\mathbf{H}^{1.6}$
12'	$8.8594\ \mathbf{H}^{1.6}$	$756\,453\ \mathbf{H}^{1.6}$	$46.75\ \mathbf{H}^{1.6}$	$30.216\mathbf{H}^{1.6}$
15'	$10.955\ \mathbf{H}^{1.6}$	$946\,542\ \mathbf{H}^{1.6}$	$57.81\ \mathbf{H}^{1.6}$	$37.364\mathbf{H}^{1.6}$
20'	$14.45\ \mathbf{H}^{1.6}$	$1\,248\,466\ \mathbf{H}^{1.6}$	$76.25\ \mathbf{H}^{1.6}$	$49.282\mathbf{H}^{1.6}$
25'	$17.944\ \mathbf{H}^{1.6}$	$1\,550\,391\ \mathbf{H}^{1.6}$	$94.69\ \mathbf{H}^{1.6}$	$61.20\mathbf{H}^{1.6}$
30'	$21.439\ \mathbf{H}^{1.6}$	$1\,852\,315\ \mathbf{H}^{1.6}$	$113.13\ \mathbf{H}^{1.6}$	$73.118\mathbf{H}^{1.6}$
40'	$28.426\ \mathbf{H}^{1.6}$	$2\,456\,000\ \mathbf{H}^{1.6}$	$150\ \mathbf{H}^{1.6}$	$96.948\mathbf{H}^{1.6}$
50'	$35.415\ \mathbf{H}^{1.6}$	$3\,059\,848\ \mathbf{H}^{1.6}$	$186.88\ \mathbf{H}^{1.6}$	$120.785\mathbf{H}^{1.6}$

(*) H expressed in feet
(**) H expressed in meters

2.1.7. Precision

The margin for error with a Parshall flume is approximately ± 3 %. To generate this degree of precision, it is important to carefully comply with all of the recommended dimensions when a flume is manufactured and installed.

2.1.8. Sources of error

The principal sources of error that reduce a flume’s precision are as follows:

- changes to standard dimensions that occur when a flume is manufactured or during its installation

  distortion: check all sections of the flume to ensure that it has not been compressed or twisted during installation.

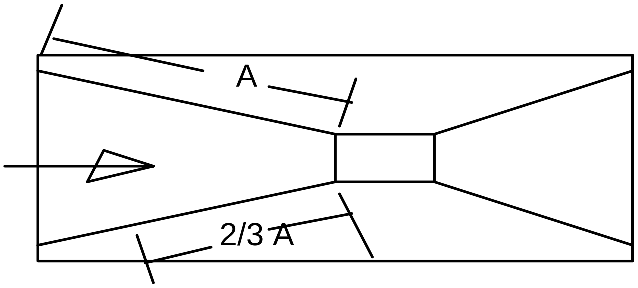
  throat width: for small flumes, a tolerance of 4 mm (1/64 in) compared to a standard dimension, is acceptable. For larger flumes, a deviation of 8 mm (1/32 in) is acceptable, (see Table 5).

  length of converging section: this section cannot be reduced, but there appears to be no restriction to extend it. The measuring point, however, must remain in a standard position.

  horizontal position: if the base of the flume is not level transversely, the average depth must be used to determine the depth/flow relationship, in other words, the depth must be measured on each side of the flume to determine the average depth.

- incorrect measuring point position

  for all sizes of flumes, the measuring point must be located within the 2/3 portion of the converging section, the distance of which must be measured along the wall, from the beginning of the throat.



- inadequate approach

  the converging section of the flume is too short to adequately correct major distortions of the approach and distribution velocity. The reader can refer to section 2.1.10 which discusses installation conditions, for an understanding of rules that regulate the approach.

- poor measurement technique in submerged flow conditions

  often, due to a lack of knowledge, a user is unaware of how to recognize or gauge a channel that is operating in submerged flow conditions and takes flow measurements at only one location, instead of at both measuring points, which this situation requires.

- obstructions in the throat section of the flume

  it is important to ensure that nothing is blocking flow in the throat of the flume, particularly in the case of small flumes. Where this occurs, liquid is forced to move over the obstacle, which increases the water level at the measuring point.

2.1.9. Selection criteria

As indicated in section 1.7 of this document, installation of a Parshall flume is the preferred type of flume where the daily flow is 1,800 m^3 and over.

Because there are a number of different Parshall flume dimensions available to measure the range of anticipated flows, other criteria should be considered when selecting a flume, such as:

- discharge: it is important to select the correct size of flume to ensure that free flow conditions are present at the maximum discharge, and to consider installation constraints;
- loss of head: for any one flow, the degree to which the water level rises, due to introducing different sizes of flumes;
- the sensitivity required to detect and measure fluctuations in water level, where there are very little variations in flow;
- the desired precision;
- the overall work that is required to install flumes of different sizes;
- the costs associated with installation of flumes of different sizes.

2.1.10. Installation details

The Parshall flume must be located in a straight section of the flow(8).

When installing a flume, it is important to ensure that none of the flume's original physical features are damaged (see Table 5).

The crest (DR), which is the bottom of the converging section of the flume, must be higher than the bottom of the channel in which it is placed. This elevation must be equal to the difference between the water depth in the channel at maximum flow (H_c), before the flume is installed, and the anticipated water depth at the measuring point h_2 ($DR = H_c - h_2$) during minimum submerged flow conditions. The crest of the flume that is introduced must be connected to the crest of the converging section by an inverted slope section that has a 1:4 ratio (vertical:horizontal) (see Figure 6).

The length of the approach section must be equivalent to at least twenty times the diameter of the water delivery pipe.

In the approach section, the slope should be less than 1 %. It is important to ensure that a steep slope does not produce a hydraulic jump in the converging section of the flume, as shown in Figure 7. It should not create too great a velocity, which will slow down the rise in water depth in the converging section.

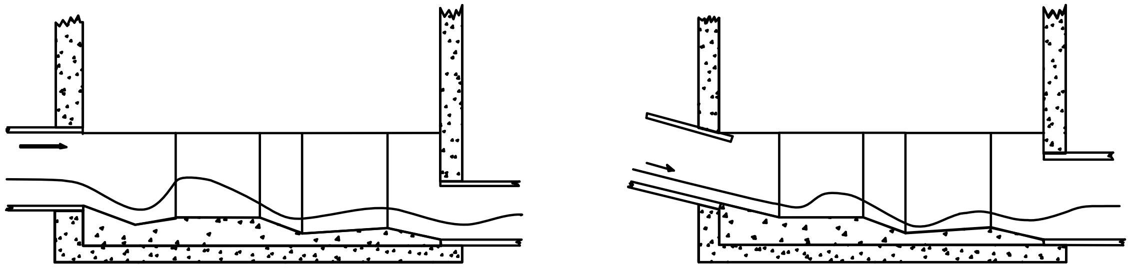
The minimum width of the approach channel should be consistent with dimension “D” of Table 2 and the maximum width should not exceed dimension “P” in the same table (more than 10 m). It is important to avoid introducing a water delivery pipe into the converging section of the flume, as shown in Figure 8.

At the outlet of the flume, there should be enough slope to allow water to discharge quickly. The slope should be approximately 2 %.

After the diverging section, there should be no pronounced curve that can restrict flow and cause a submerged flow.

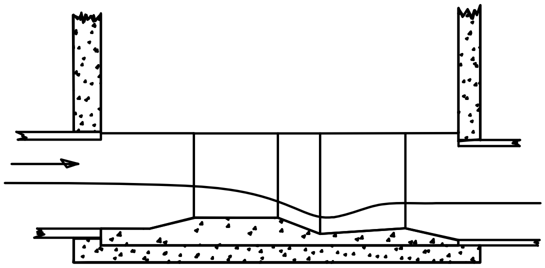
In the converging section, the stilling well conduit should be located within the middle two-thirds (2/3) section of the length of the wall and at a right angle with the wall. The crest of these conduits, that is, their bottom, must be below the level of the crest of the converging section, as shown in Figure 6, and level with the flume wall.

FIGURE 7 - PARSHALL FLUME – SLOPE OF THE APPROACH SECTION



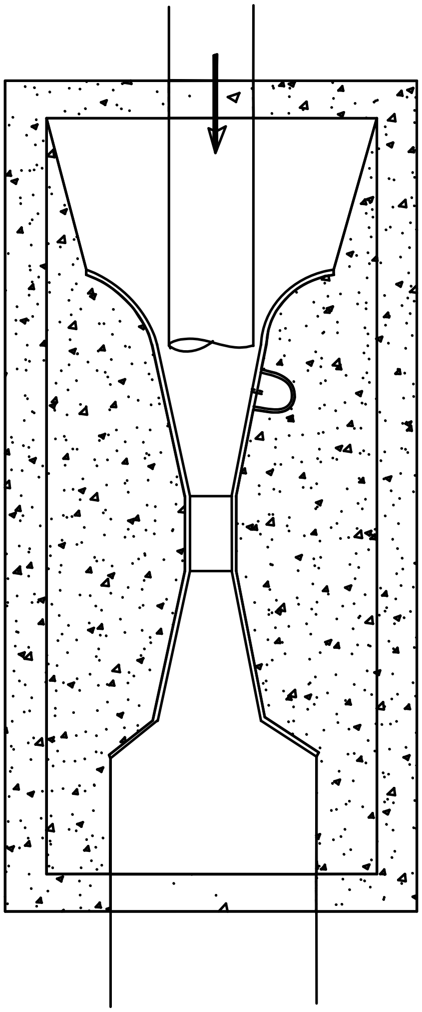
Installation of a flume that is lower than the approach channel

A flume in which the slope of the approach channel is too steep



Installation showing an adequate channel slope

FIGURE 8 - PARSHALL FLUME – JUNCTION OF APPROACH AND CONVERGING SECTIONS (SETUP THAT SHOULD BE AVOIDED)



Insertion of the delivery pipe in the converging section

2.1.11. Submerged flow

A submerged flow should be expected as soon as water reaches the crest (floor level) of the converging section; but this is not the case. The flow does not deteriorate so long as the h_2/h_1 ratio, expressed as a percentage, remains within the following values$^{(2)}$:

50 % for 25, 51 and 76 mm (1, 2 and 3 in) flumes;
60 % for 152 and 229 mm (6 and 9 in) flumes;
70 % for 305 to 2,438 mm (1 to 8 ft) flumes;
80 % for 2,438 to 15,240 mm (8 to 50 ft) flumes.

If the water depth downstream (h_2) is higher than the crest (floor level) of the converging section, measurements of the upstream depth (h_1) and downstream depth (h_2) must be taken. If the h_2/h_1 ratio exceeds these modular limits, flow is said to be submerged, and the flow measured is a function of the simultaneous measurement of both depths h_1 and h_2. Because there is currently no commercial instrument available that can take upstream and downstream measurements simultaneously and perform the corresponding calculations, a submerged flow measurement should be avoided if possible.

It has been established that the h_2/h_1 ratio can reach 67 % to 70 % before there is a significant flow deterioration. For each additional percentage, the flow reduction will also grow exponentially, as shown in Figure 9.

When the h_2/h_1 ratio reaches 100 %, there is no more flow. However, 95 % is considered to be the critical value when the Parshall flume becomes inoperative, because the difference in depth between h_1 and h_2 is so minute, the slightest error in depth measurement will result in extreme inaccuracies.

Use of this type of submerged flow channel is not recommended when the h_2/h_1 ratio exceeds 0.95 (see Figure 10).

FIGURE 9 - PARSHALL FLUME - EFFECTS OF A SUBMERGED FLOW

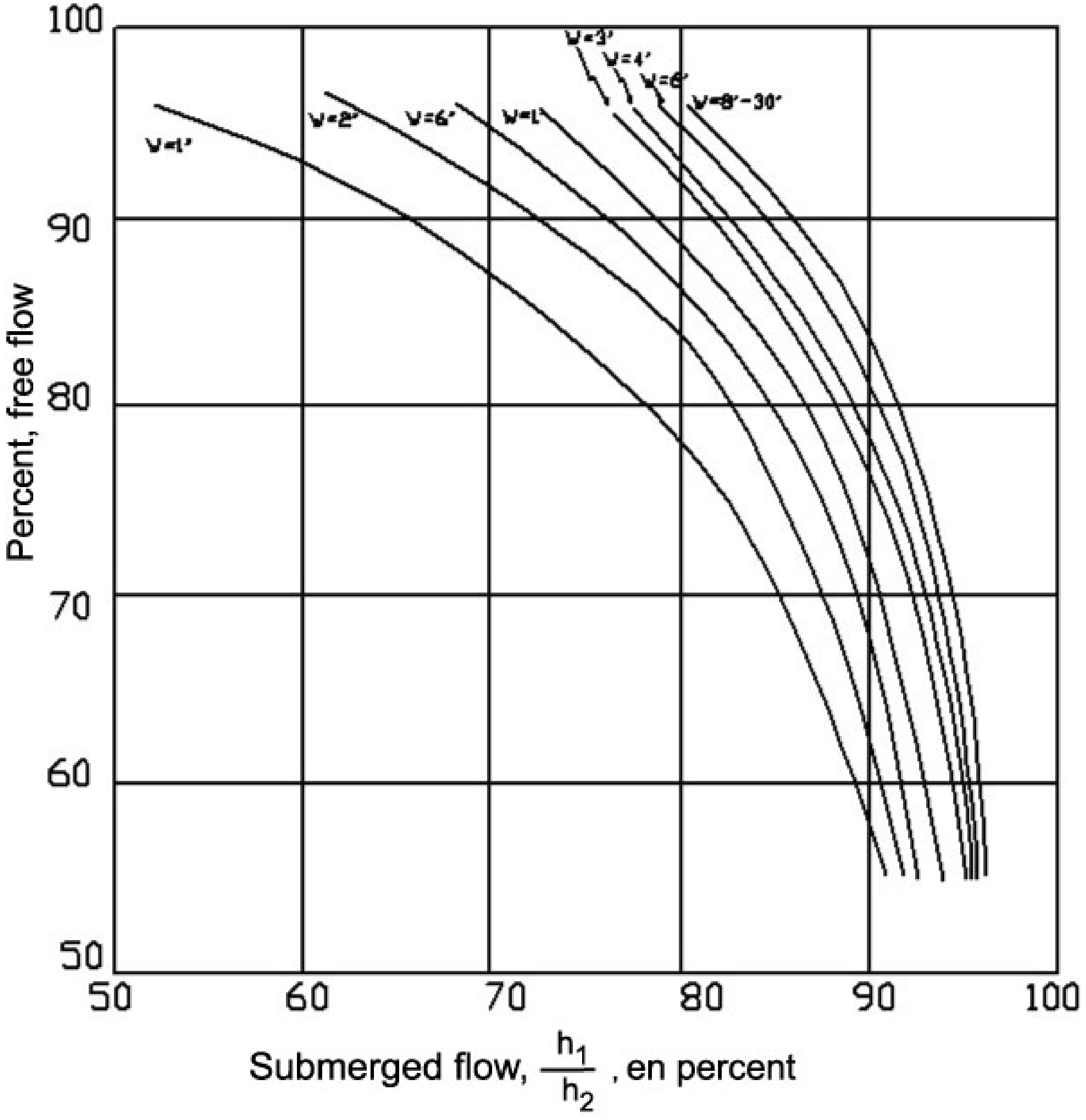
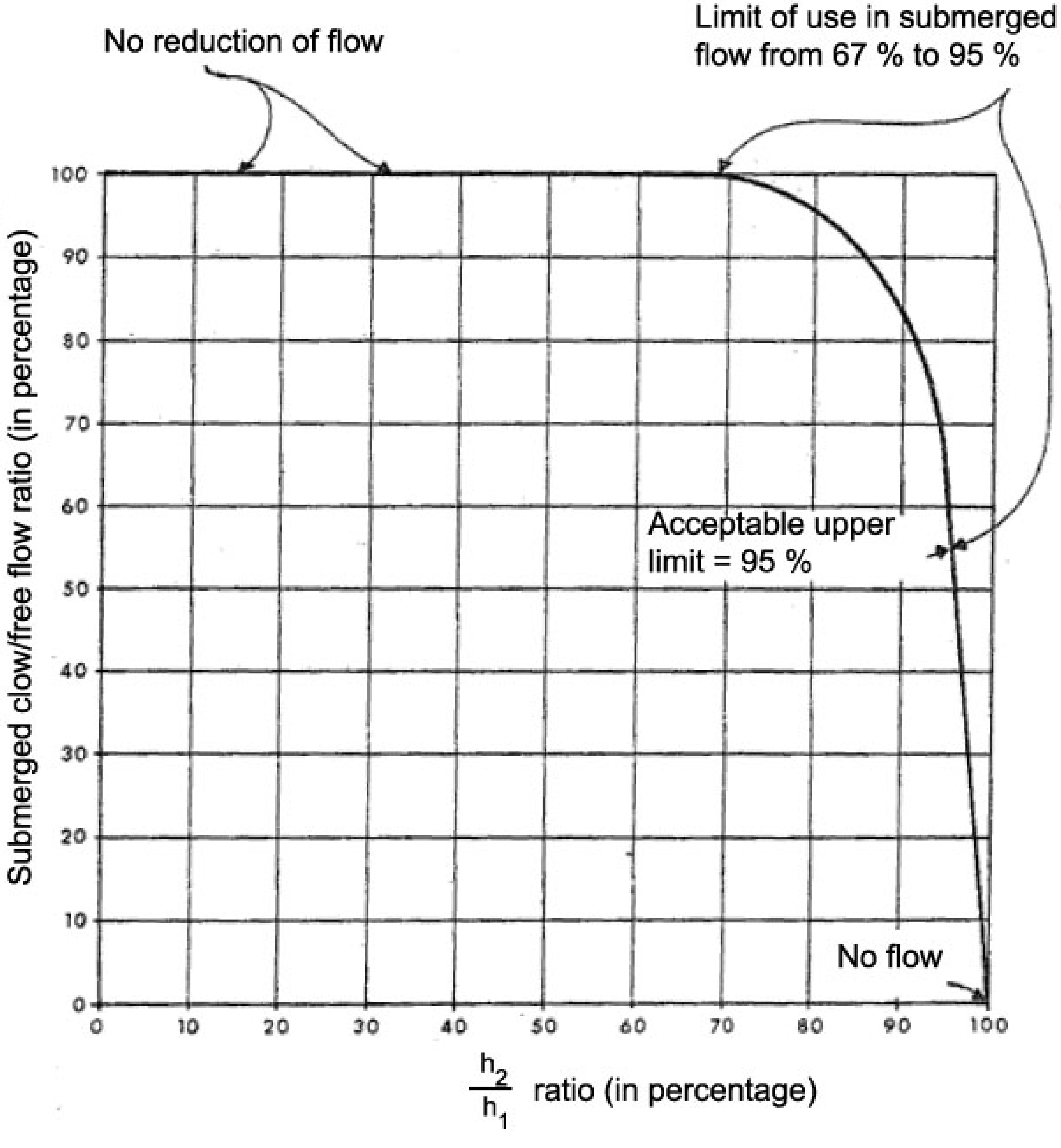


FIGURE 10 - PARSHALL FLUME - H_2/H_1 RATIO



2.1.12. Discharge equation in a submerged flow

For this type of flow regime, the discharge equation resulting from the h_1 - h_2 measurement is expressed as follows(8):

$$Q = \frac{C_1 (h_1 - h_2)^{n_1}}{(- \log h_2 / h_1)^{n_2}} \quad (10)$$

where:

Q	is the flowrate in ft^3/s;
C_1	is a constant without a unit;
h_1 and h_2	are water level depths in feet;
n_1 and n_2	are constants without a unit.

Table 8 shows values for the exponents and coefficients in the above formula.

2.1.13. Loss of head

Before installing a flume, it is important to ensure that the rise in water level in the drainage system does not cause sewers to back up in building basements. To determine the rise in water level, use the following formula:

$$R = [(H_c - h_2) + h_1 + L] \quad (11)$$

where

R	represents the rise in water level in feet, in the section upstream from the flume;
Hc	represents the water depth in the channel in feet, prior to installation of the flume, at maximum flow;
h_1	represents the anticipated water depth in feet, at the measuring point upstream from the flume;
h_2	represents the anticipated water depth in feet, at the measuring point downstream from the flume, in submerged flow conditions;
L	loss of head in feet, according to Figures 11 and 12.

TABLE 8 - COEFFICIENTS AND EXPONENTS - PARSHALL FLUME IN SUBMERGED FLOW CONDITIONS

W	C_1	n_1	n_2
(25 mm) 1″	0.299	1.55	1.000
(51 mm) 2″	0.612	1.55	1.000
(76 mm) 3″	0.915	1.55	1.000
(152 mm) 6″	1.66	1.58	1.080
(229 mm) 9″	2.51	1.53	1.060
(305 mm) 12″	3.11	1.52	1.080
(457 mm) 18″	4.42	1.54	1.115
(610 mm) 24″	5.94	1.55	1.140
(762 mm) 30″	7.22	1.555	1.150
(914 mm) 3′	8.60	1.56	1.160
(1219 mm) 4′	11.10	1.57	1.185
(1524 mm) 5′	13.55	1.58	1.205
(1829 mm) 6′	15.85	1.59	1.230
(2134 mm) 7′	18.15	1.60	1.250
(2438 mm) 8′	20.40	1.60	1.260
(3048 mm) 10′	24.79	1.59	1.275
(3658 mm) 12′	29.34	1.59	1.275
(4572 mm) 15′	36.17	1.59	1.275
(6096 mm) 20′	47.56	1.59	1.275
(7620 mm) 25′	58.95	1.59	1.275
(9144 mm) 30′	70.34	1.59	1.275
(12192 mm) 40′	93.11	1.59	1.275
(15240 mm) 50′	115.89	1.59	1.275

FIGURE 11 - LOSS OF HEAD - PARSHALL FLUMES: 1 TO 8 FEET

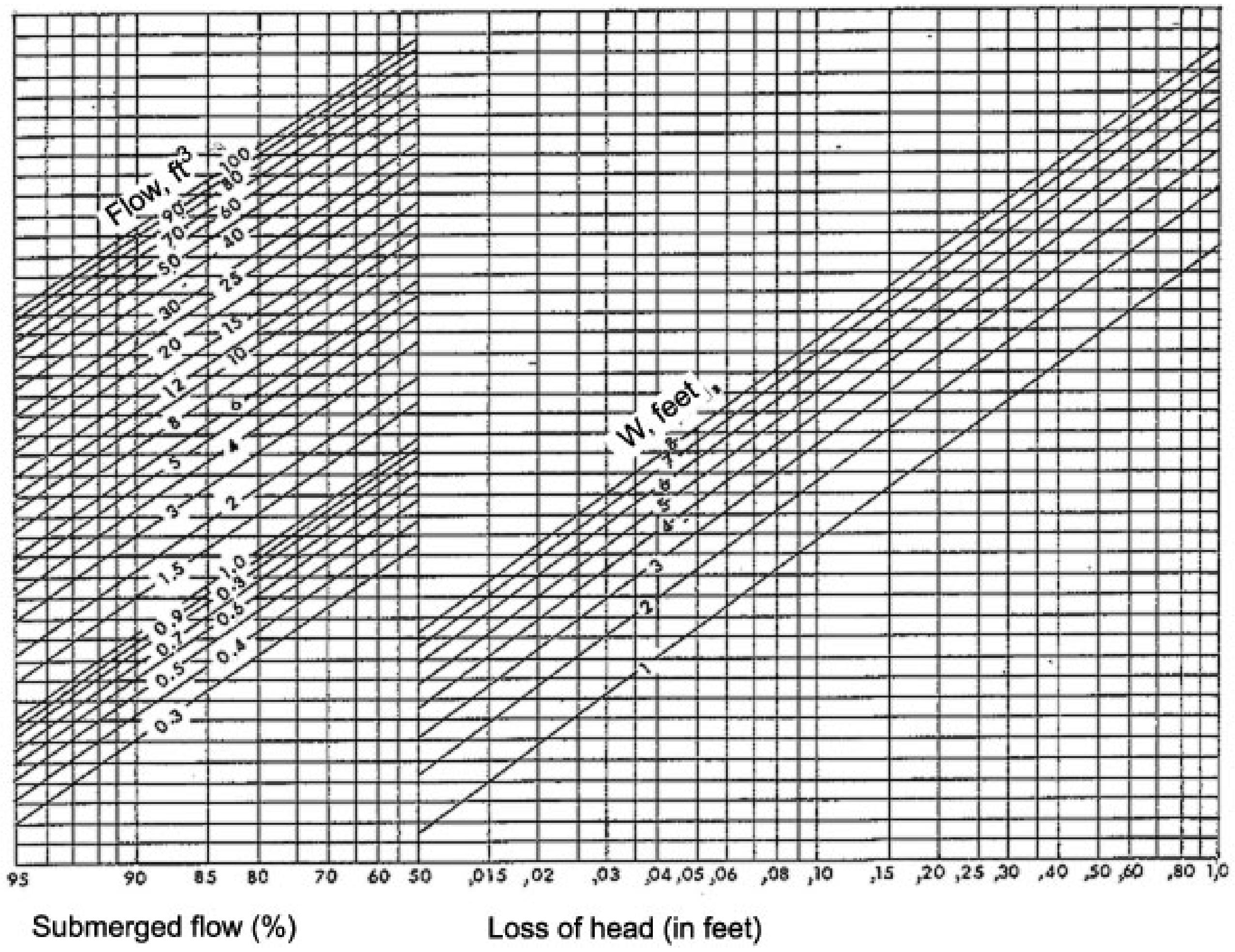
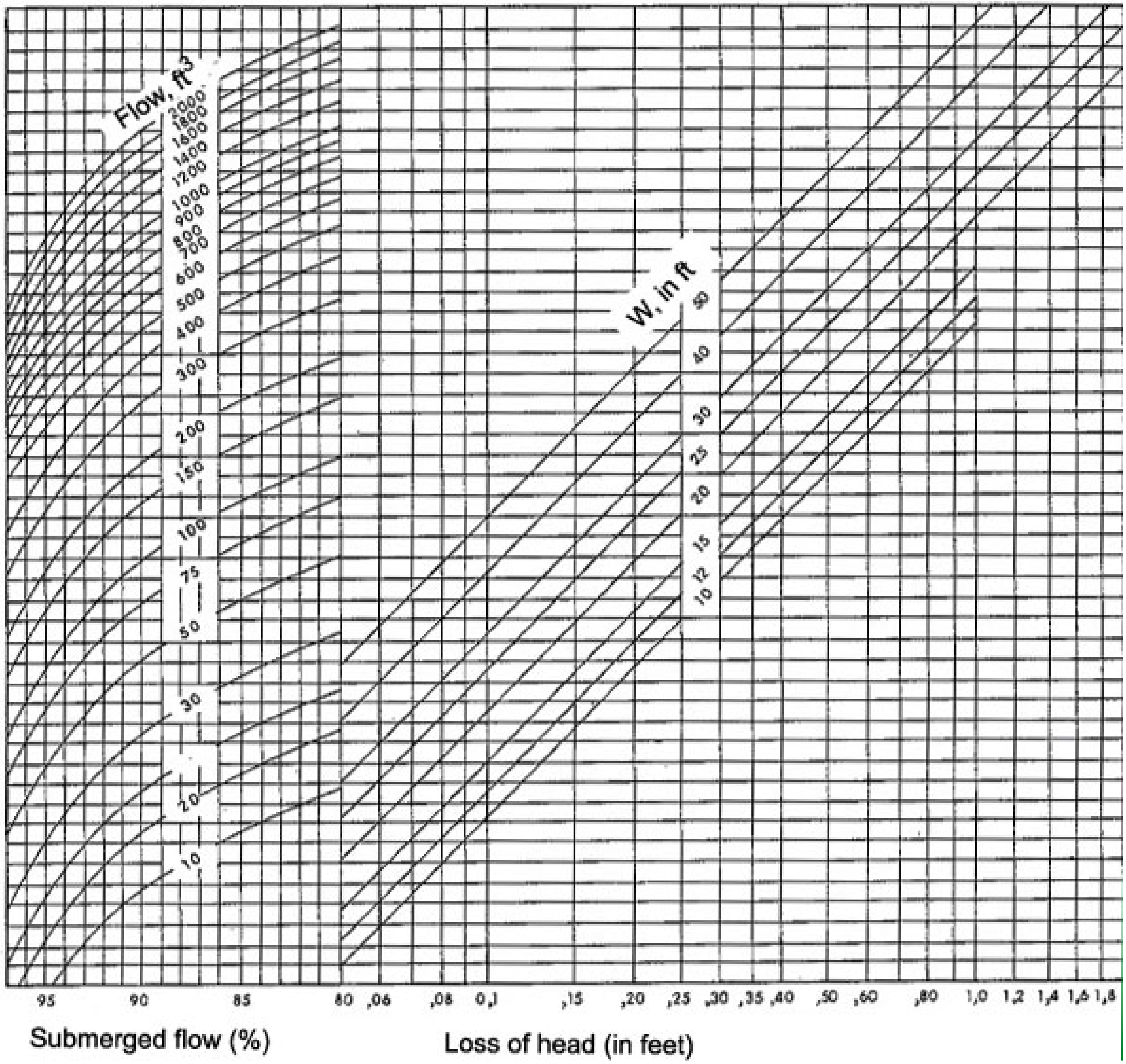


FIGURE 12 - LOSS OF HEAD - PARSHALL FLUMES: 10 TO 50 FEET



If data related to losses of head are not available, it is still possible to gauge the rise in water level using the following empirical formula:

$$R = (H_c - h_2) + (1,1 * h_1) \quad (12)$$

The terms R, H_C, h_2 and h_1 are defined in Equation 11.

To monitor the total rise, follow these steps:

- measure depth in the channel when the flow is at its maximum (H_c);
- gauge the value of the maximum flow as precisely as possible (Q_{max});
- determine what the water depth downstream from the throat section will be for the anticipated maximum flow (h_1);
- determine the size of the flume that can measure the anticipated maximum flow and create the least possible submerged flow conditions;
- define the ratio between depths, during submerged flow (h_2/h_1);
- determine how far above channel bottom the converging section of the flume will be installed (H_c - h_2).

When this evaluation is complete, inverts in buildings and basements should be inspected to ensure that the system selected does not cause a risk of flooding.

2.1.14. Modification of the flume

For specific applications, some users have made modifications to certain parts of a flume. Modifications are usually made to the diverging section and do not affect the values obtained. Modified flumes are generally used in free flow conditions.

A version of a modified flume, without a diverging section, is also used for 76 mm (3 in) flumes, as a portable flume and as a temporary measuring device. This flume is used only in free flow conditions.

Because the use of modified flumes is strongly discouraged, it is not relevant to discuss them in detail.

2.1.15. Calibration

Due to the size of tanks that are available, use of the volumetric method is usually limited to 305 mm (1 ft or less) flumes.

During calibration, the water depth in the flume at the measuring point must not vary more than 4 %, regardless of which method is used.

2.2. Palmer-Bowlus Flume

A Palmer-Bowlus flume was designed in the 1930s for use as a flume that can be inserted in an existing channel with a slope of less than 2 %.

2.2.1. Description

This flume is rounded to create a restriction and produce a greater flow velocity in the throat of the flume.

The Palmer-Bowlus is a Venturi type flume with a uniform throat. The length of the throat is equal to the diameter of the corresponding flume. Different types of restrictions have been developed, but the restriction most frequently used is trapezoidal in shape. This entire section discusses trapezoidal flumes.

Palmer-Bowlus flumes are usually made of prefabricated fiberglass that is reinforced with plastic. Although rare, these types of flumes are also made of stainless steel.

A Palmer-Bowlus flume is manufactured in sizes ranging from 102 mm (4 in) to 1067 mm (42 in). Larger flumes, up to 2438 mm (96 in), can be manufactured on special order. Standard dimensions are: 102 (4), 152 (6), 203 (8), 254 (10), 305 (12), 381 (15), 457 (18), 533 (21), 610 (24), 686 (27), 762 (30), 914 (36), 1067 (42), 1219 (48), 1372 (54) et 1524 (60) mm (in)(10).

2.2.2. Operating principle

Vertical and lateral restrictions on the flume reduce the flow area, causing the water level upstream from the throat section to rise, which is followed by a drop in water level in the throat section, resulting also in an increased flow velocity.

Flowrate can be determined simply by measuring water depth upstream from the flume, since it has been established that variations in depth are proportional to flow.

Although this type of flume can be used in submerged flow conditions, use in free flow conditions is recommended. In free flow conditions, only one measuring point is necessary to obtain flow measurements, but in submerged flow conditions, a water depth measurement downstream from the throat section must also be taken.

2.2.3. Applications

Although it is designed to measure flow in sewer systems and existing channels, a Palmer-Bowlus flume is not a temporary device. In fact, the difference in measurement between a minimum and maximum flow is relatively small. Often, if a system is expanded, the size of the flume must also be changed.

Like all flumes, a Palmer-Bowlus flume is an effective tool for flow measurement of water that contains solids. It is also relatively easy to install because it does not require a crest differential upstream or downstream.

Because of their relatively small volume, Palmer-Bowlus flumes that are under 381 mm (15 in) in diameter can be inserted into a standard sewer manhole, without the need to modify access to the manhole.

2.2.4. Dimensions

Dimensions of a Palmer-Bowlus flume depend on the diameter of the channel in which it is installed.

Unlike a Parshall flume, standards governing the dimensions and configuration of Palmer-Bowlus flumes are not stringent. It is therefore important to use the flow tables supplied by the manufacturer to obtain an accurate flow.

A Palmer-Bowlus flume, as experimented with by Ludwig, should be designed according to dimensions detailed in Table 9, and should have the shape illustrated in Figure 13(10). Palmer-Bowlus flumes on the Québec market are usually manufactured according to standards of the company Plasti-Fab Inc. Dimensions and shape are detailed in Table 10 and Figure 14(9).

2.2.5. Ranges of Measurement

Palmer-Bowlus flumes (Plasti-Fab Inc.) can measure flows varying between 2.4 m^3 per day, in the case of a 102 mm (4 in) flume, and 49,200 m^3 per day, in the case of a 762 mm (30 in) flume.

Table 11 shows recommended minimum and maximum flowrates for a Palmer-Bowlus flume in free flow conditions. This document contains data that apply only to flumes measuring 102 mm (4 in) to 762 mm (30 in) in size.

2.2.6. Discharge equation in free flow conditions

The discharge equation in free flow conditions is expressed in the following manner(10):

$$\frac{Q}{D^{5/2}} = \frac{5}{12}\sqrt{\frac{g\,z^3(1+2.4mz)^3}{(1+4.8mz)}} \qquad (13)$$

where

Q is the flowrate in m^3 or in ft^3/s;
D is the diameter of the channel in meters or feet;
g is the gravitational constant in m/s^2 or in ft/s^2;
z is the dc/D ratio;
m is the slope of the sides of the flume;
dc is the depth of the flow in the throat of the flume in meters or feet.

TABLE 9 - PALMER-BOWLUS FLUME - STANDARD DIMENSIONS ACCORDING TO LUDWIG

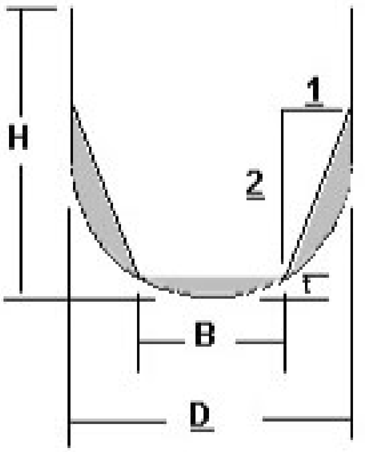
Dimensions in millimeters (and inches)

D	B	H	t	D/2	p	L
102 mm (4")	43 (1.6")	102 (4")	8 (0.3")	51 (2")	23 (9")	125 (4.9")
152 mm (6")	64 (2.5")	152 (6")	13 (0.5")	76 (3")	38 (1.5")	229 (9")
203 mm (8")	85 (3")	203 (8")	17 (0.6")	102 (4")	46 (1.8")	295 11.6")
254 mm (10")	106 (4")	254 (10")	22 (0.8")	127 (5")	61 (2.4")	376 (14.8")
305 mm (12")	127 (5")	305 (12")	25 (1")	152 (6")	76 (3")	457 (18")
381 mm (15")	159 (6.25")	381 (15")	32 (1.25")	191 (7.5")	95 (3.75")	572 (225")
457 mm (18")	191 (7.5")	457 (18")	38 (1.5")	229 (9")	114 (4.5")	686 (27")
533 mm (21")	223 (8.75")	533 (21")	45 (1.75")	267 (10.5")	133 (5.25")	800(31.5)
610 mm (24")	254 (10")	610 (24")	51 (2")	305 (12")	152 (6")	914 (36")
686 mm (27")	275 (11.25")	686 (27")	55 (2.25")	343 (13.5")	172 (6.75")	1029 (40.5")
762 mm (30")	318 (12.5")	762 (30")	64 (2.5")	381 (15")	191 (7.5")	1143 (45")
914 mm (36")	381 (15")	914 (36")	76 (3")	457 (18")	229 (9")	1372 (54")
1067 mm (42")	445 (17.5")	1067 (42")	89 (3.5")	533 (21")	267 (10.5")	1600 (63")
1219 mm (48")	508 (20")	1219 (48")	102 (4")	610 (24")	305 (12")	1829 (72")
1524 mm (60")	635 (25")	1524 (60")	127 (5")	762 (30")	381 (15")	2286 (90")

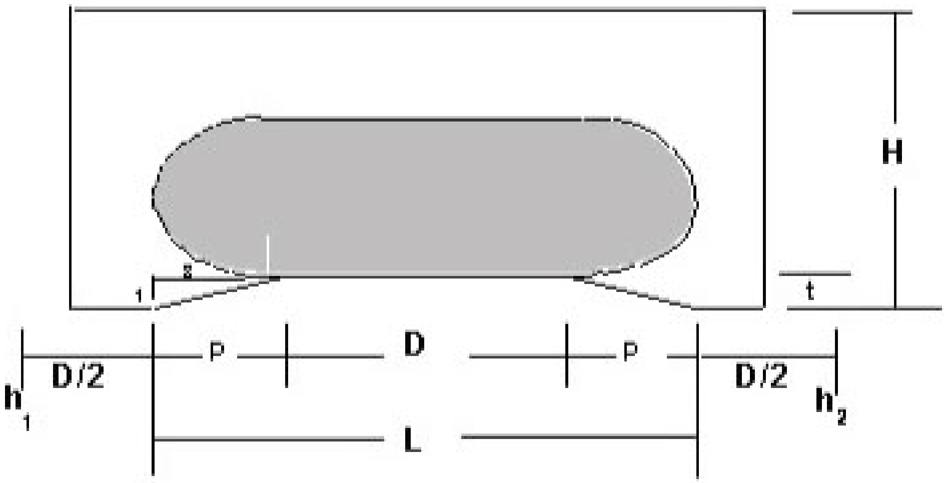
Where:

D	is the dimension of the flume;
B	is the width of the base of the flume (5D/12);
H	is the height of the flume (=D);
t	is the height difference between the crest of the flume and the channel bottom (D/12);
D/2	is the location of the measuring point;
p	is the length of the inclined section of the base (1 vertical: 3 horizontal);
L	is the total length of the base of the flume {D + 2(p)}.

FIGURE 13 - SHAPE OF A PALMER-BOWLUS FLUME ACCORDING TO LUDWIG



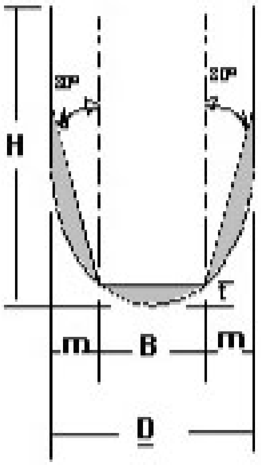
Cross section



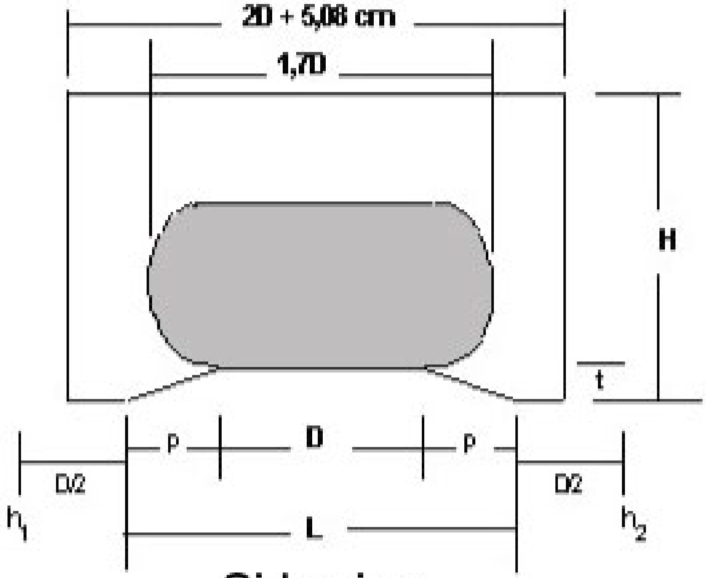
Side view

Note: Refer to Table 9 for a description of letters.

FIGURE 14 - SHAPE OF A PALMER-BOWLUS FLUME - PLASTI-FAB INC.



Cross section



Side view

Note: Refer to Table 10 for a description of letters.

TABLE 10 - PALMER-BOWLUS FLUME - STANDARD DIMENSIONS ACCORDING TO PLASTI-FAB INC.

D	B	H	t	D/2	p	L	m
102 4 "	51 2 "	102 4 "	17 0.6 "	51 2 "	51 2 "	203 8 "	25 1 "
152 6 "	76 3 "	152 6 "	25 1 "	76 3 "	76 3 "	305 12 "	40 1.5 "
203 8 "	102 4 "	203 8 "	34 1.3 "	102 4 "	102 4 "	406 16 "	51 2 "
254 10 "	127 5 "	254 10 "	42 1.6 "	127 5 "	127 5 "	508 20 "	64 2.5 "
305 12 "	152 6 "	305 12 "	51 2 "	152 6 "	152 6 "	610 24 "	76 3 "
381 15 "	191 7.5 "	381 15 "	64 2.5 "	191 7.5 "	191 7.5 "	762 30 "	96 3.75"
457 18 "	229 9 "	457 18 "	76 3 "	229 9 "	229 9 "	914 36 "	114 4.5 "
533 21 "	267 10.5 "	533 21 "	89 3.5 "	267 10.5 "	267 10.5 "	1067 42 "	133 5.25"
610 24 "	305 12 "	610 24 "	102 4 "	305 12 "	305 12 "	1219 48 "	152 6 "
686 27 "	343 13.5 "	686 27 "	114 4.5 "	343 13.5 "	343 13.5 "	1372 54 "	172 6.75"
762 30 "	381 15 "	762 30 "	127 5 "	381 15 "	381 15 "	1524 60 "	191 7.5 "
914 36 "	457 18 "	914 36 "	152 6 "	457 18 "	457 18 "	1829 72 "	229 9 "
1067 42 "	533 21 "	1067 42 "	178 7 "	533 21 "	533 21 "	2134 84 "	267 10.5"
1219 48 "	610 24 "	1219 48 "	203 8 "	610 24 "	610 24 "	2438 96 "	305 12 "
1524 60 "	762 30 "	1524 60 "	254 10 "	762 30 "	762 30 "	3048 120 "	381 15 "

where:

D is the dimension of the flume;
B is the width of the base of the flume (D/2);
H is the depth of the flume (= D);
t is the height difference between the base of the flume and the channel bottom (D/6);
D/2 is the location of the measuring point;
p is the length of the inclined section of the base (D/2);
L is the total length of the base of the flume D + 2(p);
m is the distance between the base and sides (D/4).

TABLE 11 - PALMER-BOWLUS FLUME - RECOMMENDED MINIMUM AND MAXIMUM FLOWRATES IN FREE FLOW CONDITIONS

Flume diameter mm (in)	Maximum upstream slope (%)	Minimum depth (mm)	MINIMUM FLOWRATE		Maximum depth (mm)	MAXIMUM FLOWRATE	
			l/s	m^3/d		l/s	m^3/d
102 4	2.2	15	0.2	16	60	2.2	190
152 6	2.2	33.5	0.98	85	110	8.9	770
203 8	2	45.7	2.1	181.4	149	18.96	1 638
254 10	1.8	54.8	3.45	298.1	186	32.8	2 837
305 12	1.6	67	5.6	483.8	223	51.8	4 477
381 15	1.5	82.3	9.45	816.5	277	90.1	7 780
457 18	1.4	100.6	15.53	1 341.8	332	141.8	12 254
533 21	1.4	115.8	22.08	1 907.7	390	210.7	18 202
610 24	1.4	134.1	31.72	2 740.6	445	294.5	25 445
686 27	1.4	149.4	40	3 456	500	390.8	33 768
762 30	1.4	167.6	55.22	4 771	555	509.9	44 050

Note: Values in this table are valid for flumes manufactured by Plasti-Fab Inc.

Because some manufacturers do not always follow all of Ludwig's requirements, there may be occasions where use of this formula to determine flow in a particular flume does not yield satisfactory results. Where this is the case, we recommend that when purchasing a flume, you request that the manufacturer include the calculation formula and the resulting table.

2.2.7. A flume's measurement capacity

The maximum measurement capacity for this type of flume is determined on the basis of the following principles(11):

- water depth (h_l) upstream from the flume must not exceed 90 % of the diameter (D) of the conduit: (h_l = 0.9 D);
- the flume's working depth (h_u) is equal to the allowable depth upstream (h_l), minus the depth of the flume's crest (t): (h_l - t) (see Figure 14);
- the maximum depth measurement (h_{max}) is equal to the ratio between the flume's working depth (h_u) and the size of the conduit (D): (h_u/D). This value is approximately 73 % of the flume's nominal value.

Example

For a 762 mm (30 in) flume;
D = 762 mm (30 in);
t = 127 mm (5 in)(according to Table 10);
h_l = 0.9 D, in this case: 686 mm (27 in);
h_u = h_l - t, in this case: 686 mm - 127 mm = 559 mm (27 in - 5 in = 22 in);
h_{max} = h_u/D, in this case : 559 mm/762 mm (22 in/30 in) = 0.733 or 73 %.

2.2.8. Precision

This type of flume is able to produce values that are as precise as values obtained with a Parshall flume. The flow measurement margin of error is approximately ± 3 %.

To generate this type of precision, particular attention must be taken when installing the flume, to avoid producing a submerged flow and excessive approach velocity.

2.2.9. Sources of error

The principal sources of error that can affect a flume's precision are as follows:

- changes to standard dimensions at the time of installation

  throat width: during installation, it is important to ensure that the flume is not distorted, compressed or twisted in any way, and that it maintains its original dimensions and shape;

inspection of the horizontal position: if a flume is not transversely level (perpendicular to flow), the average depth should be used to determine the depth/flow relationship. The depth should therefore be measured on each side of the flume to determine average depth;

longitudinal position: the flume may have a slight downstream incline, 6 mm maximum for small flumes {610 mm (24 in) and less} and 20 mm maximum for large flumes;

flume length: if modifications have to be made to length, they should be made in the downstream portion only, after a thorough assessment of how the precision of measurements will be affected.

- improper measuring point position

  for all flumes of this type, the measuring point must be located upstream from the flume, at a distance equal to half the diameter of the flume (D/2), the distance of which is measured from the beginning of the rise between the crest (floor) of the flume and the bottom of the channel (see Figures 13 and 14);

  the water depth must be measured from the crest of the flume and not from the channel bottom.

- sensitivity of water depth measurement

  because variations in depth related to flow variations are small, an extremely sensitive device must be used to detect the level of liquid.

- inadequate approach

  this type of flume does not have a converging section that compensates for distortions in approach velocities and their distribution. The reader can refer to section 2.2.11 for information about installation conditions to determine rules that govern approach.

- incorrect submerged flow measurement technique

  Often, due to a lack of knowledge, users do not know how to recognize and assess a flume that is operating in submerged flow conditions, and take a flow measurement in only one location, instead of at the two measuring points this situation requires.

- obstructions in the flume throat

  it is important to ensure that nothing is blocking the flume throat, particularly in the case of small flumes, since liquid will be forced to move over the obstacle, which increases water depth and distorts the measurement.

- use of the depth/flow table

  it is important to ensure that the depth/flow conversion table and flowmeter integration formula are identical to the table and formula supplied by the flume manufacturer.

2.2.10. Selection criteria

Different sizes of Palmer-Bowlus flumes can be used to measure a range of anticipated flows. Many other factors should be considered when selecting a flume. These factors include:

- discharge: it is important to select the correct size of flume to ensure operation in free flow conditions, regardless of flow pattern and system constraints;
- the minimum and maximum discharge flows;
- the sensitivity necessary to detect and measure depth fluctuations even where there is very little change in flowrate;
- the desired precision.

2.2.11. Installation specifications

A flume is usually placed directly in the channel and secured to the channel bottom. In the case of temporary setups, flumes are often incorporated in sand bag dams.

If the slope of a channel is too steep, the flume can be lifted slightly to reduce the slope, as long as the diameter of the delivery pipe is large enough to ensure that the water depth upstream from the flume does not exceed the recommended depth, that is, 90 % of the channel depth(11).

When the flume is installed, it is important to ensure that all of the original physical components remain undamaged.

The system must allow the water level upstream from the flume to rise. A higher water level must occur far enough upstream, more specifically a distance of at least 10 diameters of the conduit.

The length of the approach section must be at least 25 times the diameter of the delivery pipe(12).

The slope of the approach section must be less than 2 % for small flumes, and less than 1 % for flumes 762 mm (30 in) and over.

The flow must be uniform, well distributed and calm at the measuring point. No surface waves must be present.

If a flume is smaller than the diameter of the conduit, it must be fitted with a transition section, the length of which should be at least four times the diameter of the conduit in which it is inserted. The transition section must also be connected to the conduit by a reducer section, where the angle of reduction does not exceed 30°(9).

A steep slope in the conduit downstream will not affect the precision of measurements. This type of slope, however, is not necessary, although it may help maintain free flow conditions.

After the diverging section, there should be no sharp bends in the conduit that could restrict flow and cause a submerged flow.

2.2.12. Submerged flow

A flow is said to be submerged as soon as the water level downstream reaches the measurement threshold. Flow can be measured as long as the h_2 (water depth downstream)/h_1 (water depth upstream) ratio is less than 85 %(11).

During installation, all precautions must be taken to prevent submerged flow conditions from occurring, even if it means raising the crest of the flume or increasing the slope of the channel downstream.

2.2.13. Loss of head

There is no significant loss of head due to installation of a Palmer-Bowlus flume. At maximum flow, the water depth upstream should not exceed 90 % of the nominal depth of the channel.

2.2.14. Flume modification

If there is not enough room to install a flume, the flume can be modified to allow it to be inserted. The following modifications can be made to a flume:

- reduce the height of the flume's diverging and throat sections by cutting it at an angle. The flume can be cut from the top, in line with the threshold, up to the end of the flume, halfway up(9);
- vertically cut the flume, at any location between the end of the threshold and the end of the flume.

If the flow velocity is too strong, it can be reduced by increasing the height of the threshold. To do this, the entire flume must be lifted away from the channel bottom.

2.2.15. Calibration

See section 1.12.13 for calibration.

Due to the size of tanks available, use of the volumetric method is generally limited to flumes measuring 686 mm (27 in) and under.

During calibration, the water depth in the flume, at the measuring point, must not vary more than 3.5 %, regardless of which method is used.

For temporary systems, a simple verification of the following conditions is all that is required:

- the longitudinal and transversal sections of the flume should be level;
- the flow velocity upstream from the flume should be less than 0.6 m (2 ft)/second;
- there should be no waves or turbulence upstream from the flume;
- free flow conditions must be present;
- there are no leaks in the flume structure.

2.3. Leopold-Lagco flume

The Leopold-Lagco flume was developed in the early 1960s and introduced on the market in 1965 by F.B. Leopold Company Inc. of Pennsylvania(13).

2.3.1. Description

The Leopold-Lagco flume has a round shape. The purpose of its rounded shape is to create a restriction in the conduit, which causes a greater flow velocity in the throat of the flume.

This flume operates according to the Venturi principle. The throat is uniform and its length is equal to the diameter of the channel for which it was designed. Similar to a Palmer-Bowlus flume, its throat section has a rectangular shape.

It consists of three sections: a converging section, throat section and diverging section.

As in the case of Palmer-Bowlus flumes, the size of Leopold-Lagco flumes is defined by the diameter of the channel in which it is installed, not by the inside width of the throat section.

There are three models:

<u>permanent installation model</u>: there is a slight extension of the converging and diverging sections;

<u>insertion model</u>: outer radius of the flume corresponds to the inner radius of the channel in which it is to be installed;

<u>cutthroat model</u>: the diverging section is not as high. This flume is used on a temporary basis only.

The inner surface of the flume must be made of material that is smooth and free of irregular edges. The outer surface is made of a material that facilitates adhesion to a concrete surface.

The flume is made of fiberglass in standard sizes varying between 152 mm (6 in) and 1219 mm (48 in). Larger flumes, up to 1829 mm (72 in), can be manufactured on special order. Standard sizes in millimeters and inches are as follows: 152 (6), 203 (8), 254 (10), 305 (12), 381 (15), 457 (18), 533 (21), 610 (24), 762 (30), 914 (36), 1067 (42), and 1219 mm (48 in)(14).

2.3.2. Operating principle

Due to vertical and lateral restrictions, a Leopold-Lagco reduces the flow area, causing the water level upstream from the throat section to rise, followed by a drop in water level and an increased flow velocity.

Flow can be determined by simply measuring the water level upstream from the flume, since it has been established that depth varies according to flow.

Literature provides no information about use of this flume in submerged flow conditions and no correction formula. Use in only free flow conditions is therefore recommended.

2.3.3. Applications

A Leopold-Lagco flume is used as a main measuring device on a temporary or permanent basis. Like all flumes, it is an effective tool for measuring the flow of water that contains solids.

Due to their relatively small volume, flumes with a diameter of 381 mm (15 in) or less can be inserted in a standard sewer manhole, without the need to modify access. It is relatively easy to install because there is no need for a required distance from the bottom of the channel in which it is inserted.

2.3.4. Dimensions

The dimensions of a Leopold-Lagco flume are a function of the diameter of the conduit in which it is installed. Like a Parshall flume, standards governing dimensions and configuration of the flume are very strict.

Depending on the manufacturer, a flume should be manufactured according to the dimensions and shape shown in Table 12 and Figure 15.

2.3.5. Range of measurements

Leopold-Lagco flumes can measure flows varying between 84.2 m^3 per day, for a 152 mm (6 in) flume, and 108,445 m^3 per day, for a 1219 mm (48 in) flume.

Table 13 shows the minimum and maximum measurable flows in free flow conditions for this type of flume. For purposes of this document, only data that apply to 152 mm (6 in) and 1219 mm (48 in) flumes are shown(14).

2.3.6. Discharge equation in free flow conditions

The discharge equation resulting from the depth/flow relationship associated with free flow conditions is expressed as follows:

$$Q = KH^n \quad (14)$$

where:

Q	is the flowrate in liters or US gallons per second;
K	is the constant based on flume size;
H	is the water depth measured at point h_1 in meters or feet;
n	is the exponent constant (1.547).

Table 13 shows the values of the constant “K” for the above formula.

TABLE 12 - LEOPOLD-LAGCO FLUME - STANDARD DIMENSIONS ACCORDING TO F.B. LEOPOLD COMPANY INC.

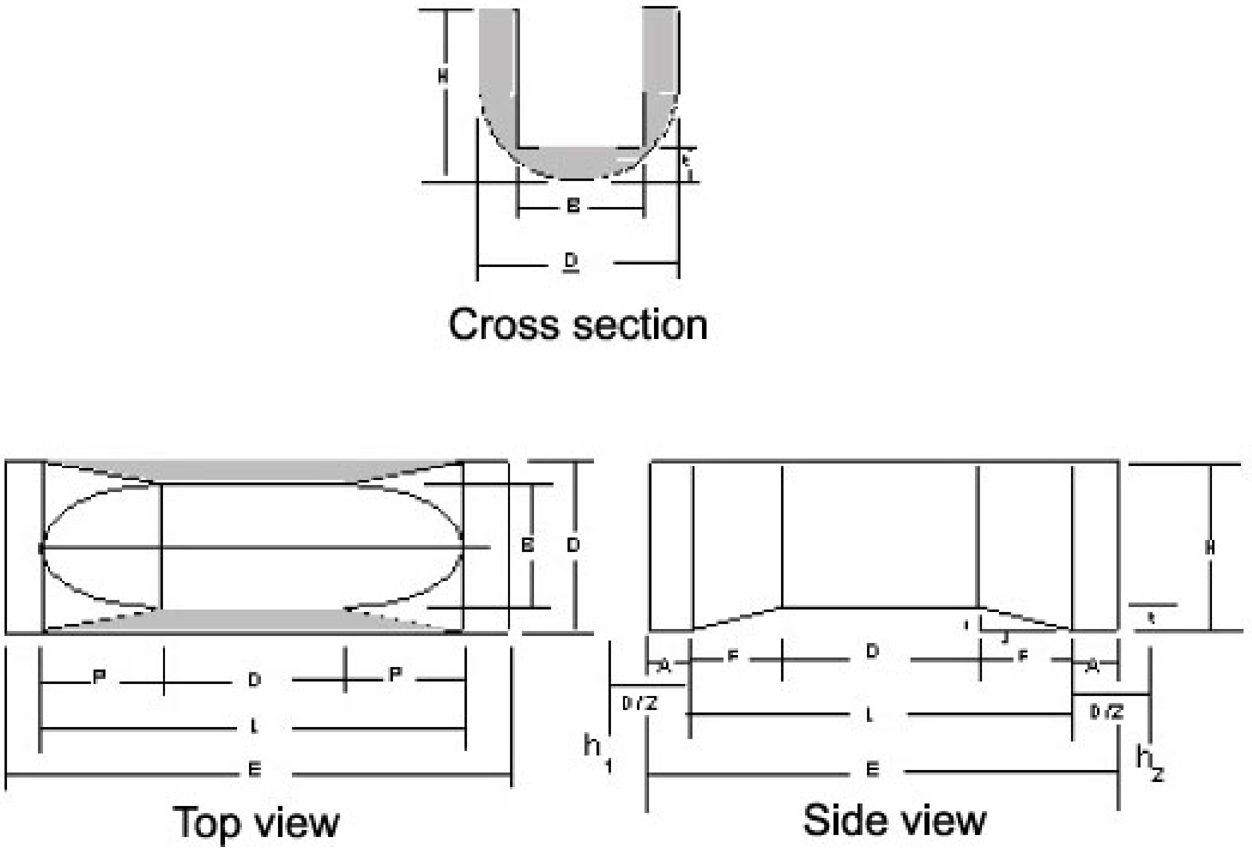
Note: measurements in millimeters and inches

D	B	H	t	D/2	P	L	A	E
152 (6)	102 (4)	152 (6)	25 (1)	76 (3)	76 (3)	305 (12)	51 (2)	406 (16)
203 (8)	136 (5.3)	203 (8)	34 (1.3)	102(4)	102(4)	406 (16)	51 (2)	508 (20)
254 (10)	169 (6.7)	254 (10)	42 (1.7)	127 (5)	127 (5)	508 (20)	51 (2)	610 (24)
305 (12)	203 (8)	305 (12)	51 (2)	152 (6)	152 (6)	610 (24)	51 (2)	711 (28)
381 (15)	254 (10	381 (15)	64 (2.5)	191 (7.5)	191 (7.5)	762 (30)	51 (2)	864 (34)
457 (18)	305 (12)	457 (18)	76 (3)	229 (9)	229 (9)	914 (36)	51 (2)	1016 (40)
533 (21)	356 (14)	533 (21)	89 (3.5)	267 (10.5)	267 (10.5)	1067 (42)	51 (2)	1168 (46)
610 (24)	406 (16)	610 (24)	102 (4)	305 (12)	305 (12)	1219 (48)	152 (6)	1524 (60)
762 (30)	508 (20)	762 (30)	127 (5)	381 (15)	381 (15)	1524 (60)	152 (6)	2134 (84)
914 (36)	610 (24)	914 (36)	152 (6)	457 (18)	457 (18)	1829 (72)	152 (6)	2438 (96)
1067 (42)	711 (28)	1067 (42)	178 (7)	533 (21)	533 (21)	2134 (84)	152 (6)	2743 (108)
1219 (48)	813 (32)	1219 (48)	203 (8)	610 (24)	610 (24)	2438 (96)	152 (6)	3048 (120)
1524 (60)	1016 (40)	1524 (60)	254 (10)	762 (30)	762 (30)	3048 (120)	152 (6)	3353 (132)
1676 (66)	1118 (44)	1676 (66)	279 (11)	838 (33)	838 (33)	3353 (132)	152 (6)	3658 (144)
1829 (72)	1219 (48)	1829 (72)	305 (12)	914 (36)	914 (36)	3658 (144)	152 (6)	3962 (156)

where:

D is the dimension of the flume that is equal to the nominal size of the channel;
B is the width of the flume throat (2/3D);
H is the height of the flume (=D);
t is the height difference between the base of the flume and the channel bottom (D/6);
D/2 is the position of the measuring point;
P is the length of the inclined section of the base (D/2);
L is the total length of the base of the flume (2D)
A is the extension of the structure
E is the total length of the structure.

FIGURE 15 - SHAPE OF LEOPOLD-LAGCO FLUME - F.B. LEOPOLD COMPANY INC.



Note: See Table 12 for a description of letters.

TABLE 13 - LEOPOLD-LAGCO FLUME - RECOMMENDED MINIMUM AND MAXIMUM FLOWRATES IN FREE FLOW CONDITIONS

Flume diameter mm (in)	K Constant	Minimum depth	MINIMUM FLOWRATE		Maximum depth	MAXIMUM FLOWRATE	
	Flow l/s gal$_{US}$/s	mm ft	l/s gal$_{US}$/s	m^3/d Mgal$_{US}$/d	mm ft	l/s gal$_{US}$/s	m^3/d Mgal$_{US}$/d
152 (6)	221.25 9.298	30 0.1	0.999 0.264	86.33 0.023	107 0.35	6.939 1.833	599.57 0.158
203 (8)	291.02 12.238	40 0.13	1.97 0.521	170.4 0.045	137 0.45	13.46 3.558	1 163.4 0.307
254 (10)	360 15.132	50 0.16	3.5 0.889	302.1 0.077	182 0.6	25.8 6.866	2 229.2 0.593
305 (12)	420.004 18.005	60 0.2	5.52 1.493	476.5 0.129	213 0.7	39.25 10.37	3 391.6 0.896
381 (15)	529.8 22.269	76 0.25	9.87 2.608	853.1 0.225	274 0.9	71.6 18.92	6 188.8 1.635
457 (18)	630.32 26.46	90 0.3	15.19 04.114	1 313.1 0.355	320 1.05	108.17 28.574	9 346 2.469
533 (21)	730.074 30.692	106 0.35	22.67 6.049	1 907.7 0.523	381 1.25	164.08 43.347	14 177 3.745
610 (24)	829.15 34.859	122 0.4	32 8.447	2 762.5 0.73	426 1.4	221.5 58.665	19 136 5.069
762 (30)	1 025.63 43.118	152 0.5	55.856 14.756	4 825.9 1.275	533 1.75	387.92 102.48	33 516 8.854
914 (36)	1 220.24 51.301	152 0.5	66.45 17.557	5 741.6 1.517	640 2.1	611.91 161.661	52 869 13.967
1067 (42)	1 413.35 59.418	198 0.65	115.504 30.514	9979.564 2.636	746 2.45	898.21 237.662	77 605 20.534
1219 (48)	1 605.15 67.482	198 0.65	131.179 34.655	11 333.8 2.994	853 2.8	1 256.15 331.851	108 531 28.672

Note: The values shown in this table are valid for flumes manufactured by F.B. Leopold Company Inc.

2.3.7. Measurement capacity of a flume

The maximum measurement capacity (Q_{max}) for this type of flume arises from the allowable maximum depth (h_{max}) measurement, which is approximately 70 % of the nominal size of the flume (D).

Therefore, for a flume with a nominal size of 457 mm (18 in), the allowable maximum depth is 320 mm (12.6 in).

2.3.8. Precision

The precision of flow measurement is comparable to that obtained with other types of flumes. According to the manufacturer, this flume creates such a high water level at the measuring point that the error associated with the evaluation of flow is approximately 2 %, so long as the flume has been installed in compliance with specific physical requirements(15).

For practical purposes, flow measurement is performed with a margin of error of ± 5 % of the actual value.

2.3.9. Sources of error

The principal sources of error that can reduce a flume's precision are as follows:

- modifications of standard dimensions during installation

  <u>throat width</u>: it is important to ensure that the flume is not distorted, compressed or twisted during installation, and that it maintains its original dimensions and shape.

  <u>inspection of the horizontal:</u> if a flume is not transversely level (perpendicular to flow), water depth should be measured on each side of the flume to determine the average depth and the depth/flow relationship.

  <u>longitudinal position</u>: the flume may have a slight downstream incline, 6 mm maximum for small flumes {610 mm (24 in) and less} and 20 mm maximum for large flumes.

  <u>flume length</u>: if modifications have to be made in the direction of length, they should be made in the downstream section only, after a thorough evaluation of effects on the precision of measurement.

- incorrect measuring point position

  for all flumes of this type, the measuring point must be located upstream from the flume, at a distance equal to half the diameter of the flume (D/2), the distance of which is measured from the beginning of the rise between the crest (floor) of the flume and the channel bottom.

  water depth must be measured from the crest of the flume and not from the channel bottom.

- sensitivity of water depth measurement

  because the variations in depth related to fluctuations in flow are small, an extremely sensitive device must be introduced to detect the level of liquid.

- inadequate approach

  this type of flume does not have a converging section that allows distortions in approach velocities and distribution to be corrected (the reader can refer to section 2.3.11, which discusses installation conditions to find out about rules that regulate approach).

- incorrect submerged flow measurement technique

  often, due to a lack of knowledge, users do not know how to recognize and assess a flume that is operating in submerged flow conditions, and take a flow measurement without taking submerged flow conditions into account.

- obstructions in the flume throat

  it is important to ensure that nothing is blocking the flume throat and causes an incorrect water depth measurement, due to the flow moving over the obstacle (particularly in the case of small flumes).

- use of the depth/flow table

  it is important to ensure that the depth/flow conversion table and flowmeter integration formula are identical to those provided by the flume supplier. The recommended maximum depth measurement should also never be exceeded.

2.3.10. Selection criteria

Although installation of a Parshall flume is recommended for a permanent measurement site, use of a Leopold-Lagco flume may be adequate.

Since a number of different models of Leopold-Lagco flumes are often available for measurement of the range of flows anticipated, other factors should be considered when selecting a flume. These factors include:

- flow: it is important to select the correct size of flume to ensure operation in free flow conditions, regardless of flow pattern and installation constraints;
- the diameter of the conduit;
- minimum and maximum flows to measure;
- the sensitivity necessary to detect and measure depth fluctuations even where there is very little variation in flow;
- the desired precision.

2.3.11. Installation specifications

A Leopold-Lagco flume is installed directly in a sewer channel and secured to the channel bottom, usually in the straight flow section, in an observation well.

It should be installed in a conduit in which the slope of the approach section is less than 2 %, in the case of small flumes, and less than 1 % for flumes 762 mm (30 in) and over. If the slope of the conduit is too steep, the flume can be lifted slightly to reduce the slope.

When the flume is installed, it is important to ensure that all of the original physical components remain undamaged.

Installation must enable the water level upstream from the flume to increase. This higher water level must occur far enough upstream, more specifically at least 10 diameters of the conduit.

The length of the approach section must be at least 25 times the diameter of the delivery pipe.

The flow must be uniform, well distributed and calm at the measuring point. No surface waves must be present.

If a flume is smaller than the diameter of the conduit, it must be fitted with a transition section, the length of which should be at least four times the diameter of the conduit in which it is installed. The transition section must also be connected to the conduit by a reducer section, where the angle of reduction does not exceed 30°.

A steep slope in the conduit downstream will not affect the precision of measurements. This type of slope, however, is not necessary, although it may help maintain free flow conditions.

After the diverging section, there should be no sharp bends in the conduit that could restrict flow and cause a submerged flow.

2.3.12. Submerged flow

A flow is said to be submerged as soon as the water level downstream reaches the measurement threshold.

Measurement in submerged flow conditions must be avoided. During installation, all precautions must be taken to prevent submerged flow conditions from occurring, even if it means raising the crest of the flume or increasing the slope of the channel downstream.

2.3.13. Loss of head

A Leopold-Lagco flume creates very little loss of head. For a flume that has a nominal dimension that corresponds to that of the conduit in which it is installed, the water depth upstream must not exceed 90 % of the nominal height of the conduit, at maximum flow.

2.3.14. Flume modifications

If there is not enough room to install a flume, the flume can be modified to allow it to be inserted. The following modifications can be made to a flume:

- reduce the height of the flume's diverging and throat sections by cutting it at an angle. The flume can be cut from the top, in line with the threshold, up to the end of the flume, halfway up;
- vertically cut the flume, at any location between the end of the threshold and the end of the flume.

2.3.15. Calibration

See section 1.12.13 for calibration.

Due to the size of tanks available, use of the volumetric method is generally limited to flumes measuring 762 mm (30 inches) and under.

During calibration, the water depth in the flume, at the measuring point, must not vary more than 3.5 %, regardless of which method is used.

For temporary systems, a simple verification of the following conditions is all that is required:

- the longitudinal and transversal sections of the flume should be level;
- the flow velocity upstream from the flume should be less than 0.6 m (2 ft)/second;
- there should be no waves or turbulence upstream from the flume;
- free flow conditions must be present;
- there are no leaks in the flume structure.

2.4. Cutthroat flume

A cutthroat flume was developed in the mid-1960s by Utah State University Water Resources Laboratory. It is used to measure flow in locations where there is no slope or very little slope(4).

2.4.1. Description

A cutthroat flume consists of a converging section and diverging section. The control section (W) does not have parallel sides because the flume consists only of a converging and diverging section. The bottom of the entire length of the flume is flat(16).

For flumes that are less than 1.37 m (4.5 ft) long (L) and 15.2 cm (0.5 ft) wide in the control section (W), the inlet of the converging section may be rounded. For larger flumes, the inlet of the converging section may have vertical walls at a 30° angle(16).

To prevent erosion due to water fall, the diverging section is usually extended by means of vertical walls, and the angle of these walls is steeper than the angle of the walls in the diverging section.

2.4.2. Operating principle

Cutthroat flumes operate according to the Venturi principle. Due to the lateral shape of its walls, the flume restricts the flow area, which causes the water level upstream from the control section to rise, followed by a sudden and significant drop of the water level in the control section, accompanied by an increase in flow velocity. The flow can be determined by simply measuring the water depth, because depth varies proportionally with flow.

Although this flume can be used in submerged flows, use in free flow conditions is strongly recommended. In free flow, a flow measurement can be obtained using only one measuring point, but in submerged flow conditions, the depth downstream from the control section must also be measured(6) (16).

2.4.3. Applications

The cutthroat flume was developed to measure flow in open natural channels, such as rivers, streams, drainage ditches, etc. with a small slope. It has been the subject of several studies that demonstrate its effectiveness as a measuring device in sewer systems and water treatment plants(17).

The geometry and operating principle of a cutthroat flume make it an effective device for measuring flow in water that contains solids. Because this flume causes only a small loss of head and requires no difference in height between the bottom of the channel and base of the flume, it is relatively easy to adapt to existing sewer systems.

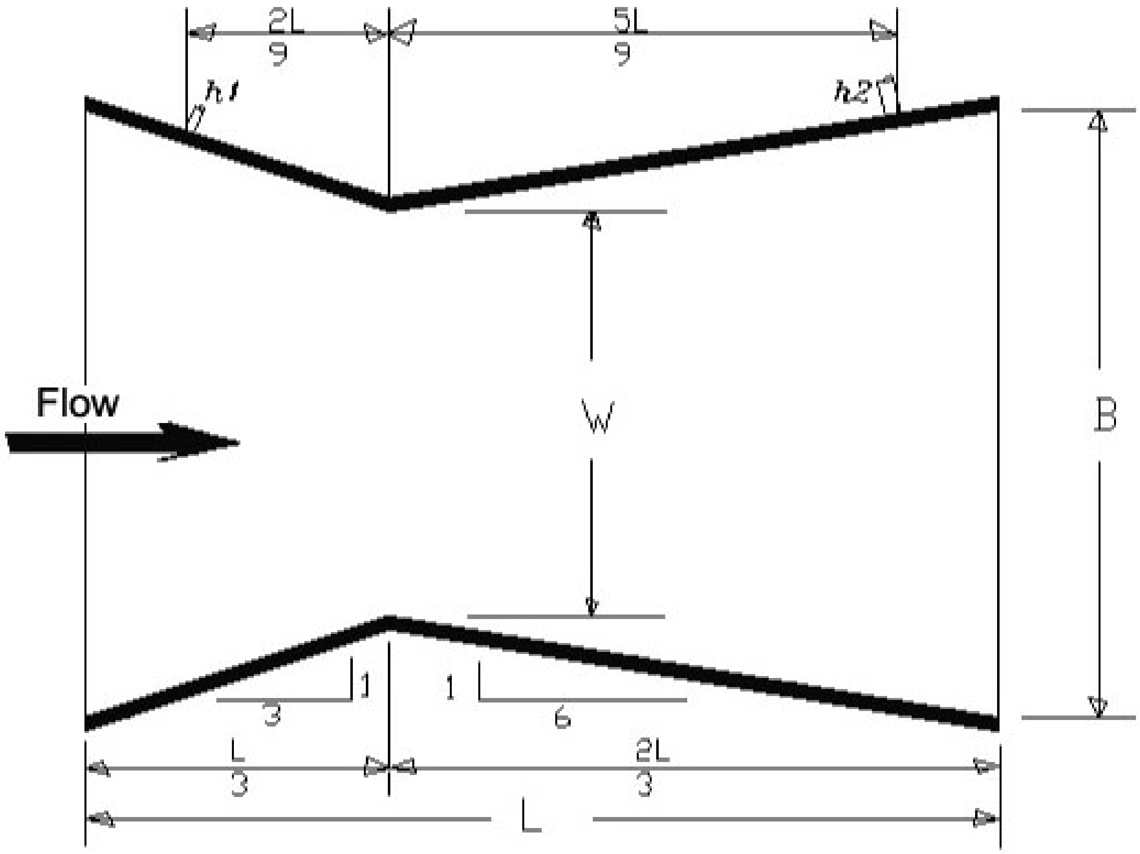
A cutthroat flume is simple and inexpensive to manufacture. It is also perfectly suited to a temporary measurement system.

2.4.4. Dimensions

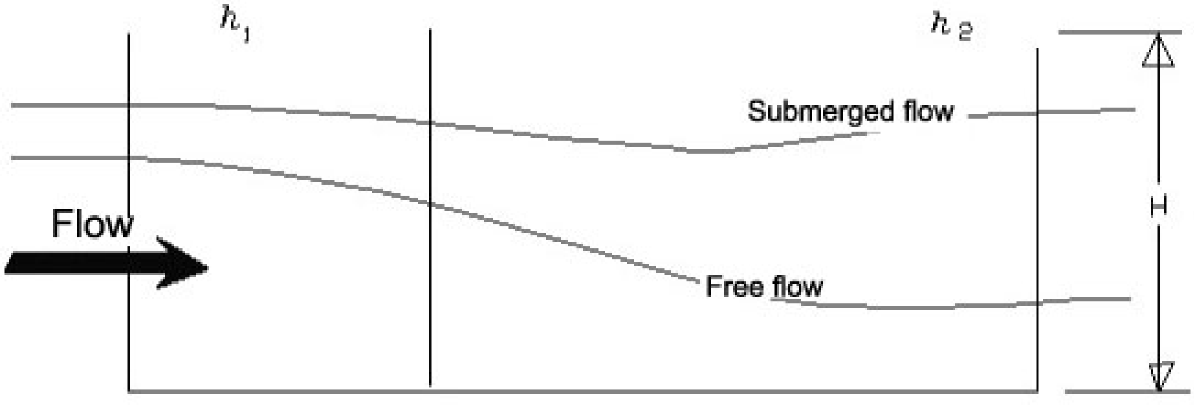
The dimension of a cutthroat flume is defined by the total length of the flume (L) and the width of the control section (constriction) (W).

Figure 16 shows the physical characteristics of a cutthroat flume and Table 14, the exact dimensions this flume should have.

FIGURE 16 - CUTTHROAT FLUME - PHYSICAL CHARACTERISTICS



Top view



Cross section

TABLE 14 - CUTTHROAT FLUME – STANDARD DIMENSIONS

Dimensions in millimeters and feet

L	W	L 1	L 2	B	H	h1	h2
2743 9’	1829 ± 0.8 6' ± 1/32"	914 3’	1829 6’	2438 8’	914 3’	610 2’	1524 5’
	1219 ±0.8 4'± 1/32"			1829 6’			
	610 ± 0.8 2'± 1/32"			1219 4’			
	305 ± 0.8 1' ± 1/32"			914 3’			
1372 4.5'	610 ± 0.8 2' ± 1/32"	457 1.5’	914 3’	914 3’	457 1.5’	305 1’	762 2.5’
	305 ± 0.8 1' ± 1/32"			610 2’			
	152 ± 0.4 0.5' ± 1/64"			457 1.5’			
	76 ± 0.4 0.25'± 1/64"			381 1.25’			
914 3’	406 ±0.8 1.33' ±1/32"	305 1’	610 2’	610 2’	305 1’	203 0.667’	508 1.667’
	203 ±0.8 0.67'± 1/32"			406 1.33’			
	102 ± 0.4 0.33' ±1/64"			305 1’			
	51 ± 0.4 0.17' ± 1/64"			254 0.834’			
457 1.5’	203 ±0.8 0.67'± 1/32"	152 0.5’	305 1’	305 1’	152 0.5’	102 0.33’	254 0.83’
	102 ± 0.4 0.33'±1/64"			203 0.667’			
	51 ± 0.4 0.17'± 1/64"			152 0.5’			
	25 ± 0.4 0.083'±1/64"			127 0.416’			

L: is the total length of the flume
L1: is equal to L/3
L2: is equal to 2L/3
B: is equal to W +L/4.5
H: is equal to L/3
h1: is equal to 2L/9
h2: is equal to 5L/9

2.4.5. Range of measurements

Cutthroat flumes can measure flows varying between 32 m^3 per day, for a flume 457 mm (1.5 ft) long with a constriction of 25 mm (0.083 ft), and 210,555 m^3 per day, for a flume 2,743 mm (9 ft) long with a constriction of 1,829 mm (6 ft).

Table 15 shows recommended minimum and maximum flowrates in free flow conditions. The data in Table 15 applies to flumes with a constriction between 25 mm (0.083 ft) and 1,829 mm (6 ft) and a length varying between 457 mm (1.5 ft) and 2,743 mm (9 ft).

2.4.6. Discharge equation in free flow conditions

The discharge equation resulting from the depth/flow relationship in free flow conditions is expressed as follows(16):

$$Q = Ch_1^{n_1} \quad (15)$$

where:

Q is the flowrate in cubic meters or cubic feet per second;
C is $KW^{1.025}$;
K is the constant according to the length of the flume and unit of measurement;
W is the dimension of the constriction in meters or feet;
h_1 is the water depth measured upstream from the constriction (W) in meters or feet;
n_1 is the exponent constant according to the length of the flume(16).

TABLE 15 - CUTTHROAT FLUME - RECOMMENDED MINIMUM AND MAXIMUM FLOWRATES FREE FLOW CONDITIONS

Flume dimensions in mm and feet		Minimum depth mm (ft)	MINIMUM FLOWRATE		Maximum depth mm (ft)	MAXIMUM FLOWRATE	
L	W		l/s	m^3/d		l/s	m^3/d
2743 9'	1829 6'	183 0.6’	280.13	24 219	732 2.4’	2 437	210 555
	1219 4'		184.99	15 983		1 608	138 954
	610 2'		90.91	7 855		790	68 284
	305 1'		44.67	3 859		388	48 297
1372 4.5'	610 2'	91 0.3'	35.06	914 3'	457 1.5'	305	26 333
	305 1'		17.23	610 2’		150	12 941
	152 0.5'		8.47	457 1.5'		74	6 359
	76 0.25'		4.16	381 1.25'		36	3 125
914 3'	406 1.33'	61 0.2’	13.9	1 200	305 1’	120.8	10 436
	203 0.67'		6.8	590		59.4	5 132
	102 0.33'		3.4	289		29.15	2 519
	51 0.17'		1.65	143		14.4	1 242
457 1,5'	203 0.67'	30 0.1'	3.14	271	152 0.5'	27.3	2 360
	102 0.33'		1.54	129		13.4	1 158
	51 0.17'		0.76	66		6.61	571
	25 0.083'		0.37	32		3.23	279

Table 16 shows the values of coefficients C and K for flow measurement in free flow conditions, according to the imperial system and metric system. Table 17 shows discharge equations for cutthroat flumes, in free flow, for values expressed in ft^3 per second and in millions of gallons US per day. Table 18 shows equations for values expressed in m^3 per second and in m^3 per day.

2.4.7. Precision

In free flow conditions, a cutthroat flume produces a precision of measurements similar to that of other flumes, so long as manufacturing and use criteria have been met. In submerged flow conditions, the standard measurement method (measurement at only one point) continues to be accurate until the h_2/h_1 ratio reaches 85 %(17).

2.4.8. Sources of error

The principle sources of error, which reduce the precision of the flume are as follows:

- modification of standard dimensions when the channel is manufactured or during installation

    throat width: for small flumes, a difference of only 4 mm (1/64 in), compared to the standard dimension, is tolerated. For larger flumes, an acceptable deviation is 8 mm (1/32 in) (see Table 14);

    length of the converging section: this section cannot be reduced, but nothing prevents it from being extended. The measuring point, however, must remain in the standard position.

TABLE 16 - CUTTHROAT FLUME - VALUES OF COEFFICIENTS C AND K IN FREE FLOW CONDITIONS

Flume dimensions in mm and feet		Imperial system		Metric system		n 1
L	W	C	K	C	K	
2743 9'	1829 6'	22	3.5	3.966	2.137	1.56
	1219 4'	14.49		2.164		
	610 2'	7.11		1.287		
	305 1'	3.5		0.631		
1372 4.5'	610 2'	8.01	3.98	1.462	2.431	1.72
	305 1'	3.98		0.717		
	152 0.5'	1.96		0.353		
	76 0.25'	0.96		0.173		
914 3'	406 1.33'	6.04	4.5	1.091	2.749	1.84
	203 0.67'	2.97		0.536		
	102 0.33'	1.459		0.262		
	51 0.17'	0.719		0.128		
457 1.5'	203 0.67'	4.03	6.1	0.727	3.725	2.15
	102 0.33'	1.975		0.355		
	51 0.17'	0.974		0.173		
	25 0.083'	0.494		0.085		

TABLE 17 - CUTTHROAT FLUME - DISCHARGE EQUATIONS IN FREE FLOW CONDITIONS (IMPERIAL SYSTEM)

FLUME DIMENSION in feet			DISCHARGE EQUATION	
L	W	H	ft^3/s	$Mgal_{US}/d$
9'	6'	3'	$3.5(W)^{1.025}(H)^{1.56}$	$2.262(W)^{1.025}(H)^{1.56}$
	4'			
	2'			
	1'			
4.5'	2'	1.5'	$3.98(W)^{1.025}(H)^{1.72}$	$2.572(W)^{1.025}(H)^{1.72}$
	1'			
	0.5'			
	0.25'			
3'	1.333'	1'	$4.5(W)^{1.025}(H)^{1.84}$	$2.908(W)^{1.025}(H)^{1.84}$
	0.667'			
	0.333'			
	0.167'			
1.5'	0.667'	0.5'	$6.1(W)^{1.025}(H)^{2.15}$	$3.942(W)^{1.025}(H)^{2.15}$
	0.333'			
	0.167'			
	0.083'			

TABLE 18 - CUTTHROAT FLUME - DISCHARGE EQUATIONS IN FREE FLOW CONDITIONS (METRIC SYSTEM)

FLUME DIMENSION in meters			DISCHARGE EQUATION	
L	W	H	m^3/s	M^3/d
2.743	1.828	0.914	$2.137(W)^{1.025}(H)^{1.56}$	$184637(W)^{1.025}(H)^{1.56}$
	1.219			
	0.609			
	0.304			
1.371	0.609	0.457	$2.431(W)^{1.025}(H)^{1.72}$	$210038(W)^{1.025}(H)^{1.72}$
	0.304			
	0.152			
	0.076			
0.914	0.406	0.305	$2.749(W)^{1.025}(H)^{1.84}$	$237514(W)^{1.025}(H)^{1.84}$
	0.203			
	0.101			
	0.050			
0.457	0.203	0.152	$3.725(W)^{1.025}(H)^{2.15}$	$321840(W)^{1.025}(H)^{2.15}$
	0.101			
	0.050			
	0.025			

transversely: if the base of the flume is not level transversely, the average depth must be used to determine the depth/flow relationship. Depth must therefore be measured on each side of the flume to determine the average depth;

longitudinally: if a flume is not level longitudinally, that is, in the direction of flow, the measurement error increases with the length of the flume. Therefore, for a flume 457 mm (1.5 ft) long, a positive slope of 2 % produces a measurement error of approximately 8 % and a positive slope of roughly 10 % produces a measurement error of approximately 45 %. However, for a flume 1,371 mm (4.5 ft) long, a positive slope of 2 % produces a measurement error of approximately 0.5 % and a positive slope of approximately 10 % produces a measurement error of approximately 30 %(18).

- incorrect measuring point position

  for all dimensions, upstream (h_1) and downstream (h_2) measuring points, must be located respectively at a distance equal to 2 L/9 and 5 L/9 from the constriction (L being the total length of the flume). This distance must be measured parallel to the centre axis of the flume.

- inadequate approach

  the converging section of the flume is too small to adequately correct all major approach velocity and distribution distortions. (The reader can refer to section 2.4.10, which discusses installation conditions, for information about rules that regulate the approach).

- poor measurement technique in submerged flow conditions

  often, due to a lack of knowledge, a user is unaware of how to recognize or gauge the degree of submerged flow and takes flow measurements at only one location, instead of at both measuring points, which this situation requires.

- obstructions in the flume throat

  it is important to ensure that nothing is blocking the flume throat and causes an incorrect reading of water depth due to the flow moving over the obstacle (mainly in small flumes).

- erosion at the outlet of the flume

  it is important to ensure that erosion does not cause the flume to move from its original position.

2.4.9. Selection criteria

Although installation of a Parshall flume is the preferred option for a permanent measurement site, a cutthroat flume is an adequate substitute.

Since a number of other cutthroat flumes can often be used to measure the anticipated range of flows, other criteria should be considered when selecting a flume, such as:

- discharge: it is important to select the correct size of flume to ensure that free flow conditions are present at maximum discharge, and to consider installation constraints;
- loss of head: for one flow, the degree to which the water level rises, due to introducing different sizes of flumes;
- the sensitivity necessary to detect and measure variations in water level, even where there is very little change in the minimum flowrate;
- the precision desired;
- the work that is required to install flumes of different sizes;
- the costs associated with installation of flumes of different sizes.

2.4.10. Installation specifications

When a flume is installed, it is important to ensure that the physical characteristics of the flume correspond to those shown in Figure 16 and Table 14.

The crest of the flume's converging section can be at the same level as the bottom of the delivery pipe, so long as this type of system does not cause a submerged flow (h_2/h_1) that is greater than the transient flow value (S_t). The transient value (S_t) is determined in the following manner(16):

Total length of flume (L)	Transient flow value (S_t)
457 mm (1.5 ft)	60 %
914 mm (3.0 ft)	65 %
1372 mm (4.5 ft)	70 %
2743 mm (9.0 ft)	80 %

To reduce or eliminate a submerged flow, the flume can be lifted and the base of the delivery pipe can be connected to the crest of the converging section by an inverted slope section with a 1:4 ratio (vertical : horizontal), as long as the anticipated water depth does not cause an overflow outside of the system.

The length of the approach section must have at least twenty times the diameter of the delivery pipe.

In the approach section, the slope should be less than 1 %. A steep slope should be avoided because it could cause a hydraulic jump in the converging section of the flume (see Figure 7) or may cause too much velocity, which will affect the rise in water level in the converging section.

The minimum width of the approach section should be consistent with dimension "B" of Table 14 and the maximum width should not exceed this dimension by more than 10 meters. It is important to avoid introducing the water delivery pipe directly in the flume's converging section (see Figure 8).

At the flume outlet, there should be enough of a slope to allow water to discharge quickly. The incline should be approximately 2 %.

After the diverging section, there should be no pronounced curve that can impede discharge and cause backflow.

The conduit for the stilling well at measuring point h_1, must be located within two-thirds (2/3) of the length of the converging section. This distance is measured parallel with the direction of flow. The conduit is also placed at a right angle to the wall and level with the wall.

The conduit for the stilling well, at measuring point h_2, must be located in the flume's diverging section, at a distance equal to 5/6 the length of the diverging section. This distance is measured parallel with the direction of flow. The conduit is placed at a right angle and level with the wall.

2.4.11. Submerged flow

One might expect a submerged flow to occur as soon as the water reaches the threshold of the converging section; but this is not the case. The flowrate is not reduced as long as the h_2/h_1 ratio, expressed as a percentage, does not exceed the transient flow values (S_t) defined in section 2.4.10.

If the depth downstream (h_2) exceeds the threshold of the converging section, upstream (h_1) and downstream (h_2) depth measurements must be taken simultaneously. If the h_2/h_1 ratio is greater than the transient flow value (S_t), flow is said to be submerged, and flow is determined on the basis of simultaneous measurements of depths h_1 and h_2.

Since there is currently no commercial instrument that is able to take simultaneous upstream and downstream measurements and perform calculations, measurements in submerged flow conditions should be avoided.

The h_2/h_1 ratio can reach the transient flow value (S_t) before there is a significant flow deterioration. Beyond this transient value, however, flow reduction grows exponentially.

If the h_2/h_1 ratio reaches 100 %, there is no more flow. However, 95 % is considered to be the limit at which a cutthroat flume can be used. Because the difference between h_1 and h_2 is so small, the slightest error in depth measurement will result in extreme inaccuracies. This type of flume should therefore not be used in submerged flow conditions if the h_2/h_1 ratio exceeds 0.95.

Flumes under 914 mm (3 feet) in length should never be used in submerged flow conditions.

2.4.12. Discharge equation in submerged flow conditions

For this type of flow regime, the discharge equation resulting from the h_1 and h_2 measurement is expressed as follows$^{(18)}$:

$$Q = \frac{C_1(h_1 - h_2)^{n_1}}{(-\log S)^{n_2}} \quad (16)$$

where:

Q is the flowrate in cubic meters or cubic feet per second;
C_1 is $KW^{1.025}$;
h_1 is the depth upstream, in meters or feet;
h_2 is the depth downstream, in meters or feet;
n_1 is the exponent constant based on the length of the flume(18);
S is the ratio between h_1 (upstream depth) and h_2 (downstream depth): h_2/h_1;
n_2 is the exponent in submerged flow conditions, according to the length of the flume ($n_2=1$);
K is the constant based on the length of the flume and unit of measurement;
W is the size of the constriction in meters or feet.

Table 19 shows the values for K and C in submerged flow conditions.

2.4.13. Loss of head

Before installing a flume, ensure that the rise in water level in the drainage system will not cause sewers to back up in building basements. Use the following formula to gauge this increase (R)(19):

$$R = h_1 + r_c + r_i - H_c \quad (17)$$

where:

R represents the rise of water in the section upstream from the flume;
H_c represents the water depth in the channel, prior to installing the flume, at maximum discharge;
h_1 represents the anticipated water depth at the measuring point upstream from the throat section;
r_i represents the height of the channel bottom;
r_c represents the height of the crest of the flume.

The units are meters or feet.

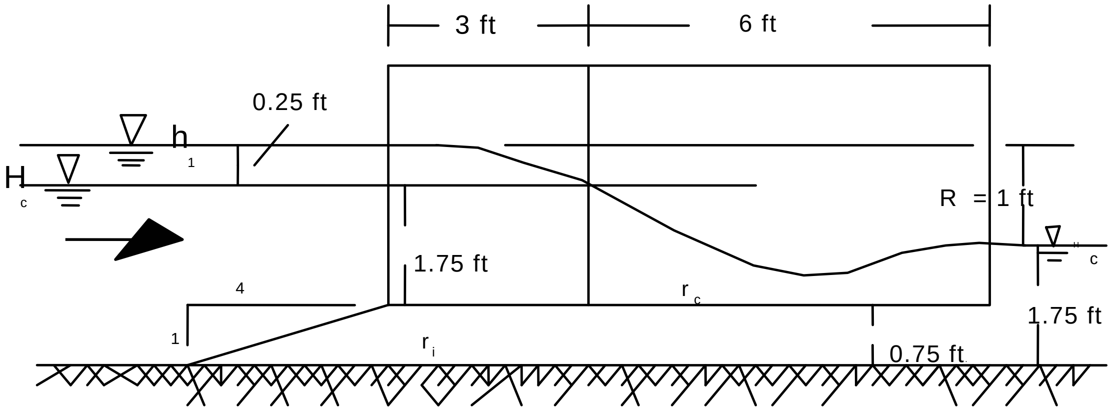
TABLE 19 - CUTTHROAT FLUME - VALUES OF COEFFICIENTS C AND K IN SUBMERGED FLOW CONDITIONS

Flume dimensions in mm and feet		Imperial system		Metric system		n 1
L	W	C	K	C	K	
2743 9'	1829 6'	10.6	1.688	1.95	1.05	1.39
	1219 4'	6.97		1.286		
	610 2'	3.43		0.633		
	305 1'	1.688		0.311		
1372 4.5'	610 2'	4.575	2.275	0.994	1.65	1.41
	305 1’	2.275		0.489		
	152 0.5’	1.12		0.239		
	76 0.25'	0.548		0.118		
914 3'	406 1.33'	2.465	2.58	0.843	2.125	1.48
	203 0.67'	1.705		0.415		
	102 0.33'	0.837		0.205		
	51 0.17'	0.413		0.101		
457 1.5'	203 0.67’	2.14	3.25	0.771	3.95	1.741
	102 0.33'	1.048		0.381		
	51 0.17'	0.516		0.187		
	25 0.083'	0.261		0.09		

Example: To measure a 0.6 m^3 (21 CFS) flow, a flume 27 m (9 ft) long with a throat 610 mm (2 ft) wide is installed. Water depth (H_c), prior to installation of the flume is 0.53 m (1.75 ft). The estimated water depth (h_1) in the flume to allow this type of flow to move through is 0.61 m (2 ft). When the base of the flume is placed 0.22 m (0.75 ft) away from the bottom of the conduit, the h_2/h_1 ratio {0.53/0.83 (1.75/2.75)} is 0.64. The flume is therefore operating in free flow conditions, because the transient flow value (S_t) has not been reached. The rise (R) in water level, or loss of head, is 0.3 m, more specifically: (0.61 - 0.53) + 0.22 {1 ft, more specifically: (2 - 1.75 + 0.75)}.

If this rise is too extreme for the network in question, the flume can be lowered to 0.08 m (0.25 ft) away from the bottom of the conduit, as long as free flow conditions continue to be maintained. The loss of head is therefore 0.16 m (0.5 ft).

If a flume is placed directly on the bottom of a conduit, the h_2/h_1 ratio {0.53/0.61 (1.75/2)} is 0.87, and the flume is operating in submerged flow conditions. The rise (R), or loss of head, however, is only 0.08 m (0.25 ft).



The steps to determine the total rise are as follows:

- measure depth in the conduit at maximum discharge (H_c);
- gauge the maximum flowrate as accurately as possible (Q_{max});
- determine what the water depth will be downstream from the throat section during the anticipated maximum discharge (h_1);
- determine the size of the flume that can be used to measure the anticipated maximum discharge, and create the least possible submerged conditions;
- determine the ratio between depths, in submerged flow conditions (h_2/h_1);
- determine how far the crest (r_c) of the flume (r_c - r_i) will be installed away from the channel bottom (r_i).

Once this evaluation of the rise in water level is complete, basement inverts in buildings should be inspected to ensure that installation will not cause a backup risk.

2.4.14. Flume modifications

It is important to use a flume that has the exact dimensions of a calibrated flume, because the depth/flow relationship for this type of flume can only be obtained through direct calibration of the flume. The depth/flow relationship for a larger flume cannot be based on the calibration of a small flume(20).

For specific applications, a flume with another throat width than those shown in Table 14 may have to be manufactured. The value of C can be obtained using the following equation(20):

$$C = K\ W^{1.025} \quad (18)$$

2.4.15. Calibration

Section 1.12.13 discusses calibration.

Due to the large size of tanks available, use of the volumetric method is usually limited to flumes less than 1372 mm (4.5 feet) in length and that have 610 mm (2 feet) of constriction.

During calibration, water depth in the flume, at the measuring point, must not vary more than 4 %, regardless of which method is used.

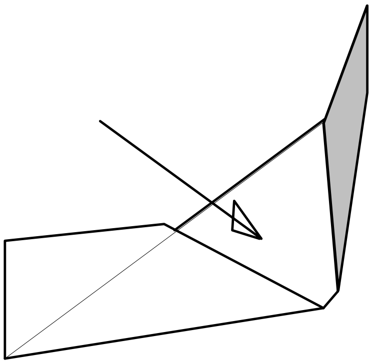
2.5. H flume

H flumes were designed in the mid-1930s by the USDA Agricultural Research Service(20). There are three categories of H flumes: Hs, H and H_L, all of which have the same shape, but differ in size and angles.

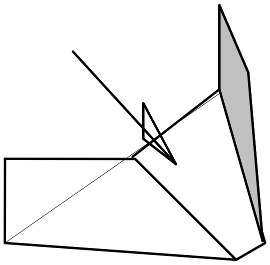
2.5.1. Description

An H flume is the result of a combination of the physical and mechanical characteristics of a weir and flume. Because of its shape, it resembles a triangular weir more than a flume. From a mechanical perspective, like flumes, it enables solids to be discharged(4).

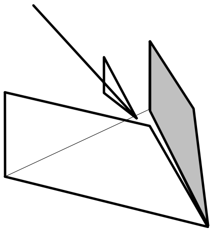
It consists of two sections: approach and control(20).



Flume HL



Flume H



Flume HS

The approach section is shaped by converging sides, and the control section consists of an opening that is the result of the shape of the converging sides.

Converging sides are cut at a 28° vertical angle for Hs flumes, 42° for H flumes and 55° for HL flumes (see Figures 17, 18 and 19). The edges form a trapezoidal opening that is narrow at the bottom and wider at the top. The angle of the opening formed by the sides, in comparison with the flow line, is 27° for Hs flumes, 37° for H flumes and 45° for HL flumes.

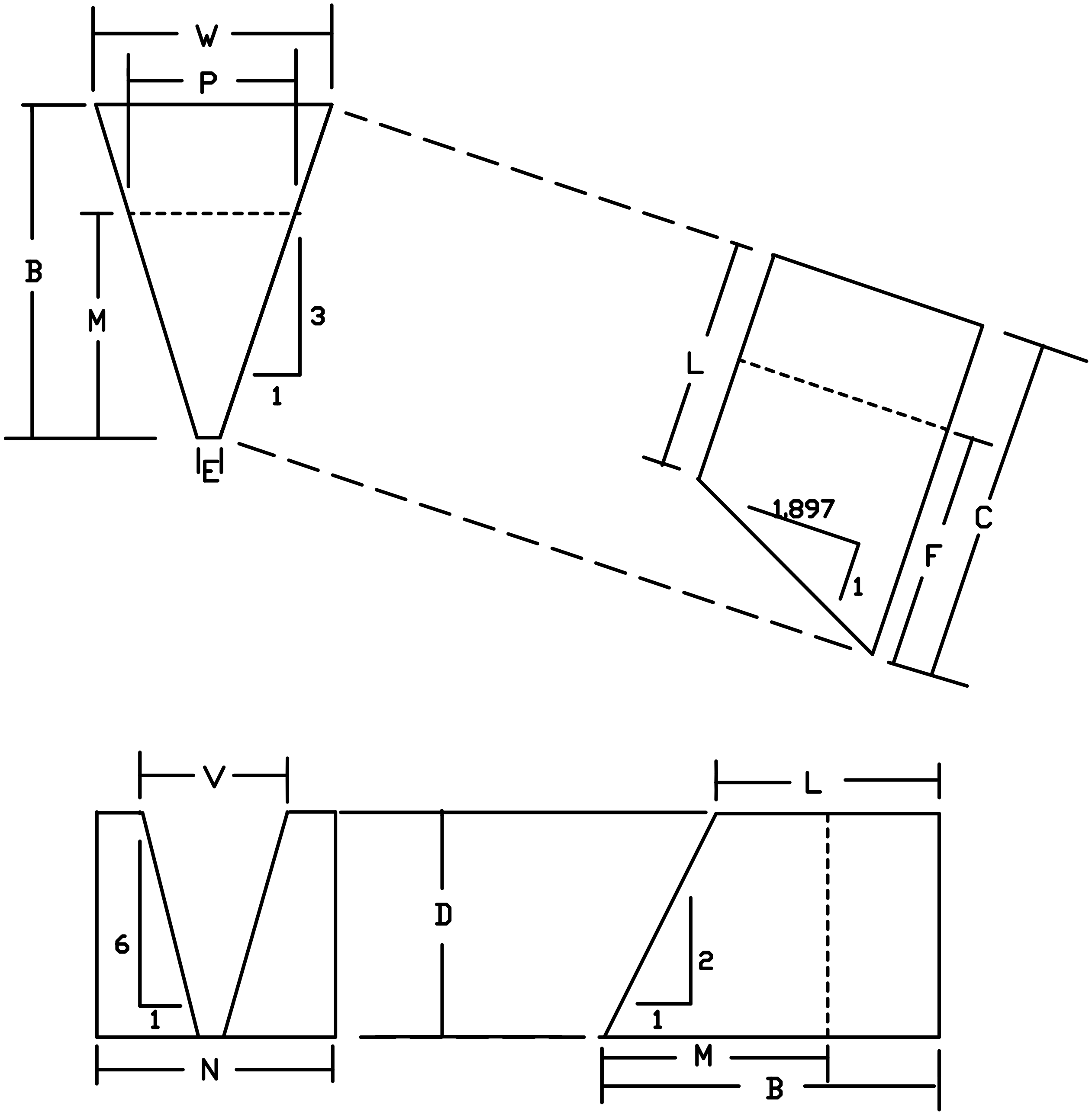
The entire underside of the flume is usually flat. An H flume may have an inclined bottom to help discharge solids when the flow is weak. There is an approximately 7° transversal slope(21) (see Figure 18).

Flumes are named according to the dimension of the device in use. A small flume is therefore an Hs type, a regular flume is an H type, and a large flume is an HL type. The ratio between width and height of the flume at the inlet of the converging section can be used to tell them apart. The W/H ratio should be 1.05 for Hs flumes, 1.9 for H flumes and 3.2 for HL flumes (see Tables 20, 21 and 22).

2.5.2. Operating principle

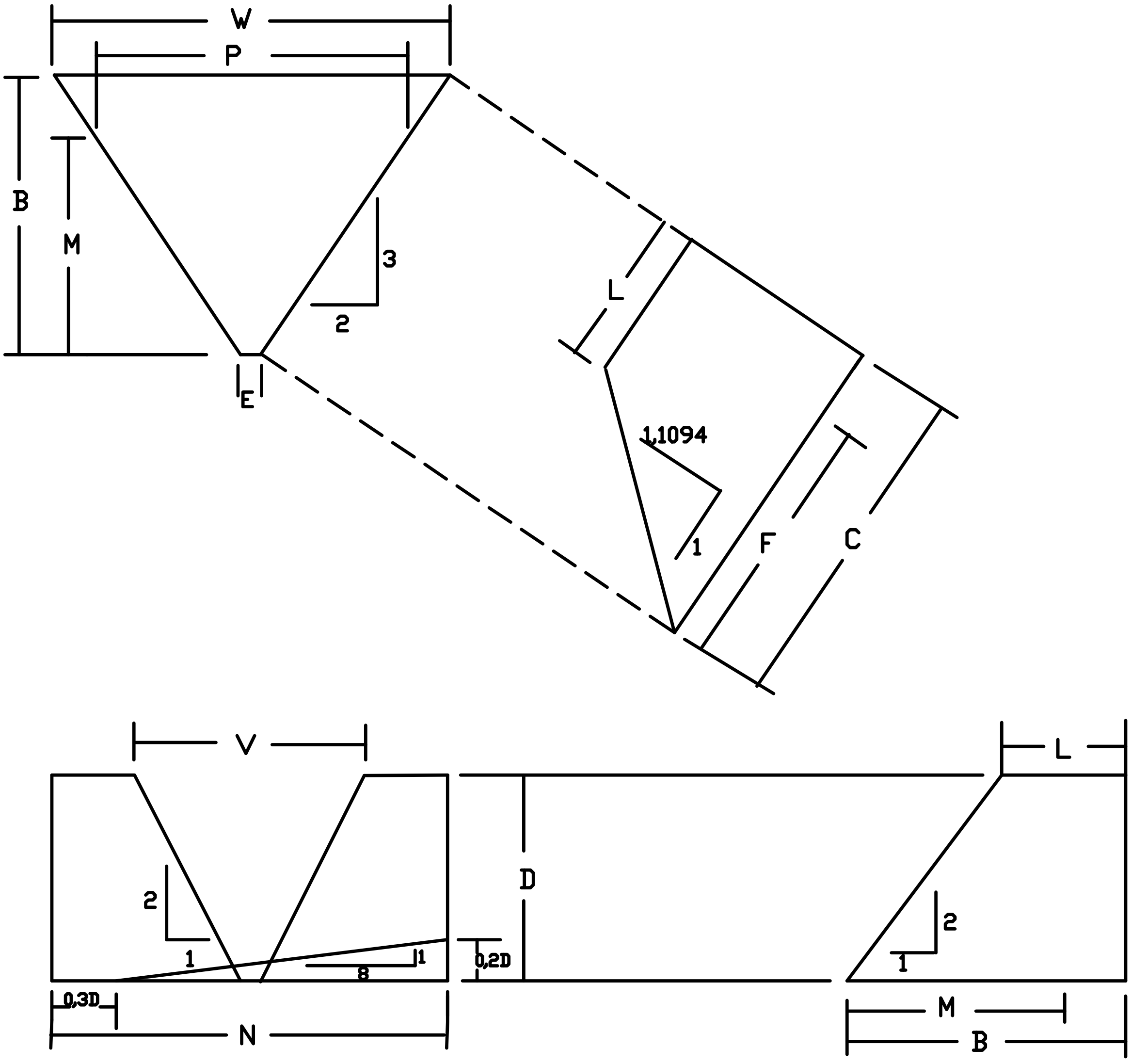
An H flume operates according to the Venturi principle. Due to lateral restrictions, the flume restricts the flow area, causing the water level upstream from the throat to rise. The flow can be obtained by simply measuring the water depth, because this depth varies proportionally with flow.

FIGURE 17 - HS FLUME - PHYSICAL CHARACTERISTICS



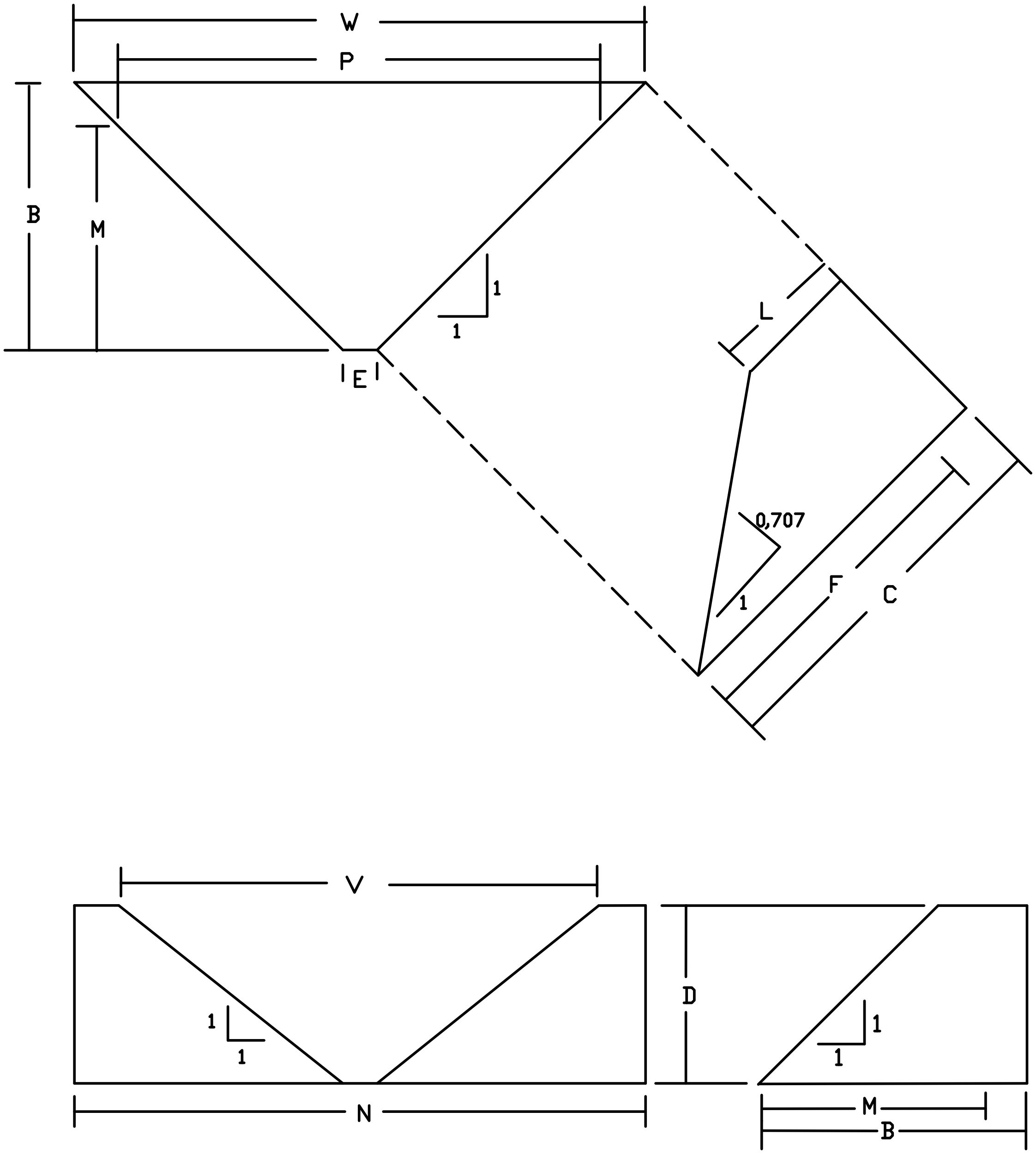
Note: See Table 20 for a description of letters.

FIGURE 18 - H FLUME - PHYSICAL CHARACTERISTICS



Note: See Table 21 for a description of letters.

FIGURE 19 - HL FLUME - PHYSICAL CHARACTERISTICS



Note: See Table 22 for a description of letters.

Although this type of flume can be used in submerged flow conditions, use in free flow conditions is strongly recommended. In a free flow situation, a flow measurement can be obtained using only one measuring point, but in submerged flow conditions, the depth downstream from the throat section must also be measured.

2.5.3. Applications

An H flume was developed to measure the flow of irrigation water from small catchment areas and surface water. Today, it is generally used to measure the flow of irrigation water, slow-flowing watercourses and water in sewer systems(7).

The geometry and operating principle of an H flume make it a very useful tool for measuring the flow of water that contains solids. This type of flume can measure a variety of different flows and provides good precision.

This type of flume is also easy to manufacture, is relatively inexpensive and is suitable for temporary measurement systems.

2.5.4. Dimensions

In order for an H flume to produce exact flow measurements, standard dimensions must be carefully respected when the flume is manufactured.

Figures 17, 18 and 19 show the physical characteristics of an H flume and Tables 20, 21 and 22, indicate the exact dimensions that each part of the flume is required to have(21).

TABLE 20 - HS FLUME – STANDARD DIMENSIONS

D	mm	ft	mm	ft	mm	ft	mm	ft	mm	ft
	122	0.4	152	0.5	183	0.6	244	0.8	305	1
W 1.05 D	128	0.42	160	0.0525	192	0.63	256	0.84	320	1.05
B 1.5 D	183	0.6	228	0.75	275	0.9	366	1.2	458	1.5
E 0.05 D	6	0.02	8	0.025	9	0.03	12	0.04	15	0.05
M 1 D	122	0.4	152	0.5	183	0.6	244	0.8	305	1
P 0.7167D	87	0.28668	109	0.35832	131	0.43002	175	0.57336	219	0.7167
N 1.05 D	128	0.42	160	0.0525	192	0.63	256	0.84	320	1.05
V 0.383 D	47	0.1532	58	0.1915	70	0.2298	93	0.3064	117	0.383
C 1.5811D	193	0.63244	241	0.79055	289	0.94866	386	1.26488	482	1.5811
L 1.054 D	129	0.4216	160	0.527	193	0.6324	257	0.8432	321	1.054
F 1.054 D	129	0.4216	160	0.527	193	0.6324	257	0.8432	321	1.054

where:

D: total depth of the flume;
W: width of the approach section;
B: length of the flume base;
E: width of the throat section at its base;
M: measuring point;
P: width of the base at the measuring point;
N: total width of the flume;
V: width of throat section at top;
C: length of the bottom of sides;
L: length of the top of sides;
F: measuring point on the side.

TABLE 21 - H FLUME – STANDARD DIMENSIONS

D	W 1.9 D	B 1.35 D	E 0.1 D	M 1.05 D	P 1.5 D	N 1.9 D	V 1.1 D	C 1.6225 D	L 0.721 D	F 1.2619 D	t 0.2 D	Y 0.3 D
152 0.5’	289 0.95	205 0.675	15 0.05	160 0.525	228 0.75	289 0.95	167 0.55	247 0.81125	110 0.3605	192 0.63096	30 0.1	46 0.15
229 0.75'	435 1.425	309 1.0125	23 0.075	240 0.7875	344 1.125	435 1.425	252 0.825	372 1.21688	165 0.5408	288 0.94643	46 0.15	69 0.225
305 1’	580 1.9	412 1.35	31 0.1	320 1.05	458 1.5	580 1.9	336 1.1	495 1.6225	220 0.721	385 1.2619	61 0.2	91 0.3
457 1.5’	868 2.85	617 2.025	46 0.15	480 1.575	686 2.85	868 2.85	503 1.65	741 2.43375	330 1.0815	577 1.89285	91 0.3	137 0.45
610 2’	1159 3.8	824 2.7	61 0.2	641 2.1	915 3	1159 3.8	671 2.2	990 3.245	440 1.442	769 2.5238	122 0.4	183 0.6
762 2.5’	1448 4.75	1029 3.375	76 0.25	800 2.625	1143 3.75	1448 4.75	838 2.75	1236 4.05625	549 1.8025	962 3.15475	152 0.5	229 0.75
914 3’	1737 5.7	1234 4.05	91 0.3	960 3.15	1371 4.5	1737 5.7	1005 3.3	1483 4.8675	659 2.163	1154 3.7857	183 0.6	274 0.9

Where:

D: total depth of the flume;
W: width of the approach section;
B: length of the base of the flume;
E: width of the throat section at its base;
V: width of the throat section at the top;
P: width of the base at the measuring point;
N: total width of the flume;
L: length of the top of sides;
C: length of the base of sides;
M: measuring point;
F: measuring point on the side;
t: height of the bottom slope;
Y: distance between the beginning of the sloped bottom and side of the flume.

TABLE 22 - HL FLUME – STANDARD DIMENSIONS

D	mm	ft	mm	ft	mm	ft	mm	ft	mm	ft
	610	2	762	2.5	914	3	1067	3.5	1219	4
W 3.2 D	1952	6.4	2438	8	2925	9.6	3414	11.2	3901	12.8
B 1.5 D	915	3	1143	3.75	1371	4.5	1600	5.25	1829	6
E 0.2 D	122	0.4	152	0.5	183	0.6	213	0.7	244	0.8
M 1.25 D	763	2.5	953	3.125	1143	3.75	1334	4.375	1524	5
P 2.7 D	1647	5.4	2057	6.75	2468	8.1	2881	9.45	3291	10.8
N 3.2 D	1952	6.4	2438	8	2925	9.6	3414	11.2	3901	12.8
V 2.2 D	1342	4.4	1676	5.5	2011	6.6	2347	7.7	2682	8.8
C 2.1213D	1293	4.2426	1616	5.30325	1940	6.3639	2263	7.42455	2586	8.4852
L 0.707 D	431	1.414	539	1.7675	646	2.121	754	2.4745	862	2.828
F 1.7678D	1078	3.5356	1347	4.4195	1616	5.3034	1886	6.1873	2155	7.0712

Where:

D: total depth of flume;
W: width of the approach section;
B: length of the flume base;
E: width of throat section at bottom;
V: width of throat section at top;
F: measuring point on the side;
P: width of base at the measuring point;
N: total width of the flume;
L: length of the top of sides;
C: length of the base of sides;
M: measuring point.

TABLE 23 - H FLUME - RECOMMENDED MINIMUM AND MAXIMUM FLOWRATES IN FREE FLOW CONDITIONS

Flume dimensions mm and feet		Minimum depth mm (ft)	MINIMUM FLOWRATE		Maximum depth mm (ft)	MAXIMUM FLOWRATE	
	D		l/s	m^3/d		l/s	m^3/d
Hs	122 0.4'	6 0.02	0.0046	0.3981	122 0.4'	2.407	208
	152 0.5'	6 0.02	0.0056	0.4834	152 0.5'	3.964	342.5
	183 0.6'	6 0.02	0.0066	0.5687	183 0.6'	6.513	562.7
	244 0.8'	6 0.02	0.0086	0.7393	244 0.8'	13.31	1 150
	305 1'	6 0.02	0.0105	0.9099	305 1'	23.22	2 006
H	152 0.5'	6 0.02	0.0113	0.976	152 0.5'	9.91	856.3
	229 0.75'	6 0.02	0.0169	1.46	229 0.75'	27.47	2 373
	305 1'	6 0.02	0.0198	1.953	305 1'	56.4	4 869
	457 1.5'	6 0.02	0.0311	2.687	457 1.5'	155.5	13 432
	610 2v	6 0.02	0.0396	3.425	610 2'	320	27 646
	762 2.5'	6 0.02	0.051	4.404	762 2.5'	558	48 198
	914 3'	6 0.02	0.0595	5.138	914 3'	881	76 089
H_L	610 2'	6 0.02	0.077	6.63	610 2’	50.6	50 644
	762 2.5'	6 0.02	0.095	8.208	762 2.5'	88.6	88 567
	914 3'	6 0.02	0.113	9.787	914 3’	139.5	139 456
	1067 3.5'	6 0.02	0.132	11.366	1067 3.5'	205	205 269
	1219 4'	6 0.02	0.15	12.944	1219 4'	286	286 251

2.5.5. Ranges of measurement

H flumes can be used to measure flowrates between 0.3981 m^3 per day, for an Hs flume 122 mm (0.4 ft) high, and 286,251 m^3 per day, for an HL flume 1219 mm (4 ft) high.

Table 23 shows recommended minimum and maximum flowrates for each type of H flume(21).

2.5.6. Discharge equation in free flow conditions

Discharge equations resulting from the depth/flow relationship in free flow conditions, are extremely complex. For this reason, working with depth/flow tables supplied by manufacturers is recommended. Equations can, however, be very useful to determine the flowrate of flumes with dimensions that are slightly different from standard dimensions. The total flow measured by an H flume is the result of the sum of amounts of water measured at different depths in the throat section. Flow measurements in an H flume require the use of three equations(20).

One equation is used to determine the flow for one depth of water in the flume, below 0.03 m (0.1 ft). A second equation is used to determine the flow at a water depth said to be in transition, that is, between 0.03 and 0.06 m (0.1 and 0.2 ft). The third equation is required for water depths in excess of 0.06 m (0.2 ft).

For water depths below 0.03 m (0.1 ft) (low flows), the equation is:

- for Hs, H and H_L flumes(20):

$$Q = A_o\,(2B_o + B_i h)(h)(h - 0{,}01)^{A_i} \qquad (19)$$

For depths between 0.03 and 0.06 m (0.1 and 0.2 ft) (transitional flows), the equation is:

- for Hs, H and H_L flumes(20):

$$Q = (K_o B_o + K_i B_i h)\sqrt{2g\,h^{3/2}} \qquad (20)$$

For depths greater than 0.06 m (0.2 ft), (main flows), the discharge equation is:

- Hs and H flumes(20):

$$Q = [(E_o + E_i D)B_o + (F_o + F_i D)B_i(h + \frac{V^2}{2g})]\sqrt{2g(h + \frac{V^2}{2g})^{3/2}} \qquad (21)$$

- for H_L flumes(20):

$$Q = (K_o B_o + K_i B_i h)\sqrt{2\,gh^{3/2}} \qquad (22)$$

The values of coefficients and exponents used in the above formulas are shown in Table 24.

TABLE 24 - H FLUME - COEFFICIENT AND EXPONENT VALUES

Coefficients and exponents	D mm ft	Hs		D mm ft	H		D mm ft	HL	
		mcs	cfs		mcs	cfs		mcs	cfs
A_o		2.238	393		1.705 s 1.822	3.14 s 3.30		2.023	3.57
A_i		0.526	0.526		0.486 s 0.5	0.486 s 0.5		0.522	0.522
B_o	122 0.4	3	0.01	152 0.5	8	0.025	610 2	62	0.2
	152 0.5	4	0.0125	229 0.75	11	0.0375	762 2.5	76	0.25
	183 0.6	5	0.015	305 1	15	0.05	914 3	91	0.3
	244 0.8	6	0.02	457 1.5	23	0.075	1 067 3.5	107	0.35
	305 1	8	0.025	610 2	31	0.1	1 219 4	122	0.4
				762 2.5	38	0.125			
				914 3	46	0.15			
B_i		51	0.1667		152	0.5		305	1
E_o		0.861	0.861		0.612 s 0.630	0.612 s 0.630			
E_i		0.367	0.112		0.686 s 0.571	0.209 s 0.174			
F_o		0.479 0.2	0.479 2.7		0.409 s 0.4	0.409 s 0.4			
F_i		-0.115 61	-0.035 824		-0.079 s -0.059	-0.024 s -0.018			
K_o	122 0.4	0.707	0.707	152 0.5	0.738 s 0.799	0.378 s 0.799	610 2		
	152 0.5	0.738	0.738	229 0.75	0.736	0.736	762 2.5		
	183 0.6	0.752	0.752	305 1	0.705 s 0.755	0.705 s 0.755	914 3		
	244 0.8	0.76 0.76	0.76	457 1.5	0.71 s 0.751	0.71 s 0.751	1 067 3.5		
	305 1	0.755	0.755	610 2	0.711 s 0.748	0.711 s 0.748	1 219 4	0.7804	0.7804
				762 2.5	0.712 s 0745	0.712 s 0.745			
				914 3	0.713 s 0744	0.713 s 0.744			
K_i	122 0.4	0.537	0.537	152 0.5	0.399 s 0.381	0.399 s 0.381	610 2		
	152 0.5	0.538	0.538	229 0.75	0.409	0.409	762 2.5		
	183 0.6	0.545	0.545	305 1	0.448 s.0416	0.448 s 0.416	914 3		
	244 0.8	0.572	0.572	457 1.5	0.472 s 0.435	0.472 s 0.435	1 067 3.5		
	305 1	0.614	0.614	610 2	0.498 s.0456	0.498 s 0.456	1 219 4	0.3788	0.3788
				762 2.5	0.525 s 0.479	0.525 s 0.479			
				914 3	0.551 s 0.502	0.551 s 0.502			

2.5.7. Precision

In free flow conditions, the precision of an H flume is comparable to that of other flumes. Hs flumes that are used to measure small flows, are the most accurate. To obtain this type of precision, flumes must be manufactured with extreme attention to detail and installation, in compliance with standard dimensions.

2.5.8. Sources of error

The principal sources of error that interfere with the precision of a flume are as follows:

- changes to standard dimensions, made when the flume is manufactured or during installation

  transversely: the flume must be level transversely, notwithstanding remarks in section 2.5.1.

  longitudinally: in the direction of flow, a positive slope of 2 % will generate a measurement error of approximately 1 %.

- incorrect measuring point position

  the measuring point upstream must be located at a distance equal to D for Hs flumes; at 1.05 D for H flumes; and 1.25 D, for H_L(4)(6)(20)(21) flumes. D is the dimension for the total height of the flume.

Note: Distance D must be measured parallel to the flume's central axis, from the discharge point and upstream.

- inadequate approach

  the converging section of the flume is too small to adequately correct all major approach velocity and distribution distortions (The reader can refer to section 2.5.10 which discusses installation conditions, for information about rules that regulate the approach.).

- poor measurement technique in submerged flow

  often, the user, due to a lack of knowledge, does not know how to recognize and gauge the degree of submerged flow and takes a flow measurement in one location only, instead of the two measuring points this situation requires.

- obstructions in the flume throat

  it is important to ensure that nothing is blocking the flume throat and causes an incorrect reading of water depth due to the flow moving over the obstacle, mainly in small flumes.

- erosion at the outlet of the flume

  it is important to ensure that erosion does not cause the flume to move and that its original longitudinal position remains horizontal.

2.5.9. Selection criteria

Although installation of a Parshall flume is the preferred option at a permanent measurement site, an H flume may be adequate.

Since a number of other flumes can often be used to measure the anticipated range of flows, other criteria should be considered when selecting a flume, such as:

- discharge: it is important to select the correct size of flume to ensure that free flow conditions are present at maximum discharge, and to consider installation constraints;
- loss of head: for one flow, the degree to which the water level rises, due to introducing different sizes of flumes;
- the sensitivity necessary to detect and measure variations in water level, even where there is very little change in the minimum flowrate;
- the desired precision;
- the overall work that is required to install flumes of different sizes;
- the costs associated with installation of flumes of different sizes.

2.5.10. Installation specifications

When a flume is installed, it is important to ensure that the flume's physical characteristics correspond to those shown in Figures 17, 18 and 19 and Tables 20, 21 and 22.

The crest of the flume's converging section must be at the same level as the base of the delivery pipe(12).

The length of the flume's approach section must be equal to at least five times the flume's total height(12).

The slope should be less than 1 % in the approach section. Care should be taken to ensure that a steep slope does not cause a hydraulic jump in the flume's converging section (see Figure 7), or that it does not create too great a velocity, which could result in a lower water depth in the converging section.

The width of the approach channel should be equal to dimension "W" in Tables 20, 21 and 22. It is important ensure that the water delivery pipe does not discharge directly into the flume's converging section (see Figure 8).

Ideally, there should be a drop at the outlet of the flume(12). The discharge channel should have enough slope to allow water to flow immediately. This slope should be at least 2 %.

At the flume outlet, there should be no pronounced curve that can restrict flow and cause a submerged flow.

2.5.11. Submerged flow

The upstream depth measurement becomes distorted, as soon as the downstream depth reaches 10 % of the upstream depth. Where this is the case, the upstream depth is 0.3 % greater than its normal depth. If the downstream depth is at 50 % of the depth upstream, the upstream depth is 2.6 % greater than its normal depth(20).

If the downstream depth (h_2) is greater at the threshold of the converging section, simultaneous measurements must be taken of the upstream (h_1) and downstream (h_2) depths. If the h_2/h_1 ratio is greater than 30 %, the flow is said to be submerged, and the flow measurement arises from the simultaneous measurement of both depths h_1 and h_2. Since there is currently no commercial instrument that is able to simultaneously take upstream and downstream measurements and perform calculations, measurements should not be taken in submerged flow conditions.

The h_2/h_1 ratio may reach 40 % before there is a significant flow measurement error. For each additional percentage, the flow reduction will increase exponentially.

If the h_2/h_1 ratio reaches 100 %, there is no more flow. However, 95 % is considered to be the threshold value where the H flume is no longer effective, because the difference in depth between h_1 and h_2 is so small, the slightest depth measurement error will result in extreme inaccuracies. This type of flume should therefore not be used in submerged flow conditions if the h_2/h_1 ratio is greater than 0.95.

2.5.12. Discharge equation in submerged flow conditions

The following equation(20) can be used to determine the depth/flow relationship, if the flume was operating in free flow conditions.

$$\frac{h_1}{h_{\text{mod}}} = 1 + 0{,}000175(e^{h_2/h_1})^{5.44} \quad (23)$$

where:

h_1 is the depth upstream from the throat section, in meters or feet;
h_2 is the depth downstream from the throat section, in meters or feet;
e is 2.71828;
h_{mod} is the depth upstream, in meters or feet, if the flume was operating in free flow conditions.

If the depth in free flow conditions is calculated, the applicable equations shown in section 2.5.6, are used to determine flow.

2.5.13. Flume modification

To obtain accurate measurements, the dimensions shown in Tables 20, 21 and 22 must be used correctly. The slightest modification to flume dimensions will require the flume to be calibrated.

2.5.14. Calibration

Section 1.12.13 discusses calibration.

Due to the size of the tanks available, use of the volumetric method is usually limited to H flumes smaller than 610 mm (2 ft).

During calibration, water depth in the flume, at the measuring point, must not vary more than 2 %.

3. DESCRIPTION OF THIN-PLATED WEIRS

The sections that follow discuss thin-plate weirs that may be in use at temporary or permanent test sites.

3.1. General

Weirs are generally used to measure the flow of effluents that contain very small amounts of suspended solids. When these weirs are built and installed according to standards and used under well-controlled conditions, they yield accurate flow measurements.

3.1.1. Operating principle

Flow measurement in thin-plate weirs depends on water depth in the weir, size and shape of the weir and an experimentally determined coefficient that also takes into account the unit of measurement, the geometric dimensions of the approach channel and water dynamics.

3.1.2. General applications

Due to the variety of its geometric shape and dimensions, this type of measuring device can measure a wide range of flows (0.25 l/s to 10,619 l/s). To obtain as accurate a measurement as possible, triangular weirs should be used for small flows and trapezoidal and rectangular weirs should be used for larger flows(22).

These primary measuring devices are generally used on a temporary rather than permanent basis. They can be used in sewer pipes, but require constant monitoring, to ensure that conduits do not become blocked by deposited solids upstream from the weir.

The specific application to each type of weir will be discussed further in the sections that follow.

3.1.3. Installation specifications

Manufacturing a code installation is recommended, rather than trying to estimate the effects of nonstandard conditions and trying to correct the values obtained.

Weirs must be installed in a straight flow section.

A weir must be installed in rectangular-shape flow channels or in measuring chambers that simulate rectangular-shape channels(22).

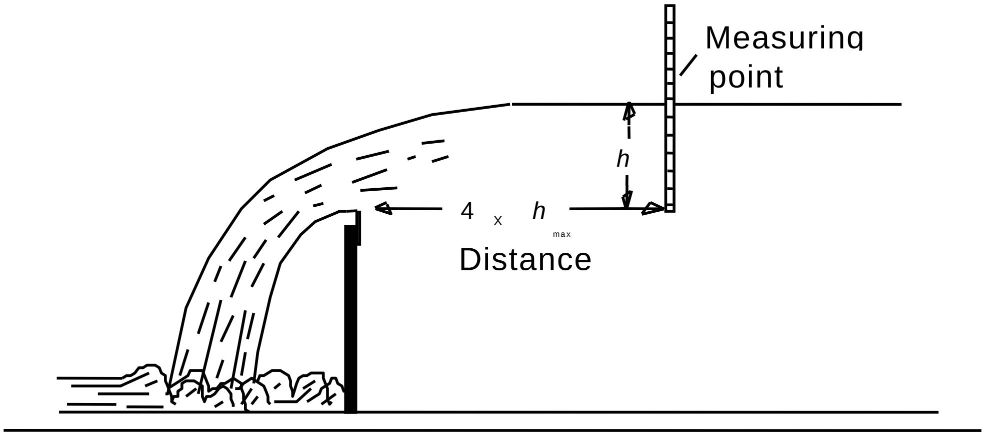
The weir must be vertical and perpendicular to the sides of the flow channel(22) and level on all axes.

Seams that join the weir, sides and bottom of the channel must be water-tight and resilient.

The geometric shape of the weir must be cut as precisely as possible.

The weir must be clean and held in place securely. It must be able to resist the strongest flows without distortion or damage(22).

The length of the approach section (L_a) must be at least 10 times the length of the nappe (L_n)(22) or 20 times the maximum water depth (h_{max}) measured in the weir. Usually, the length of the wall is equal to twice the maximum height.



DISTANCE FROM THE MEASURING POINT UPSTREAM THE OVERFLOW

L_a = length of the approach section
L_n = length of the nappe
h = depth at the measuring point
h_{max} = maximum depth at the measuring point

Example: For a rectangular weir where the nappe is 0.60 m (2 ft) long and the maximum water depth is 0.3 m (1 ft), the length of the approach section should be 6 m (20 ft).

If a weir is located in a measuring chamber, the chamber should be large enough to accommodate the recommended approach length(22).

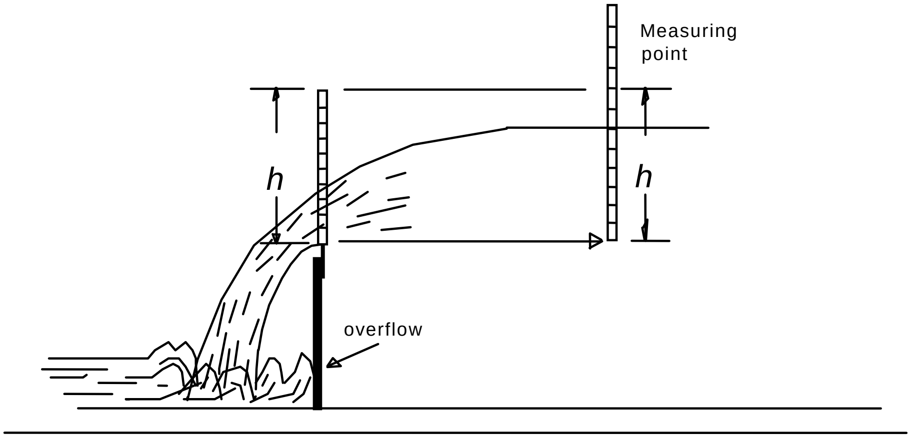
There should be no curve, no fall and no connection in the channel(4).

The slope of the approach section should be less than 2 %. It is important to ensure that a steep slope does not cause a hydraulic jump in the converging section of the weir, or that it does not cause too great a velocity, which will distort the flow measurement.

Flow in the approach section must be uniform, must have no turbulence and must be well distributed, so that the average approach velocity, measured at a point upstream, is less than 0.09 m/s or 0.3 ft/s(2) (23).

A system of baffles can be installed to enable a better flow distribution. Baffles, however, must be located upstream from the approach section(22).

The measuring point must be located far enough upstream to ensure that it is not affected by the weir's drawdown effect. The recommended distance is 4 to 5 times the maximum depth(22).



TRANSFER OF THE ZERO POINT MEASUREMENT

The zero point measurement must correspond exactly to the weir's zero point. To determine the zero point, a water depth measurement taken directly on the weir crest will not be reliable due to the drawdown effect. The zero point of the weir must be transferred precisely to the measuring point, with the help of a level(22).

A permanent staff gauge must be installed at the measuring point. The zero on the gauge must correspond to the level of the weir crest. The staff gauge is considered the true measurement of depth.

Flow measurements can be taken directly in the approach section, as long as the measuring device does not cause too much turbulence. If a device causes turbulence, flow measurements must be taken in a stilling well connected to the approach section(22). Stilling wells must be installed according to standards prescribed in Table 7 of this document.

The wells must be large enough to enable installation and operation of the flowmeter level detector without interference, or the need to clean the stilling well.

To avoid taking a measurement in a submerged flow, due to backwater, the discharge channel must be large enough to allow water to be discharged immediately during maximum flow.

The water level downstream from the weir must always be lower than the height of the weir crest. An acceptable minimum distance between the water level downstream and the crest is 61 mm (0.2 ft)(2).

3.1.4. Loss of head

Weirs are measurement devices that produce the greatest loss of head. Before installing a weir, it is important to check that the rise in water level in the drainage system will not cause sewers to back up in buildings and basements.

The following formula is used to gauge the rise in water level:

$$R = (h_p + h_1) + (0{,}2\, h_1) \qquad (24)$$

where:

R represents the rise of water in the section upstream from the weir;
h_p represents the crest height of the weir;
h_1 represents the anticipated maximum water depth at the measuring point, upstream from the weir.

The units of measurement generally used are meters or feet.

3.1.5. Submerged flow

Weirs are designed to operate only in free flow conditions. In submerged flow conditions, they will only produce an approximate flow measurement(3). Weirs should not be used in submerged flow conditions.

3.1.6. Discharge equation in submerged flow conditions

It is useful to discuss the relevance of this equation because use of this type of measuring device, in submerged flow conditions, provides only an approximate indication of the absolute flow and the measurements that are obtained are not acceptable.

3.1.7. Selection criteria

The following criteria must be considered when selecting weirs:

- the presence of suspended solids in effluent;
- the difference in water levels upstream and downstream;
- the desired precision of measurements;
- the dimensions and shape of the flow channel;
- the range of flowrates;
- installation difficulties;
- the tolerated rise in water level upstream from the weir.

3.1.8. Sources of error

The following sources of error can affect the precision of a weir(22):

- the estimate of coefficient C_e (defined in section 3.2.4);
- measurement of the length or angle of the weir b_e (defined in section 3.2.4);
- measurement of water depth (h) in the weir;
- flow velocity in the approach section;
- presence of sediment in the approach section;
- scaling and obstruction of the weir caused by debris;
- damage, wear and roughness of the weir;
- the water tightness of the weir;
- backflow and submerged flow;
- insufficient ventilation under the nappe;
- rounding of the weir crest.

3.1.9. Maintenance

Because weirs cause solids to deposit, the weir and approach section require regular maintenance to ensure precise measurement.

The approach section must be free of deposits or plant material that can affect flow.

The section downstream from the weir must be free of obstacles that cause backwater and submerged flow conditions.

The weir crest must be cleaned of all deposits. Particular care must be taken to thoroughly clean the “V” notch in triangular weirs, but to avoid any damage.

The frequency of cleaning will be largely influenced by the shape of the weir and the type of effluent.

> **Example**: A triangular weir will require more frequent cleaning than a rectangular weir. A triangular weir installed in an effluent that contains large amounts of solids will require more frequent cleaning than the same type of weir placed in an effluent that contains very few solids.

The weir must be checked for leaks(22).

The transverse of a weir crest must be checked and adjusted where necessary.

The stilling well must be cleaned regularly and the calibration of the flowmeter, checked and adjusted if necessary.

3.1.10. Calibration

To ensure that a weir produces accurate measurements, it must be calibrated immediately after installation, and when a deterioration of readings is suspected or noted (see section 1.12.13).

The volumetric method is used only when the following conditions are present(5):

- there is a regular-shaped tank, the capacity of which, at different levels, can be measured with 99 % precision;
- for each test, the water depth in the weir is stable at the measuring point, that is, it does not vary more than 3 %.

Due to the size of tanks available, this method is generally limited to the size of weirs listed in Table 25.

The dilution method, using a salt or tracer chemical, is used when:

- the measuring weir is too large for use of the volumetric method;
- the water depth in the weir is stable, at the measuring point, for each test, in other words, it does not vary more than 3 %;
- there is no regular-shape tank, the capacity of which at different levels, can be calibrated precisely.

During calibration of the weir, all of the information relevant to installation and the weir's condition must be recorded. The calibration procedures and method of measuring water depth in the weir and flow from the weir must be described in detail. All of this information must be kept as a reference document during the entire period the weir is in use.

3.1.11. Classification

A weir is classified as a thin-plate weir if the thickness of the crest is 3 mm (1/8 in). The name of the weir is derived from its geometric shape.

The sections that follow describe the most common types of weirs in use.

TABLE 25 - WEIR CALIBRATION - VOLUMETRIC METHOD - LIMITED DIMENSIONS

Type of weir	Maximum water depth	
	Millimeters	Feet
Triangular 60°	893	2.93
Triangular 90°	716	2.35
Rectangular with contractions 0.61 (2’)	811	2.66
Rectangular avec contractions 0.762 (2.5’)	643	2.11
Rectangular with contractions 0.914 (3’)	549	1.8
Rectangular with contractions 1.219 (4’)	436	1.43
Rectangular with contractions 1.524 (5’)	369	1.21
Rectangular with contractions 1.829 (6’)	323	1.06
Rectangular with contractions 2.438 (8’)	265	0.87
Rectangular with contractions 3.048 (10’)	229	0.75
Rectangular with contractions 0.152 (1.5’)	799	2.62
Rectangular with contractions 0.61 (2’)	661	2.17
Rectangular with contractions 0.762 (2.5’)	558	1.83
Rectangular with contractions 0.914 (3’)	503	1.65
Rectangular with contractions 1.219 (4’)	415	1.36
Rectangular with contractions 1.524 (5’)	357	1.17
Rectangular with contractions 1.829 (6’)	317	1.04
Rectangular with contractions 2.438 (8’)	262	0.86
Rectangular with contractions 3.048 (10’)	226	0.74
Cipolletti 0.152 (1.5’)	796	2.61
Cipolletti 0.61 (2’)	655	2.15
Cipolletti 0.762 (2.5’)	564	1.85
Cipolletti 0.914 (3’)	500	1.64
Cipolletti 1.219 (4’)	411	1.35
Cipolletti 1.524 (5’)	357	1.17
Cipolletti 1.829 (6’)	317	1.04
Cipolletti 2.438 (8’)	259	0.85
Cipolletti 3.048 (10’)	226	0.74

3.2. Rectangular weir without contractions

3.2.1. Description

A weir is said to be without contraction when its sides are shaped by the sides of the canal and when flow covers the entire width of the channel.

It consists of a straight-edge plate, that is placed perpendicular to the flow and that is level horizontally and vertically.

3.2.2. Dimensions

To ensure that this type of weir produces accurate flow measurements, standard dimensions must be respected during manufacturing and installation.

Figure 20 shows the physical characteristics of a rectangular weir without contraction and the standard dimensions of each one of its parts.

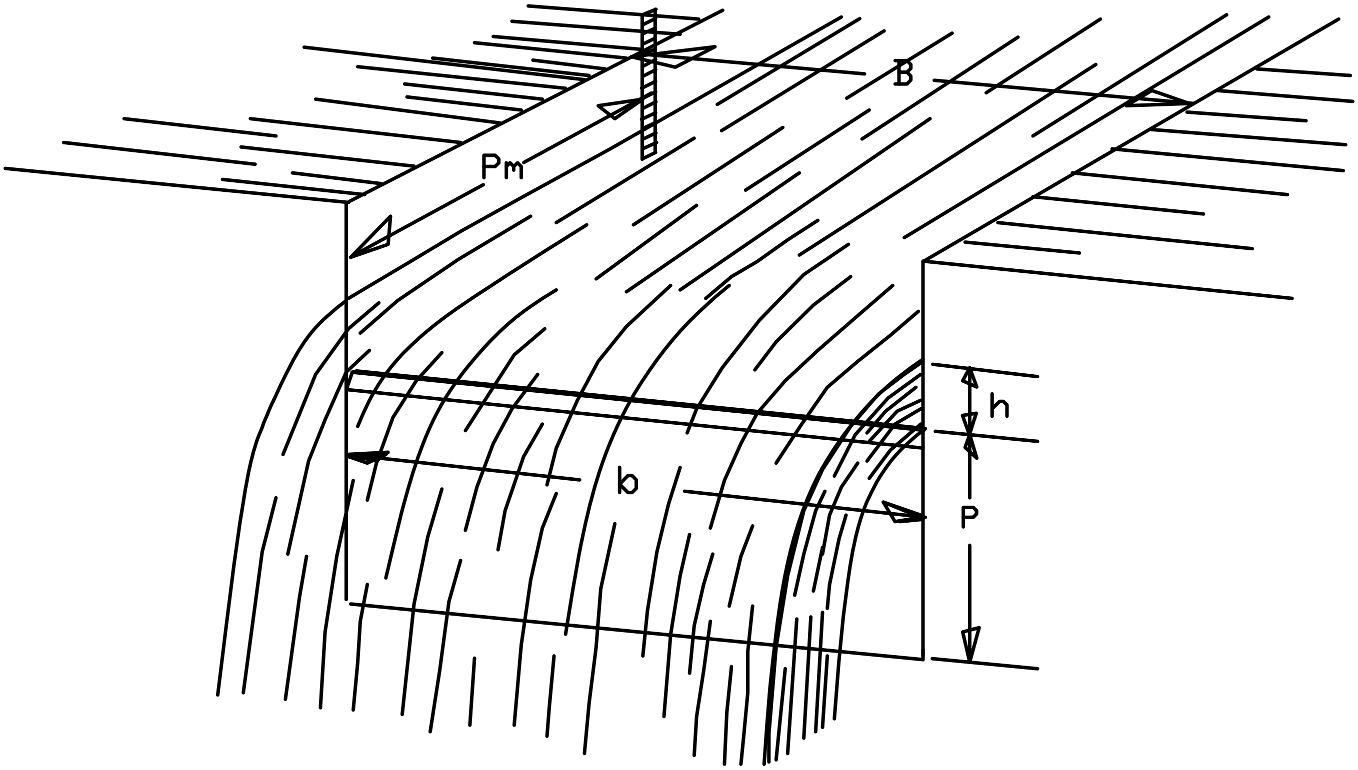
In addition to the information provided in Figure 20, it is important to take into account the following considerations when a weir is manufactured:

<u>Length</u>

The minimum length (b) for this type of weir is 305 mm (1 ft). However, the length of the weir must be at least twice the maximum measurement height(4).

The standard length of weirs increases in increments of 152 mm (0.5 ft) sections for weirs smaller than 914 mm (3 ft), and 305 mm (1 ft) sections for weirs larger than 914 mm (3 ft).

FIGURE 20 - RECTANGULAR WEIR WITHOUT CONTRACTIONS - PHYSICAL CHARACTERISTICS



B: width of approach channel – minimum width of 305 mm (1 ft);

B: length of weir – length equal to the width of the approach channel;

P: crest height – distance between the base of the canal and the weir crest; it is equal to at least twice the maximum water depth (h_{max}) in the weir;

h: water depth in the weir, at the measuring point;

Pm: location of the measuring point – located upstream from the weir, at a distance equal to 4 times the maximum water depth (h_{max}) in the weir.

For cost reasons, the maximum length for this type of weir generally does not exceed 2.4 m (8 ft).

Height

The minimum and maximum height should be kept respectively at 61 mm (0.2 ft) and 610 mm (2 ft)(4).

The height between the weir crest and bottom of the channel must be at least 305 mm (1 ft). The crest height is an extremely important factor because it is this element that contributes to reducing the approach velocity.

3.2.3. Range of measurements

Rectangular weirs without contraction can measure flows between 8.4 l/s (1.9 gal_{UK}/s), for a weir 305 mm (1 ft) long and 61 mm (0.2 ft) high and 10,534 l/s (2,317 gal_{UK}/s) for a weir 3 m (10 ft) long and 1,524 mm (5 ft) high.

Table 26 shows the range of recommended flows in free flow conditions, for weirs of varying dimensions.

3.2.4. Discharge equation in free flow conditions

Water flow in a weir is significantly influenced by the physical characteristics of the weir and the approach channel. Ideally, the equation should reflect these factors of influence. In the case of weirs, there is no universal equation that can accommodate all factors that control flow or that can apply to all types of systems(24).

TABLE 26 - RECTANGULAR WEIR WITHOUT CONTRACTION - RECOMMENDED MINIMUM AND MAXIMUM FLOWRATES IN FREE FLOW CONDITIONS

Width of the nappe		Minimum depth		Minimum flowrate		Maximum depth		Maximum flowrate	
m	ft	mm	ft	l/s	gal_{UK}/s	mm	ft	l/s	gal_{UK}/s
0.3	1	61	0.2	8.44	1.86	152	0.5	33.41	7.35
0.5	1.5	61	0.2	12.66	2.78	229	0.75	91.75	20.18
0.6	2	61	0.2	16.88	3.71	305	1.0	188.6	41.49
0.8	2.5	61	0.2	21.10	4.64	381	1.25	328.5	72.26
0.9	3	61	0.2	25.32	5.57	457	1.5	521	114.61
1.2	4	61	0.2	33.76	7.41	610	2.0	1068	234.83
1.5	5	61	0.2	42.20	9.28	762	2.5	1863	409.87
1.8	6	61	0.2	50.64	11.15	1829	3.0	2945	647.82
2.4	8	61	0.2	67.52	14.82	1219	4.0	6032	1326.8
3	10	61	0.2	84.40	18.56	1524	5.0	10534	2317.2

The Francis equation is a simple equation, that yields an adequate flow measurement with a margin of error of ± 1 %, where the depth of the water in the weir is less than 1/3 the length of the crest. Precision declines if the ratio between water depth and length of the crest increases {± 1 % margin of error (ratio 1:3) of ± 30 % (ratio 1:1)}(2).

The discharge equation, which is the result of the depth/flow relationship associated with free flow conditions, is as follows:

$$Q = Cb\,h^{3/2} \quad (25)$$

where:

Q is the flowrate in cubic meters or feet per second;
C is the coefficient (1.8384 for m^3/s and 3.33 for ft^3/s);
b is the length of the weir crest in meters or feet;
h is the water depth measured in the weir, in meters or feet.

Use of the Kindsvater-Carter equation, which is considered more accurate than the Francis equation, is beginning to become more common, particularly if the water depth in the weir is greater than 1/3 the length of the crest(20). The equation is as follows:

$$Q = 2/3\sqrt{2g}(0.602 + 0.075h/P)(b - 0.001)(h + 0.001)^{3/2} \qquad (26)$$

The equation can be reduced to the following form(6):

$$Q = C_e b_e h_e^{3/2} \qquad (27)$$

Where:

Q is flowrate in cubic meters and cubic feet per second;
C_e is the coefficient (1.8876 + 0.4 h/P for m^3/s and 3.4186 + 0.4 h/P for ft^3/s;
b is the length of the weir crest in meters or feet;
b_e is the effective length of the weir crest in meters (b – 0.001)(20) or in feet (b - 0.003)(6);
h is the water depth measured in the weir, in meters or feet, at the measuring point;
h_e is the effective water depth in meters (h + 0.001) or in feet (h + 0.003);
P is the crest height in meters or feet.

This equation is more advantageous because it includes the flow velocity in the approach section. This factor therefore does not have to be taken into account when results are compiled.

3.2.5. Precision

In free flow conditions, the precision of measurements using a rectangular weir with no contraction is similar to that of flumes. In laboratory conditions, the margin of error for this type of weir is between ± 1.5 and ± 2 %(3).

In the field, this type of weir can produce, under ideal installation conditions, measurements with a 5 % error(23). Effective control of the approach velocity is extremely important, however, because an approach velocity that is too strong can increase the measurement error to over 20 %(6).

3.2.6. Corrections

Submerged flow

If a weir is operating in submerged flow conditions, the only way to remedy the situation is to modify measurement systems or simply change the type of measuring device, to create free flow conditions.

Inadequate approach velocity

The approach velocity can be corrected simply by increasing the weir's crest height. If this change cannot be made due to the systems present, use of the Kindsvater-Carter equation is recommended, because it takes the approach velocity into account.

If the Francis equation is used, the approach velocity can be corrected by replacing $\mathbf{h^{3/2}}$ in the equation, with equation 25$^{(6)}$:

$$(h + h_c)^{3/2} - h_c^{3/2} \qquad (28)$$

The equation therefore becomes as follows$^{(6)}$:

$$Q_c = Cb[(h + h_c)^{3/2} - h_c^{3/2}] \qquad (29)$$

where:

Q_c is the corrected flowrate in m^3/s or ft^3/s;
C is the coefficient (1.8384 for m^3/s and 3.33 for ft^3/s);
b is the length of the weir crest in meters or feet;
h is the water depth measured in meters or feet;
h_c is $V^2/2g$;
V is the velocity measured in m/s or in ft/s;
g is the gravitational constant in m/s^2 or ft/s^2.

3.3. Rectangular weir with contractions

A rectangular weir with contractions is a weir where the opening is smaller than the channel in which is it placed.

3.3.1. Description

This type of weir is built with a rectangular opening and is placed in the centre of the channel. It is a sharp-crested weir, placed perpendicular to the direction of flow and is horizontally and vertically level.

3.3.2. Dimensions

To ensure that this type of weir produces accurate flow measurements, standard dimensions must be respected when it is manufactured and during installation.

Figure 21 shows the physical characteristics of a rectangular weir with contractions and the standard dimensions of each part.

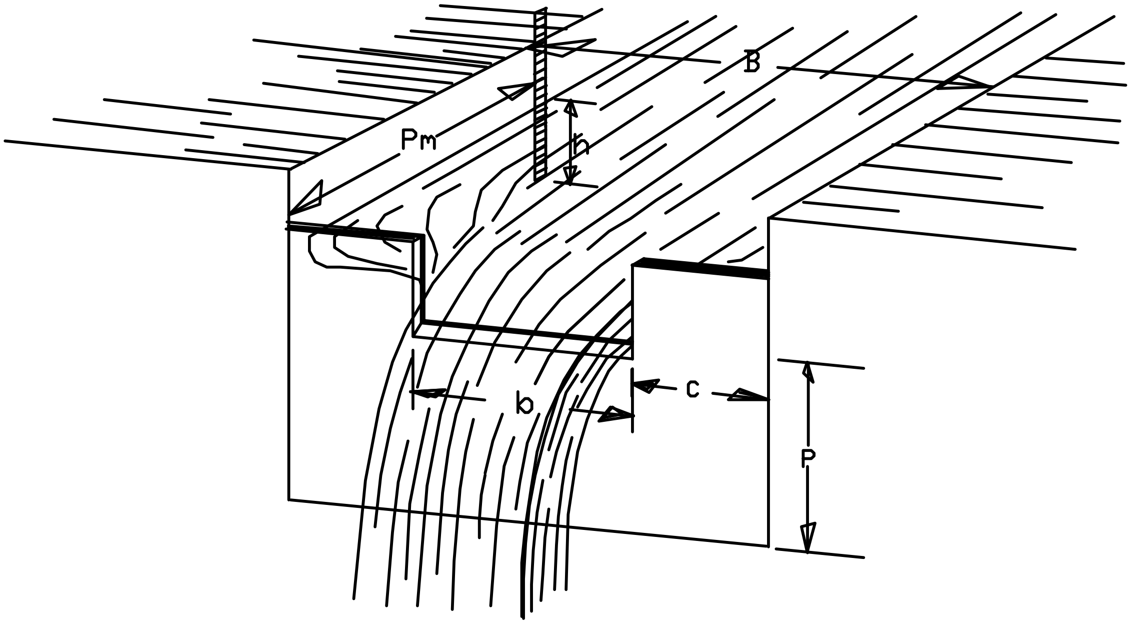
In addition to the information provided in Figure 21, it is important to take the following into account when a weir is manufactured:

length

The minimum length (b) for this type of weir is 305 mm (1 ft), however, the length of the weir must be at least twice the maximum measurement height (h_{max})(4).

The length of weirs (b) increases in increments of 152 mm (0.5 ft) sections, for weirs under 914 mm (3 ft), and by 305 mm (1 ft) sections, for weirs over 914 mm (3 ft).

FIGURE 21 - RECTANGULAR WEIR WITH CONTRACTIONS - PHYSICAL CHARACTERISTICS



B: width of approach channel – minimum width of 305 mm (1 ft);

b: length of weir – minimum length of 305 mm (1 ft);

P: crest height – distance between the bottom of the canal and the weir crest; is equal to at least twice the maximum water depth (h_{max}) in the weir;

h: water depth in the weir, at the measuring point;

Pm: location of the measuring point - located upstream from the weir, at a distance equal to at least 4 times the maximum water depth (h_{max}) in the weir;

c: side contractions – equal to at least twice the maximum water depth (h_{max}) in the weir, 305 mm (1 ft) minimum.

For cost reasons, the maximum length for this type of weir usually does not exceed 2.4 m (8 ft).

The length of side contractions (c) should never be less than 305 mm (1 ft).

height

The minimum and maximum height measurement should preferably be maintained respectively at 61 mm (0.2 ft) and 610 mm (2 ft)$^{(4)}$.

The height between the weir crest and bottom of the channel (P) must be at least 305 mm (1 ft). The crest height is an extremely important factor because it is this element that contributes to reducing the approach velocity.

3.3.3. Range of measurements

Rectangular weirs with contractions can measure flows between 8.1 l/s (1.8 gal_{UK}/s) for a weir 305 mm (1 ft) in length and 61 mm (0.2 ft) height, and 9,486 l/s (2,087 gal_{UK}/s) for a weir 3 m (10 ft) long and 1,524 mm (5 ft) high.

Table 27 shows the recommended range of measurements in free flow conditions, for weirs of varying dimensions.

3.3.4. Discharge equation in free flow conditions

Water flow in a weir is significantly influenced by the physical characteristics of the weir and the approach channel. Ideally, the equation should reflect these factors of influence. In the case of weirs, there is no universal equation that can accommodate all factors that control flow or that can apply to all types of systems$^{(24)}$.

The Francis equation is the discharge equation that is generally used for the depth/flow relationship associated with free flow conditions. The equation is expressed as follows:

$$Q = C(b - 0.1nh)h^{3/2} \qquad (30)$$

where:

Q is the flowrate in cubic meters or cubic feet per second;
C is the coefficient (1.8384 for m^3/s and 3.33 for ft^3/s);
b is the length of the weir crest in meters or feet;
n is the number of contractions;
h is the water depth measured in the weir in meters or feet.

The Kindsvater-Carter equation takes into account the properties of the liquid. Because the weir has contractions, a different coefficient is used to include the effect of the width of the weir compared to the width of the canal. The value of the effective length of the crest (b_e) is also different (20). This equation is as follows:

$$Q = C\sqrt{g}(1-0.0035\frac{h}{P})(b+0.0025)(h+0.001)^{3/2} \qquad (31)$$

where:

Q	is the flowrate in m^3 or ft^3/s;
C	is the coefficient (0.554 for m^3/s and 0.560 for ft^3/s);
g	is gravity in m/s^2 or ft/s^2;
b	is the length of the weir crest in meters or feet;
h	is the water depth measured in the weir in meters or feet;
P	is the crest height in meters or feet.

TABLE 27 - RECTANGULAR WEIR WITH CONTRACTIONS - RECOMMENDED MINIMUM AND MAXIMUM FLOWRATES IN FREE FLOW CONDITIONS

Width of the nappe		Minimum depth		Minimum flowrate		Maximum depth		Maximum flowrate	
m	ft	mm	ft	l/s	gal$_{UK}$/s	mm	ft	l/s	gal$_{UK}$/s
0.3	1	61	0.2	8.1	1.78	152	0.5	30	6.6
0.5	1.5	61	0.2	12.32	2.71	229	0.75	82.7	18.19
0.6	2	61	0.2	16.54	3.64	305	1.0	169.6	37.3
0.8	2.5	61	0.2	20.76	4.57	381	1.25	297.3	65.4
0.9	3	61	0.2	24.98	5.49	457	1.5	467.2	102.78
1.2	4	61	0.2	33.41	7.35	610	2.0	960	211.16
1.5	5	61	0.2	41.91	9.22	762	2.5	1676	368.72
1.8	6	61	0.2	50.12	11.03	1829	3.0	2645	581.8
2.4	8	61	0.2	67.11	14.76	1219	4.0	5437	1196
3	10	61	0.2	84.10	18.5	1524	5.0	9486	2086.7

3.3.5. Precision

In free flow conditions, a rectangular weir with contractions produces a precision similar to that of flumes. Laboratory tests with this type of weir show a margin for error of approximately ± 1.5 to 2 %(3).

In the field, under ideal installation conditions, this weir can produce measurements with a margin of error of ± 5 %(22). Proper control of the approach velocity is very important, however, because an approach velocity that is too fast can increase the error for measurement above 20 %(6).

3.3.6. Corrections

Submerged flow

If a weir is operating in submerged flow conditions, the only way to remedy the situation is to change the measurement systems or simply change the type of device, to create free flow conditions.

Inadequate approach velocity

The approach velocity can be corrected by increasing only the crest height of the weir. If the crest height cannot be increased due to the type of installation present, use of the Kindsvater-Carter equation is recommended.

If the Francis equation is used, it is possible to correct for the approach velocity by replacing $\mathbf{h^{3/2}}$ in the equation with:

$$(h+h_c)^{3/2}-h_c^{3/2} \qquad (32)$$

The equation therefore becomes(6):

$$Q_c = C(b-0.1nh)[(h+h_c)^{3/2}-h_c^{3/2}] \qquad (33)$$

where:

Q_c is the corrected flowrate in m^3/s or ft^3/s;
C is the coefficient (0.554 for m^3/s and 0.560 for ft^3/s);
b is the length of the weir crest in meters or feet;
h is the water depth measured in meters or feet;
h_c is $V^2/2g$;
V is the velocity measured in m/s or ft/s;
g is the gravity constant in m/s^2 or ft/s^2.

Length of contractions

If side contractions do not comply with standard manufacturing dimensions, an error results in the flow measurement, which can be corrected by changing a few parameters in the Kindsvater-Carter equation.

The equation is therefore as follows(20):

$$Q = C\sqrt{g}(1 + ah/P)(b + k)(h + 0.001)^{3/2} \qquad (34)$$

where:

Q is the flowrate in m^3/s or ft^3/s;
C is the variable coefficient as a function of the b/B ratio; where b and B are respectively the widths of the weir and approach channel;
b is the length of the weir crest in meters or feet;
h is the water depth measured in meters or feet;
g is gravity in m/s^2 or ft/s^2;
a is the variable coefficient as a function of the b/B ratio; where b and B are respectively the widths of the weir and the approach channel;
k is the variable coefficient as a function of the b/B ratio; that is, the ratio between the width of the weir (b) and width of the approach channel (B);
P is the crest height in meters or feet.

The values of coefficients “a”, “C” and “k” are shown in Table 28.

TABLE 28 - RECTANGULAR WEIR WITH CONTRACTIONS - COEFFICIENTS “a”, “C” AND “k”

b/B ratio	a		C		k	
	meters	feet	meters	feet	meters	feet
0.9	0.107	0.351	0.564	0.507	0.0038	0.0125
0.8	0.076	0.249	0.562	0.520	0.0042	0.0138
0.7	0.050	0.164	0.560	0.532	0.0040	0.0131
0.6	0.030	0.098	0.559	0.543	0.0035	0.0115
0.5	0.022	0.072	0.558	0.546	0.0030	0.0098
0.4	0.020	0.066	0.557	0.552	0.0027	0.0089
0.3	0.003	0.010	0.556	0.556	0.0025	0.0082
0.2 - 0.0	-0.003	-0.010	0.555	0.559	0.0025	0.0082

b/B = ratio between the width of the weir (b) and the width of the approach channel (B).

3.4. Trapezoidal weir (Cipolletti)

A trapezoidal weir (Cipolletti) is similar in all respects to a rectangular weir with contractions, except that the side edges are sloped (1:4).

3.4.1. Description

A trapezoidal weir consists of a converging opening that slopes downward. The weir is placed in the centre of the channel, allowing water to move through and enabling measurements of the amount of water moving through. It is a sharp-crested weir, with sloped sides that is placed perpendicular to the direction of flow and is horizontally and vertically level(4).

3.4.2. Dimensions

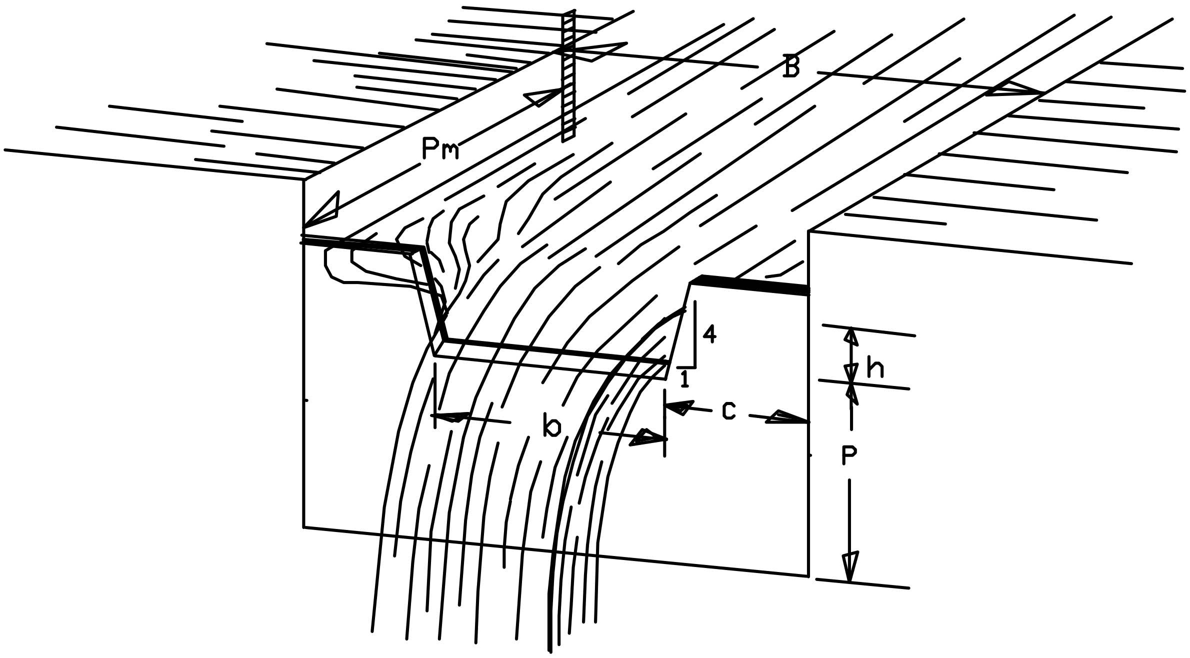
To ensure that this type of weir produces accurate flow measurements, standard dimensions must be respected during manufacturing and installation.

Figure 22 shows the physical characteristics of a trapezoidal weir and the dimensions of each of its parts.

In addition to the information provided in Figure 22, the following considerations must be examined:

> The length of the weir crest (b) must be at least twice the maximum water depth in the weir (h_{max}).
>
> The minimum and maximum depth, at the measuring point, should ideally be maintained at 61 mm (0.2 ft) and 610 mm (2 ft) respectively(4).
>
> The length of side contractions must never be less than 305 mm (1 ft) and the slope angle of crests is 14.04° (ratio of the length of sides 1:4).

FIGURE 22 - TRAPEZOIDAL WEIR (CIPOLLETTI) - PHYSICAL CHARACTERISTICS



B: width of approach channel – minimum width of 305 mm (1 ft);

b: length of weir – minimum length of 305 mm (1 ft);

P: crest height – distance between the channel bottom and the weir crest; it is also at least twice the maximum water depth (h_{max}) in the weir;

h: water depth in the weir, at the measuring point;

Pm: location of the measuring point - located upstream from the weir, at a distance equal to at least 4 times the maximum water depth (h_{max}) that may be measured in the weir;

c: side contractions – equal to at least twice the maximum water depth (h_{max}) in the weir, 305 mm (1 ft) minimum.

3.4.3. Range of measurements

Trapezoidal weirs (Cipolletti) can measure flowrates between 8.5 l/s (1.9 gal_{UK}/s) for a weir 305 mm (1 ft) in length and 61 mm (0.2 ft) high, and 10 619 l/s (2,336 gal_{UK}/s) for a weir 3 m (10 ft) long and 1,524 mm (5 ft) high.

Table 29 shows the recommended measuring range in free flow conditions, for different sizes of trapezoidal weirs.

3.4.4. Discharge equation in free flow conditions

The physical characteristics of a weir and the approach channel significantly affect water flow in the weir. Ideally, the discharge equation should accommodate all of these factors. For this type of weir, there is no universal equation that accommodates all of the factors that govern flow and that can apply to all types of systems.

The discharge equation resulting from the depth/flow relationship in free flow conditions is as follows:

$$Q = Cb\,h^{3/2} \qquad (35)$$

where:

Q is the flowrate in cubic meters or cubic feet per second;
C is the coefficient (1.859 for m^3/s and 3.367 for ft^3/s);
b is the length of the weir crest in meters or feet;
h is the water depth in meters or feet, at the measuring point.

TABLE 29 - TRAPEZOIDAL WEIR (CIPOLLETTI) - RECOMMENDED MINIMUM AND MAXIMUM FLOWRATES IN FREE FLOW CONDITIONS

Width of nappe		Minimum depth		Minimum flow		Maximum depth		Maximum flow	
m	ft	mm	ft	l/s	gal$_{UK}$/s	mm	ft	l/s	gal$_{UK}$/s
0.3	1	61	0.2	8.52	1.87	152	0.5	33.7	7.41
0.5	1.5	61	0.2	12.8	2.82	229	0.75	92.88	20.43
0.6	2	61	0.2	17.05	3.75	305	1.0	190.6	41.92
0.8	2.5	61	0.2	21.32	4.69	381	1.25	334.1	73.5
0.9	3	61	0.2	25.57	5.62	457	1.5	526.7	115.9
1.2	4	61	0.2	33.98	7.47	610	2.0	1079	237.3
1.5	5	61	0.2	42.76	9.41	762	2.5	1883	414.2
1.8	6	61	0.2	51.25	11.27	1829	3.0	2973	654
2.4	8	61	0.2	68.24	15.01	1219	4.0	6060	1333
3	10	61	0.2	85.23	18.75	1524	5.0	10619	2335.9

3.4.5. Precision

In free flow conditions, measurements made with a trapezoidal weir are less accurate than other types of measurement weirs(2).

In the field, this type of weir can produce, under ideal installation conditions, measurements with a margin of error of ± 5 to ± 7 %(22). Proper control of the approach velocity is very important however, because too great a velocity of approach can raise the margin for error to over 30 %(6).

3.4.6. Corrections

Submerged flow

When a weir is operating in submerged flow conditions, the only way to correct the situation is to change the setup, or simply change the type of measuring device, to produce free flow conditions.

Inadequate approach velocity

The approach velocity can be corrected simply by varying the crest height of the weir. If the crest height cannot be increased due to the manner in which the weir has been installed, the approach velocity can be corrected by replacing "$\mathbf{h}^{3/2}$" in equation 35 with(2):

$$(h + 1.5\,h_c)^{3/2} \quad (36)$$

The equation therefore becomes:

$$Q_c = Cb(h + 1.5\,h_c)^{3/2} \quad (37)$$

where:

Q_c	is the corrected flowrate in m^3/s or ft^3/s;
C	is the coefficient (1.8384 for m^3/s and 3.33 for ft^3/s);
b	is the length of the weir crest in meters or feet, at the measuring point;
h	is the water depth measured in meters or feet;
h_c	is $V^2/2g$;
V	is the velocity measured in m/s or ft/s;
g	is the gravity in m/s^2 or ft/s^2.

Length of contractions

If side contractions do not comply with manufacturing dimensions, this will cause a flow measurement error. None of the documents cited provides a method that takes this factor into account.

To obtain an accurate flow measurement, it is important to ensure that the weir complies with standards. If the weir cannot be modified, it should be calibrated according to the volumetric method or dilution method.

3.5. Triangular weir

A triangular weir is the most simple and most common type of weir.

3.5.1. Description

A triangular weir has a vertical V-notch in a thin plate and is placed in the centre of the flow channel. It is a sharp-crested weir that is placed perpendicular to flow.

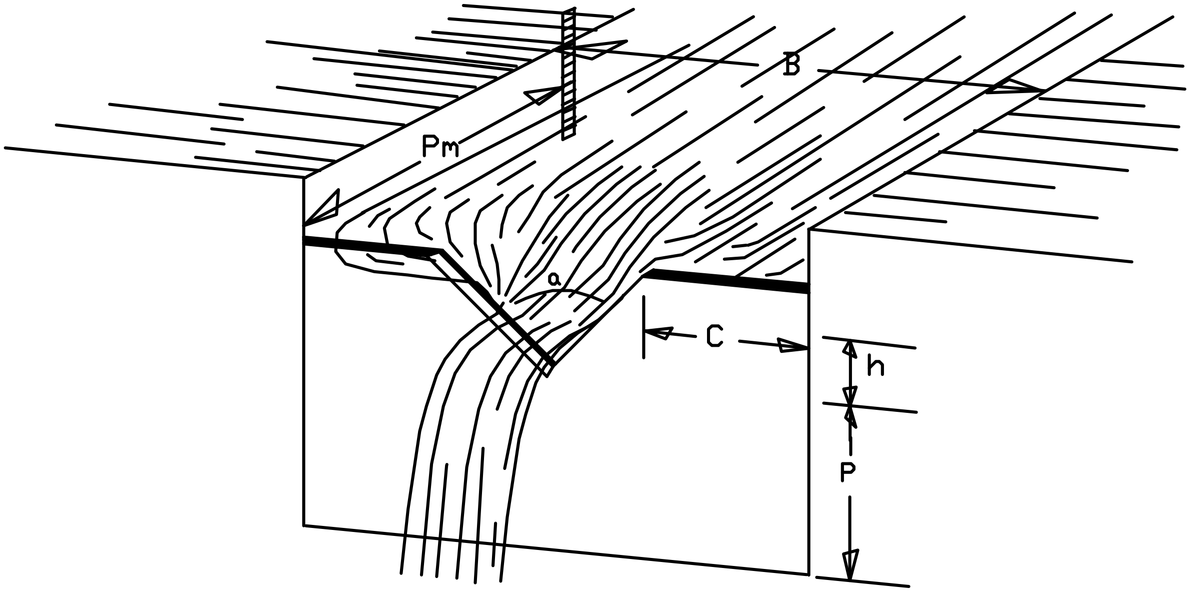
The most common weirs are 90° weirs, for larger flow measurements, and 45° weirs for medium-range flow measurements. In certain situations, 60° weirs are used for intermediate to larger flows, and 30° or 22.5° weirs are used for very small flows.

3.5.2. Dimensions

In order for a triangular weir to produce accurate flow measurements, standard dimensions must be respected during manufacturing and installation.

Figure 23 shows the physical characteristics of a triangular weir and the dimensions of each of its parts.

FIGURE 23 - TRIANGULAR WEIR - PHYSICAL CHARACTERISTICS



B: width of approach channel – minimum width of 305 mm (1 ft);

α: weir angle;

P: crest height - distance between the channel bottom and the weir crest; it is equal to at least twice the maximum water depth (h_{max}) in the weir;

h: water depth in the reservoir, at the measuring point;

Pm: location of the measuring point – located upstream from the weir, at a distance equal to at least 4 times the maximum water depth (h_{max}) in the weir;

C: side contractions – equal to at least twice the maximum water depth (h_{max}) in the weir, 305 mm (1 ft) minimum.

In addition to the information provided in Figure 23, the following considerations must be examined.

> The minimum and maximum depth at the measuring point should be maintained at 61 mm (0.2 ft) and 610 mm (2 ft) respectively(4).
>
> The length of side contractions (c) should never be less than 305 mm (1 ft).
>
> The bisecting line of the angle of the notch must be vertical and at an equal distance from the sides of the flow channel(25).

3.5.3. Range of measurements

Triangular weirs can measure flowrates between 0.252 l/s (0.055 gal_{UK}/s), for a 22.5° weir that is 61 mm (0.2 ft) high, and 400.4 l/s (88.1 gal_{UK}/s), for a 90° weir that is 610 mm (2 ft) high. This type of weir is an excellent instrument for measuring small flows(6).

Table 30 shows the recommended range of measurements in free flow conditions, for different sizes of triangular weirs.

3.5.4. Discharge equation in free flow conditions

The physical characteristics of a weir and the approach channel significantly affect water flow in the weir. Ideally, the discharge equation should take all of these factors into account. For this type of weir, there is no universal equation that accommodates all of the factors that govern flow or that can apply to all types of systems(24).

TABLE 30 - TRIANGULAR WEIR - RECOMMENDED MINIMUM AND MAXIMUM FLOWRATES IN FREE FLOW CONDITIONS

Angle of weir	Minimum depth		Minimum flowrate		Maximum depth		Maximum flowrate	
Degrees	mm	ft	l/s	gal$_{UK}$/s	mm	ft	l/s	gal$_{UK}$/s
22.5	61	0.2	0.252	0.055	610	2.0	79.6	17.51
30	61	0.2	0.343	0.075	610	2.0	108.3	23.82
45	61	0.2	0.524	0.115	610	2.0	165.8	36.47
60	61	0.2	0.731	0.161	610	2.0	231.2	50.85
90	61	0.2	1.266	0.278	610	2.0	400.4	88.08

The discharge equation resulting from the depth/flow relationship in free flow conditions is as follows(23):

$$Q = C(8/15)\sqrt{2}g(\tan\theta/2)h^{5/2} \quad (38)$$

where:

Q is the flowrate in m^3/s or ft^3/s;
C is the coefficient f (h/P,P/B,θ);
h is water depth in meters or feet;
P is the crest height in meters or feet;
B is the width of the approach channel in meters or feet;
θ is the angle of the weir;
g is the gravitational constant in m/s^2 or ft/s^2.

If the weir angle is accurate, the equation can be solved by combining all of the constants into one coefficient "C". The formula is as follows(4):

$$Q = C^1 h^{5/2} \quad (39)$$

where:

Q is the flowrate in m^3/s or ft^3/s;
C^1 is the coefficient, the value of which varies according to the angle of the weir and unit of measurement;
h is the water depth in the weir in meters or feet.

Table 31 shows the values of coefficient "C^1", according to the angle of the weir and the system of measurement in use.

TABLE 31 - TRIANGULAR WEIR - VALUE OF COEFFICIENT “C^1”

Angle of the weir	Value of coefficient “C^1”			
	Metric system		Imperial system	
Degree	m^3/d	l/s	ft^3/s	gal$_{UK}$/s
22.5	23,668	273.94	0.497	3.096
30	32,192	372.6	0.676	4.211
45	49,289	570.5	1.035	6.447
60	68,719	795.4	1.443	8.988
90	119,052	1377.9	2.5	15.572

3.5.5. Precision

In free flow conditions, a triangular weir is more precise then other types of weirs(2). In the laboratory, the error for flow measure is between 1 and 2 %(3). In the field, measurements with this type of weir produce a ± 2 to ± 5 % margin of error, under optimum installation conditions(22). Proper control of the approach velocity is very important however, because too great a velocity of approach can raise the margin for error to over 30(6).

3.5.6. Corrections

Submerged flow

When a weir is operating in submerged flow conditions, the only way to correct the situation is to change the setup, or simply change the type of measuring device, to produce free flow conditions.

Inadequate approach velocity

The approach velocity can be corrected simply by varying the crest height of the weir.

If a weir is installed with standard side contractions ($C \geq 2\ h_{max}$), the approach speed is usually slow and adequate.

Length of contractions

If side contractions do not comply with manufacturing dimensions, this will cause a flow measurement error. None of the reference documents consulted includes a method that takes this factor into account.

To obtain a precise flow measurement, it is important to construct a weir according to standards. If a weir cannot be modified, it must be calibrated according to the volumetric or dilution method.

3.6. Combined weir

A combined weir is used in special situations, where another measuring device is not suitable for measuring anticipated flows. Although it may consist of a variety of geometric shapes, it is usually the combination of a rectangular weir and a V-notch weir.

The paragraphs that follow discuss the combination of a 90° V-notch weir and rectangular weir with contractions. The resulting device is considered to be a standard combined weir.

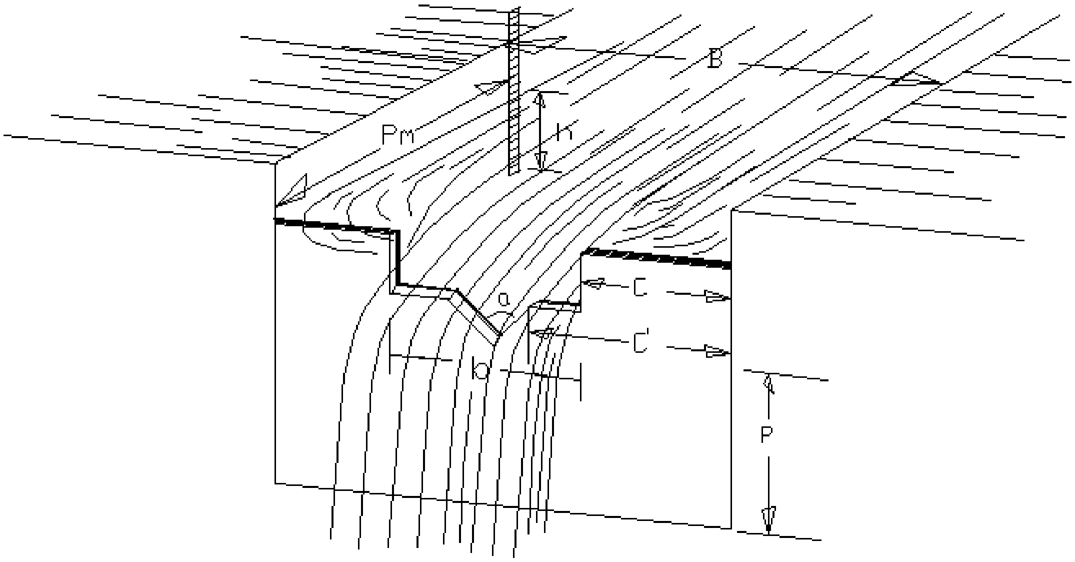
3.6.1. Description

A combined weir is a rectangular weir with a 90° V-notch, that is symmetrical and has a V-notch in the centre of the crest. It consists of a thin plate, that is placed vertically in the centre of a flow channel. It is a sharp-crested weir, that is placed perpendicular to flow.

3.6.2. Dimensions

There are no clearly defined manufacturing standards for this type of weir. Each component, however, should be constructed according to conventional manufacturing standards for rectangular weirs with contractions and 90° triangular weirs. The depth of a triangular weir and rectangular weir may vary according to contractions, based on measuring needs. Figure 24 shows the physical characteristics of a combined weir (rectangular-triangular) and the dimensions of each of its parts.

FIGURE 24 - COMBINED WEIR - PHYSICAL CHARACTERISTICS



B: width of approach channel – minimum width of 610 mm (2 ft);

b: length of the weir – minimum length of 305 mm (1 ft);

θ: angle of the weir;

P: crest height – equal to at least twice the maximum water depth (h_{max}) in the weir;

h: water depth in the weir – depth of measurement;

Pm: location of the measuring point – located upstream from the weir, at a distance equal to at least 4 times the maximum water depth (h_{max}) in the weir;

C: side contractions of a rectangular weir – equal to twice the maximum water depth (h_{max}) in the weir;

C1: side contractions of a triangular weir – equal to twice the maximum water depth (h_{max}), supposing that this weir operates alone.

In addition to the information provided in Figure 24, the following considerations must be examined.

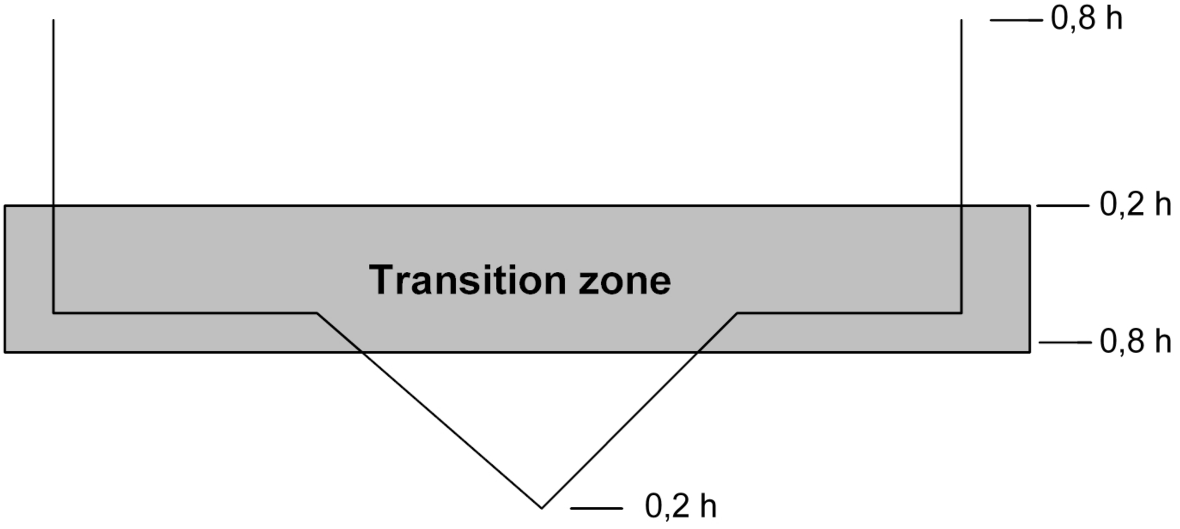
Side contractions (C and C_1) should never be less than 305 mm (1 ft) in length.

The bisecting line of the angle of the notch must be vertical and at an equal distance from the sides of the rectangular weir and flow channel.

3.6.3. Range of measurements

Combined weirs can be used to measure a wide range of flows. However, only two flow ranges are recommended: a range between 0.2 and 0.8 the height of the triangular weir and a range between 0.2 and 0.8 the height of the rectangular weir. The zone between 0.8 the height of the triangular weir and 0.2 the height of the rectangular weir should therefore be considered the transition zone, and flows in this area should be ignored and deemed inaccurate.

The following figure shows the transition zone deemed to be inaccurate:



Example: Suppose that a combined weir with a triangular section 457 mm (1.5 ft) high and a rectangular section, 914 mm (3 ft), is used. The sections that can be used for measurement are therefore those between 91 mm (0.3 ft) and 366 mm (1.2 ft), in the case of the triangular weir, and between 183 mm (0.6 ft) and 732 mm (2.4 ft), in the case of the rectangular weir.

If this type of weir is used, it is important to ensure first that the measurement period in the transition zone will be very brief, to ensure as accurate a measurement as possible.

Since this weir is a combination of two weirs that can vary significantly in size, it is difficult to draft a table of recommended minimum and maximum flowrates in free flow conditions. The reader should refer to tables shown in the sections that apply to the type of weir selected.

3.6.4. Discharge equation in free flow conditions

Use of a combined weir as a method of flow measurement has been the subject of very little laboratory and field research. The discharge equation that is shown was therefore formulated on the basis of a limited number of tests(2).

The resulting discharge equation for the depth/flow relationship in free flow conditions, is as follows(2):

$$Q = Ch_t^{1.72} - d + eb\,h_r^{1.5} \quad (40)$$

where:

Q	is the flowrate in m^3/s or ft^3/s;
C	constant (5.2 in metric measurements, or 3.9 in imperial measurements);
h_t	is the water depth in meters or feet in the triangular section;
d	constant (0.04 in metric measurements, or 1.5 in imperial measurements);
h_r	is the water depth in meters or feet in the rectangular section;
e	constant (1.82 in metric measurements or 3.3 in imperial measurements);
b	is the width in meters or feet in the rectangular section.

Calculations must be performed as though the two weirs operated independently of one another. In practice, depth at the measuring point (h_m) is the only measurement obtained. Water depth measurements in the triangular and rectangular sections (h_t and h_r) are obtained in the following manner:

$0 \leq h_t \leq$ height of the triangle

If $h_m = h_{tmax}$ (height of the triangle) $h_r = 0$

If $h_m > h_{tmax} \Rightarrow h_r = h_m - h_t$

If $h_m < h_{tmax} \Rightarrow h_t = h_m$ and $h_r = 0$

3.6.5. Precision

In free flow conditions, a combined weir will be less precise other measurement weirs(2). In the laboratory, the margin of error for this type of weir is approximately ± 3 to 5 %(3).

In the field, under ideal installation conditions, this weir can provide measurements with a margin of error of approximately 5 to 10 %(22). Proper control of the approach speed, however, is extremely important because an approach velocity that is too fast can increase the margin of error to over 30 %(6).

3.6.6. Corrections

Submerged flow

If a weir is operating in submerged flow conditions, the only way to remedy the situation is to change the measurement setup or simply change the type of device, to create free flow conditions.

Inadequate approach velocity

The approach velocity can be corrected by simply varying the crest height of the weir.

If a weir is installed with complete side contractions, the approach velocity is usually slow and acceptable.

Length of contractions

If side contractions do not comply with manufacturing dimensions, this will produce a flow measurement error. None of the reference documents consulted includes a method that takes this factor into account.

To obtain an accurate flow measurement, it is therefore important to use a weir that complies with standards. If a weir cannot be modified, calibration will have to be performed using the volumetric or dilution method.

3.7. Compound weir

A compound weir is often designed by “THEL-MAR”, the name of a manufacturer. There are two types of compound weirs: triangular and combined. The measurement capability of combined compound weirs is better than triangular compound weirs, but they are not as accurate.

3.7.1. Description

A combined compound weir is more commonly used. It consists of a rectangular weir and triangular weir. It is a rectangular weir with a symmetrical 90° V-notch in the centre of the crest. This is a sharp-crested weir, that is placed perpendicular to the flow.

A combined weir is manufactured using a thin, vertical transparent slab of plastic, placed in the centre of a metal frame that is used as a mounting bracket in the flow channel. The weir is secured in the metal frame with a rubber airtight seal that provides slight flexibility. The calibration lines are in 2 mm increments, and the unit of measurement is US gallons per day(26).

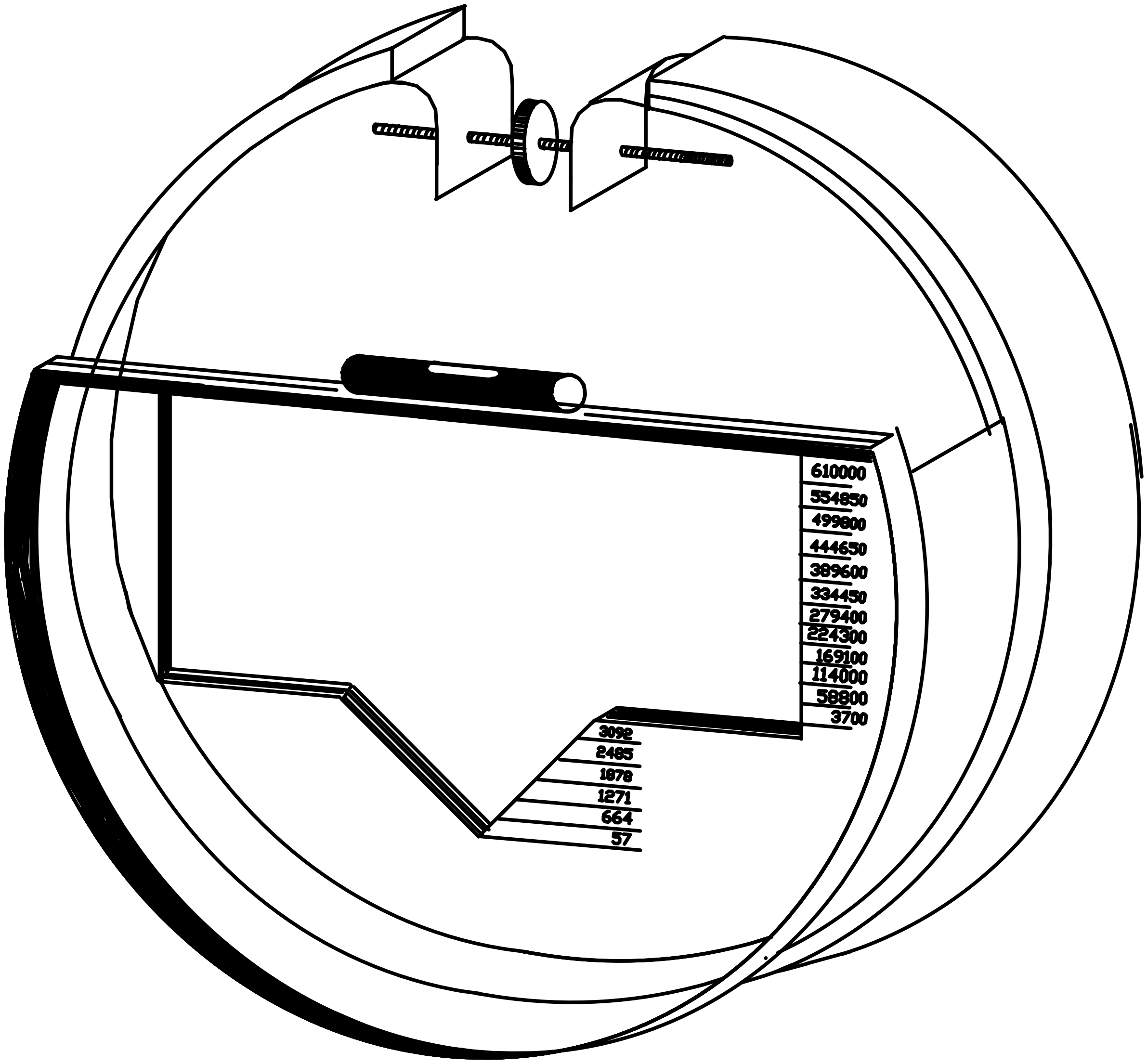
Figure 25 shows a compound weir.

3.7.2. Dimensions

Manufacturing standards for this type of weir are determined by the manufacturer. There is little concern about the size of components, because the weir is not manufactured or modified at the installation site. When repairing this type of weir, it is important to ensure that each component maintains its initial dimensions.

The dimension of compound weirs usually corresponds to the diameter of the support ring. Standard dimensions are 152, 203, 254, 305, 356, 381 and 406 mm (6, 8, 10, 12, 14, 15, and 16 inches)(26).

FIGURE 25 -COMPOUND WEIR - PHYSICAL CHARACTERISTICS



3.7.3. Range of measurements

Compound weirs can be used for a flow range between 174,128 liters (46,000 US gallons) per day to 2,309,094 liters (610,000 US gallons) per day. Table 32 shows the measurement capability of different weirs(26).

3.7.4. Uses

A compound weir is used to obtain an instant flow measurement. It is designed to be installed at the channel discharge and the flow measurement is taken in the upstream section.

This type of weir must never be used for continuous measurements, for the following reasons:

- It significantly restricts a channel's nominal capacity. Its upper measurement capacity is limited to 35 % of a pipe's nominal capacity(26).
- Because the crest height is low, the approach velocity cannot be controlled. It is also easy to cause a submerged flow without being aware that this has occurred.
- Solids such as paper, foul this type of weir easily and cause obstruction. This results in measurement errors.
- Fluctuations in flowrate cause a lot of turbulence and impair precision.

It is important to ensure that the flow reaches a permanent pattern before taking a flow reading, to minimize errors. The waiting time is 15 minutes, but a waiting time of one hour can sometimes be required before a reading can be taken.

This type of weir should only be used in situations where the water's approach velocity is less than 0.5 m/s (1.5 ft/s), because the greater the velocity, the less accurate the measurement.

TABLE 32 - COMPOUND WEIR - MEASUREMENT CAPACITY

Size of weir	Maximum flowrate	
	l/d	gal_{US}/d
152 mm (6 in)	174,128	46,000
203 mm (8 in)	469,390	124,000
254 mm (10 in)	885,784	234,000
305 mm (12 in)	1,366,530	361,000
356 mm (14 in)	1,366,530	361,000
381 mm (15 in)	2,309,094	610,000
406 mm (16 in)	2,309,094	610,000

3.7.5. Discharge equation in free flow conditions

Compound weirs are calibrated in the laboratory by the manufacturer. Installation conditions in a manhole are therefore simulated(26). No flow formula is supplied with this type of weir.

3.7.6. Submerged flow

This type of weir is designed to operate in free flow conditions. In submerged flow situations, it will produce an approximate flow value. Use in submerged flows is therefore not recommended.

3.7.7. Precision

In the laboratory, the margin of error is ± 2 to 3 %. In the field, under optimum installation conditions, the margin of error for this type of weir is approximately ± 10 to 15 %. Effective control of the approach velocity and the flow stability are extremely important.

4. OTHER METHODS OF MEASUREMENT

The methods of measurement discussed in the sections that follow do not require installation of a primary measuring device and usually allow instant flow measurements to be taken.

These methods are used when primary measuring devices cannot be installed for physical or cost reasons. When carried out precisely, these methods yield flow measurements with a margin of error of less than 10 %.

4.1. Use of tracers

Two techniques are generally used to measure flow with the use of tracers, namely(15):

- travel time technique (section 4.1.2);
- tracer dilution technique (section 4.1.3).

Each of these methods can be used to measure flowrates in closed or open conduits. Use in open conduits will be discussed in this section.

4.1.1. General

Generally, anything that is water soluble, detectable and that can be measured at different concentrations, can be used as a tracer.

4.1.1.1 Types of tracers

Three categories of tracers are generally used:

Chemical tracers:

the salts that are generally used include: sodium chloride ($NaCl$), potassium chloride (KCl), lithium chloride ($LiCl$), manganese sulfate ($MnSO_4$) and a few others(27).

Dyes:

the compounds generally use are fluorescein, potassium permanganate, methylene blue, rhodamine WT(27).

Radioactive tracers:

the following isotopes are commonly used: sodium 24, bromine 82, iodine 132(27) (28).

4.1.1.2 Characteristics of tracers

The principal characteristics of tracers are as follows:

- water solubility;
- ability to be detected at different levels.

4.1.1.3 Choosing a tracer

Certain criteria must be considered before selecting a tracer. These include:

- ease of use and preparation (solid/liquid);
- effect of chemical interference;
- sensitivity to chemical breakdown;
- sensitivity to photochemical breakdown;
- absence of or a small concentration of tracer in discharge;
- stability of the tracer;
- absorption of the tracer;
- water solubility;
- effect of tracer on the environment and human health;
- simple and accurate analysis;
- minimum detectable limit of the tracer in water;
- availability of the tracer;
- comparative amounts that are required for work;
- cost.

4.1.1.4 Preparation of tracers

Usually before any amount of tracer is removed from a container, the contents should be shaken well to eliminate deposits and to produce a homogeneous solution.

The method of preparing a concentrated solution of lithium chloride, described in section 4.1.1.4.1 of this chapter, applies to preparation of any chemical tracer.

The method of preparing a concentrated rhodamine WT solution, described in section 4.1.1.4.2 of this chapter, applies to preparation of a colored tracer.

4.1.1.4.1 Preparation of a concentrated lithium chloride solution

The following equation is used to prepare a lithium chloride solution that has a specific concentration of tracer:

$$P_s = C_t V \text{ x } \frac{PM_s}{PM_t} \qquad (41)$$

where:

P_s is the weight of salt in mg;
C_t is the concentration of tracer in mg/l;
V is the volume of solution required in liters;
PM_s is the molecular weight of salt in grams;
PM_t is the molecular weight of the tracer in grams.

Therefore, to prepare 10 liters of a 10,000 mg/l solution of lithium and knowing that:

– the density of water	is 1.0 g/cm^3
– the density of LiCl	is 2.068 g/cm^3
– the molecular weight of LiCl	is 42.392 g
– the molecular weight of Li	is 6.939 g

To determine the amount of LiCl necessary to prepare the solution, established values are placed in the above equation, which appears as follows:

$$P_s = \frac{10{,}000 \text{ mg}}{4} \times 10 \text{ l} \times \frac{42.392 \text{ g}}{6.939 \text{ g}} = 610.9 \text{ g} \qquad (42)$$

4.1.1.4.2 Preparation of a concentrated rhodamine WT solution

Rhodamine WT is available in an aqueous solution at a concentration of 20 %. Because this dye is relatively viscous and adheres to walls, it should be diluted with enough distilled or demineralized water to be able to inject a precise amount. From the original solution, a specific amount of tracer, at an established concentration, can be prepared using the following equation(29):

$$C_n = C_i S_g \left[\frac{V_d}{V_f}\right] \qquad (43)$$

where:

C_n is the new desired concentration;
C_i is the initial concentration of the tracer;

S_g	is the specific weight of the tracer at the initial concentration;
V_f	is the final volume of the new solution ($V_d + V_w$);
V_d	is the volume of the tracer at the initial concentration added;
V_w	is the volume of purified water added.

To prepare 10 liters of a 50 000 ppb solution de rhodamine WT from a 20 % solution, knowing that the specific weight of rhodamine WT 20 % is 1.19, simply substitute the known values in the above solution and solve the equation as follows:

$$C_n = C_i S_g \left(\frac{V_d}{V_f}\right) \quad (44)$$

$$50{,}000\ ppb = 200{,}000\ ppm(1.19)\left(\frac{a}{10\ l}\right) \quad (45)$$

$$a = \left(\frac{50{,}000\ ppb.}{200{,}000\ ppm.*1{,}000}\right)(10\ \ l)\left(\frac{1}{1.19}\right) \quad (46)$$

$$a = \left(\frac{1}{400}\right)\left(\frac{1\ l}{1.19}\right) \quad (47)$$

$$a = \frac{1 l}{476} \quad a = \frac{1{,}000\ ml}{476} \quad a = 2.1ml \quad (48)$$

If the device is calibrated by the manufacturer or if the user has the necessary calibrators, the concentration of the stock solution can be determined. The solution is diluted at a concentration that can be read by a fluorometer and the initial concentration (C_i) is calculated using the above equation. For greater precision, the density of the stock solution should be verified with a hydrometer to reduce the chance of error when the original concentration is measured.

Use of laboratory equipment (pipette, volumetric flask, fluorometer) requires prior training, and a laboratory should be consulted before work begins. The high viscosity of rhodamine WT complicates the use of pipettes.

4.1.2. Travel time method

The flow measurement method based on determining the travel time of a tracer was developed in 1927(30).

4.1.2.1 General

Use of this method requires extremely accurate measurements in the flow area of the distance and time traveled, between the injection point and test point.

4.1.2.1.1 Principle of the method

The method consists of quickly injecting a large volume of tracer into a stream of water and determining the average velocity at which the tracer moves. On the basis of this principle, flow can be determined using the following formula(30):

$$Q = \frac{V}{t_c} \quad (49)$$

where:

Q flowrate in cubic meters or cubic feet per time unit;
V volume of the conduit or flow section (AL), in meters or cubic feet;
A cross section of the measuring section in square meters or feet;
L distance in meters or feet between the detectors;
t_c the time that has elapsed between the time of injection and movement of the centre portion of the cloud to the test point.

4.1.2.1.2 General applications

This method is used for the following applications:

- flow measurement in open and closed conduits, where the discharge cross section is uniform;
- calibration of pumps, turbines, open or closed conduits and the primary measuring device(31).

4.1.2.1.3 Advantages of the method

- Loss of part of the tracer does not affect results;
- results do not depend on the tracer's long-term storage life;
- does not require a sophisticated instrument for injection in open channels;
- enables flow measurements where other methods cannot be implemented;
- enables flow measurements in sections of the system where observation wells have small diameters;
- enables measurement of large flows;
- does not require precise laboratory measurements of the concentration of a tracer;
- requires a small amount of tracer.

4.1.2.1.4 Disadvantages of the method

- provides only a point-specific flow measurement;
- requires the discharge to have a uniform flow(30);
- requires a precise measurement of time between the injection point and test point(30);
- requires a few development tests before actual tests can be performed(31);
- requires an accurate measurement of the area of the discharge section(30);
- the procedure requires trained personnel and must be performed with attention to detail;
- requires a uniform cross section of discharge and a straight section of conduit(31).

4.1.2.1.5 Injection equipment

The type of injection equipment required will vary according to the type of discharge system present. The tracer that is used also has no bearing or very little bearing on the type of injection equipment used.

The following equipment is required:

- automatic control valves;
- an injection pump;
- a deflection device to create turbulence in the flow;
- a mixing tank for the solution;
- gasket seals;
- hose and couplings.

4.1.2.1.6 Detection and measuring equipment

The type of detection and measuring equipment that is used will depend on the discharge system that is present and the type of tracer used.

4.1.2.1.7 Injection procedure

The tracing solution is injected quickly into the water current. The period of injection may vary according to the situation, but usually lasts less than one second. The injection system consists of a cylindrical chamber that contains a solution and pneumatic piston, which forces a sudden discharge of the tracer out of the chamber.

A few feet upstream from the injection point, a mechanism capable of causing turbulence must be installed in the discharge, to enable the injected solution to mix quickly and thoroughly.

4.1.2.1.8 Personnel

This procedure requires skilled personnel who have the necessary field experience. At least three persons will be required for the procedure.

4.1.2.1.9 Measurement of flow area

The flow area is determined in the following manner(31):

- The inside dimension of the conduit is measured using an inside caliper that takes measurements to within one thousandths of a meter (thousandths of a foot). The diameter is measured on at least three proportional angles, to ensure that the conduit is perfectly round. The number of readings varies according to the difference between the readings obtained and the nominal dimension of the conduit.

- Flow depth in the conduit is measured from the bottom of the conduit. The width of the flow area is measured and the centre point corresponds to the centre of the conduit, unless the conduit is not round.

4.1.2.1.10 Calculation of flowrate

The flowrate corresponds to the product of the average velocity measured and the area of the flow section. The unit of measurement is cubic meters per second or cubic feet per second.

4.1.2.1.11 Segment of measurement

When choosing a segment of measurement, it is important to look for the following conditions:
- a straight segment in the system;
- no obstruction and no serious deposits in any portion of the segment of measurement(31);
- no inflow or loss of liquid between the injection and sampling points(1);
- access necessary to perform all measurements with precision;
- a stable and constant flow.

4.1.2.1.11.1 Injection point

When choosing an injection point, it is important to check the following conditions:
- access for personnel and equipment;
- the presence of or circumstances that can create a turbulent flow to allow the tracer to mix;
- a location that does not interfere with vehicular traffic.

4.1.2.1.11.2 Sampling point

When selecting a sampling point, it is important to check for the following conditions:

- access for personnel and equipment;
- flow must be stable, constant and smooth to enable accurate measurement of the flow area;
- a location that does not interfere with vehicular traffic.

4.1.2.2 Use of a chemical tracer

A chemical tracer is one of the three types of tracers that can be used to perform flow measurements using the time travel method.

4.1.2.2.1 Principle of use

The method involving use of a chemical tracer (brine) is based on the fact that the presence of a salt increases the electrical conductivity of water (2). Enough salt must be added to allow conductivity to increase (27) (31). The change in conductivity is detected and the time for a given volume of liquid to travel between two observation points is measured.

4.1.2.2.2 Applications of chemical tracers

Chemical tracers can be used in almost any situation. They are particularly well suited for measurement of waters that contain large amounts of organic matter. They are highly soluble and stable.

It is important, however, to verify the environmental impact use of a tracer may have on the receiving water.

4.1.2.2.3 Preparation of chemical tracers

A saline solution (NaCl) with a density between 1.01 and 1.04 is usually prepared. Use of another tracer requires a similar concentration. A few tests should normally be performed to determine what concentration will be required for an optimum reading.

Enough solution should be prepared to allow five tests to be performed, in addition to development tests. It is important to take the estimated flowrate into account, to determine exactly how much solution will be required.

4.1.2.2.4 Advantages of chemical tracers

- the tracer is stable;
- the tracer is soluble;
- the tracer is not affected by the water’s pH level;
- the tracer is detectable, even if there are large amounts of suspended matter;
- the tracer remains stable, even in the presence of oxidizing agents such as chlorine.

4.1.2.2.5 Disadvantages of chemical tracers

- chemical tracers can be expensive.

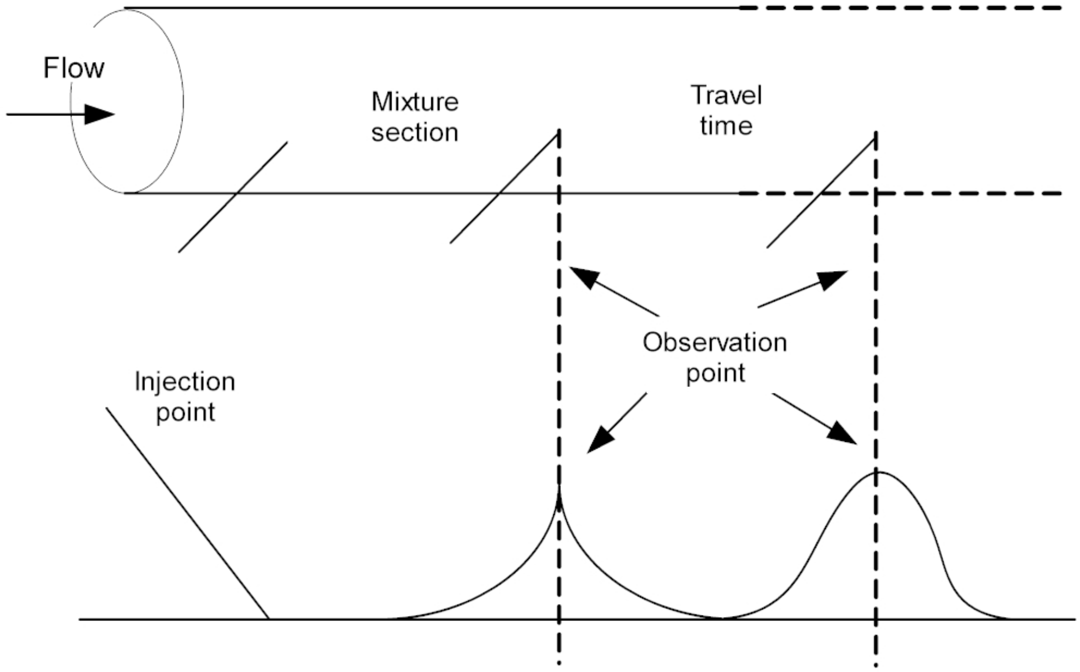
4.1.2.2.6 Detection and measurement equipment

The following equipment is required:

- detecting electrodes;
- a galvanometer;
- a chronometer;
- a recording instrument.

4.1.2.2.7 Position of electrodes

A pair of electrodes is placed in two locations in the flow section, far enough away from one another to allow an accurate measurement of how long it takes for the brine to reach each point. The first electrode must be positioned at a distance equal to at least four times the diameter of the conduit downstream from the injection point (31). The distance of the second electrode will vary according to conditions at the site. However, the electrodes must be far enough away from one another so that when the tracer can no longer be detected at the first test point, it begins to be detected at the second point.



4.1.2.2.8 Detection and measurement procedure

Electrodes are connected to a recording instrument. When movement of a tracer to each point is detected, the instrument plots a curve on the chart to represent the stream's electrical conductivity. The amount of time that has elapsed between the centre point of both chart curves is measured in seconds (2).

The average velocity is calculated on the basis of at least five tests.

The deviation between the lowest and highest velocity measured during the five tests must be less than 5 %. A larger deviation requires a complete review of the procedure and repeating the tests.

4.1.2.2.9 Preliminary tests

Before conducting calibration tests, it is important to perform a few preliminary tests to determine the following:

- the liquid's natural conductivity, which will be used as the basis for measurements (point zero);
- the concentration of the brine necessary to create an adequate difference in conductivity;
- the correct location of detection electrodes.

4.1.2.2.10 Precision

When performed by skilled personnel, this method of measurement yields a value that deviates no more than ± 1 % from the actual value.

4.1.2.2.11 Causes of error

The principal causes of error include:

– speed of injection	if the injection time is too long, movement of the brine to the observation points may be difficult to detect due to dilution in the flow;
– volume measurement in the flow section	the measurement must be extremely accurate, and particular care must be taken to correctly locate the flow section. Because the distance between the injection point and observation point is very short, a flow measurement must also be performed with extreme precision;
– travel time	to minimize errors, the plotting of curves should be timed and the time interval between each peak should be calculated using a chronometer that is separate from the recording instrument.

4.1.2.3 Use of a dye tracer

Use of a dye tracer is becoming increasingly more common to perform a flow measurement using the time travel method.

4.1.2.3.1 Principle of use

This method is based on a visual observation of a change in color of flow. It is therefore important to determine the time necessary for a colored cloud to travel the distance between the injection point and test point.

4.1.2.3.2 Applications of dye tracers

The use of dyes may appear limited due to the interferences that are often present during sample analysis. Each case must be assessed on the basis of preliminary tests before authorizing use.

Dyes are well suited to flow measurements in water that contains only very small amounts of suspended matter, very little organic matter, no oxidizing agents and where the pH is relatively neutral. Experience shows, however, that dye tracers can be used even if water pH is acid or alkaline, if the sample is neutralized before analysis. The presence of organic matter or suspended matter can also be blocked if the sample undergoes centrifugation before analysis.

It is also important to verify the toxicity of dyes before use to ensure that there are no contraindications related to potential use in water.

4.1.2.3.3 Preparation of dye tracers

Prepare dye tracers by diluting the concentrated product with distilled water. The concentration of the solution will depends on an estimate of the flowrate. The final concentration, after mixture with the flow, which is easily visible to the eye, should be approximately 25 to 50 µg/l (ppb)(32).

The amount of tracer necessary to carry out work can be determined on the basis of the following equation:

$$V_s = \frac{KC_pQL}{10^5 v} \qquad (50)$$

where:

C_p is the desired maximum concentration at the test point, in µg/l (ppb);
K is the constant (133.84 for metric units and 3.79 for imperial units);
L is the length of the measurement segment, in meters or feet;
Q is the flowrate of the discharge gauged in cubic meters/second or cubic feet/second;
V_s is the volume of the tracer (rhodamine WT 20 %) that is required, in milliliters;
v is the average flow velocity, in meters/second or feet/second.

A few tests are usually required to determine the concentration that is necessary to obtain optimum results.

There should be enough tracer dye to allow five tests to be performed, in addition to development tests. It is important to take the estimated flowrate into account, to determine the exact amount of tracer that is required.

4.1.2.3.4 Advantages of tracer dyes

- tracer dyes are extremely water soluble;
- they are inexpensive;
- the visibility of the tracer simplifies the task;
- tracers can be prepared quickly and easily;
- very little detection and measuring equipment is required.

4.1.2.3.5 Disadvantages of dye tracers

Some experience and good judgment are required to find the centre of the cloud. Use of a fluorometer can significantly reduce uncertainty and improve precision. The following factors should also be considered.

- It is difficult to determine if the cloud observed is the average cloud or simply a surface cloud(1);
- A tracer cannot be used where certain oxidizing agents such as chlorine are present;
- A tracer may be destroyed in the presence of extreme pH levels;
- The presence of solids or organic matter can cause interference;
- Glass equipment must absolutely be used.

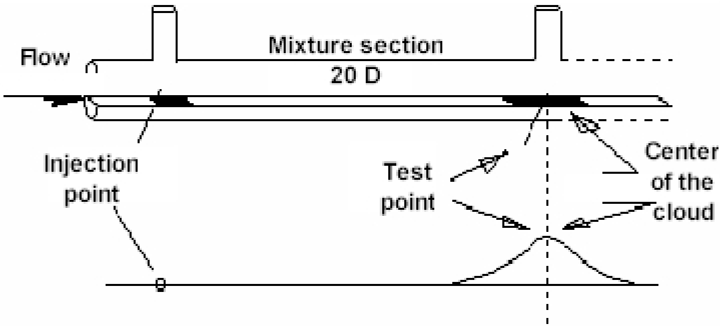
4.1.2.3.6 Detection and measurement equipment

The following instruments are required:

- a chronometer;
- a sampling device;
- a colorimeter or fluorometer.

4.1.2.3.7 Position of test point

The test point should be located far enough away from the injection point to allow the tracer to mix with water. Enough distance should also be allowed to enable an accurate measurement of the amount of time that elapses between the moment of injection and movement of the dye to the test point.



The distance required between the injection point and test point will vary according to flow conditions and depending on how fast the mixture occurs. The more turbulent the flow at the injection point, the shorter the distance. Nonetheless, the distance between the injection point and test point should be no more than twenty diameters of the conduit.

4.1.2.3.8 Detection and measurement procedure

The detection procedure can consist of a visual detection of dye at the test point, without the need for a concentration measurement over time. This method of detection, however, is not enough to guarantee an accurate measurement, because pinpointing the actual centre of the cloud of dye is subjective. The cloud that appears at the surface is also not necessarily representative of an average cloud.

The recommended method of detection therefore consists of using a colorimeter or fluorometer to measure the concentration of dye at the test point and plotting the curve of concentrations as a function of time to determine the centre of the cloud. This method requires sampling at very rapid intervals (within thirty seconds of one another).

The centre point of the curve coincides with movement of the cloud to the test point. The amount of time that elapses between the moment of injection and the centre point of the curve is measured in seconds (2).

Velocity is the average velocity calculated on the basis of results obtained for each test.

The deviation in values between the lowest and highest velocity measured during the five tests must be less then 5 %. A higher deviation requires a complete review of the procedure and repeating tests.

4.1.2.3.9 Preliminary tests

Before performing calibration tests, a few preparatory tests must be performed to determine the following:

- the effluent’s natural color and the concentration of dye necessary to obtain adequate coloring;
- the exact location of the test point;
- effluent interference.

4.1.2.3.10 Precision

When performed by skilled personnel, this method of measurement yields flow measurements with a deviation of no more than ± 1 % of the actual measurement.

4.1.2.3.11 Causes for error

The principal causes for error are as follows:

– speed of injection	if the injection time is too long, the curve of concentration as a function of time at the test point may be too large, making it difficult to determine the centre point of the cloud of dye;
– measurement of the volume of the flow area	the measurement must be extremely precise, and particular care must be taken to locate the flow area exactly. Because the distance between the injection point and observation point is extremely short, the flow measurement must also be very precise;
– travel time	to minimize errors, a chronometer must be used to track the amount of time that elapses between the injection point and test point and to plot the curve of concentrations over time, until the natural concentration reappears.

4.1.2.4 Use of a radioactive tracer

Use of a radioactive tracer is an expensive method that is not in common use.

4.1.2.4.1 Principle of use

This method is based on the fact that a tracer added to the discharge increases the natural radioactivity of water. The change in radioactivity is detected to determine the amount of time that elapses for the tracer to move between two observation points.

4.1.2.4.2 Applications of radioactive tracers

Radioactive tracers can be used in almost any situation. They are particularly well adapted to measurement of water that contains large amounts of suspended matter and organic matter.

Before use, it is important to ensure that a radioactive tracer will not affect the receiving water.

4.1.2.4.3 Preparation of radioactive tracers

Radioactive tracers usually do not require any particular preparation and are used as is. The amount of tracer used depends on the estimated flowrate. A few tests are usually required to determine how much tracer is necessary to obtain optimum results. There must be enough tracers available to allow five tests to be performed, in addition to development tests.

4.1.2.4.4 Advantages of radioactive tracers

- Only very small concentrations are necessary to detect the tracer, since the natural radioactivity of effluents is negligible (28).
- Portable instruments can be used for on-site detection and measurement.

4.1.2.4.5 Disadvantages of radioactive tracers

- The tracer must be stored in a lead container until it is used (28).
- Special precautions have to be taken to protect the health and safety of workers.
- The public perception of radioactive agents is negative.
- Isotopes, detection equipment and measuring instruments are expensive.
- This tracer is normally used to measure large-volume flows.
- It can pose a hazard to humans, wildlife and vegetation.

4.1.2.4.6 Detection and measurement equipment

The following equipment is required:

- a chronometer;
- a scintillation detector;
- a sampling instrument;
- 20 liters containers.

4.1.2.4.7 Position of test point

The test point should be located far enough away from the injection point to allow the tracer to mix with water. Enough distance should also be allowed to enable an accurate measurement of the amount of time that elapses between the moment of injection and movement of the dye to the test point.

The distance required between the injection point and test point will vary according to flow conditions and depending on how fast the mixture occurs. The more turbulent the flow at the injection point, the shorter the distance. Nonetheless, the distance between the injection point and test point should be no more than twenty diameters of the conduit.

4.1.2.4.8 Detection and measurement procedure

The procedure for detecting radioactive tracers consists of measuring their activity using scintillation detectors. The degree of activity is recorded by plotting a curve on recording chart paper as a function of time.

This procedure requires immerging the detector in the flow. The detector must be surrounded by enough liquid on all sides, between 0.5 and l meter, depending on the type of isotope used.

Samples can also be taken and placed in 20 liters containers for later sample analysis. This method requires taking a large number of samples at very rapid intervals (within thirty seconds of one another).

The centre point of the curve coincides with movement of the cloud of radioactive tracer to the test point. The time that elapses between the moment of injection and the centre point of the curve is measured in seconds (2).

Velocity is the average velocity calculated on the basis of results obtained for each test.

The deviation between the lowest and highest velocity measurements during the five tests must be less than 5 %. A larger deviation requires a complete review of the procedure and repeating tests.

4.1.2.4.9 Preliminary tests

Before conducting calibration tests, it is important to perform a few preliminary tests to determine the following:

- the liquid's natural radiation, that will be used as the basis for measurements (point zero);
- the amount of radioactive substances that are required to obtain an adequate reading of activity at the test point;
- the correct location of the test point.

4.1.2.4.10 Precision

When performed by skilled personnel, this method of measurement yields a value that deviates no more than ± 1 % from the absolute value.

4.1.2.4.11 Causes of error

The principal causes of error are:

– speed of injection	if the injection time is too long, the curve of concentration as a function of time at the test point may be too long, making it difficult to determine the centre point of the cloud;
– volume measurement in the flow section	the measurement must be extremely accurate, and particular care must be taken to correctly locate the flow section. Furthermore, because the distance between the injection point and observation point is very short, the flow measurement must be performed with extreme precision;
– travel time	travel time is gauged using a chronometer. The amount of time that elapses between injection and the time it takes to completely plot a curve of concentrations, and the position of the centre point of the curve determines the travel time.

4.1.3. Dilution measurement method

Flow measurement using the dilution measurement method can be performed using any type of tracer. For the purpose of this document, lithium chloride and rhodamine WT will be discussed, because these two tracers are commonly used.

4.1.3.1 General

Use of the dilution method allows you to determine flow without the need to measure dimensions of the flow section.

The dilution method is based on a measurement of color, conductivity, fluorescence, chemical concentration or radioactivity.

4.1.3.1.1 Principle of the method

The method consists of measuring the degree of dilution of an amount of tracer, injected into a flow, once it has been completely mixed (28) (30).

On the basis of this principle, flow can be determined using the following equation (33):

$$Q_1 C_1 = Q_2 C_2 \quad (51)$$

where:

Q_1 is the injection flow of the tracer;
C_1 is the concentration of tracer injected;
Q_2 is the desired flowrate;
C_2 is the concentration of tracer mixed in the flow.

The principle appears simple enough; however, practical application requires a thorough understanding of the dispersion process.

4.1.3.1.2 General applications

This method can be used to measure flow in an open or closed conduit.

In an open conduit, this method is used when:
- the flow is too fast and turbulent(30);
- the measurement segment is too irregular;
- the measurement segment contains debris and deposits(30);
- the segment area and flow velocities are variable(30);
- access to the measurement segment poses a risk of accident(30);
- some portions of the measurement segment can only be accessed through small diameter observation wells.

4.1.3.1.3 Advantages of the method

- enables flow measurements where other methods cannot be used;
- allows large flows to be measured;
- produces extremely accurate measurements; the method can therefore be used to counter-check measurement setups and movement of liquids at the site(28);
- does not require knowledge of dimensions of the flow area and flow velocity(28);
- enables flow measurements in a closed or open conduit.

4.1.3.1.4 Disadvantages of the method

- tracers are expensive;
- the method usually yields only momentary flow measurements;
- the procedure requires trained personnel;
- the procedure requires a lot of time(28);
- an number of parameters that can cause interference must be considered when selecting a tracer and must be measured during use;
- flow measurement is not always immediately available.

4.1.3.1.5 Injection equipment

The type of equipment required to carry out the dilution method will vary according to the flow system present at the site and the method of measurement used. The tracer that is used has no bearing or very little bearing on the type of injection equipment used.

The following equipment is required:

- an injection instrument;
- a deflection device to create turbulence in the flow at the injection point;
- a mixing tank for the solution;
- a tracer;
- a chronometer;
- graduated containers (cylinders, flasks, pipettes, test tubes) to prepare the stock solution, calibrate the injection instrument, store the stock solution, collect samples and store samples;
- a hose and couplings.

4.1.3.1.6 Personnel

This method requires technical personnel who have relevant training and experience. It is difficult to carry out work with fewer than three people.

4.1.3.1.7 Types of tracers

Go to section 4.1.1.1 for more information about tracers.

4.1.3.1.8 Recovery index (I_r)

Whether you use a slug injection or constant injection technique, when using chemical tracers and dyes, it is always important to perform tests to determine the recovery index (I_r). A recovery index is required to demonstrate the accuracy of the method and it allows you to determine the correction factor that applies during the flow calculation (34).

4.1.3.1.8.1 Procedure to determine the recovery index

The procedure to determine the recovery index consists of two steps: theoretical calculation of the concentration after mixing and laboratory testing.

4.1.3.1.8.1.1 Theoretical calculation

Based on the principle that if the initial concentration of a tracer is known, it is possible to make a theoretical calculation of the concentration of a specific amount of tracer once it is mixed with a predetermined volume of water.

Example: A tracer with an injection concentration of 4000 ppb is used to perform tests. If 1 ml of tracer is mixed with 999 ml of water, the theoretical concentration of the tracer after mixing is 4 ppb.

4.1.3.1.8.1.2 Laboratory testing

Laboratory recovering tests consist of comparing the amount of tracer recovered and the established theoretical value, when the tracer is mixed with the following:

- a solution that has no chance of interfering with the tracer, usually distilled water or demineralized water;
- water from the discharge, usually taken upstream from the injection point.

Testing procedures are as follows:

> Three volumetric flasks, of 1000 ml are used. One (1) ml of tracer is placed in each of the volumetric flasks. The first flask is filled to the mark with distilled or demineralized water, and the two other volumetric flasks are filled with water from the flow. Each flask is then shaken to obtain a uniform mixture. A sample is taken from each flask and the concentration of tracer after mixture is measured in each case. The concentrations recorded are compared with the theoretical concentration that was determined ahead of time.
>
> The concentration of tracer, after mixture with distilled water, must be equal to the theoretical concentration. Any deviation with the theoretical value will be considered an error in handling. If the deviation is too large (± 1 %), all tests must be repeated.
>
> The concentration of the tracer, after mixture with water from the flow, is compared with the concentration of the solution prepared with distilled water. The value obtained for each solution must be identical. Any deviation between these two values is defined as a recovery index.
>
> **Example**: The theoretical value determined above was 4 ppb. The value obtained with distilled water is also 4 ppb. The value obtained with water from the flow is 3.8 ppb. The recovery index is therefore 0.95, or 3.8 ppb/4 ppb.

4.1.3.1.9 Mixing conditions

To ensure that measurements are successful, sampling must be carried out at a point far enough downstream from the injection point and the tracer must mix with the flow well.

The following conditions help to create proper mixing:
- a turbulent flow at the injection point;
- a long enough measurement segment;
- a water depth at the injection point comparable to the average depth in the measurement segment.

To determine if mixture is complete, use the following formula recommended by Rimmar(27):

$$\left(\frac{\hat{C} - \bar{C}}{\bar{C}}\right) 100 < 1\,\% \qquad (52)$$

where:

$\hat{C}$ is the maximum concentration at a point in the test section, in mg/l or µg/l;
$\bar{C}$ is the average concentration for all points in the control section, in mg/l or µg/l.

In pipelines, this calculation method does not determine the effectiveness of mixing. Since measurement segments are not as wide as rivers and since walls in a flow segment are usually quite uniform, sampling at the test point should be carried out at one point, not at three points in the cross section. Use the equation shown in section 4.1.3.1.10 to determine the correct length of the measurement segment.

4.1.3.1.10 Measurement segment

The measurement segment must contain few locations of dead water (such as observation wells) which increase retention time and cause small concentrations of the tracer to appear, and are more difficult to measure accurately. A rapid cross section mixture reduces measurement time and the length of the measuring segment. Water depth plays an important role in the mixing process (30).

The following conditions should be examined when choosing a measurement segment:

- a turbulent flow that allows the tracer to mix effectively;
- a long enough measuring segment to ensure proper mixing.

The following factors should also be considered:

- an inflow of liquid between the injection and sampling point, which increases the distance necessary to obtain proper mixing(3) (30);
- loss of liquid between the injection and sampling points, which can misrepresent results.

Use the following formula to determine the length of the segment necessary to ensure adequate mixing$^{(30)}$:

$$L_m = k\left(\frac{v B^2}{E_z}\right) \quad (53)$$

where:

L_m is the length of mixture in meters or feet;
k is a constant (0.46 with the metric system and 0.14 with the imperial system);
v is the average velocity of flow in meters or feet per second;
B is the average width of flow in meters or feet;
E_z is 1.13 ($d^{3/2} S^{1/2}$); or 0.2 ($d * u$);
g is the gravitational constant (9.8 meters/s^2 or 32.17 feet/s^2);
d is the average depth of the in meters or feet;
s is the slope of the flow area in meters per meter or feet per foot;
u is equal to $(g\ dS)^{1/2}$

The length that is determined is measured from the last water inflow point, upstream from the sampling point.

In a river, the above equation should yield a result that corresponds to approximately 30 to 40 times the average width of the measurement segment.

For an artificial channel, the recommended length is at least 20 times the diameter of the conduit, because for small conduits (< 0.6 meters or 2 feet), the equation produces lower values.

4.1.3.1.10.1 Injection point

- An injection point must be chosen beforehand in order to ensure that it can be accessed.
- It must be located in a turbulent flow. A turbulent flow can be created when necessary.
- Access to the injection point must be secure.
- It must be located at a site that does not interfere with vehicular traffic.
- It must be large enough to enable injection equipment to be installed.

4.1.3.1.10.2 Sampling point

- A sampling point must be chosen beforehand, in accordance with access and security criteria.
- The presence or absence of turbulence is of little importance.
- It must be located at a site that does not interfere with vehicular traffic and that is large enough to allow sampling equipment to be set up.

4.1.3.1.11 Method of execution

Flow measurement using the dilution method can be performed using a slug injection or constant injection of a tracer.

4.1.3.2 Slug injection

This method is sometimes called the total recovery method.

4.1.3.2.1 Principle of the method

Flow is calculated according to the rate at which a tracer is diluted with the flow, based on a complete evaluation of its mass downstream from the injection point.

This principle may translate into the following equation, which expresses flow as a function the mass of the tracer (30):

$$Q = \frac{M}{A_c} \qquad (54)$$

where:

Q is the volume of the flow measured;
M is the mass of the tracer injected;
A_c is the area located below the response curve following satisfactory mixing of the tracer with the flow (30).

This measurement method requires an exact knowledge of the total amount of tracer that is injected and the concentration of tracer in the flow, throughout the entire period it can be detected.

The discharge equation is therefore as follows (35):

$$(C_1 - C_0)V = Q_S \int_o^t (C_2 - C_0)dt \qquad (55)$$

where:

Q_s	is the flowrate;
C_o	is the natural concentration of tracer in the flow, prior to injection;
C_1	is the concentration of tracer injected;
C_2	is the concentration of tracer following mixing;
V	is the volume of the tracer injection;
dt	is the elapsed time (t_3 - t_2);
t_3	is the time of the end of movement of the tracer to the test point, in minutes;
t_2	is the time of the beginning of the movement of the tracer to the test point, in minutes.

If the natural concentration (C_o) of the tracer in the flow is negligible, the equation can be simplified as follows:

$$Q_s = V \frac{C_1}{\int_o^t C_2 \, dt} \qquad (56)$$

4.1.3.2.2 Uses

The slug injection measurement method is used where:

- radioactive tracers are used. This is almost the only method that can be used with this type of tracer (30);
- the measurement segment is relatively short. Long segments can result in a loss of tracer and cause unsatisfactory measurements(30);
- the injection equipment available is limited(30).

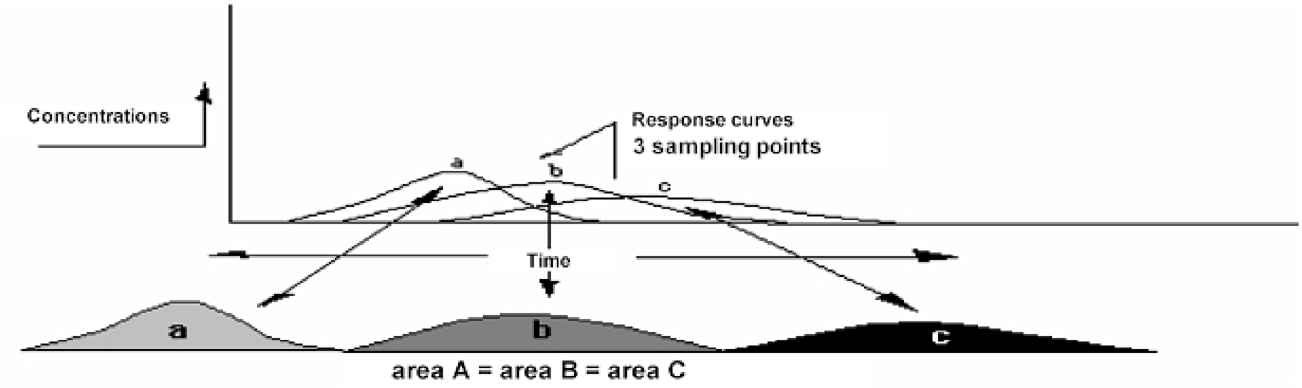
4.1.3.2.3 Implementation

The slug injection method consists of introducing a known amount of tracer to the flow as quickly as possible and measuring the concentration of the tracer downstream at regular intervals in order to plot dilution-flow response curves. Because the measurement segment is usually relatively short, the time it takes for a tracer to move downstream rarely exceeds more than one hour (30).

The success of implementing this formula lies in the fact that the mass of the tracer injected is totally recovered at the test point. Calculation of recovery consists of multiplying the area of the response curve

(A_c) {concentration by the amount of time that has elapsed (C_2) (dt)}, by the flowrate (Q_s). It is therefore extremely important to ensure that the area of the response curve (A_c) is representative of the dilution of the tracer injected (31).

The response curve must be measured relatively further downstream from the injection point to enable adequate mixing. Once mixing has occurred, the surface below the concentration curve as a function of time is the same, regardless of the shape of the curve, for samples taken at different points along the width of the discharge (30).



At least 30 samples are required to plot this curve (35).

When using this measurement method, follow these steps:

- <u>Select the measurement segment</u>

  Estimate the characteristics of the measurement segment:

  - average width (B);
  - average depth (d);
  - velocity of flow (v);
  - flowrate (Q);
  - slope of the measurement segment (s).

  Determine the length of the measurement segment required.

  The required length is calculated according to equation 53 in section 4.1.3.1.10.

- Choosing a tracer

Examine the discharge for parameters that may interfere with tracers, such as the pH, color, presence of suspended matter, presence of minerals, etc., and determine the tracer's recovery index according to the method described in section 4.1.3.1.8 of this document.

Select the tracer that is best suited to conditions, based on information gathered and criteria listed in section 4.1.1.3.

- Preparing the tracer

The tracer is prepared according to the method described in section 4.1.1.4.

To determine the amount of tracer required to carry out work, the following information must be available:

- the concentration of the tracer at the time of injection (C_1);
- the projected concentration of the tracer after mixing with the discharge (C_2);
- the estimated flowrate of the effluent discharge (Q);
- the estimated time it takes the tracer to migrate to the test point (t_F - t_1).

The projected concentration of the tracer after mixture with the discharge (C_2) must be at least 20 times the natural concentration of the discharge and must be between 0 and 20 µg/l in the case of rhodamine WT, and between 0 and 3 mg/l in the case of lithium chloride (LiCl)(3) (30) (33).

Once these four parameters are known, the amount of tracer required can be determined using the following equation:

$$V = \frac{C_2}{C_1} Q(t_F - t_1)1000 \qquad (57)$$

where:

V is the amount of tracer required, in milliliters;
C_1 is the concentration of the tracer at the time of injection in mg/l;
C_2 is the concentration of the tracer after mixing with the discharge, in mg/l;
Q is the estimated flowrate in liters per minute;
t_F is the end time for migration of the tracer, in minutes;
t_1 is the start time for migration of the tracer, in minutes.

- <u>Field work</u>

Tracer injection:

- instantly inject the total amount of the prepared tracer into the measurement segment, in the centre of the discharge. Injection should be performed using a container with a very large opening to ensure that all of the solution is emptied immediately;
- when injecting the tracer, ensure that no amount of the tracer is lost due to splashing, etc. by introducing the tracer into the discharge at least 2 to 3 inches away from the surface, especially if the procedure is carried out in relatively tight quarters, such as manholes;
- begin timing begins, notify individuals at the sampling point that the tracer has been injected;
- measure and record water depth in the measurement segment to ensure that the flow remains constant.

Sampling:

Two types of samples are taken, control samples and measurement samples.

The purpose of control samples is:

- to verify and quantize the natural presence of tracer in the discharge;
- to verify the stability of or fluctuations in the natural concentration of the tracer in the discharge;
- to verify the concentration of the tracer injected.

Control samples:

- a water sample (preferably two) is taken in the measurement segment to determine the natural concentration of tracer in the water. These samples are taken even before beginning to handle the tracer, every three minutes throughout the procedure and at the end of the injection, to ensure that there have been no changes in the natural concentration (27);
- the sample must be taken at a location that is representative of the quality of flow, without risk of contamination by the tracer (27);
- an approximately 50 ml sample (preferably two) of the injection solution should be taken, to verify the concentration of solution and to prepare calibration standards, if necessary (30).

Measurement samples:

- samples are taken at the test point after the tracer has been injected;
- they help to determine the concentration of the tracer after mixing and to ascertain the flow measurement in the measurement segment.

Sampling must be carried out during the entire time the tracer is present. It must begin before the tracer arrives at the test point and must continue until no further sign of the tracer is present.

A large number of samples are required to ensure that the tracer has completely migrated.

In the case of wide channels, samples must be taken at three points, at 1/6, 3/6 and 5/6 of the width of the channel if:

- the channel is wider than 8 feet and has uniform and seamless walls (example: concrete conduit);
- the channel is wider than 6 feet and has uniform but irregular sides (example: ditch).

Sampling must continue after an estimate of how long it takes the tracer to migrate. Sampling must continue for at least three to four times the amount of time that is required for the maximum concentration of the tracer to migrate to the test point. For example, if the maximum concentration is projected to migrate to the test point 10 minutes after injection, sampling must continue after these ten minutes for a period of at least 20 minutes (preferably 40 minutes).

Samples must be taken in brief intervals, less than one minute apart, and the exact time of sampling must be noted for each sample.

Each sample must be identified and prepared immediately for shipment to the laboratory. Samples must be stored out of direct sunlight, particularly in the case of light-sensitive tracers, such as dyes (30).

Sampling must be carried out by two individuals; one to take samples, the other to note and record the exact time of sampling (30).

To gauge the retention time of the maximum concentration of the tracer at the text point, it is common practice to use a dye to perform a preliminary test and to measure the travel time on the basis of the visual effect of the mixture. If the tracer is invisible, a dye can be added to the stock solution for viewing and to omit the need to perform a preliminary test. The total retention time is projected to last four times longer than the time necessary for the maximum concentration to migrate (30).

- Analysis of results

  The concentration of tracers is usually determined in a laboratory. If the tracer is a dye, it may be more convenient to analyze the sample at the site, but this procedure is not mandatory. If samples are analyzed at the site, they must still be stored for future reference.

4.1.3.2.4 Advantages of a slug injection

- Injection of a tracer does not require a sophisticated instrument.
- Injection of a tracer requires few personnel and little time.
- Less tracer is required when using the slug injection method, compared to the constant injection method. To measure smaller flows, 3 to 5 times less tracer is required than the amount required for the constant injection method. To measure large flows, the difference is marginal.

4.1.3.2.5 Disadvantages of slug injection

- The entire sequence must be sampled (27).
- Requires a large number of samples.
- Can only be used to measure the segment where the flow is stable.

4.1.3.2.6 Interpretation of results

Once samples have been taken at three points, a concentration curve in relation to time is plotted for each sampling point and the area of each curve is measured.

The mixture is uniform when areas under the curves are identical. An average curve is plotted on the basis of these three curves (30).

The flow is determined through use of the equation in section 4.1.3.2.1.

4.1.3.2.7 Causes for error

To minimize errors due to handling, the following points should be verified:

- the concentration of the stock solution;
- rapid injection (in one go) of the tracer;
- the amount of tracer injected;
- loss of the tracer due to splashing at the time of injection;
- deterioration of the tracing solution;
- a lack of consistency of the tracing solution prior to injection;

- contamination of sampling containers;
- changes in flowrate during measurement.

4.1.3.2.8 Precision

Under normal conditions, the method is accurate to within ± 3 % (27).

4.1.3.3 Constant injection

The constant injection method is an uninterrupted sequence of slug injections of minimum amounts of a tracer. It is usually preferred over the slug injection method, due largely to its superior precision.

4.1.3.3.1 Principle of the method

The constant flow injection method consists of measuring the concentration of the tracer present at the test point when a state of stability is achieved (30).

The following equation establishes the relationship between flow of the tracer and flow of effluent (30):

$$Q_2 = Q_1 \frac{C_1}{C_2} \quad (58)$$

where:

Q_2 is the flowrate measured;
Q_1 is the injection rate of the tracer;
C_2 is the concentration of the tracer after mixing with the discharge;
C_1 is the concentration of the tracer at the injection point, before mixing with the discharge.

4.1.3.3.2 Uses

The constant injection measurement method is used when:

- the natural concentration of the tracer in the discharge may vary;
- the flowrate may vary during tests;
- the greatest precision possible is desired(3o).

4.1.3.3.3 Procedure

This method consists of injecting a known concentration of tracer at a constant rate, and measuring the concentration after homogeneous mixing with the discharge. The exact injection rate and exact concentration of the tracer must be known.

The injection rate must be much slower than the flow of effluent, and the optimum measurement concentration must be much greater than the natural concentration of tracer in the effluent.

To factor in the natural concentration level, the equation is as follows (27):

$$Q_2 = Q_1\left(\frac{C_1}{C_2 - C_0}\right) \quad (59)$$

Where:

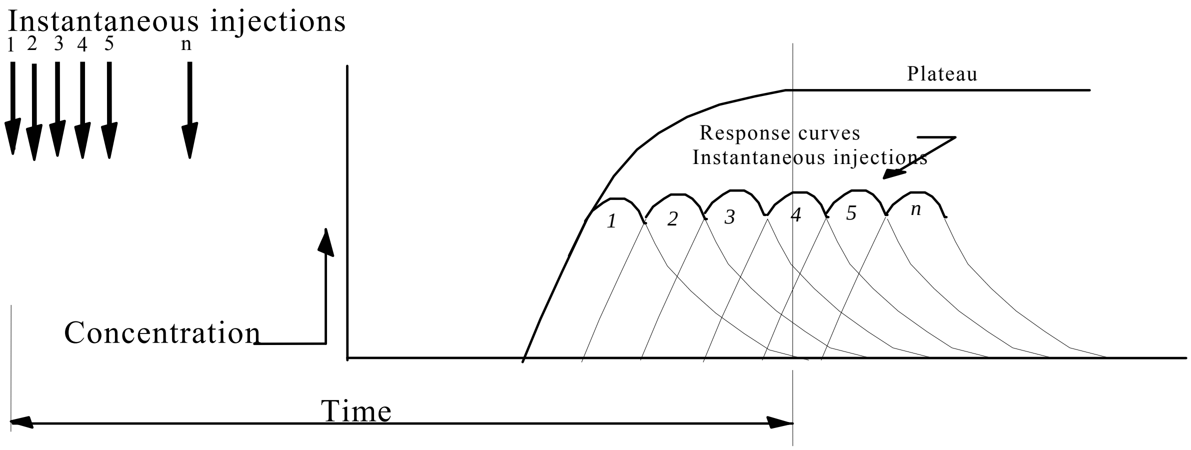
Q_2 is the flowrate of the discharge;
Q_1 is the rate of injection of the tracer;
C_1 is the concentration of the tracer injected;
C_0 is the natural concentration of the tracer in the effluent;
C_2 is the concentration of the tracer after mixture with the discharge.

Since four variables are known, it is possible to calculate the flowrate of the discharge.

Unlike a slug injection, the response time of the curve does not have to be determined, only the point where the maximum concentration is achieved and maintained (plateau). Once this condition of stability is achieved, the principle of mass conservation applies and the amount of tracer injected (Q_1C_1) is equal to the amount of tracer that migrates to the test point (Q_2C_2)(30).

The time necessary to measure the flow using one or more methods is approximately the same (30). The constant injection method, however, has the advantage of being able to cover a longer period of measurement, by extending the injection after a plateau has been reached.

The time required to reach the point of equilibrium through continuous injection can be determined precisely by examining the response time of the curve that is generated with the slug injection method, as shown below.



The above chart shows that the beginning of the plateau, according to the continuous method, coincides with the moment the tracer disappears, if only one injection was made using the instant method. In practice, the constant injection period should be slightly longer than the period required to generate the first response curve, using the instant method(30).

This method requires the following steps:

- Choosing a measurement segment

  Estimate the characteristics of the measurement segment:

  - average width (B);
  - average depth (d);
  - flow velocity (v);
  - flowrate (Q);
  - slope of the measurement segment (s).

  Determine the length of the segment required, using equation 53 in section 4.1.3.1.10.

- Choosing a tracer

  Examine parameters in the discharge that may interfere with tracers, such as the pH, color, presence of suspended matter, presence of minerals, etc., and determine the tracer's recovery index according to the method described in section 4.1.3.1.8 of this document.

  Select the tracer that is best suited to conditions, based on information gathered and criteria listed in 4.1.1.3.

- Preparing the tracer

The tracer is prepared according to the method described in section 4.1.1.4.

To determine the amount of tracer that will be required for the procedure, the following information must be known:

- the concentration of the tracer at the time of injection (C_1);
- the projected concentration of the tracer after mixing with the discharge (C_2);
- the estimated flowrate of the effluent discharge (Q_2);
- the estimated time it takes the tracer to migrate to the test point ($t_3 - t_2$) in minutes;
- the elapsed time of the injection after a plateau has been reached, in minutes.

Once these five parameters are known, the amount of tracer required can be determined using the following equation:

$$V = (t_f - t_i + t_p)\frac{Q_2 C_2}{C_1} \quad (60)$$

where:

V	is the amount of tracer required in liters;
C_1	is the concentration of tracer at the time of injection in mg/l;
C_2	is the concentration of the tracer after mixing with the discharge, in mg/l;
Q_2	is the estimated flowrate in liters per minute;
t_f	is the end time for migration of the tracer, in minutes;
t_i	is the start time for migration of the tracer, in minutes;
t_p	is the injection time after a plateau has been reached, in minutes.

A slightly larger amount (5 %) of tracer should be prepared than the amount calculated for this work, in order to be prepared for the unexpected.

- Field work

Tracer injection:

A known concentration of the tracer is injected continuously into the discharge, using an instrument for which the injection rate can be adjusted and controlled. The principal instruments used include: Mariotte vase, constant level vessel and feed pumps.

No amount of tracer should be lost when it is injected; ensure that no amount of the tracer is lost due to splashing, by introducing the tracer into the discharge at least 2 to 3 inches away from the surface of the water, especially when the procedure is carried out in relatively tight quarters, such as manholes.

The injection tube must not touch the water surface, to prevent tracer from being carried by the stream and subsequently distorting the rate of injection.

The injection instrument must be calibrated before and after use to verify if the flow has remained constant.

No air bubbles should be present in the injection system, to maintain a continuous presence of tracing solution in the tube.

The tracer solution should be placed in a graduated container; the level of solution must be recorded at time 0.2, 0.4, 0.6 and 0.8 of the total time of injection. This observation serves as a counter-check to ensure that the rate of injection is consistent.

Sampling:

There are two types of samples: control samples and measurement samples.

The purpose of control samples is:

- to verify and quantize the natural presence of tracer in the discharge;
- verify the stability of or fluctuations in the natural concentration of the tracer in the discharge;
- verify the concentration of the injection solution;
- determine the tracer recovery rate.

Control samples:

- a water sample (preferably two) is taken in the measurement segment, to determine natural concentration of tracer in the water and any variations in concentration. These samples are taken even before beginning to handle the tracer, every three minutes throughout the procedure and at the end of the injection (27).

  The sample must be taken at a location that is representative of the quality of flow, without risk of contamination by the tracer (30).

- A sample (preferably two) of the injection solution should be taken at the beginning and end of the procedure, to verify the concentration of solution.

Measurement samples:

Measurement samples are taken in the discharge, downstream from the tracer injection point. These samples are used to determine the concentration of tracer at the test point.

Enough samples must be taken to plot a minimum number of points on the response curve, that is, three points on the upward curve and nine points on the plateau.

Sampling must begin before the tracer migrates to the test point, and must continue after a plateau has been reached.

In the case of large channels, samples should be taken at three points, at 1/6, 3/6 and 5/6 the width of the channel if:

- the channel is wider than 8 feet and has uniform and seamless walls (example: concrete conduit);
- the channel is wider than 6 feet and has uniform but irregular sides (example: ditch).

Samples must be taken at brief intervals, no more than five minutes apart and at every minute, once a plateau is reached.

The exact time of sampling must be indicated for each sample.

Each sample must be identified and prepared immediately for shipment to the laboratory. Samples must be stored out of direct sunlight, particularly in the case of light-sensitive tracers(30).

Sampling must be carried out by two individuals; one to take samples, the other to note and record the exact time of sampling(30).

It is common practice to use a dye to perform a preliminary test and to measure travel time on the basis of the visual effect of the mixture. If a chemical tracer is used, a dye can be added (so long as it does not cause interference) to omit the need to perform a preliminary test.

- <u>Analysis of results;</u>

The concentration of tracers is usually determined in a laboratory. If the tracer is a dye, it may be more convenient to analyze the sample at the site; samples must nonetheless be stored for future reference.

4.1.3.3.4 Advantages of constant injection

Fewer samples are required for analysis than the slug injection method.

This method enables measurements to be taken in segments where the flow in not constant, so long as the injection time is extended and the interval between samples is less than one minute.

This method provides greater precision than the slug injection method.

4.1.3.3.5 Disadvantages of constant injection

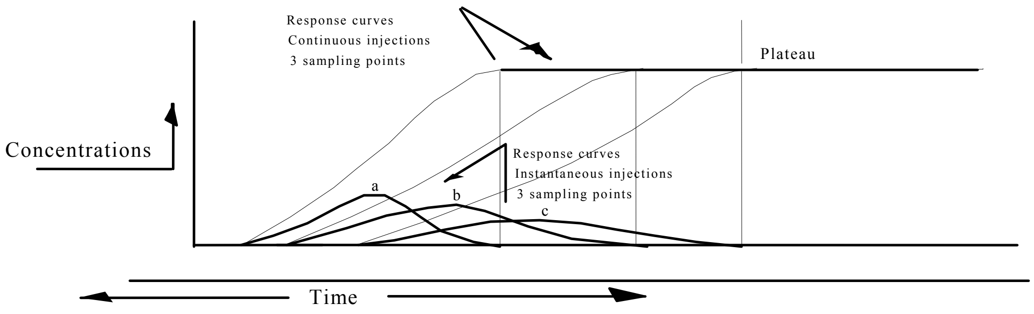
Injection of the tracer requires continuous attention.

Injection of the tracer requires an injection instrument, the rate of which can be adjusted and controlled precisely.

To measure smaller flows, 3 to 5 times more tracer is required than the amount required for the slug injection method. To measure large flows, the difference is marginal.

4.1.3.3.6 Interpretation of results

Once samples have been taken at three points, a concentration curve as a function of time is plotted for each sampling point.



An identical profile for all three curves indicates that the mixture is uniform and that the duration of injection is satisfactory.

The tracer injection period must be sufficient to produce three identical curves, and only concentrations situated on the plateau should be used to calculate the flowrate.

The stability (plateau) between the three points is rarely reached at the same moment, because the transversal flow velocities are different between each point.

Flow is determined using the following equation:

$$Q_2 = Q_1\left(\frac{C_1}{C_2 - C_0}\right) \quad (61)$$

where:

Q_1 is the tracer injection rate in ml/min;
C_0 is the natural concentration of tracer in the effluent in µg/l;
C_1 is the injection concentration of the tracer in mg/l;
C_2 is the concentration of the tracer at the test point in µg/l;
Q_2 is the flowrate of the discharge in l/min.

If recovery tests (I_r) show a deviation between the analytical value measured and the theoretical value, due to interferences between the tracer and effluent, to obtain the absolute flow, the recovery index (I_r) must be included in the above formula to reflect this situation.

The formula is therefore as follows:

$$Q_2 = Q_1\left(\frac{C_1}{C_2 - C_0}\right)I_r \quad (62)$$

4.1.3.3.7 Causes of error

The principal causes of error and items to verify to minimize errors are as follows:

CAUSES OF ERROR	CORRECTIONS
Non-uniform tracer solution	Constant mixing during injection
Error regarding the concentration of stock solution	Compare the theoretical value with the analytical value
Inadequate mixture of the tracer solution with the effluent	Change the sampling points, create turbulence at the tracer injection point
Breakdown of the tracer solution during injection	Protect the solution from exposure to direct sunlight during the entire operation
Breakdown of the tracer solution upon contact with the flow	Perform recovery tests before and during measurements
Unstable rate of injection	- Calibrate the injection instrument at the beginning and end of procedure; - check for the presence of air bubbles in the injection system; - place the tracer solution in a graduated container and take note of the volume that is injected at different moments during the injection procedure; - do not allow the injection tube to come into contact with the water surface
Loss of tracer solution at the injection point	Position the injection tube near the water surface to prevent splashing
Analysis problems	In the event that sampling containers have been contaminated, check the analytical method and rate of recovery
Large deviation in concentrations on the plateau of the curve	Verify the permanence of the flow pattern by continuously recording the water depth in the measurement segment

4.1.3.3.8 Precision

In normal conditions, the deviation in measurements using the constant injection method is approximately 1 %, which means that it is accurate to within 99 %(27).

4.2. Volumetric method

In the case of small flows, the volumetric method often appears to be the simplest method for performing a point-specific measurement.

4.2.1. Principle of the method

This method, which is a "gauged-capacity" type, consists of filling a container, the exact volume of which is known, and tracking the time required to fill it. The following equation interprets the relation between the flow, volume and time:

$$Q = V/t \qquad (63)$$

where:

Q is the flowrate as a function of time unit;
V is the volume;
t is the time unit.

4.2.2. Applications

The volumetric method is generally used for:

- point-specific flow measurements;
- flow measurements where the flowrate is steady;
- calibration of primary measuring devices.

This method can be adapted using a tipping bucket to obtain continuous flow measurements. Use of this device, however, is limited to flowrates of less than 150 m^3/h.

4.2.3. Advantages

The principal advantages of the volumetric method are:

- the speed at which it can be performed;
- the extreme precision of results;
- its cost-effectiveness.

4.2.4. Disadvantages

The principal disadvantages of this method are:

- usually limited to measuring small flowrates (< 100 liters/minute);
- usually allows only point-specific measurements to be taken;
- to measure large flows, requires the presence of a regular shape reservoir, the capacity of which at different levels can be measured with 99 % precision.

4.2.5. Equipment required

To measure small flowrates (< 100 liters/minute):

- a graduated container (± 20 liters);
- a chronometer.

To measure large flowrates (> 100 liters/minute):

- a tank of suitable dimensions;
- a tape measure;
- a level indicator;
- a chronometer.

4.2.6. Personnel

Two individuals are usually required to perform this type of measurement.

4.2.7. Procedure

There are two techniques to measure small flows:

- the first technique consists of filling a container, the exact volume of which is known, and using a chronometer to calculate how long it takes to fill the container;
- the second consists of calculating the time necessary to fill a container and then evaluating the amount of liquid recovered by weighing the liquid or measuring its volume.

For this type of measurement, the flow should originate from a conduit with a free-fall discharge.

For measurement of large flows, the method consists of:

- precisely calibrating a regular shaped tank, in order to be able to determine its volume, at all levels, with 99 % precision;
- track the amount of time that is required to vary the water level between the initial level and final level.

4.2.7.1 Number of tests

The method requires three tests to be performed. The deviation between each test must not exceed 2 %. If deviation is greater than 2 %, determine the causes and repeat the entire operation.

4.2.7.2 Test period

In all cases, time is calculated in seconds.

To measure large flowrates, each test should take at least five minutes.

To measure small flowrates, each test should take at least the number of seconds indicated:

Flowrate (liters per minute)	Time in seconds
10	120
20	60
30	40
40	30
50	25
60	20
70	17
80	15
90	12
100	12

4.2.8. Precision

A flow measurement using the volumetric method may yield results with a deviation of ± 1 %, when measurement is carried out with attention to detail.

- The volume of a container must be measured precisely, because most errors can be attributed to this variable.

- If the dimensions cannot be measured exactly, the volume can be deducted by weighing. This method, however, can be burdensome and even impracticable, in the case of large flowrates.

4.3. Flow measurement using pumping stations

Flow measurement using pumping stations provides real-time information about the amount of water that is moving in the drainage system.

4.3.1. Measurement principle

Flow measurement using pumping stations requires knowledge of the operating time and capacity of each pumping station.

The following equation applies:

$$V = Q_p t \quad (64)$$

where:

V is the total volume drawn by a pump in m^3;
Q_p is the pump's absolute flowrate in m^3 as a function of time;
t is the time measured.

To determine the capacity of a pump or pumps in a pumping well, refer to the curves that are characteristic of the pumps, which are supplied by the manufacturer. This method may, however, include some errors that may significantly affect the precision of a measurement (wear of the pump motor, wear of the pump itself, deviation of the static head, viscosity of liquid, etc.). Pumps must therefore be calibrated.

4.3.2. Applications

Measurement of flow using pumping stations allows the following:

- to determine the amount of water flowing through particular sections of a drainage network, when several pumping stations are connected to the same network;
- to determine the amount of water flowing in real time through a drainage network and to become aware of changes in flow;
- to determine the amount of infiltration water in the drainage network;
- to quantize the volume of water flowing through a network, over long periods.

To determine the volume of water a pumping station supplies over long periods, simply keep track of the operating time of pumps, by installing a timer in the pump control panel. Since the period of operation of one or more pumps (at a constant speed) is directly proportional to the volume delivered by the pumps, the total volume delivered by a pump can be determined.

4.3.3. Calibration of pumps

Calibration of pumping stations consists of precisely determining the volume of water each pump can deliver over a given period, at a constant speed. To ascertain the absolute volumetric flowrate for each pump, the volume (V) variable has to be determined and the time (t) variable has to be measured.

A pump's capacity is expressed by the following relation:

$$Q_p = \frac{V}{t_p} \quad (65)$$

where:

Q_p is the pump's capacity;
V is the volume pumped in m^3;
t_p is the time that is required to pump the volume (V).

4.3.4. Personnel and equipment

Calibration of a pumping station requires at least two individuals and use of the following equipment:

- a chronometer;
- a tape measure.

4.3.5. Information that should be noted

The following information must be verified and noted when calibrating a pumping station:

- the serial number of pumps and their inspections;
- original pump specifications;
- the type of pumping well (wet, dry);
- the normal position of high-level and low-level alarms, if present;
- the presence of an overflow drain, and where it is located in the well;
- the existence of submerged conduits supplying the well;
- the presence of and status of check valves.

4.3.6. Advantages

Flow measurement using pumping stations has the following advantages:

- requires few personnel;
- requires little equipment;
- flow can be measured over very long time periods.

4.3.7. Disadvantages

Flow measurement using pumping stations has the following disadvantages:

- pumping stations must be closely monitored;
- does not take into account spillovers from overflow pipes;
- cannot be carried out with using variable-flow pumps;
- the precision of measurements is variable and depends on how often calibrations are performed.

4.3.8. Calibration method

Regardless of the shape of the pumping well, it is important first to determine the exact volume that will be pumped and the amount of time the pump will require to transfer the exact volume of water.

4.3.8.1 Calculation of the pumping volume

The most common calculation of the volume of wells in the water treatment field is based on geometric features.

4.3.8.1.1 Rectangular wells

Calculation of the surface of a well (A)

To determine the surface of a well, the following equation must be used to measure the horizontal section of a well:

$$A = L * l \quad (66)$$

where:

A is the surface of a well in square meters (m^2);
L is the length of a well in meters (m);
l is the width of a well in meters (m).

4.3.8.1.2 Circular well

Calculation of the surface of a well (A)

To determine the surface of a well, the horizontal section must be measured using the following equation:

$$A = \frac{\pi D^2}{4} \quad (67)$$

where:

A is the surface of a well in square meters (m^2);
D is the diameter of a well in meters (m);
π is equal to 3.1416.

Calculation of the depth of water pumped (h)

The depth of the water (h) pumped is the result of the difference between the water level in the well, immediately before pumps are started (h_0), and the water level in the well (h_f), immediately after pumps are stopped, which translates into the following equation:

$$h = h_0 - h_f \quad (68)$$

Calculation of the pumping volume (V)

To calculate the pumping volume, the area of the well must be combined with the depth of the water pumped. This operation results in the following equation:

$$V = Ah \quad (69)$$

where:

V is the volume of water pumped in cubic meters (m^3) per time unit;
A is the surface of s well in square meters (m^2);
h is the depth of water pumped in meters (m).

Note: In the case of small wells that contain submerged pumps, the volume occupied by the pumps and any other accessories must be subtracted from the total volume of the pumping well.

4.3.8.2 Calculation of pumping time

Pumping time (t_p) is the amount of time that pumps are in operation, that is, the amount of time that elapses between the time pumps are started (t_0) and stopped (t_f), and is represented by the following equation:

$$t_p = t_f - t_0 \qquad (70)$$

4.3.8.2.1 Insulated wells

If a pumping well is insulated, that is, if the flow of water entering the pumping well is drawn off, the pump capacity is determined in the following manner:

- the pumping volume (V), as described above;
- the pumping time, that is, the amount of time a pump requires (t_p) to extract a determined volume (V) is measured.

A pump's absolute flow is determined using the following equation:

$$Q_p = \frac{V}{t_p} \qquad (71)$$

where:

Q_p is the pump's absolute flowrate in m^3/sec;
V is the volume of water extracted by the pump;
t_p is the time necessary to extract the volume of water V.

Note: A pumping well should be insulated during calibration, to reduce the risk of error.

4.3.8.2.2 Uninsulated wells

If a pumping well cannot be insulated, that is, if the flow of water entering the pumping well cannot be extracted, the following is required:

- establish the inlet flow;
- determine the pump's flow capacity.

To establish the inlet flow:

- measure the water-level recovery time (t_r), that is, the time it takes the water level in a well to rise to a determined height (h_r);

- determine the water-level recovery flowrate (Q_{in}) using the following equation:

$$Q_{in} = \frac{V}{t_r} \qquad (72)$$

where:

Q_{in} is the flow entering the pumping station;
V is the volume of the water-level recovery, ($V = A*h_r$);
t_r is the time of the water-level recovery;
A is the area of the well;
h_r is the height of the water-level recovery.

To determine the pump's flow capacity:

- establish the pumping volume (V), as described above;
- determine the pumping time, that is, the time the pump requires (t_p) to extract a determined volume (V).

The pump's absolute flow capacity is determined using the following equation:

$$Q_p = Q_{in} + \frac{V}{t_p} \qquad (73)$$

where:

Q_p is the pump's absolute flow capacity in m^3 as a function of time unit;
Q_{in} is the flowrate entering the pumping station, in m^3 as a function of time unit;
V is the volume of water extracted by the pump, in m^3;
t_p is the time necessary to extract the volume (V).

Note: Insulation of a pumping well during calibration is recommended, to reduce error.

4.3.8.3 Calibration conditions

Pumps should be calibrated under the following conditions:

- normal pump operating conditions are present;

- time and pumping volume are calculated when the pump reaches its permanent running speed, because starting and stopping a pump causes a transient flow pattern, from no flow to maximum flow;

- ensure that valves on the pump pressure line are watertight to prevent a backflow of water into the pumping well;

- in the case of uninsulated wells, the inlet flowrate (Q_{in}) is constant.

4.3.8.4 Number of tests

When a pumping station is calibrated, **at least** three separate test runs must be performed on each pump during solo operation, and three tests during combined operation, depending on how pumps are set up.

To be acceptable, the deviation between each test must be less than 5 % of the average test value. If the deviation exceeds 5 %, all tests must be repeated.

The average for all three tests represents the pump's capacity.

4.3.8.5 Frequency of calibration

Pumps must be calibrated each year if:

- the pumps are operated;
- the pumps have been rebuilt;
- major repairs, that may affect the pump's capacity, are carried out.

4.3.8.6 Precision of calibration

The precision of the pump calibration method depends on the precision of the pumping volume and pumping time measurement.

The dimensional parameter variable is usually the water depth. If a constant systematic error is presumed, the greater the water depth, the smaller the error.

> **Example:** Presuming a systematic water depth measurement error of 2 cm, for a depth of 0.5 m, the error will be ± 4 %; and for a depth of 4 m, the error will only be ± 0.5 %.

The maximum systematic error, for the time variable, likely cannot be reduced to less than two seconds for a complete pumping cycle (start – stop). Presuming a constant systematic error, the longer the pumping time, the smaller the error.

> **Example:** For a pumping time of 20 seconds, the error will be ± 10 % and for a pumping time of 3 minutes and 20 seconds, the error will be ± 1 %.

To obtain a calibration precision of approximately 95 %, the pumping time must be longer than 1 minute and the depth of the water pumped, deeper than one meter.

4.4. Area/velocity method

The method of determining the area and velocity of flow is perhaps the most common method of measuring the flowrate of a river.

4.4.1. General

This method of evaluating the flowrate of a watercourse has been in use since the mid-XIXth century.

4.4.2. Method principle

The method consists of accurately measuring a cross section area and the flow velocity. According to this principle, the flowrate can be determined using the following equation:

$$Q = AU \quad (74)$$

where:

Q is the flowrate in cubic feet or meters per time unit;
A is the area of the cross section in square feet or meters;
U is the average flow velocity in feet or meters per time unit.

4.4.3. Applications

- measurement of the flowrate of rivers and large artificial channels;
- flow measurement in an open conduit where the flow cross section is uniform;
- flow measurement of large closed conduits(6).

4.4.4. Advantages

The principal advantages of the area and velocity method are:

- low operating costs;
- does not require use of sophisticated instruments;
- results are available immediately.

4.4.5. Disadvantages

The principal disadvantages of this method are:

- does not provide point-specific flow readings;
- requires a uniform discharge during the entire measurement procedure;
- requires a uniform flow cross section, the section of the conduit must be straight and the slope must be uniform;

- requires a number of tests to be performed when the area of the section is large;
- requires deep enough water to ensure that instruments are completely submerged;
- cannot be used in conduits smaller than 203 mm (8 inches);
- the presence of fouling suspended matter and large debris hinders operation of the measuring instrument;
- requires attention to detail during measurements to ensure that errors remain at acceptable levels.

4.4.6. Equipment to measure velocity

The most common equipments for measuring velocity in clear water and in water that may contain suspended matter are:

- hydrographic flow meters;
- hydrostatic probes.

4.4.6.1 Hydrographic flow meters

The operating principle of a flow meter is based on the relationship between a liquid's flow velocity and the rotation speed of the moving part of the flow meter (cup or propeller). The number of revolutions made by the propeller is recorded by a tachometer over a given period. Because different propellers can be adapted to a flow meter and because each has a different correlation, the number of revolutions can be converted into speed. A minimum speed of 0.15 m/s and a maximum speed of 6 m/s is required to produce representative results.

The horizontal shaft of the flow meter must be positioned below the water surface, at a distance equal to at least 1.5 times the height of the rotor. The position of the rotor axis must be parallel with the direction of flow and level with the surface.

A flow meter must be checked before and after use to ensure that it is operating correctly. The propeller or cup must be able to perform revolutions for at least four minutes, in free air conditions and where it is protected from wind. If a test is inconclusive, the ball bearings should be checked. Instruments that do not meet these requirements must be repaired and calibrated by the manufacturer(6).

A propeller must be selected on the basis of measurement conditions. A propeller must always be used in combination with the flow meter that was used to determine the equation to convert the number of revolutions per minute into speed.

4.4.6.2 Hydrostatic probes

The operating principle of hydrostatic probes is based on the relationship between the flow velocity of a liquid and fluctuations in an electrical signal to the detection electrodes. Faraday's law respecting magnetic flux density shows that a voltage develops in a conductor when it crosses an electrical field.

A detection probe consists of an electromagnet that produces a magnetic field and two detection electrodes located 180° from one another. Voltage fluctuations in the detector as a liquid moves through are amplified and converted to suction to produce a direct reading of the flow velocity. A speed of at least 0.5 ft/s (0.15 m/s) is required to produce representative results.

The horizontal shaft of the detection probe must be positioned below the water surface, at a distance of less than 1.5 times the height of the probe and, from the bottom, a distance that is at least equal to 3 times the height of the probe. The shaft of the detection probe must be parallel with the direction of flow and level with the surface.

The detection probe must be checked before and after use to ensure that it is operating correctly. When placed in a non-metallic container, the detection probe must show a speed of less than 30 mm/s (0.1 ft/s), if it is stationary. If the probe is moved within a container, the speed of movement must be positive. Instruments that do not meet these requirements must be repaired and calibrated by the manufacturer(6).

4.4.7. Water depth measurement

During the entire velocity measurement procedure, water depth must be monitored using a pengraph device. The graphic record must be stored for consultation.

4.4.8. Position of the measuring point

When selecting a measuring point, the following conditions should be verified:

- access for personnel and equipment;
- a straight measuring segment over a distance equal to at least 25 times the width of the flow;
- a regular shape conduit (or channel) that has no deposits on the walls;
- the measuring point must not be located near a bend, connection or obstacle that might disrupt flow, over a distance equal to at least 25 times the width of the flow;
- water deep enough to allow measurement instruments to be submerged;
- there is no suspended matter that can interfere with operation of measurement instruments;
- sections in the measurement segment where flows diverge, converge or that show backwash, contra-flows and vortexes, should be avoided.

The exact location of the measuring point and a complete description of its layout must be specified in the report.

4.4.9. Flow area

Measurement of the flow area requires enormous precision to minimize the percentage of error. Flow area is determined in the following manner:

- for a circular conduit,

  The inside dimension of the conduit is measured using an inside caliper that takes measurements to within one thousandths of a meter (thousandths of a foot). The diameter is measured on at least three proportional angles, to ensure that the conduit is perfectly round. The number of readings varies according to the difference between the readings obtained and the nominal dimension of the conduit.

  Flow depth in the conduit is measured from the centre of the conduit. To determine the centre position of the conduit, measure the width of the flow area. The centre point of the flow area is the centre of the conduit, unless the conduit is not round;

- for another type of conduit or channel,

  the width of the flow area is determined using a tape measure or, in the case of very wide channels, using an optical measuring device. Flow depth is measured at several points spaced along the horizontal axis in the following manner:

  - for channels measuring 4,572 mm (15 feet) and over, at intervals equal to 5 % the total width of the channel;
  - for 2,438 to 4,572 mm (8 to 15 feet) channels, at intervals equal to 10 % of the total width of the channel;
  - for 610 to 2,438 mm (2 to 8 feet) channels, at intervals equal to 20 % of the channel's total width;
  - for channels measuring 610 mm (2 feet) or less, at intervals equal to 30 % of the total width of the channel.

  The profile of the section measured is printed on graph paper and the area of the section is measured using a planimeter.

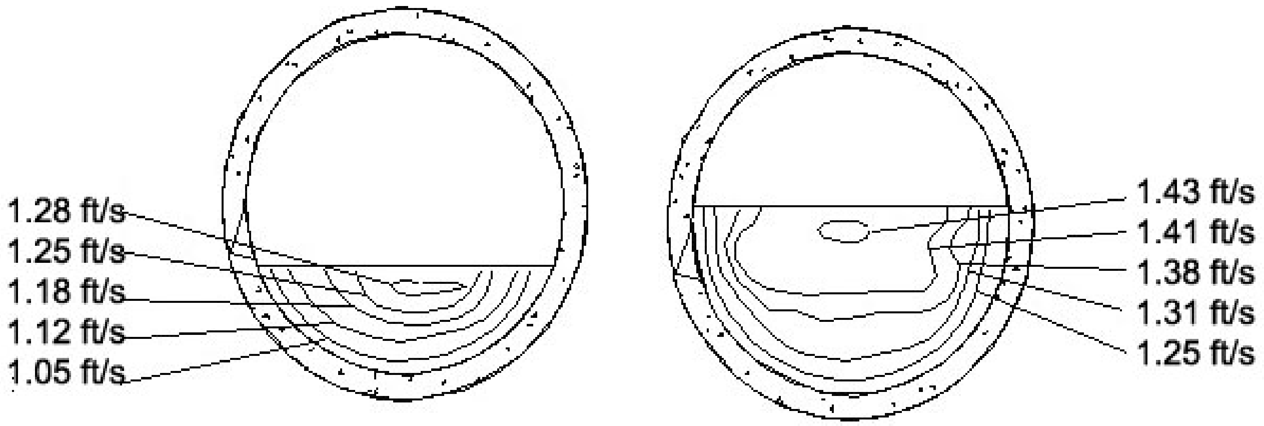
4.4.10. Water depth measurement

This method requires a discharge that is flowing at a steady rate during the entire measurement procedure. To verify if a discharge has a steady flow, water depth measuring equipment that produces a graphic record must be set up. The difference between the lowest depth reading and highest depth reading should be less than 5 %. If the difference is greater than 5 %, all measurements must be repeated(5).

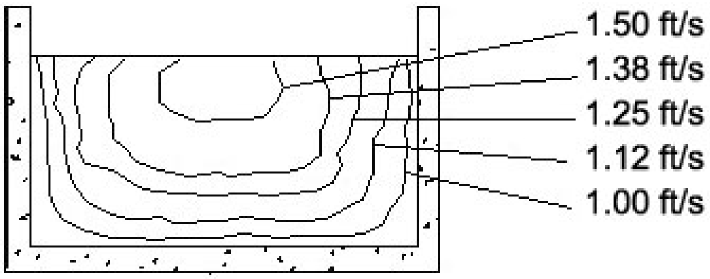
4.4.11. Velocity measurement

Since the flow area consists of a series of currents moving at different speeds, velocity measurements should be taken at different locations to obtain an accurate profile of velocities (see Figure 26).

FIGURE 26 - EXAMPLES OF HOW CURRENT VELOCITIES ARE DISTRIBUTED IN A FLOW SECTION



Circular flow area



Rectangular flow area

Velocity measurements should be taken at the same time as a depth measurement, to ensure the representativeness of results.

Each velocity measurement should last at least 60 seconds and should be repeated at least five times (36). The deviation in measurements, between the lowest and highest velocity, measured during all five tests at the same point, must be less than 5 %. A higher rate of deviation will require all tests to be repeated again at the same point (36).

Velocity measurements are carried out along verticals and the space between measurements should be as follows:

- for channels measuring 4,572 mm (15 feet) and over, 5 % of the total width of the channel;
- for 2,438 to 4,572 mm (8 to 15 feet) channels, 10 % of the total width of the channel;
- for 610 to 2,438 mm (2 to 8 feet) channels, 20 % of the total width of the channel;
- for channels 610 mm (2 feet) or less, 30 % of the channel's total width.

For depth, the measuring points are established as follows:

- for depths less than 610 mm (2 feet), at 0.6 times the total depth measured from the surface;
- for depths 610 mm (2 feet) and over, at 0.2 and 0.8 times the total depth measured from the surface. This is the average for velocities measured along a vertical axis that determines the velocity of this section of the flow area;
- if the deviation between the number of revolutions between two verticals exceeds 10 %, measurements should be repeated and the distance between verticals reduced.

The velocity of the flow area is determined by finding the sum of average velocities measured along verticals, divided by the number of verticals.

4.4.12. Calculation of flow

Flow is the average velocity multiplied by the flow area measured. The unit of measurement is cubic meter per second or cubic foot per second.

4.4.13. Precision

The characteristic fluctuation, expressed as a percentage of the average velocity for a flow meter, should not exceed 5 %. If all of the precautions listed above have been taken, and if measurements are conducted under optimum conditions, the error of the method should be less than 10 %.

4.4.14. Causes of error

The principal causes of error are as follows:

- instrument handling, more specifically the position of the probe in relation to the direction of flow;
- precision of the instrument;

- lack of precision of the flow area measurement. Particular care must be taken to locate the flow area;
- unstable flow conditions.

5. COMPARISON OF THE PRECISION AND ACCURACY OF VOLUMETRIC, DILUTION AND FLOW METER METHODS

An inspection of the characteristics of a channel is recommended in this booklet to determine the reliability of a flow measurement system. To confirm that a channel is operating correctly, many in the field choose an extraneous inspection using an alternative measurement, the most common of which is a flow meter.

Although one or more inspection measurements are not very significant in terms of mathematics, it is important to acknowledge that two similar results are an indication that reinforces a presumption that a measuring device is operating correctly. Reference is made to this type of observation frequently, which contributes to perpetuating the practice, although we have certain reservations. A detailed statistical examination of this matter does not fall within the realm of this booklet. What we can say essentially that a conclusion of adequate operation depends on the difference that is tolerated between both instruments. The difference depends on systematic errors of instruments and their respective precision.

The section that follows summarizes topics discussed in the booklet and compares the principal sources of error associated with the three testing methods. The concepts of precision and accuracy are presented as a means of underscoring how the principal causes of error can lead an applied scientist to mistakenly conclude that a measuring device is operating correctly or incorrectly, based on a few tests.

5.1. Precision and accuracy

There are two fundamental concepts related to measurement in the scientific field: precision and accuracy.

Precision refers to the proximity of a series of measurements compared to one another, without regard for the degree of reconciliation between an average for these measurements and the true value, which incidentally is often unknown. Distribution or deviation is therefore defined on the basis of random differences that exist between measurements. It is obtained by comparing each individual measurement to an observed average. In this booklet, use of the term "precision" indicates the degree of similarity of values. Deviation is additional data. Therefore 99 % precision involves a deviation of 1 %.

To reduce the number of random errors, simply repeat a measurement several times. The higher the number of sources of deviation in the process or the greater the number of individual variations, the higher the risk of obtaining a different value compared to the true value. Precision is often expressed in terms of deviation, standard deviation or variation coefficient. Statistics allow a quantitative understanding of the reduction of range of variation in relation to the number of measurements. This reduction is a function of the square root of the number of measurements.

Accuracy refers to the affinity of one method or process to produce a result that is equal to the true result, considering only the source of error that can cause a bias. For example, a one-meter ruler that is only 95 cm long will produce results that are 5 % negatively biased or with a systematic error of -5 %.

In one sense, the accuracy of a measurement method is more important than its precision, because a lack of accuracy is a source of bias that systematically distorts all results. A bias is more serious than a chance variation, particularly when it cannot be estimated or, worse, observed. It leaves the experimenter with data that are positively or negatively distorted compared to the true value. Repeating the measurement simply confirms this result.

For an instrument to be deemed fit for use to verify another instrument, the precision of measurements of this instrument must be at least as good as the precision of the instrument to be tested. Where this is not the case, a large number of measurements should be taken to statistically compensate for the lack of precision. Obviously, use of a method that could cause a serious bias is unacceptable.

When these concepts are applied to different flow measurement techniques, the following comments can be made.

5.2. Volumetric method

The volumetric method is the most direct testing method. The causes of deviation are based on the precision of the volume measurement of the container and the filling time.

The only sources of bias are the volume measurement of a tank and time-keeping, but the sources of bias can be reduced to a point of becoming negligible. If the accuracy of the volume of a tank is questionable, the volume of a liquid can be figured out by weighing it. Random errors of time or volume measurements can be assessed relatively easily. Natural fluctuations in flow are taken into account by the channel and by the instrument. Their effect on precision and accuracy depends on the time and precision of response of a secondary measuring device and the simultaneity of operations. To accommodate natural fluctuations in flow, measurements should be taken close to one another. A correction that reflects a time delay can also be used if this condition cannot be met.

If fundamental inspections have been made and if recommendations in this booklet have been followed, this instrument produces an unbiased result with a high degree of precision. In most cases, it is a reliable cost-effective method.

5.3. Dilution method

The large number of procedures involved in the dilution method is a source of random variations that, when incorrectly gauged or tested, can also become sources of bias. For example, the constant injection method often produces the following errors:

- an unstable flow of the injection pump;
- absorption or reaction of the tracer with the effluent (tracer recovery index);

- inadequate mixing of the tracer at the test point;
- the natural presence of tracer in the flow;
- analysis errors.

A fluctuation in flowrate during measurement can also be added. Theoretically, the tracer takes this fluctuation into account. An increase in flowrate will be accompanied by a decrease in the concentration of tracer. However, because these changes occur also instantaneously, the likelihood is uncertain, since dispersion may not occur fast enough to reflect a corresponding and instantaneous adjustment in concentration. Nonetheless, when fluctuations in flowrate (variation divided by the average flow) are small and random, that is, as positive as they are negative, this can be deemed an error where the mathematical expectation is zero. Under these conditions, it is a cause for error that is not readily a source of bias, so long as the variations remain small, as indicated in this booklet.

Stability of the output capacity of the tracer injection pump can become a cause for bias if, for example, the output capacity drops during injection as a measurement is being carried out, perhaps due to a fluctuation in pressure between the pump and tracer solution.

Similar annotations apply to other causes of error. They are all controllable and measurable; but if they are not checked, they can introduce bias.

Uniform mixing at the test point is probably the cause of error that is most difficult to control. This error also causes a systematic under-estimation or over-estimation of flowrate, depending if sampling takes place in a zone where the concentration of tracer is respectively too high or too low.

Therefore, the dilution method involves a certain number of causes of error that must be controlled to prevent bias from showing up. The large number of possible sources of deviation may require a large number of measurements in order to obtain satisfactory precision.

5.4. Flow meter method

There are fewer procedures involved in use of the flow meter method compared to use of the dilution method, which is the likely reason it is so popular (37, 38, 39). There are, however, a number of causes of bias.

First, is the inability to take measurements near the walls of a channel where velocity is lower, which results in an over-estimation of flow. This source of error takes on more importance if a channel is smaller or if the depth of liquid declines. It is the cause of an uncontrolled bias, but the effect declines as the volume of water increases relative to the surface of the walls exposed to the flow. Low water depth or walls that are close together and prevent a large number of measurements from being taken can cause significant bias.

There are also other causes of bias that are easier to verify, including:

- the presence of matter that adheres to surfaces or large debris and causes a reduction of the rotation speed;

- the fragility of an instrument, the calibration of which can be affected by a number of factors, such as impacts, compression, rust, etc. The user must maintain an exact calibration at all times, which imposes some restrictions because there are very few companies that offer this type of service;

- the presence of a deformed flow, backwater, etc, can introduce serious bias. This error can be controlled if the individual conducting measurements can change the measuring point. For some types of instruments, the angle of insertion is another variable that requires special attention. However, use of another flow meter located on a representative spot may compensate for variations in flowrate.

There are few random errors related to use of this instrument. They can be summarized as an error in the reading of rotation speed and an error of positioning the instrument in the flow. Under uniform flow conditions, this error is negligible, but it takes on more importance if turbulence are present. The flow meter method offers acceptable precision if favorable conditions are present.

This method is affected mainly by errors that can cause bias. If there is not a sufficient flow of liquid, the bias may be significant and the situation may not be able to be remedied. Even if the origin of other biases is known, it may be difficult to determine their effect. Use of this instrument may also lead to confusion if the causes of biases are not known.

A measuring instrument must therefore be checked after an examination of flow characteristics and on the basis of a professional judgment of how each method is used.

REFERENCES

1. MANNING ENVIRONMENTAL CORP., *Flumes*, Publication # FL-778, Manning Environmental Corp., Santa Cruz.

2. UNITED STATES DEPARTMENT OF THE INTERIOR, *Water Measurement Manuel, 2nd edition revised,* reprinted 1974 – reprinted 1981, Denver, 327 p.

3. BONNIN, J., *Débits des liquides à l'air libre*, Association française de normalisation, R-2310, R-2311, 33 p.

4. GRANT, D. M., *Open Channel Flow Measurement Handbook*, 1st edition, Lincoln, Instrumentation Specialties Company (1979).

5. AMERICAN SOCIETY FOR TESTING AND MATERIALS, *Annual Book of ASTM Standard: Water and Environmental Technology Water (1)*, volume 11.01, Philadelphia (1987).

6. COMPTON, P. R., KULIN, G., *A Guide to Methods and Standards for the Measurement of Water Flow*, Washington, National Bureau of Standards Special Publication 421, Institute for Basic Standards (1975), 97 p.

7. GRANT, D. M., *ISCO Open Channel Flow Measurement Handbook*, 2nd edition, ISCO Inc., Environmental Division (1988).

8. SKOGERBOE, G. V., HYATT, L., ENGLAND, J. D. and JOHNSON, J. R., *Design and Calibration of Submerged Open Channel Flow Measurement Structures: Part 2, Parshall Flumes*, PRWG 31-3, Logan, Utah Water Research Laboratory, Utah State University, 1967.

9. PLASTI-FAB INC., *Product Bulletin No. PB 1, LP-5M-2-80*, Plasti-Fab inc., Tualatin, Oregon (1980).

10. LUDWIG, J. H., LUDWIG, R. G., *Design of Palmer-Bowlus Flumes*, Journal Sewage and Industrial Wastes, vol. 23, no. 9, p. 1097-1107 (September 1951).

11. WELLS, E. A., Gotaas, H. B., *Design of Venturi Flumes in Circular Conduits,* Paper No. 2937, Transactions of ASCE, vol. 121, p. 749-775 (1956).

12. GRANT, D. M., *ISCO Open Channel Flow Measurement Handbook*, ISCO Inc., Lincoln, NE 68501,Third Edition (1989).

13. F.B. LEOPOLD COMPANY INC., "*Catalog No. 661"*, F.B. Leopold-lagco Inc., Zelienople, Pensylvenia, 16063 (1969).

14. F.B. LEOPOLD COMPANY INC., *Catalog No. 652-B*, F.B. Leopold-lagco Inc., Zelienople, Pensylvenia, 16063 (1974).

15. MARSALEK, J., *Instrumentation for field studies of urban runoff*, Research report No. 42, Environmental Management Service, Canada Centre for Inland Waters, Burlington, Ontario (1973).

16. SKOGERBOE, Gaylord V., Bennett, Ray, S. and WALKER, Wynn R., *Generalized Discharge Relations for Cutthroad Flumes*, Journal of the Irrigation and Drainage Division, ASCE, Vol. 98, No. IR4, p. 569-583 (Dec. 1974).

17. WALKER, W. R., Skogerboe, G. V. and Bennet, R. S., *Flow-measuring flume for wastewater treatment plants*, Journal of the Water Pollution Control Federation, Vol. 45, No. 3, p. 542-550 (mars 1973).

18. SKOGERBOE, Gaylord V., Walker, Wynn R., Wu, Tsu-Yang and Bennet, Ray S., *Slope-Discharge Ratings for Cutthroat Flumes*, Transactions of American Society of Agricultural Engineers, Vol. 16, No. 1 (1973).

19. SKOGERBOE, Gaylord V., Hyatt, Leon M., *Rectangular Cutthroat Flow Measuring Flumes*, Journal of the Irrigation and Drainage Division, ASCE, IR4, p. 1-13 (Dec. 1967).

20. ACKERS, P., White, W. R., Perkins, J. A., Harrison, A. M., *Weirs and Flumes for Flow Measurement*, John Wiley & Sons Ltd. (1978).

21. GWINN, W. R. and Parson, D. A., *Discharge Equations for Hs, H, and HL Flumes*, Journal of the Hydraulics Division, ASCE, Vol. 102 (jan. 1976), No. HY1, Proc. Paper 11874, p. 73-88.

22. INTERNATIONAL STANDARD ORGANISATION, *Water Flow Measurement in Open Channels Using Weirs and Venturi Flumes - Part 1: Thin-Plate Weirs* ,ISO Standard No. : 1438/1, First Edition (April, 1980).

23. AMERICAN SOCIETY FOR TESTING AND MATERIALS, *Annual Book of ASTM, Standards Water and Environmental Technology*, Part 31, Water, Philadelphia, PA. (1980).

24. KINDSVATER, C. E., Carter, R. W., *Discharge Characteristics of Rectangular Thin-plate Weirs*, Journal of the Hydraulic Division of the ASCE, Vol. 83, No. HY6/1453 (Dec. 1957).

25. SHEN, J., *Discharge Characteristics of Triangular-notch Thin-plate Weirs*, U.S. Department of Interior, Geological Survey, Draft for I.S.O. (July 1960).

26. THEL-MAR COMPANY, *A Volumetric Weir for Measuring Flows Thru Manholes*, Publication # 1-1-78, Thel-Mar Company, Lansdale, PA. 19446 (1978).

27. COLLINGE, V. K. and Simpson, James R., *Dilution Techniques for Flow Measurement*, University of Newcastle Upon Tyne, Department of Civil Engineering (1963).

28. WERRELL, W. L., *Stream Gaging by Injection of Tracer Elements,* M. Sc. Thesis, Arizona University, Tuscon (1967).

29. WILSON, Jr., J. F., Cobb, Ernest D. and Kilpatrick, Frederick A., *Fluorometric Procedures for Dye Tracing*, Chap. A12, Book 3, Revised 1986, Applications of Hydraulics, Techniques of Water Resources Investigations of the U.S. Geological Survey (1986).

30. KILPATRICK, Frederick A. and Cobb, Ernest D., *Measurement of Discharge Using Tracers*, Chap. A16, Book 3, Applications of Hydraulics, Techniques of Water Resources Investigations of the U.S. Geological Survey (1985).

31. THOMAS, Charles W. and Dexter, Robert B., *Modern Equipment for Application of Salt Velocity Method of Discharge Measurement for Performance Tests*, U.S. Department of Interior, Bureau of Reclamation, Denver, Colorado.

32. WILSON Jr., James F., *Fluorometric Procedures for Dye Tracing*, Chap. A12, Book 3, Applications of Hydraulics, Techniques of Water Resources Investigations of the U.S. Geological Survey (1968).

33. COLE, J.A., *Dilution Gauging by Inorganic Tracers; Notably the Plateau Method, Using Dichromates*, Symposium on river flow measurements, Loughborough, 1969, London Institution of Water Engineers, p. 111-146 (1969).

34. TURNER DESIGNS, *Flow Measurements in Sanitary Sewers by Dye Dilution*, *Fluorometric Facts*, Bulletin SS 7-80, Turner Designs, Mountain View, California.

35. BELLAMY, R. J., *An Evaluation of Chemical Gauging Techniques*, New Zealand Ministry of Works, Water and Soil Division, Hydrological Research, Progress Report No. 6 (1971).

36. INTERNATIONAL STANDARD ORGANISATION, *Liquid Flow Measurement in Open Channels - Velocity-area Methods - Collection and Processing of Data for Determination of Errors in Measurement*, ISO 1088, Second Edition (1985).

37. FRENCH, Richard H., *Open-channel Hydraulics*, McGraw-Hill Book Company, New York (1985).

38. MARSH-MCBIRNEY, INC., *Instruction Manual, Model 201, Portable Water Current Meter*, Publication 201-676, Marsh-McBirney, Inc., Gaithersburg, Maryland, (1981).

BIBLIOGRAPHY

AASTAD, Johan and Szgnen, Reinhardt, *Discharge Measurements by Means of a Salt Solution "The Relative Dilution Method"*, p. 289 - 292.

AGG, A. R., Mitchell, N. T. and Eden, G. E., *The Use or Lithium as a Tracer for Measuring Rates of Flow of Water or Sewage,* Water Pollution Research Laboratory, Stevenage, Paper no. 2, p. 240-245 (1960).

ASSOCIATION GÉNÉRALE DES HYGIÉNISTES ET TECHNICIENS MUNICIPAUX. *Les stations de pompage d'eau*, 3^e édition, 445 p. (1986).

BARSBY, A., *Determination of Mixing Lengths in Dilution Gaugin*g, Symposium on Geochem, Precipitation, Evaporation, Soil-Moisture, Hydrom, Bern 1967, Int. Ass. SCI Hydrol, Pub no. 78, p. 395-407 (1968).

BOLCHO, C. and Fisher, T. J., *Control of Industrial Wastewater Discharges in the North West of England*, Water Science Technology, vol. 25, no. 1, p. 53-59, IAWPCR (1992).

BENNETT, R.S., *Cutthroat Flume Discharge Relations*, M.Sc. Thesis, Agricultural Engineering Dept., Colorado State University., Fort Collins, Colorado (1972).

BERMEL, K. J., *Hydraulic Influence of Modifications to the San Dimas Critical Depth Measuring Flume*, Transaction of Geophysic Union, vol. 31, no. 5, p. 763-770 (Oct. 1950).

BLUMBERG, A. F., Galperin, B. and O'Connor, D. J., *Modeling Vertical Structure of Open- Channel Flows*, Journal of Hydraulic Engineering, vol. 118, no. 8, p. 1119-1134, ASCE (August 1992).

BSATA, Abdalla, *Instrumentation et automation des procédés industriels*, Applications à l'industrie de l'eau, Cégep de Saint-Laurent, Édition Le Griffon d'argile, Québec.

CARTER, Rolland W., et Anderson, Irving E., *Accuracy of Current Meter Measurements*, Journal of the Hydraulics Division, Proceeding of the American Society of Civil Engineers, vol. HY 4, p. 105 - 115 (Jul 1963).

CHANDRA, U., Aoki, P. E., Ramos e Silva, J. A. and Castagnet, A. C., *Measurement of Flow and Direction of Ground Water by Radioactive Tracers : Hydrological Evaluation of a Waste Disposal Site at "Instituto de Pesquisas Energéticas E Nucleares (IPEN)*", IPEN Pub. 28, Institut de recherches énergétiques et nucléaires, Sao Paulo, Brésil (1981).

CHASE BECKER, Edith, Payne, Faith N., *Selected Techniques in Water Resources Investigations, 1966-67*, Geological Survey Water-Supply, Paper 1892, Department of the Interior, U.S. Government Printing Office, Washington, D.C. 20402 (1968).

CHEN, C. L., Clyde, C. G., Chu, M. S. and Wei, C. Y., *Calibration of Parshall Flumes with Non-Standards Entrance Transitions*, Utah Water Research Laboratory, Utah State University, Logan, Utah (March 1972).

CHIU, C. L., *Variation of Velocity Distribution Along Nonuniform Open-Channel Flow*, Journal of Hydraulic Engineering, vol. 118, no. 7, p. 989-1001, ASCE (July 1992).

CHOW, Ven Te, *Open-Channel Hydraulics*, McGraw-Hill Book Company, New York (1959).

COBB, E. D. and Bailey, J. F., *Measurement of Discharge by Dye-Dilution Methods,* Book 1, Chapter 14 - Hydraulic Measurement and Computation, Surface Water Techniques, U. S. Department of the Interior Geological Survey (Aug. 1965).

COLE, John A., *Prediction of Mixing Lengths for River Flow Gaging*, Proceedings American Society of Civil Engineers, Journal Hydraulic Division, vol. 100, no. 8, p. 1167-1172 (1974).

COMMISSION INTERNATIONALE DES IRRIGATIONS ET DU DRAINAGE, *Dictionnaire technique multilingue des irrigations et du drainage*, Central Office, Chanakyapuri, New Delhi.

CROMPTON & KNOWLES CANADA LIMITED, *Intracid Rhodamine WT liquid*, Fiche signalitique, Anjou, Québec (1991)

CSÉPAI, L. and Kastanek, F., *Flow Regulation by Automatically Controlled Overflow Weirs*, Water Resources, vol. 26, no. 5, p.625-628 (1992).

DEANER, David G., *Effect of Chlorine on Fluorescent Dyes*, Journal of Water Pollution Control Federation (WPCF), vol. 45, no. 3, p. 507-514 (Mar. 1973).

DIPLAS, P., *Hydraulic Geometry of Threshold Channels*, Journal of Hydraulic Engineering, vol. 118, no. 4, ASCE, p. 597-614 (Apr. 1992).

DISKIN, M. H., *Temporary Flow Measurement in Sewers and Drains*, Journal of the Hydraulic Division, ASCE Proceedings, vol. 89, no. HY4, p. 141-159 (Jul. 1963).

DISKIN, M. H., *Sharp Crested Weirs for Circular Channels*, Water and Water Engineering, vol. 75, p. 309-313 (Aug. 1971).

DUMAS, Henry, *La méthode chimique pour la mesure du débit des cours d'eau, La Houille Blanche*, no. 5, p. 690-701 (oct.-nov. 1952), no. 1, p. 51-57 (janv.- fév. 1953), no. 3, p. 360-373 (juin-juil. 1953).

ENGEL, P., *A Universal Calibration Equation for Price Meters and Similar Instruments,* Scientific Series no. 65, Environment Canada, Inland Waters Directorate, Burlington, Ontario (1976).

ENVIRONMENT CANADA, *Sampling for Water Quality*, Water Quality Branch, Inland Waters Directorate, Ottawa (1983).

FEUERSTEIN, Donald L. and Selleck, Robert E., *Fluorescent Tracers for Dispersion Measurements*, Journal of the Sanitary Engineering Division, Procedings of the American Society of Civil Engineers, vol. 89, no. SA 4 (Aug. 1963).

FISHER, Hugo B., *Flow Measurements with Fluorescent Tracers*, ASCE, Paper no. 1, p. 139-140 (Jan. 1967).

FOGLER, Scott H. and Brown, L. F., *Elements of Chemical Reaction Engineering*, Second Edition, Prentice Hall International Series in the Physical and Chemical Engineering Sciences, p. 708-727.

FOSTER, William S., *How to Determine Waste Water Flow*, The American City and County, vol. 92, no. 3, p. 61-62 (Mar. 1977).

GILMAN, K., *Application of a Residence Time Model to Dilution Gauging, with Particular Reference to the Problem of Changing Discharge*, Hydrological Sciences Bulletin, vol. 20, no. 4, p. 523-537 (Dec. 1975).

GOODELL, B. C., Watt, J. P. C. and Zorich, T. M., *Streamflow Volumes and Hydrographs by Fluorescent Dyes*, Int. Un. of Forestry Res. Organizations (1967)

GOTOH, Shigeru., Witlin, William G., *New Signal Processing Approach in Electromagnetic Flowmeters*, Yokogawa Hokushin Electric Corp., Tokyo, Japan (1982).

HAGER, W.H., *Design Procedure for Flow Over Side Weirs,* ASCE, vol. 117, no. 1 (1991).

HAGER, W.H., *Dividing Flow in Open Channels*, ASCE, vol. 116, no. 3, p. 634-637 (1990).

HAMMER, Mark J., *Water and Waste-Water Technology, SI Version*, John Wiley & Sons Inc., New York.

HARRIS, James P., Kacman, Stephen A., Forest, Grant and Tomcik, John, *Flow Monitoring Techniques in Sanitary Sewers*, Deeds and Data, Water Pollution Control Federation, Washington, D.C. (July 1974).

HELMES, Tucker C., Lipsett, Michael J., Owen, Patricia A. and Sigman, Caroline C., *Health and Environments Aspects of Rhodamine-Based Dyes*, Final Report, SRI Project LSC-3614, SRI International, Menlo Park, CA 94025 (1983).

HENDERSON, F.M., *Open-channel Flow*, The Macmillan Co., New York (1966).

HOLLEY, E. R., *Dilution Method of Discharge Measurement in Pipes*, National Bureau of Standards Special Publication 484, Proceedings of the Symposium on Flow in Open Channels and Closed Conduits, Gaithersburg, MD (Feb. 1977).

HORN, D.R. and DEE, N., *Technical Report no. 5 of the Storm Drainage Research Project*, Dept. of Environmental Engineering Science, Johns Hopkins University (Jan. 1967).

HORTON, R.E., *Weir Experiments*, Government Printing Office, Washington, D.C. (1907).

HUBER, W.C., *Two-point Stage Measurements for Calculation of Urban Runoff Hydrograph*, A paper presented at the 22nd Annual Specialty Conference, Hydraulics Division, ASCE, Knoxville, Tenn. (July 31-Aug.3, 1974).

HYATT, M.L., *Design, Calibration, and Evaluation of a Trapezoidal Measuring Flume by Model Study*, M.S. thesis, Civil Engineering Department, Utah State University, Logan, Utah (Mar. 1965).

INTERNATIONAL STANDARD ORGANIZATION, *Liquid Flow Measurement in Open Channels by Weirs and Flumes - Rectangular Broad-Crested Weirs*, ISO 3846, Second Edition (1989).

INTERNATIONAL STANDARD ORGANIZATION, *Mesure de débit des liquides dans les canaux découverts - canaux jaugeurs à col rectangulaire*, *à col trapézoïdal et à col en U*, ISO 4359, première édition (1983).

INTERNATIONAL STANDARDS ORGANIZATION, *Mesure de débit des liquides dans les canaux découverts au moyen de déversoirs et de canaux jaugeurs - déversoirs à profil triangulaire*, ISO 4360, deuxième édition (1984).

INTERNATIONAL STANDARDS ORGANIZATION, *Mesure de débit des liquides dans les canaux découverts - déversoirs en V ouvert*, ISO 4377, deuxième édition (1990).

INTERNATIONAL STANDARDS ORGANIZATION, *Mesure de débit des fluides - calcul de l'erreur limite sur une mesure de débit*, ISO 5168, première édition (1978).

INTERNATIONAL STANDARDS ORGANIZATION, *Évaluation de l'incertitude dans l'calibration et l'utilisation des appareils de mesure du débit - partie 1 : relation d'calibration linéaires*, ISO 7066-1, première édition (1989).

JACOBI, J. P., *Pumping Stations as Flowmeters*, WPCF, Deeds and Data, p. 1-4 (July 1975).

KARNEY Bryan W. and McInnis, Duncan, *Efficient Calculation of Transient Flow in Simple Pipe Networks*, Journal of Hydraulic Engineering, vol. 118, no. 7, p. 1014 - 1030, ASCE (Jul. 1992).

KATZ, Brian G. and Fisher, Gary T., *A Comparison of Selected Methods for Measuring Flowrate in a Circular Storm Sewer*, International Symposium on Urban Hydrology, Hydraulics and Sediment Control, University of Kentucky, Lexington, Kentucky (Jul. 1983).

KERN, Robert, *Measuring Flow in Pipes With Orifices and Nozzles*, Journal of Chemical Engineering, p. 72 - 78 (Feb. 1975).

KILPATRICK, F. A., *Flow Calibration by Dye-Dilution Measurement*, Journal of Civil Engineer, ASCE, vol. 38, no. 2, p. 74-76 (Feb. 1968).

KILPATRICK, F.A., *Flow Measurements with Fluorescent Tracers*, Journal of Hydraulics Division, ASCE, vol. 93, no. 4, p. 298 - 308 (Jul. 1967).

KILPATRICK, F.A., *Dosage Requirements for Slug Injections of Rhodamine BA and WT Dyes,* Geological Survey Professional Paper 700-B, Geological Survey Research, U.S. Government Printing Office, Washington, DC (1970).

KIRKPATRICK, George A., *A Review of Flow Measuring Devices*, Proceedings of a Research Conference Urban Runoff Quantity and Quality, Published by ASCE, p. 191-198, New York (1975).

KNAPP, John A., Schaake, Jr., John C., Viessman, Jr., Warren and Associate Members ASCE, *Measuring Rainfall and Runoff at Storm-water Inlets*, Journal of the Hydraulics Division, Proceeding of the American Society of Civil Engineers (Sep. 1963).

KRIZEK, Raymond J., Mosonyl and, Emil F., *Water Resources Instrumentation, Volume 1, Measuring and Sensing Methods*, Proceedings of the International Seminar and Exposition on Water

Resources Instrumentation, June 4-6 1974, Chicago, Ill., Distributed by Ann Arbor Science Publishers Inc., Ann Arbor, Michigan (1975).

LESBROS, J., et Damez, F., *La mesure des grands débits en conduits fermés, Inventaire, comparaison et évolution des diverses techniques pour la mesure des grands débits d'eau (Instruments de mesure mécaniques et non mécaniques)* – 2^{e} partie, La technique de l'eau et de l'assainissement, Nos 433/434 (1983).

LEWIS PUBLISHERS INC., *Submersible Sewage Pumping Systems Handbook,* 120 p. (1988).

LI, S.G., Venkataraman, L. and Mclaughlin D., *Stochastic Theory for Irregular Stream Modeling. Part I: Flow Resistance*, Journal of Hydraulic Engineering, vol. 118, no. 8, p. 1079 - 1090, ASCE (Aug. 1992).

LYN, D. A., *Turbulence Characteristics of Sediment-Laden Flows in Open Channels*, Journal of Hydraulic Engineering, ASCE, vol. 118, no. 7, p. 971-988 (Jul. 1992).

MAHESHWARI, B. L. and McMahon, T. A., *Modeling Shallow Overland Flow in Surface Irrigation*, Journal of Irrigation and Drainage Engineering, vol. 118, no. 2, p. 201-217, ASCE (Mar./Apr. 1992).

MASON, Martin A., Scott, Cloyd H., Culbertson, James R. and Worstell, R. V., *Flow Measurements with Fluorescent Tracers*, Journal of the Hydraulics Division, ASCE, vol. 93, no. 3 (May 1967).

MINISTÈRE DE L'AGRICULTURE, *Mesure des faibles débits d'eaux usées par auget basculeur*, Centre national du machinisme agricole du génie rural, des eaux et des forêts (CEMAGREF), Division qualité des eaux, pêche et pisciculture, Paris (1982).

MORGAN, W. H., Kempf, D. and Phillips, R. E., *Validation of Use of Dye-Dilution Method for Flow Measurement in Large Open and Closed Channel Flows*, NBS Special Publication, Proceedings of the Symposium on Flow Measurement in Open Channels and Closed Conduits, Gaithersburg (Oct. 1977).

MOUGENOT, G., *Measuring Sewage Flow Using Weirs and Flumes*, Water & Sewage Works, July 1974, p. 78-81.

NAFFRECHOUX, N., Mazas, N. and Thomas, O., *Identification rapide de la composante industrielle d'une eau résiduaire*, Laboratoire de Chimie et Ingénierie de l'Environnement, ESIGEC, Université de Savoie, France, Environmental Technology, vol. 12, p. 325-332 (Mai 1990).

NEDVED, T. K., Fochtman, E. G., Langdon, W. M. and Sullivan, F. O., *Instrumentation for Measurement of Wastewater Flow*, Journal of the Water Pollution Control Federation, vol. 44, no. 5, p. 820-828 (May 1955).

OFFICE DES NORMES GÉNÉRALES DU CANADA, *Liquid Flow Measurement in Open Channels - Establishment and Operation of a Gauging Station,* CAN/CGSB-157.3-M91, Canadian General Standards Board, Ottawa, Ontario (Jul. 1991).

OFFICE DES NORMES GÉNÉRALES DU CANADA, *Liquid Flow Measurement in Open Channels - Vocabulary and Symbols*, CAN/CGSB-157.1-M91, Canadian General Standards Board, Ottawa, Ontario (Aug. 1991).

OFFICE DES NORMES GÉNÉRALES DU CANADA, *Mesure de débit des liquides dans les canaux découverts - partie 2 : détermination de la relation hauteur-débit,* CAN/CGSB-157.4-M91/ISO 1100-2 :1982, Canadian General Standards Board, Ottawa (juin 1991).

PAINE, John N., *Open-Channel Flow Algorithm in Newton-Raphson Form*, Journal of Irrigation and Drainage Engineering, vol. 118, no. 2, p. 306-319,ASCE (Mar./Apr. 1992).

PFANNKUCH, Hans-Olaf, *Elsevier's Dictionary of Hydrology*, Elsevier Publishing Company, New York (1969).

PLASTI-FAB INC., *Product Bulletin Trapezoidal Flumes no. T-1,* Tualatin, Oregon 97062 (1977).

PLASTI-FAB INC., *Technical Bulletin no. HF-2*, Tualatin, Oregon 97062 (1977).

POIRIER, Guy, Desjardins, Raymond, Brière, François et Dagenais, Danielle, *Mesure en continu de débits d'eaux usées à l'aide d'un traceur fluorescent, la rhodamine WT*, Sciences et techniques de l'eau, vol. 20, no. 2, Québec (Mai 1987).

POISSANT, L. and Béron, P., *Design and Operation of an Automatic Sequential Rainfall Sampler*, Water Resources, vol. 26, no. 4, p. 547-551 (1992).

PRATT, E. A., *Another Proportional-flow Weir : Sutro Weir,* Engineering News, vol. 72, no. 9, p. 462-463 (Aug. 1914).

RABOSKY, J. G. and Koraido, D. L., *Gaging and Sampling Industrial Wastewaters*, ASCE (Jan, 1973).

REPLOGLE, John A., Meyers, Lloyd E., Asce, F. and Brust, K. J., *Flow Measurements With Fluorescent Tracers*, Proceeding ASCE, Journal of the Hydraulics Division, vol. 92, no. HY5, p. 1-15 (Sep. 1966).

REPLOGLE, John A., Meyers, Lloyd E., Asce, F. and Brust, K. J., *Flow Measurements with Fluorescent Tracers*, Closure, Journal of the Hydraulics Division, vol. 94, no. HY2, p. 552-555 (Mar. 1968).

RICHARD, Renald, *Mesure de débit*, Ministère de l'Environnement du Québec, Direction de l'assainissement de l'eau (Nov. 1981).

ROBINSON, A. R. and Chamberlain, A .R., *Trapezoidal Flumes for Open-channel Flow Measurement,* Transactions of The American Society of Agricultural Engineers, vol. 3, no. 2, p. 120-128 (1960).

ROBINSON, A.R., *Trapezoidal Flumes for Measuring Flow in Irrigation Channels,* ARS 41-140, Agricultural Research Service, U.S. Department of Agriculture (March 1968).

SCHAEFFER, David J., Kerster, Harold W., Bauer, Darryll R., Rees, Kim and McCormick, Steve, *Composite Samples Overestimate Waste Load*, Journal WPCF, vol. 55, no. 11, p. 1387-1392 (Nov. 1983).

SCOTT, C. H., Norman, V. W.' and Fields, F. K., *Reduction of Fluorescence of Two Tracer Dyes by Contact with a Fine Sediment,* Geological Survey Research 1969, U. S. Geological Survey Professional Paper 650-B, p. B164 - B168 (1969).

SCOTT, R. W. W., et al., *Developments in Flow Measurement*, Applied Science Publishers Inc., Englewood, New Jersey (1982).

SISSON, W., *Estimating Flows through Parshall Flumes*, Plant Engineering, vol. 120 (Oct. 1980).

SKOGERBOE, Gaylord V., Hyatt, Leon M. and Eggleston, Keith O., *Design and Calibration of Submerged Open Channel Flow Measurement Structures. Part I. Submerged Flow*, Report WG31-2, Office of Water Resources Research, U. S Department of the Interior, Utah Centre for Water Resources Research, Utah State University, Logan, Utah (Feb. 1967).

SMART, P. L. and Laidlaw, I., M., S., *An Evaluation of Some Fluorescent Dyes for Water Tracing*, Water Resources Research, vol. 13, no. 1 (Feb. 1977).

SMOOT, George F., *Are Individual Current-Meter Ratings Necessary?*, Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers (Mar. 1968).

SOENKSEN, Philip J., *Automatic Tracer-Dilution Method Used for Stage-Dilution Ratings and Stream flow Hydrographs on Small Iowa Streams***,** Water-Resources Investigations Report 89-4187, U. S. Geological Survey, Denver, Colorado (1990).

SOUCEK, E., Howe, H. E. and Mavis, F. T., *Sutro Weir Investigations Furnish Discharge Coefficients*, Engineering News-Record (Nov. 1936).

SPENCER, E. A. and Tudhope, J. S., *A Literature Survey of the Salt-Dilution Method of Flow Measurement,* Journal I. W. E., vol. 12, no. 2, pp 127-138 (1958).

SPENCER, E. A., Tudhope, J. S. and Morris, Miss. J. I. N., *Flow Measurement by the SaltDilution Method*, National Engineering Laboratory, Fluids Report no. 68, East Killbride (1958).

SPRENKLE, R. E., *Piping Arrangements for Acceptable Flow Meter Accuracy*, Transaction of the ASME, vol. 67 (Jul. 1945).

STANBRO, W. D. and Pyrch, D. A., *Stability of Rhodamine WT in Saline Waters,* Water Resources Research, vol. 15, no. 6 (Dec. 1979).

STEINBACK, B. J., *Effluent Flowmeter Calibration Using Fluorescent Dye Tracer,* Journal of Pulp and Paper Canada 88: 12 (1987).

STEVENS, John C., *Temporary Flow Measurements in Sewers and Drains*, ASCE Proceedings, vol. 34, no. HY6 (Nov. 1964).

STEVENS WATER RESOURCES PRODUCTS, *Stevens Water Resources Data Book,* 3rd Edition, Leupold & Stevens Inc., Beaverton, Ore., 97075 (1974).

STRILAEFF, P. W., *Single Velocity Method in Measuring Discharge*, Department of the Environment, Inland Waters Branch, Water Survey of Canada, Winnipeg, Canada (1971).

TARAZI, D. S., Hiser, L. L., Childers, R. E. and Boldt, C. A., *Comparison of Wastewater Sampling Techniques*, Journal of Water Pollution Control Federation, vol. 42, no. 5, p. 708 - 732 (May 1970).

TCHOBANOGLOUS, George, *Wastewater Engineering: Collection and Pumping of Wastewater*, Metcalf & Eddy Inc., McGraw-Hill Book Company, New York (1981).

TELEDYNE GURLEY, *Direct Reading Current Meter*, Instruction Book Gurley No 665, Troy, New York.

THORSEN, T. and Oen, R., *How to Measure Industrial Wastewater Flow*, Journal of Chemical Engineering (Feb. 1975).

TRIESTE, Douglas J., *Evaluation of Supercritical/Subcritical Flows in High-Gradient Channel,* Journal of Hydraulic Engineering, American Society of Civil Engineers, vol. 118, no. 8 (Aug. 1992).

TURNER DESIGNS, *Dye Studies/Chlorophyll/Oil Measurement*, Field Fluorometry, Form 10-1084-7.5M, Turner Designs, Mountain View, California.

TURNER DESIGNS, *Flow Measurements,* Fluorometric Facts, Turner Designs, Mountain View, California.

U. S. ENVIRONMENTAL PROTECTION AGENCY, *Flow Equalization*, EPA Technology Transfer Seminar Publication, EPA 625/4-74-006 (May 1974).

U.S. ENVIRONMENTAL PROTECTION AGENCY, *Flow Measurement Instrumentation*, Design Information Report, Journal WPCF, vol. 58, no. 10 (Oct. 1986).

U. S. ENVIRONMENTAL PROTECTION AGENCY, *Handbook for Monitoring Industrial Wastewater*, Associated Water & Air Resources Engineers, Environmental Protection Agency Technology Transfer Publication (August 1973).

U.S. ENVIRONMENTAL PROTECTION AGENCY, *NPDES Compliance Flow Measurement Manual*, MCD-77, Office of Water Enforcement and Permits Enforcement Division, Compliance Branch, Washington, D.C. (Sep. 1981).

U.S. ENVIRONMENTAL PROTECTION AGENCY, *NPDES Compliance Sampling Inspection Manual,* Office of Water Enforcement, Enforcement Division, Compliance Branch, Washington, D.C. (1979).

UNITED STATES DEPARTMEENT OF THE INTERIOR, *Water Measurement Manuel*, Bureau of Reclamation, Denver Colorado, Second Edition, 1967.

WENZEL, Jr., H. G., *A Critical Review of Methods of Measuring Discharge Within a Sewer Pipe,* ASCE, Urban Water Resources Research Program, Tech. Memo no. 4 (Sep. 1968).

WILLIAMS, R. T. and Bridges, J. W., *Fluorescence of Solutions: A Review*, Journal of Clinical Pathology (1964).

WILSON, A.L., *Precision and Bias of the Results of Dilution Gaugings*, Symposium on Hydrometry Sep 1970, International Association of Hydrological Sciences Publication, no. 99, vol. 1, p. 289-299 (1973).

WILSON Jr., J. F., *Time-of-Travel Measurements and Other Applications of Dye Tracing,* Water Resources Division, U.S. Geological Survey, Cheyenne, Wyoming

YOTSUKURA, Nobuhiro and Cobb, Ernest D., *Transverse Diffusion of Solutes in Natural Streams*, Geological Survey Professional Paper 582-C, U. S. Government Printing Office, Washington, D.C. (1972).

Ministère du
Développement durable,
de l'Environnement
et des Parcs
Québec