Information Paper 4.1.1
Methods to Observe, Estimate, or Measure Flow

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1.0 About this Information Paper

(This section is essentially common to all DQM Information Papers. If you have seen it already, please skip to Section 2 below). This Information Paper is a new type of guidance. It has been created for our new integrated system of guidance and tools for water quality monitoring called "the Data Quality Management (DQM) System". DQM is implemented by the Clean Water Team (CWT) where needed to support collection of **reliable** data of **known quality** in a fully documented, **scientifically defensible** manner. Most DQM materials are delivered in Parameter-Specific Folders, which provide both the traditional "protocol" materials and new, expanded guidance in three types of inter-related documents: Fact Sheet, Information Paper, and Standard Operation Procedures. Background information on the ecological significance of each parameter and the regulatory benchmarks that have been developed for it is summarized in the FACT SHEET. The technical information on measurement methodology is provided in this IP with its method-menu. Then there are several detailed standard operating procedures (SOPs) that provide step-by-step instructions for each instrument or method, as well as instrument-specific Quality Assurance/Quality Control procedures and data validation checklists.

This Information Paper (IP), a part of the Parameter-Specific Folder for Flow, provides "big picture" technical information on flow observation, estimation, or measurements. If you are a Trainer or a Technical Leader of any monitoring project, this may help you select a good method or methods to collect and communicate information about flow in your water body.

Section 2 of this IP introduces a "method menu" table with a list of ways that may be used to measure and record flow. In Section 3, a description of the different physical principles underlying the measurement methods is provided. Section 4 provides practical tips and advice on flow observation, estimation, or measurements, including the units of measurement; this information is based on our cumulative experience (The Clean Water Team and others). This section is meant to be updated as we learn more. Finally, the "Sources & Resources" section (Section 5) provides a list of available SOPs as well as references, contacts, and website leads into further information.

2.0 Ways to Observe, Estimate, or Measure Flow

Table 4.1.1-1 shows the major ways to collect and communicate flow information. The list should be reviewed during the initial phases of a group's monitoring activities so that the approach(es) matching available resources and operators' skill can be implemented early in the Project. This list captures major approaches but does not include all available methods, and the reader is encouraged to seek more information.

Table 4.1.1-1: Major Ways to Observe, Estimate, and Measure Flow

Code *(Note a)*	Method Name	Device(s)	Recorded Characteristic	Usable Range *(Note b)*	Cost	Labor (time)	Limitations	Extent of Error (percent of Result)
	Observation	Eyes	Flow Condition *(Note c)*	All	None	0.1 min	Verbal only	Not applicable
	Virtual Bucket	Eyes	Estimated Discharge	0.1 to 20 quart/sec	None	1 min		50-200%
	Visual Estimate	Eyes	Estimated Discharge	All	None	1 min		50-200%
	Container & Timepiece	Apron, bucket, watch	Volume, time	0.1 to 10 quart/sec	$20	5 to 30 min	Requires high slope or step	10%
	Float Method	Float or Orange Peel, watch	Current velocity, width, depth	1 to 100 cfs	$20 to $100	10 to 30 min	Wadable streams only (Note d)	30 to 100% *(Note e)*
FLO	Current Velocity Meter	Hand-held Current Velocity Meter	Current velocity, width, depth	1 to 100 cfs	>$500	10 to 120 min	Wadable streams only (Note d)	5 to 50% *(Note e)*
FLO	Current Velocity Meter	Suspended Velocity Meter	Current velocity, width, depth	>10 cfs	>$500	10 to 120 min	Requires bridge or crane	2 to 50% *(Note e)*
STG, DEP	Stage & Rating Curve	Staff Gauge or Wire Gauge, or Depth Sensor	Stage (water level)	>10 cfs	$20	1 min	Requires updated rating curve	10 to 50% (Note f)
	Altered Channel	Chutes, flumes, Parshalls, Weirs	Stage (water level)	Various	Various	Various	Require appropriate locations for installation	2 to 20%
	Tracers	Dyes, salts	Concentration	All	>$100	2-10 min	May be harmful	2 to 30%

Notes: (a) The Codes on the left are consistent with the Instrument codes used in all other DQM materials
(b) Ranges are for natural channels. Units used in this table are English (quart/sec, cfs). Metric equivalents: One liter is approximately one quart, 20 liters fill a five-gallon bucket.
(c) Flow conditions are communicated in the DQM by one of the following six verbal categories: Dry; Isolated Pools; Trickle (<1 l/sec); <20 l/sec; >20 l/sec; waterway full no observed flow.
(d) Assumptions: operator is wading to take depth measurements (and current velocity measurements).
(e) Requires length-measuring devices as well. Precision of a flow measurement depends on the number of segments measured across the channel (i.e., the number of 'rectangles' the cross-section was divided into); more segments take longer but give better resolution and less error. Accuracy depends on instrument calibration and quality of length measuring devices (tapes and stadia rods).
(f) Error depends on accuracy of gauge, the precision of gauge reading, and the confidence-intervals of the rating curve
General: Labor time may vary depending on site conditions and the number of segments & depths. Costs also vary.

Once you have formulated the monitoring question, decided which parameters you need to measure, developed your sampling design, and determined how much error you can tolerate in your flow measurements, you can refer to this menu again and find the method or device that will work for you. But here is the caveat for flow. Whereas the selection of other kinds of field measurements depends on anticipated operators' skill, time availability, and funding, you have to consider additional factors when selecting a method to measure flow. Often you do not have much choice in finding the 'right' cross section or a smooth run having the length needed for using the float method. You cannot control the flow conditions either, and these dictate whether you will be able to wade or not (high end flows), or whether you can use a meter or not (low end flows, or trickle). A flow chart that 'channels' these decisions is provided in the companion document to this IP (CARCD 2001).

2.1 The difference between observations, estimates, and measurements

As you have noted, Table 4.1.1-1 contains three options for capturing flow information. All three options are based on the concept that flow of water through a pipe or a channel, commonly called 'discharge' or 'flow rate' or 'flow discharge rate', can be quantified as the volume of water that passes through (the pipe or channel) in a unit of time.

2.1.1 Observations

The first option is to **observe** the creek and choose one verbal category that describes it best. The categories offered for Flow Conditions in the DQM Field Data sheets (and in Note c above) are underlined: Dry Creekbed; Isolated Pools; Trickle (<1 quart/sec); 1 to 20 quart/sec; >20 quart/sec; waterway full no observed flow. These categories include a language for communicating 'zero flow' and 'no flow' situations with detail that is very relevant for data interpretation, detail that falls between the cracks when only numerical flow data are captured. Observations are not intended to yield numbers, but when one of the six verbal categories offered is recorded, that Result can be easily used in a database. Observation options for moving waters are based on visualization (see section 3.1.2 below for more detail); they do not (and cannot) include information on the magnitude of flow beyond a given, 'perceptible' range.

2.1.2 Estimates

The second option is to **estimate** the volume that passes through per unit time, either by visualizing all the water going into a container and estimating the time it would take to fill it (e.g., using the 'Virtual Bucket' method), or by estimating the average velocity of objects moving with the water and the average dimensions of the channel cross section (width and depth) – and then computing the estimated volume (e.g., the 'Visual Estimate' method). Well-trained operators can do this when they are using skills acquired from previous experience in actually measuring these things, again and again and again….

The results of flow discharge estimates may be reported in one of two ways: (a) as a number, in volume per unit time; (b) as a numeric range category, for example, if the estimate yielded 12 cfs, it would fall within the category of 10-20 cfs. The first option **must be distinguished**

clearly from actual measurements, preferably by naming the parameter "Flow Estimate" as opposed to "Flow discharge". STORET provides a "Result Type" category called 'Estimated', but data users mining the "Flow Discharge" field may not always look into that field when retrieving data. Either way, operators practicing numeric estimates should also provide, for each Result, a realistic estimate of the range of their confidence (i.e., by recording that they believe that the 'true' Result could not fall below this minimum value or above that maximum value.)

2.1.3 Measurements

The third option is to actually **measure** the volume, velocity, channel dimensions, stage, or any other of the characteristics required to compute the volume that passes through per unit time. The results of flow discharge measurements are also given in numbers (volume per unit time), but each one is generated – with the known range of error around it – using actual measurements of the needed characteristics. Section 3 below is focused on this third option, Flow Discharge Measurement.

3.0 Principles and Applications of Flow Discharge Measurement Methods

To understand what flow is and how to select the best option to measure flow, the reader is referred to the TAC 'theory and practice' paper on flow (CARCD 2001). This paper was developed by A. Feng, M. Abramson, and N. Berg, members of the Flow Work Group established by The Technical Advisory Council for citizen Monitoring. For the extremely avid reader, flow discharge measurement principles and issues are discussed in great depth in the guidance provided by USGS. The following sections present but a brief summary of all that knowledge.

3.1 Volume per Unit Time (Direct Measure)

3.1.1. The 'Container & Timepiece' Method

The simplest way to measure the flow through a pipe is to collect the outflow for a given period of time in a container, and measure the volume of water that had accumulated in the container during that time. The measurement units normally used are quarts per second (about 1 liter per second); quart/minute or gallon/minute (GPM); cubic meter per hour, etc. (see section 4.2 for a discussion of measurement units). When the flow through a channel is in the order of magnitude of up to 20 quart/sec (5 gal/sec), the water can be channeled into a flexible "apron" that discharges into a bucket, and the rate at which the bucket is filled can be measured. This concept is the basis for the 'Container & Timepiece' method in Table 4.1.1-1, a method that uses a temporary weir (or an apron & sandbags assembly) combined with a container and a watch.

The challenges of the apron procedure are to get all the water in the channel to flow into the apron, and to have a sufficient "step" under the apron discharge that would accommodate a container. Finding natural or constructed chutes can help, and use of other accessories such as flumes is also possible (also see section 3.4 below). If a bucket is too tall, another option is to use a flatter tray and transfer the water into a graduated cylinder later, for volume measurement. Many hydrologists have used plumber's patty (a water-insoluble, pliable matter used in plumbing) to fashion a temporary weir across the channel, with a spout that can easily direct all the flow into a container.

Success of the 'Container & Timepiece' method depends on the ingenuity and patience of the operator, but when creative ideas are engaged, the sky is the limit! There are several advantages to this approach, namely:

- The 'Container & Timepiece' (and the tracers) are the only methods that allows for high quality flow discharge measurements in natural channels in the range of less than 3 gal/sec (12 liter/sec), where all methods based on current velocity measurements are not effective
- It can generate **reliable** data of **known quality** in a fully documented, **scientifically defensible** manner.
- It can provide Results with a very narrow range of error.
- It does not require expensive equipment, and takes a reasonable amount of time to perform
- It does not require outstanding expertise, and can easily be taught to any Field Operator.

3.1.2 The 'Virtual Bucket' method

The same concept – flow into a container - is used for the 'Virtual Bucket' method that provides a very rough estimate of flow by visualization and is also referred to as the 'Imaginary container' method. The operator imagines that all the water in the channel is directed into one container, and estimates the time it would take to fill it, or estimates the portion (half, quarter, etc) that will be filled in one second. Depending on the actual flow discharge, one can imagine a 5-gal bucket, or a 1-gal jug, or even a 1-quart jar.

This method is very subjective and is associated with a very wide range of error, but it can provide an order of magnitude of flow rate up to about 20 quart/sec. In fact, the operator engaged in Observations of flow conditions (see section 2.1 above) needs to do this kind of visualization in order to decide whether the appropriate category is Trickle (<1 quart/sec); 1 to 20 quart/sec; or >20 quart/sec. As mentioned in section 2.1 above, the operators must provide the perceived range of error with each Result. At this time (April 2004) the method still needs to be tested and undergo 'groundtruthing' against the 'Container & Timepiece' method with numerous operators.

The advantages of the Virtual Bucket method include:

- It does not require any equipment,
- Operators do not get wet or muddy,
- It can be done in a few seconds,
- It can resolve between conditions that spell life or death to aquatic organisms.

The scarcity or lack of flow information is severely limiting our ability to interpret water quality data. There are (very few) methods that can provide flow rate data in the range of 0.1 to 20 quart/sec, but the time it takes to measure it "properly" is sometimes prohibitive. Thus, many datasets are still generated without accompanying flow data. Under these circumstances, having less accurate and less precise data is better that not having any flow information at all, and Virtual Bucket data can be extremely usable (particularly when reported with associated error).

3.2 Current Velocity and Cross Section (Velocity-Area Approach)

In an ideal rectangular channel the flow rate can be computed from the current velocity (e.g., in feet per second), the width of the channel (in feet), and the depth of the water in the channel (in feet). The volume displaced is described in ftXftXft:sec, or cubic feet per second. However, nature creates complications: current velocities vary in different parts of the channel and stream channels are never made of ideal rectangles.

Current velocity is not uniform even in a straight and smooth channel due to shear forces (which are basically caused by the water molecules rubbing against each other). To put it simply, bank molecules do not move at all, water molecules in the center (farthest from the bank) move fastest, and all the other water molecules are "crunched" in between. A similar set of forces works vertically along the water column to slow down the molecules closer to the bottom or closer to the air, but here the picture is not symmetrical at all. Fortunately, hydrologist have developed a series of empirical formulae that help us 'factor-in' these mysterious forces. For example, they tell us that we need to multiply the velocity measured at the surface by a factor of 0.85 to get an average representation of the entire water column. However, for accurate results the velocity should be measured at more than one depth.

All the flow rate measurement methods practiced in situ require knowledge of the cross section, and there is always uncertainty and error associated with cross-section dimensions. These can be diminished by breaking the cross section to as many as possible rectangles, to account for minute morphological features. Breaking the cross section to many rectangles is also essential for applying the correct velocity to each rectangle (see graphics in the SOP-4.1.1.4). In reality, the number of rectangles may range from one (entire cross section) to over 20, depending on the operator's time availability and the tolerated error. Some users find that a one-point velocity measurement at the surface and at the flow centroid, combined with measurement of stream width and depth at that point, yields usable flow discharge data. Despite the wide margin of uncertainty these users feel that having this data is better than not having any data at all.

Devices to measure cross section dimensions include yardsticks, tape measures, stadia rods, or any other appropriate length-measurement instrument.

Current velocity can be measured in several ways:

- **Float:** The velocity is measured as the distance traveled by an object (e.g., an orange peel, or a lemon, or another clearly visible object of density slightly less than water) per unit time. Advantages: (a) The floats do not cost much and (b) they are readily available. Disadvantages: (a) Floats float! They cannot be deployed at a desired depth below the surface; (b) a float does not navigate! It is carried by eddies so it is usually not possible to control its course of movement in the channel; and (c) the method requires a longish stretch of straight channel (for the float to travel at least 20 seconds) and that may not be always available.

- **Mechanical velocity meters:** the flowing water rotates a moving part and the circular motion is translated to velocity units. Mechanical meters utilize horizontal-axis impeller (e.g., Valeport meters) or vertical axis "cups" (e.g., Price type AA meters). These meters can be rigged to a hand-held device, or suspended from a wire with a hefty weight underneath them. Advantages: They can provide separate measurements of velocity because we can control the measurement location and depth, and – if well maintained and frequently calibrated – they can generate data of high accuracy and precision. Disadvantages: They require great care in handling and storage, they can be used only in situations limited to wading or suspension from a bridge, and they cannot measure trickles.
- **Electromagnetic current meters:** These are based on Faraday's Law which states that a conductor (water with salts in it) moving in a magnetic field (generated by the probe) produces a voltage that varies linearly with the flow velocity. Electrodes in the probe detect the voltage generated by the flowing water. The common shape of electromagnetic probes (e.g., Marsh McBirney meters) is that of a truncated tear drop. Advantages: can be compact, accurate, and precise. Disadvantages: they are prone to fouling, require either wading or a bridge, and are not usable form measuring very low flows. These probes are sometimes called "velocity sensors", although the term is mostly used in conjunction with media other than water.

Because natural stream channels are not perfect, when flow rates fall below about 20 quart/sec (a little less than 1 cfs) it often becomes impossible to measure current velocity – no matter how tiny or pigmy your propeller is, or how agile your orange peel is.

3.3 Rating Curves and Stage Measurements

In a given channel, the water level rises and the current velocity increases as the flow discharge increases. In other words, when more water has to pass through the channel, water is higher and faster. There is a constant relationship between stage (water level) and discharge (which is a function of current velocity and cross section dimensions) for each situation of flow conditions (i.e., for each discharge value). This relationship is established empirically and it is expected to remain the same as long as the morphological features of the channel do not change.

Now, if each situation of flow conditions (discharge rate) has its own characteristic stage (water level), and we know them all, we can infer the flow discharge rate from a simple measurement of stage. Moreover, we can plot the stage values as a function of corresponding discharge rates and generate what is known as a 'rating curve'. The mathematical formula that describes that curve – usually a very complex polynom – can be used to "back-calculate" the discharge from any stage measurement done at that location. The method called 'Stage& Rating Curve' in Table 4.1.1-1 is based on this principle, and enables generation of large flow-rate datasets simply by recording stage, or deployment of automatic instruments and data-loggers to obtain a continuous picture of flow rates.

Establishing a rating curve for a given location requires that the segment be carefully chosen and that multiple discharge rate measurements be taken during different flow conditions (winter, spring, summer, and fall, rain and shine, wet and dry weather). The rating curve also needs to be verified every few years and after every catastrophic sediment movement event in the channel (see USGS guidance). However, once a rating curve has been established for a given Station, generating flow discharge data is as easy as recording stage.

3.4 Channel Alterations

As mentioned earlier, life is much simpler when we try to measure flow discharge in a perfect channel, so folks sometimes make changes to the channel, either temporarily or permanently, to make it as perfect as it gets. There are portable flumes that come with a "built-in rating curve" that can be installed temporarily in a creekbed at the prescribed angle. When all flow is directed into it, the stage data in the flume are sufficient to calculate flow rates. The USGS has built countless installations in their gauging Stations over the years; these concrete flumes, notched weirs, and parshalls have been (and still are) used to generate the most comprehensive flow dataset in the Nation.

3.5 Tracers and Other methods

Tracer methods involve putting a detectable substance (such as fluorescent dye, or salt) in the stream and following its progress downstream. Advantages include simplicity and usefulness in small streams or braided channels where floats or meters do not work well. A major drawback is the potential harmful effects of these substances to aquatic life, but careful dosing can overcome this problem. Other limitations include the complex calculations required to obtain flow rate values from fluorescence or conductivity readings downstream (CARCD 2001).

Hydraulic Jump methods are based on a physical response of flowing water: When a thin object like a ruler or wading rod is positioned vertically in flowing water, there is a small increase in height of the water where the water hits the rod. This increase is known as the hydraulic jump. Velocity can be calculated based on the hydraulic jump, using a complex formula (CARCD 2001).

4.0 General Tips about Flow Information

Information about flow conditions is essential for interpretation of most water quality measurements. To support this use, even data associated with a wide range of error are helpful. In contrast, data users who are charged with calculating the loads of potential pollutants that are carried downstream by the flowing water will need much "tighter" data and will not be able to tolerate a wide range of error. The challenge is to figure out which method to use for the purpose we have in mind, and how much resources (equipment $$ and time) we will need. These decisions should be done during the Project planning phase.

An important part of method selection relies on the anticipated flow discharge rates to be measured during the Project. Different river or creek systems have different 'sensitivities' to variations in flow rate. Flow rates in the range of 0.1 to 20 quart/sec usually 'fall between the cracks' of established velocity measurement methods. However the difference between 1 quart/sec and 10 quart/sec can spell death or life to critters in small streams, so we do need to know the flow conditions, even at that level of detail. In large rivers with complex ecosystems and sensitive fisheries, the difference between 50 and 25 cfs could spell disaster if the river is receiving a lot of nutrient and is highly eutrified, so we may need to choose the method that will be able to tell us whether it is closer to 25 or to 50 cfs.

4.1 Quality Control, Check, Record, and Report (CCRR) guidance for flow

(This paragraph is essentially common to all DQM-IPs. If you have seen it already, please skip to the second paragraph in this Section). The DQM guidance and tools provide ways to Control, Check, Record, and Report (CCRR) the quality of numerous water quality measurements. Essentially, **"Control"** is about things we can do to improve accuracy, precision, resolution, detection limit, and range of our measurement. **"Check"** is for things we cannot control but need to know. **"Record"** is about the language we use to express our findings and about entering these findings into the "placeholders" on our forms or spreadsheet. **"Report"** is about the way we calculate the data quality indicators of accuracy and precision so they can be shared with others. CCRR procedures are added on top of the generic quality assurance procedures such as keeping everything clean, waiting for stabilization of the reading, and keeping good records. Because each type of procedure, instrument, or kit requires its unique CCRR actions (that cannot be generalized for all measurement devices), the step-by-step instructions for these actions are provided in the instrument-specific standard operating procedures (SOP).

4.2 Endpoints and Units of Measurement for flow rates

As is evident from the vast flow measurement guidance you may read, flow is a calculated endpoint (meaning it is based on 'raw data' representing individual length and velocity measurements). The DQM system provides a worksheet template, with placeholders for the raw data and formulae that calculate the endpoints. The Result, in volume per time, can then be copied into a Result spreadsheet that also holds other WQ Results, and together be transferred into a database.

However, the choice of measurement units is still not straightforward in the US, and different people use different units. All the English measurement system users agree that inches are a bit confusing especially when you try to do math, and are not well supported by spreadsheet programs. So…if you *must* use English units, use decimal feet. It is highly recommended to use the metric measurement system for flow measurement, especially if measuring current velocity and cross section. The most widely used metric units for this purpose are centimeters (about two-fifths of an inch) or meters (very close to a yard). The author is saying this because millimeters are too small for this type of work (One centimeter has ten millimeters in it; one inch has about 25), and decimeters are simply not popular. In small streams you can do it in centimeters (one thousand cubic centimeters equals one liter); example: if the velocity is 20 cm/sec, the average depth is 10 cm, and the average width is 40 cm, then your flow rate is 20x10x40=8000 cubic cm per second, or 8 liter/sec. One liter is very close to one quart.

5.0 Sources and Resources

This IP is an integral part of the Data Quality Management (DQM) System implemented by the Clean Water Team, the Citizen Monitoring Program of the California State Water Resources Control Board.

For an electronic copy, to find many more CWT guidance documents, or to find the contact information for your Regional CWT Coordinator, visit our website at www.swrcb.ca.gov/nps/volunteer.html

If you wish to cite this IP in other texts you can use "CWT 2004" and reference it as follows: "Clean Water Team (CWT) 2004. Methods observe, estimate or measure flow, DQM IP-4.1.1(Flow). in: The Clean Water Team Guidance Compendium for Watershed Monitoring and Assessment, Version 2.0. Division of Water Quality, California State Water Resources Control Board (SWRCB), Sacramento, CA."

Available SOPs (2004 Compendium)

- SOP-4.1.1.3 Float.
- SOP-4.1.1.4 Velocity Meter

REFERENCES

California Association of Resource Conservation District (CARCD). (~2001). Flow. in: Guidelines for Citizen Monitors: Products of the 2000-2001 Technical Advisory Council on Citizen Monitoring. Prepared in collaboration with the Wild On Watershed Program and the Clean Water Team for the Citizen Monitoring Program of the State Water Resources Control Board. Sacramento, CA.

United States Geological Survey (USGS): try http://water.usgs.gov/dwq/FieldMaual