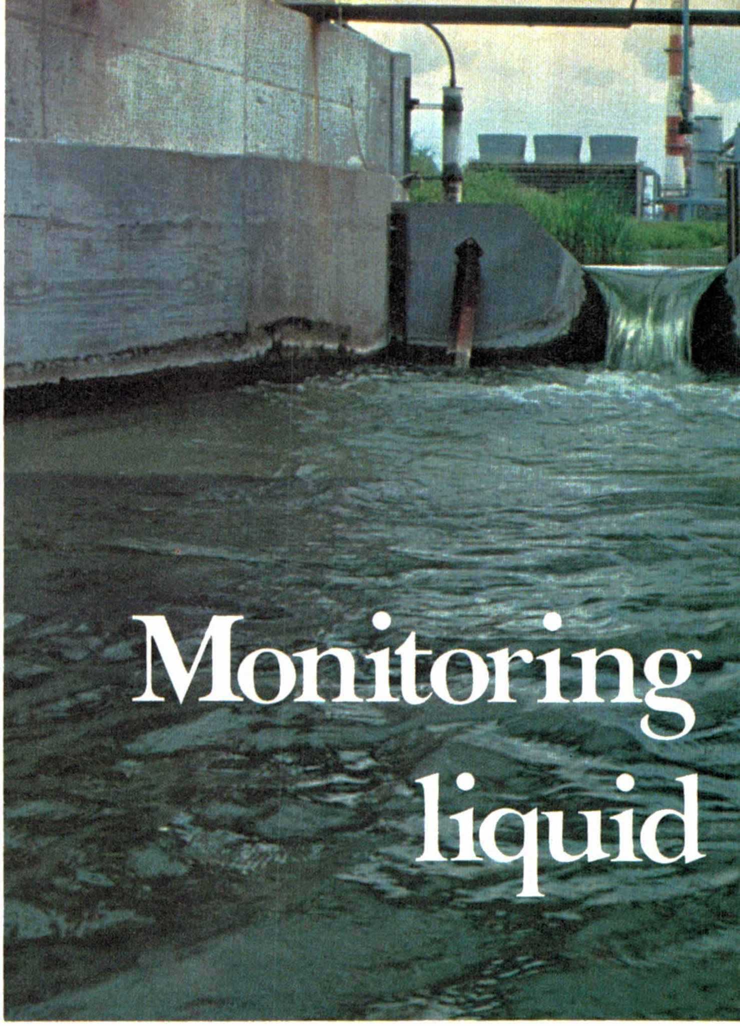


Monitoring liquid

The only way to tell if a plant is complying with pollution limits is by accurately measuring flows and by taking truly representative samples.

David L. Russell, P.E., *Hooker Chemicals Co.*

☐ Effluent monitoring, as it is currently practiced, is more an art than a science—despite the sophisticated sample-collection equipment currently in use. In fact, by careful selection of the sampling method and frequency, and analytical methodology, one can obtain almost any answer desired.

Why monitor?

In the attempt to gather information by effluent monitoring, we are frequently called upon to answer certain types of questions about plant operations. One main purpose of monitoring is to determine the plant's degree of permit compliance. Other purposes include gathering information for process control, as well as determining the contribution of a particular event or process (e.g., what might the effect of rainfall be on the plant effluent?).

Compliance monitoring is used to determine the degree of the plant's compliance with effluent regulations. Federal and state laws and city sewer ordinances are becoming more restrictive, and the current EPA emphases on industrial cost recovery and discharge of toxic pollutants will make accurate effluent monitoring more important. It is to this subject area that we will address ourselves—and particularly with regard to the NPDES (National Pollutant Discharge Elimination System) permit regulations.

The Consolidated Permit Regulations, which include NPDES permits, 40 CFR 122.11,* 122.62-63, have substantially changed the manner in which monitoring data are to be reported. In general, effluent monitoring must be reported, (1) if the samples are of the type and duration required by the permit, (2) if the sample is analyzed by approved analytical methods (as in 40 CFR 136 or approved equivalent), and (3) if the sample was collected at a point that is not materially different from the monitoring location as specified in the permit. Other types of sampling, however, may not have to be reported—but see your lawyer before you decide what *not* to report.

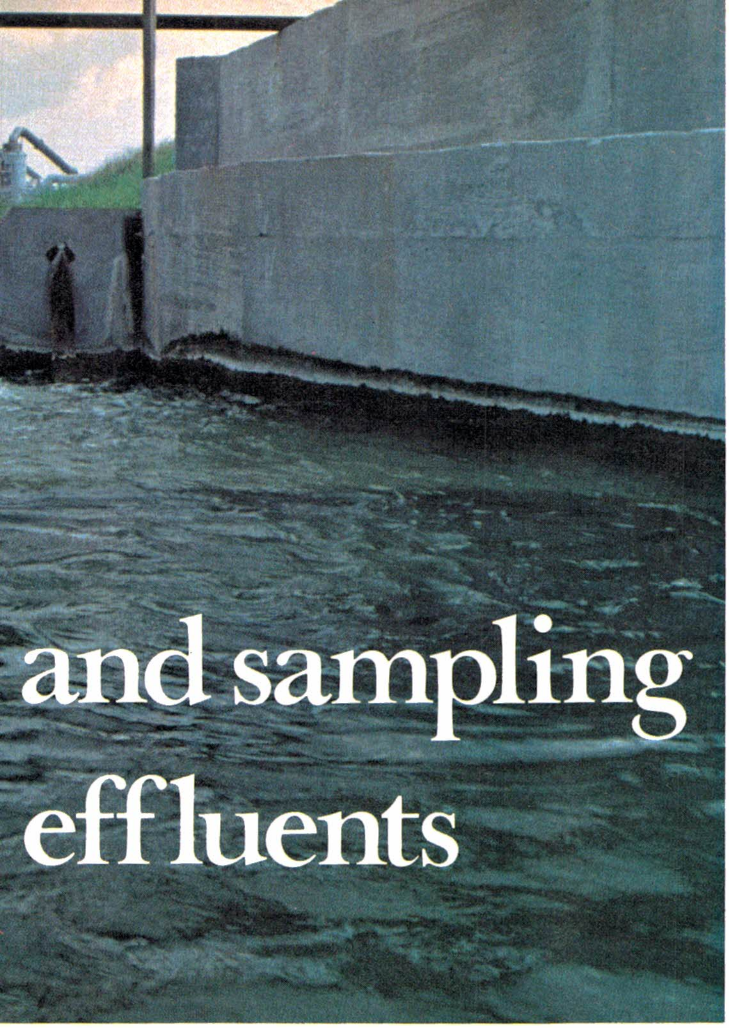
Accurate monitoring

Let us first distinguish between sampling and monitoring. Sampling is the physical process of collecting an aliquot of water or wastewater. Monitoring is the entire data-collection effort, which encompasses flow measurement, analyses, and the like, as well as sampling. Many factors must be considered in planning a waste-stream monitoring program if one is to obtain accurate and representative data. This planning process is analogous to having to know most of the answers in order to be able to ask the right questions. Three of the most important questions are: What data do I need?; How will I handle it?; and Am I (or my management) ready to take specific action (or suffer the consequences) because I now have new information? The answers will go far in reducing monitoring for the sake of data generation.

Other considerations in developing a monitoring program, which will be discussed below, include: type of sample to be collected, type of pollutants to be sampled, (i.e., suspended solids, liquids, multilayered systems, etc.), volume of sample to be collected, time and duration of sample collection, transport and handling of the sample, analytical methodology for sample analysis, and proportionality or representativeness of the sample. The final consideration—How representative is the sample?—is the most difficult to answer, despite one's level of practical experience.

Within reasonable limits, and on almost any given waste stream from a chemical or other plant, one can obtain any desired effluent value. This depends primarily upon where and how one monitors. The most accurate part of any monitoring or data-gathering operation is in the analytical laboratory, while the least accurate part—and the one most frequently ignored—is

*Title 40, Code of Federal Regulations, Part 122.11.



and sampling effluents

in the collection and handling of the sample, and in field measurements.

The most desirable answer to be obtained from an effluent monitoring program is the one that represents the true situation. Unreliable monitoring programs can lead to results either too high or too low, and each situation can have its own consequences. High results can lead to overstatement of the control problem, and the installation of expensive technology or overly large pollution-control equipment, as well as reporting of permit violations when none exist. Similarly, low results from a monitoring program can conceal actual problems, mask inadequate process-control situations, and may also lead to enforcement problems when the errors in the results are discovered.

One chemical company conducted an inadequate and inaccurate waste-characterization study (monitoring program), and used this information to design a major pollution-control system that cost several million dollars more than was spent by a sister plant in the same company. The difference was that the second plant had reliable data about its waste sources.

Spill-control reporting also requires accurate effluent monitoring, especially where non-reporting of spills of hazardous substances may lead to assessment of fines and penalties under Section 311 of the Clean Water Act (see 40 CFR 116 and 117). Some states routinely use misdemeanor (criminal) statutes against plant managers and other company officials as a means of enforcing spill-control regulations, and failure to detect a discharge is generally not an acceptable defense against a charge of failure to report a hazardous substance spill.

It is important to know what and how much may have been discharged in your plant effluent, and it is important to be able to defend your data against challenge in a legal arena.

Planning a monitoring program

Data distributions

Most effluent data are non-normally distributed [*1*], a fact that most regulatory agencies do not, or cannot, deal with in writing discharge permits. Assuming the uniform distribution of values around a central mean is not proper for most wastewater data.

Fig. 1 indicates the difference between normal and non-normal distributions. One of the important differences about a non-normal distribution is that the calculation of a confidence interval (standard deviation) about the data mean (average) is peculiar to the data distribution; the interval may be larger in one direction than in the other.

The assumption of normality of the distribution is recognized by many statisticians as a convenience for data manipulation, and is very often used despite the lack of confirmation of the assumptions [*2*]. The normal-distribution assumption is frequently encountered in the process of permit writing, where a 3.0 multiplier on the average is used to set the upper bound of the permit—or the Permit Daily Maximum value.

If the actual data are log-normally distributed, as in the example in Fig. 1b, the upper 3σ confidence interval may be substantially larger than the 3σ factor used in the normal-distribution assumption.

The fit of a particular data set needs to be checked against an assumed model. Weibull, Gamma and other distributions may fit a particular set of environmentally related data better than the log-normal or normal distributions [*2,19*]. Frequently we have too few data points (less than 30) to permit statistical verification for a fit to a particular distribution, and must resort to data plotting. Ref. 3 and 4 contain a good discussion of data plotting and fitting techniques.

Flow metering

Based upon an informal poll among representatives of the chemical industry, it is estimated that fewer than 10% of all effluents have been rigorously and independently checked for accuracy of the effluent-flow measuring device. Most checking generally consists of verification of the depth of flow in the effluent flowmeter (which is insufficient under normal conditions).

Many of the effluent flowmeters are, due to their design, accurate to within no better than $\pm10\%$; a few are accurate to within $\pm5\%$ or less. As will be discussed below, many other installations may have discharge measurement errors of better than 25%.

Other flow-measuring devices, while properly in-

Statistical example

Assumptions: 1) Normal distribution of sample data. 2) Existing NPDES permit limit is 400 lb/d total suspended solids (TSS). 3) Wastewater flow is 2 million gal/d. 4) Analytical variance is ±15% or ±4 mg/L for TSS. 5) Proposed permit limit is 300 lb/d.

How many samples are required to detect the difference?

Confidence interval = 90%, $Z_\alpha = 1.65$, $Z_\beta = 1.65$

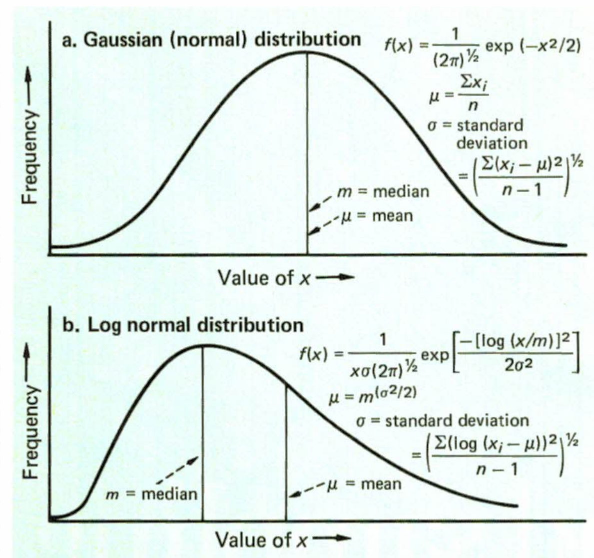
$$n = \frac{(Z_\alpha + Z_\beta)^2}{(\Delta/\sigma)^2}$$

$$\sigma = 400 \times 0.15 = 60 \text{ lb}$$

$$\Delta = 400 - 300 = 100 \text{ lb/d}$$

$$n = (1.65 + 1.65)^2/(100/60)^2 = 3.92 \text{ or } 4 \text{ samples/d}$$

Then, to determine the difference between a permit limit of 300 versus 400 lb/d would require 4 TSS samples/d at stated accuracy and confidence intervals.



Normal distributions Fig. 1

stalled, are allowed to fall into disrepair or are improperly or infrequently maintained; hence, the numbers obtained may be unreliable.

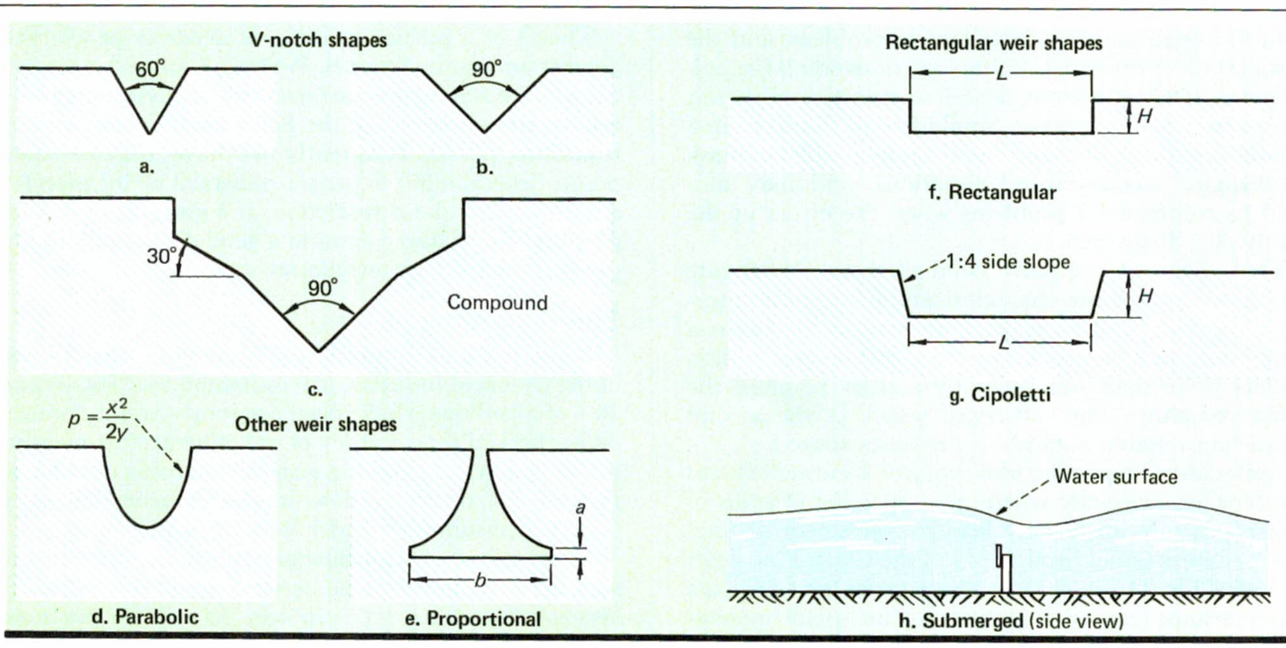
Material selection

The materials of construction of the sampler and sample container are important considerations in any monitoring program. Contamination or absorption by the sampling equipment or the sample container can alter the results obtained. Examples include the adsorption of mercury and other metals onto glass bottles, and the leaching of phthalates from vinyl tubing. In one case the metal apparently "disappears," and in the other, phthalate contamination shows up where none actually exists.

Another consequence of improper material selection in the sampler is a high frequency of breakdown or high maintenance of the sampling equipment. Problems include abrasion of tubing on peristaltic pumps and of other pump parts due to high concentrations of suspended solids, and plugging of sampling lines due to material surfaces that accumulate grease and oil.

Sampler selection and proportionality

The ability of a sampler to collect a representative sample from a waste stream must be questioned. The



Various shapes used for weirs Fig. 2

amount of variability obtained between samplers and sampling methods can vary up to almost 30%, depending upon the fluctuation of the flow and concentration, and upon the sampling scheme selected. The errors accidentally introduced and unaccounted for in sampling may have as much effect on the quality of the sample as do the shape and location of the sampling probe in the waste stream being monitored.

The shape, size, location, and intake velocity of the sampling probe may bias the sample in either direction. Suspended-solids sampling is particularly susceptible to interference from improper sample-probe conditions, and from improper sample-line transport velocities.

A good sampling station, that will produce accurate and reliable data, requires attention to design and installation details. What follows is a detailed discussion of what makes a good installation, and some of the practical and theoretical considerations behind the installation.

Flow measurement

Effluent-discharge measurement devices can generally be divided into two classes—those that operate with a free water surface (open-channel flowmeters), and those that do not. Many engineers are more familiar with the theory and practice of closed-conduit flow measurement than they are with open-channel flowmeters.

Closed-conduit flow measuring devices generally rely on pressure drop (venturi, orifice meters, etc.), electromagnetic induction (magmeters) or sound-velocity differential as their principal method of operation. These devices are generally very accurate, often to within 1% over the full range of flows encountered. All of these devices, however, require detailed engineering at the time of their installation, and periodic maintenance; each has well-defined installation and operating criteria that must be carefully observed if the flow measurements are to be accurate.

Generally, chemical engineers are less familiar with the theory and practice of open-channel flow measurement. The open-channel flowmeter is generally the least considered device in the plant, but is frequently required to make accurate flow measurements over a range considered impractical for a venturi tube or a magmeter. Unfortunately, many open-channel flowmeters receive neither good attention during installation, nor good maintenance after installation.

The depth and velocity of water in an open channel are related to each other by the Bernoulli theorem. For a given channel, the slope, channel roughness and flow volume determine the depth of channel flow. This depth—at constant flow—is called the normal depth, y_n.

Also, for each channel, there exists a depth and velocity combination such that the specific energy in the fluid is at a minimum. The depth under these conditions is the critical depth, y_c.

The theory of open channel flow is quite elaborate, and is beyond the scope of this article. An excellent discussion of the theory will be found in Ref. 5.

Frequently, where flows are large, or flow-metering installations are remote, or too expensive, engineers rely on the Manning equation to calculate the discharge through a channel:

$$Q = (1.486/n)R^{2/3}S^{1/2}A \qquad (1)$$

where Q = discharge; R = hydraulic radius, or wetted area/wetted perimeter; S = channel slope; A = wetted channel area; and n = Manning roughness coefficient. An extensive table of these coefficients for different types of channels will be found in Ref. 5, pp. 110–113.

When the flow is at other than the normal depth for the channel it is an indication that the stream velocity is changing in response to upstream or downstream conditions, and that the relationship between flow and depth needs close inspection.

Where a metering location has been selected in a short level conduit whose upstream slope is steep, the velocity in the pipe at this level section will be high and the depth of flow will be both below the normal depth and below the critical depth for the channel, or $y < y_c < y_n$. This condition is known as supercritical flow; in this case a large change in channel flow will result in a very small change in the depth of flow, which makes flow computation based upon depth measurement very tricky. Also, for this condition, the depth of the flow may suddenly increase by a phenomenon known as hydraulic jump. This too is an indicator of unstable flow conditions.

At the critical depth in a channel, there is only one relationship between discharge and depth, that is, there is only one depth for a given discharge. All weirs and flumes rely upon this relationship to measure flow.

Discharge equations for common weir shapes — Table I

Figure	Name	Discharge equation	Comments
2a	60° V-notch	$Q = 1.43\, H^{2.5}$	Approximate formula
2b	90° V-notch	$Q = 2.49\, H^{2.48}$	
2c	Combination	$Q = 3.9\, H^{1.72} - 1.5 + 3.3\, Lh^{1.5}$	See Ref. 7
2d	Parabolic	$Q = 1.512\, p^{0.478}\, h^2$	$Q \propto h^2$
2e	Proportional	$Q = Ca^{1/2}\, b\sqrt{2g}\,(h - \frac{a}{3})$	$0.625 < C < 0.600$ $Q \propto h$
2f	Rectangular	$Q = 3.33\, H^{3/2}(L - 0.2H)$	Fully contracted ends
2g	Cipolletti	$Q = 3.367\, LH^{1.5}$	
2h	Submerged	$Q = 3.33\, L\,(n\,H)^{3/2}$	n = tabular correction for submergence ratio.

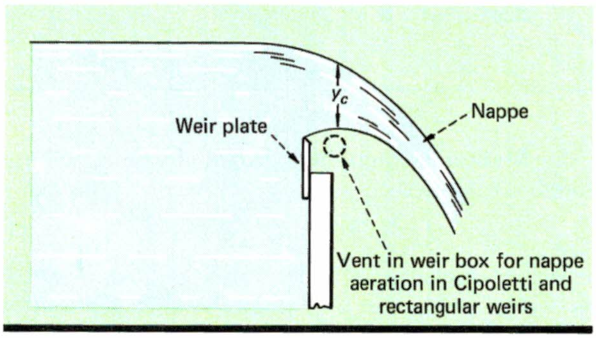
Weirs

Weirs come in a variety of shapes, sizes and materials of construction. Weirs are either notched or cut shapes, depending upon the amount of flow, the accuracy desired in flow measuring, the permissible head loss, and the purpose of installation.

Fig. 2 and Table I show the more-common weir shapes and calculated discharge equations.

Construction details need to be closely followed if the weir is to give consistent, reliable measurements. (Do not just rely on the manufacturer's brochure!) The weir-depth-to-discharge relationship is governed by the development of critical depth, but for the weir, the flow generally passes through critical depth after it has left the weir plate (see Fig. 3). Accordingly then, a weir does not provide an opportunity to directly measure the critical depth-flow relationship.

When the effluent flow over a weir passes through the critical depth, the flow may be subject to forces that can interfere with the discharge-depth relationship measured by the weir. The interferences are generally negative, in that they cause the weir to indicate lower discharges than actually occur. The types of interferences encountered depend largely upon the type of weir, but some common mistakes can be avoided.



Development of critical flow in a weir **Fig. 3**

One of the most common errors, frequently unobserved and uncorrected, in weir calculations is neglect of the approach velocity at the face of the weir. The correction for approach velocity is:

$$h = v^2/2g \quad (2)$$

where h = head, ft; v = average approach velocity on weir plate = channel-flow/channel-area; g = acceleration due to gravity.

The approach velocity correction is generally additive to the height of water over the weir. An example of the type and magnitude of the correction is given in the example in Table II. The corrections in the table are taken from the Water Measurement Manual, [*7*]. This manual is a very practical guide for anyone seeking to measure flow accurately, and also contains suggested box dimensions for installation of weirs to reduce the approach velocity to the weir plate (see Fig. 4).

Weirs come in a variety of shapes. The Sutro or proportional weir is unique, because the flow is directly proportional to the height of the liquid in the weir, permitting direct and simple checks on the flow, and on the flow recorders and other equipment.

Weirs, like all other equipment, require engineering

Discharge coefficient increase for approach velocity in weirs (from Ref. 7) **Table II**

v*	H†											
	0.2	0.4	0.6	0.8	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
0.4	1.014	1.007	1.004	1.004	1.004	1.002	1.002	1.002	1.001	1.001	1.001	1.001
0.5	1.027	1.013	1.009	1.006	1.006	1.004	1.003	1.002	1.002	1.002	1.001	1.001
0.6	1.037	1.019	1.013	1.009	1.008	1.005	1.004	1.003	1.003	1.002	1.002	1.002
0.7	1.050	1.026	1.017	1.013	1.011	1.007	1.006	1.004	1.004	1.003	1.003	1.002
0.8	1.064	1.033	1.022	1.016	1.014	1.009	1.007	1.006	1.005	1.004	1.003	1.003
0.9	1.082	1.042	1.029	1.021	1.018	1.012	1.009	1.007	1.006	1.005	1.005	1.004
1.0	1.098	1.051	1.034	1.027	1.022	1.015	1.011	1.009	1.007	1.006	1.005	1.005
1.1	1.122	1.062	1.041	1.031	1.026	1.017	1.013	1.011	1.009	1.008	1.007	1.006
1.2	1.141	1.072	1.049	1.037	1.031	1.021	1.016	1.013	1.011	1.009	1.008	1.007
1.3	1.163	1.084	1.057	1.043	1.036	1.024	1.018	1.015	1.012	1.011	1.009	1.008
1.4	1.186	1.096	1.066	1.050	1.041	1.028	1.021	1.017	1.014	1.012	1.011	1.010
1.5	1.208	1.109	1.075	1.057	1.047	1.032	1.024	1.019	1.016	1.014	1.012	1.011
1.6	1.225	1.122	1.084	1.065	1.052	1.035	1.027	1.022	1.018	1.016	1.014	1.012
1.7	1.254	1.135	1.093	1.071	1.059	1.040	1.031	1.025	1.021	1.018	1.016	1.014
1.8	1.277	1.149	1.104	1.080	1.065	1.045	1.034	1.027	1.023	1.020	1.017	1.016
1.9	1.308	1.165	1.115	1.089	1.072	1.049	1.038	1.030	1.026	1.022	1.019	1.017
2.0	1.335	1.181	1.126	1.097	1.079	1.055	1.042	1.034	1.028	1.025	1.021	1.019
2.1	1.363	1.197	1.137	1.106	1.087	1.060	1.046	1.037	1.031	1.027	1.024	1.021
2.2	1.391	1.213	1.149	1.118	1.094	1.065	1.050	1.039	1.034	1.029	1.026	1.023
2.3	1.420	1.231	1.161	1.124	1.102	1.071	1.054	1.044	1.037	1.032	1.028	1.025
2.4	1.449	1.248	1.176	1.134	1.110	1.077	1.059	1.047	1.040	1.034	1.030	1.027
2.5	1.480	1.266	1.187	1.145	1.119	1.083	1.063	1.051	1.043	1.037	1.033	1.029
2.6	1.511	1.285	1.200	1.155	1.128	1.088	1.068	1.055	1.046	1.040	1.035	1.032
2.7	1.542	1.303	1.213	1.166	1.137	1.095	1.073	1.059	1.050	1.043	1.038	1.034
2.8	1.573	1.322	1.228	1.178	1.146	1.100	1.078	1.063	1.053	1.046	1.041	1.036
2.9	1.606	1.341	1.242	1.189	1.155	1.108	1.083	1.067	1.057	1.049	1.043	1.039
3.0	1.637	1.361	1.256	1.199	1.165	1.115	1.088	1.072	1.061	1.053	1.046	1.041

*v = average approach velocity, ft/sec
†H = average height over weir, ft
Values in body of table H are weir-discharge correction-ratios

design as well as calibration if they are to provide reliable measurements.

Flumes

A flume is a channel section of known geometry, in which the flow is forced through the critical depth at a given section. The uniform distribution of flow across the flume throat, the development of critical depth, and the relationship between flow and upstream water depth make the flume a very accurate measuring device for open-channel flow. Some popular flume shapes are shown in Fig. 5a–5c.

A flume represents a restriction in a channel. Development of critical flow in the flume's throat causes the upstream depth in the flume to rise in relation to increasing flow. This phenomenon cancels out the approach-velocity correction needed for weirs.

A variety of upstream and downstream conditions can affect a flume's accuracy. High approach velocities ($v > 5$ ft/s), turbulence at the flume, or nonuniformly distributed approaching flow (such as after a channel bend or sharp turn) can all cause the flume to yield unreliable flow measurements. The upstream channel flow should generally be at or above normal and critical depth for the channel ($y > y_n > y_c$), to avoid the hydraulic phenomena known as rapid flow and hydraulic jumps, which can cause large measurement errors.

In closed conduits, where Palmer-Bowlus flumes are frequently used, the installation of the flume can restrict the flow and cause the upstream free-water elevation to approach or exceed the top of the sewer, causing pressure flow through the flume. Wells and Gottas [*8*] have determined that high approach velocities in a closed conduit can cause the actual discharge to be up to 130% of that indicated by the flume.

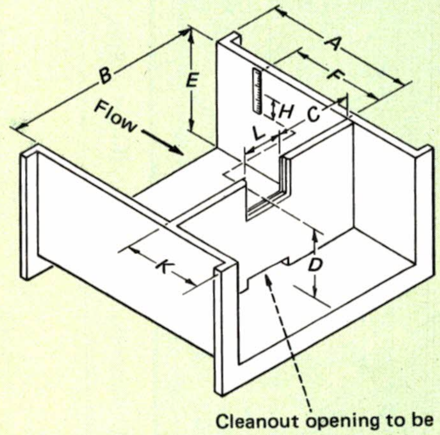
The Parshall flume is one of the best-studied flumes, and has many of the measurement errors identified. The Palmer-Bowlus shape has become very popular because of the development of plastic inserts that cost less than the Parshall shape, and can be used inside sewer lines. The cutthroat flume (Fig. 5c) is not as popular as either the Palmer-Bowlus or Parshall shapes, but has the advantage of having a flat approach and throat-channel floor, and is one of the few that have hydraulic calibration data for non-horizontal flume installation (which may result from settling or downstream hydraulic scour of the foundation after installation) [*9*]. The cutthroat flume is generally less sensitive to downstream submergence than the other shapes.

In the majority of flume installations, only a single upstream depth-of-flow measurement is made. However, when downstream conditions back water up into the throat of the flume, a second depth measurement is required when the depth in the flume throat exceeds 50–70% of the upstream flow depth. This effect is called submergence, and reduces the actual discharge of the flume. The throat-upstream depth ratio ($100 \times Hb/Ha$) is referred to as the percentage of submergence, and the reduction in flow from typical submergence effects can be determined by graphs [*7*].

Flumes provide accurate flowmetering measurements, but it is necessary to check the upstream and downstream conditions if the results are to be reliable.

The improper installation (tilting or misalignment) of a weir plate or flume that results in uneven distribution of the flow can cause difficult-to-detect systematic errors in flow measurement that may not be caught until after several calibration tests have been made.

Partial submergence of flumes may be corrected for by charts and formulas, but the partial submergence of

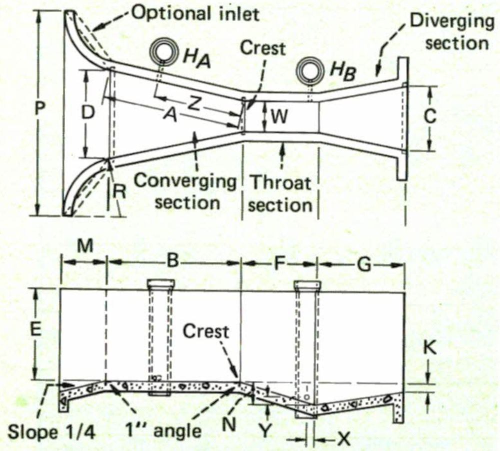


	H	L	A	K	B	E*	C	D	F
Discharge, sec-ft	Maximum head, ft	Length of weir crest, ft	Length of box above weir notch, ft	Length of box below weir notch, ft	Total width of box, ft	Total depth of box, ft	Distance from end of crest to side of box, ft	Distance from crest to bottom of box, ft	Gage distance, ft
¼ to 3	1.0	1	6	2	3	3	1	1½	4
2 to 5	1.1	1½	7	3	4	3	1¼	1½	4½
4 to 8	1.2	2	8	4	5	3½	1½	1¾	5
6 to 14	1.3	3	9	5	7	4	2	2	5½
10 to 22	1.5	4	10	6	9	4	2½	2	6
15 to 35	1.5	6	12	6	11½	4½	2¾	2½	6
20 to 50	1.5	8	16	8	14	4¾	3	2¾	8
25 to 60	1.5	10	20	8	17	5	3½	3	8
				90° V-notch weir					
½ to 2½	1.00	–	6	2	5	3	–	1½	4
2 to 4⅓	1.25	–	6½	3	6½	3¼	–	1½	5

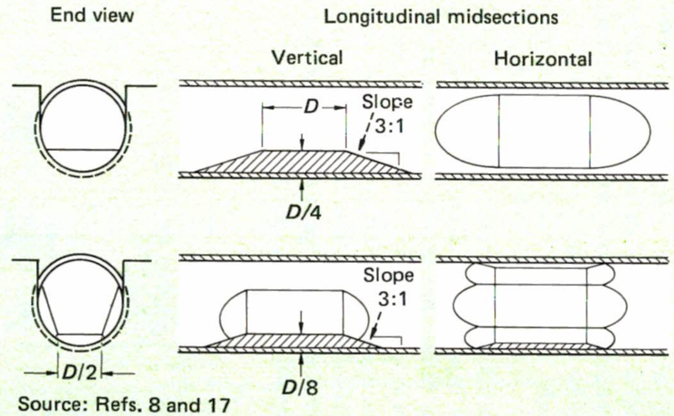
*This distance allows about 6 inches freeboard above highest water level in the weir box.

Source: Ref. 7

Suggested weir-box dimensions **Fig. 4**

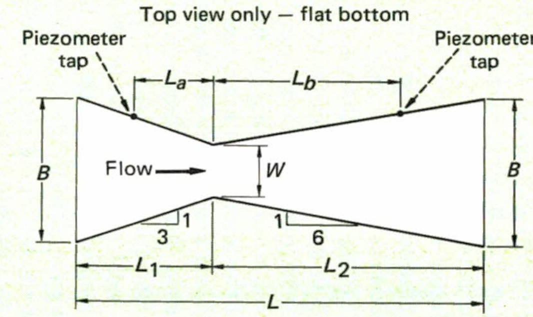


a. Plan and sectional elevation of concrete Parshall measuring flume



Source: Refs. 8 and 17

b. Palmer Bowlus flume



$B = W + 2L_1/3 = W + L_2/3$

$L_a = 2L/9$

$L_b = 5L/9$

Source: Ref. 9

c. Cutthroat flume

W	A	Z	B	C	D	E	F	G	K	N	R	M	P	X	Y	Free-flow capacity: Minimum	Free-flow capacity: Maximum
Ft-In.	Ft-In.	Ft-In.	Ft-In.	Ft-In.	Ft-In.	Ft	Ft	Ft	In.	In.	Ft-In.	Ft-In.	Ft-In.	In.	In.	cfs	cfs
0–3	1– 6-3/8	1– 1/4	1– 6	0–7	0–10-3/16	2	1/2	1	1	2-1/4	1–4	1–0	2– 6-1/4	1	1-1/2	0.03	1.9
0–6	2– 7/16	1– 4-5/16	2– 0	1–3-1/2	1– 3-5/8	2	1	2	3	4-1/2	1–4	1–0	2–11-1/2	2	3	0.05	3.9
0–9	2–10-5/8	1–11-1/8	2–10	1–3	1–10-5/8	2-1/2	1	1-1/2	3	4-1/2	1–4	1–0	3– 6-1/2	2	3	0.09	8.9
1–0	4– 6	3– 0	4– 4-7/8	2–0	2– 9-1/4	3	2	3	3	9	1–8	1–3	4–10-3/4	2	3	0.11	16.1
1–6	4– 9	3– 2	4– 7-7/8	2–6	3– 4-3/8	3	2	3	3	9	1–8	1–3	5– 6	2	3	0.15	24.6
2–0	5– 0	3– 4	4–10-7/8	3–0	3–11-1/2	3	2	3	3	9	1–8	1–3	6– 1	2	3	0.42	33.1
3–0	5– 6	3– 8	5– 4-3/4	4–0	5– 1-7/8	3	2	3	3	9	1–8	1–3	7– 3-1/2	2	3	0.61	50.4
4–0	6– 0	4– 0	5–10-5/8	5–0	6– 4-1/4	3	2	3	3	9	2–0	1–6	8–10-3/4	2	3	1.3	67.9
5–0	6– 6	4– 4	6– 4-1/2	6–0	7– 6-5/8	3	2	3	3	9	2–0	1–6	10– 1-1/4	2	3	1.6	85.6
6–0	7– 0	4– 8	6–10-3/8	7–0	8– 9	3	2	3	3	9	2–0	1–6	11– 3-1/2	2	3	2.6	103.5
7–0	7– 6	5– 0	7– 4-1/4	8–0	9–11-3/8	3	2	3	3	9	2–0	1–6	12– 6	2	3	3.0	121.4
8–0	8– 0	5– 4	7–10-1/8	9–0	11– 1-3/4	3	2	3	3	9	2–0	1–6	13– 8-1/4	2	3	3.5	139.5
10	14– 3-1/4	6– 0	14	12–0	15– 7-1/4	4	3	6	6	13-1/2	8–0	6–0	32– 0	12	9	6	200
12	16– 3-3/4	6– 8	16	14–8	18– 4-3/4	5	3	8	6	13-1/2	9–0	8–0	35– 0	12	9	8	350
15	25– 6	7– 8	25	18–4	25– 0	6	4	10	9	18	11–0	9–0	40– 0	12	9	8	600
20	25– 6	9– 4	25	24–0	30– 0	7	6	12	12	27	12–0	10–0	48– 0	12	9	10	1,000
25	25– 6	11– 0	25	29–4	35– 0	7	6	13	12	27	12–0	10–0	55– 0	12	9	15	1,200
30	26– 6-3/4	12– 8	26	34–8	40– 4-3/4	7	6	14	12	27	12–0	10–0	64– 0	12	9	15	1,500
40	27– 7-1/2	16– 0	27	45–4	50– 9-1/2	7	6	16	12	27	13–0	11–0	80– 0	12	9	20	2,000
50	27– 7-1/2	19– 4	27	56–8	60– 9-1/2	7	6	20	12	27	13–0	11–0	95– 0	12	9	25	3,000

Parshall flume, with dimensions for various throat widths, and other common flume types

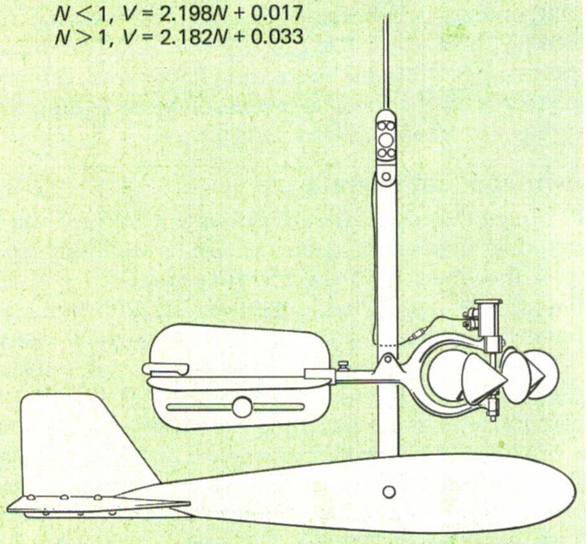
Fig. 5

Typical rating equation:

N = revolutions /s, V = velocity-ft/s

$N < 1$, $V = 2.198N + 0.017$

$N > 1$, $V = 2.182N + 0.033$



Price-type current meter for flow measurement Fig. 6

Methods of wastewater sample collection — Table III

Method	Compositing principle	Comment
Continuous	Constant sample pumping rate	May lack representativeness
Continuous	Sample pumping rate proportional to effluent flowrate	Requires flow measurement and may be difficult to achieve, practically.
Periodic	Constant sample volume, constant time interval between samples.	May lack representativeness for variable flows and concentrations.
Periodic	Constant sample volume, time interval between samples proportional to stream flow.	Requires accurate flow measurement.
Periodic	Constant time interval between samples, sample volume proportional to total stream volume since last sample.	May require manual compositing from chart and may lack representativeness.
Periodic	Constant time interval between samples, sample volume proportional to stream-flow at time of sampling.	May be difficult to achieve in practice. Requires accurate flow measurement

a weir invalidates the measurement readings, and while there are theoretical ways of estimating the discharge over a partially submerged weir, it is best to avoid having to use them.

Almost every measuring device has some types of errors, either in the device itself or in its electronic and mechanical interfaces. We need to be aware of the types of errors in the overall system, and the way they affect measurements made by the device.

Depth measurement

Because the relationship between flow and depth is well defined for many types of metering installations, it is easy to determine a depth and then calculate discharge from known formulas. Depth of flow in a channel or height over a weir is generally measured by floats, pressure taps, sonic reflection, resistance, or conductance. Each of these methods has certain advantages, although for given installations, one may perform as well as another.

Surface-level measuring devices are generally subject to interference from wave action, weather, and floating objects in the channel. Unless the device is in a stilling well (Fig. 5a), or relies upon pressure measurement, these interferences can render depth readings unreliable. Check sensitivity of any surface measuring device to interferences, as well as for overall accuracy.

At one installation, a surface-contact probe was being used to measure depth of flow. The instrument worked reliably in calm weather, but due to its installation, and lack of protection, gave unreliable readings every time the wind was more than 9 knots. In this specific situation, the cable connecting to the level sensor was over 15 ft long.

In another instance, a bubbler device, sensing depth of flow by pressure, was found to give unreliable readings because of an unrecognized problem in the flow distribution pattern. When the flow pattern was corrected, the unreliability ceased.

Almost all instruments currently in use in effluent monitoring rely upon an electrical or mechanical device to convert depth readings to an integrated signal (to totalize flow readings). All equipment manufacturers readily admit that there exists a certain accuracy limit to each of the electrical and mechanical systems, but few point out that the overall accuracy is no better than the least accurate portion of the system. However, the integrating system is generally more reliable than the depth measuring system.

In some effluent flowmetering practices, a float with a range of 20 in. vertical travel may be connected to a signal conditioner that measures angular displacement at a hinge; the depth of flow is recorded on a 3-in. strip-chart recorder, to three "significant" figures! Even more absurd is the totalizer on this system, which integrates the total flow in ten-gallon units.

Floats, gear-drives, recording pens, paper tape and charts, all may cause inaccuracies in measurements. Floats tend to lag depth increases on increasing flow, and trail depth on decreasing flow. Cut cams and chart drives are generally subject to more constant bias in one direction unless they are subject to temperature variation. Chart paper will change dimensions with changes in humidity and temperature (pen recording devices have been alternately praised and cursed by engineers since their invention). The *Stevens Water Resources Data Book* [*10*] provides an excellent discussion of the types of errors caused by some of this equipment, and how to correct for those errors.

Even small errors in depth measurement can lead to large errors in flow measurement, because the relationship between depth and flow is generally exponential [*11*]. A relatively small recorder-integrator error of about 3% on the total mechanical system plus a 3%

depth error can cause flow measurement uncertainty of almost 9%.

Recordkeeping

Before leaving the subject of flowmetering—a word about the recordkeeping requirements of the NPDES Permit system is necessary. 40 CFR 122.7 (j) (*Fed. Reg.* p. 33426) specifically prescribes the type of records that must be kept (and that includes instrument calibration and maintenance records). Such records must be retained for three years. It is possible that in litigation, or in permit negotiations, the maintenance and calibration records on the flowmeter and sampling equipment may have to be introduced as evidence.

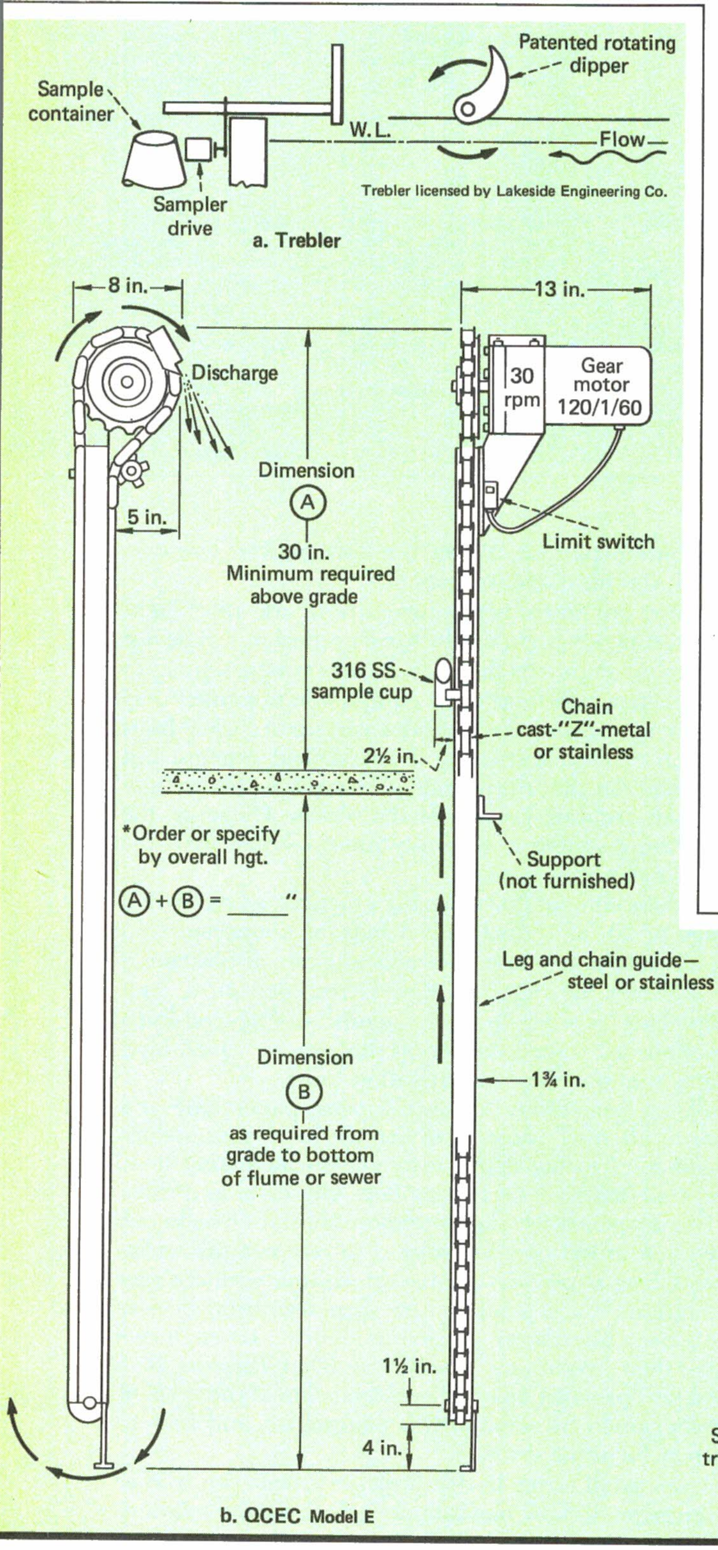
Flowmeter calibration

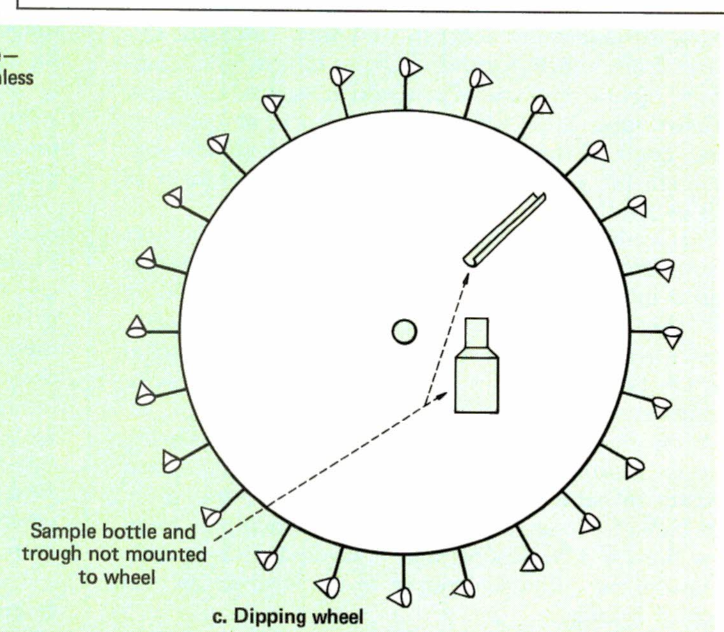
Flowmeter equipment calibration can be very time-consuming, depending upon the size, accessibility and type of flowmeter, and the accuracy desired.

One of the most reliable methods of calibrating an effluent flowmeter is with a Price-type current meter, which is depicted in Fig. 6. Price or Pygmy-type current meters and their use are described in Ref. 7 and 14. These instruments are relatively expensive (over $1,000) but provide almost primary-standard accuracy as long as they are well maintained. The current meters, in new or reconditioned shape, have an overall accuracy within 3% for velocities below 0.5 ft/s, and within 1.5% for velocities greater than 1.0 ft/s [*12,13*]. At velocities less than 0.3 ft/s, Price-type current meters should not be used.

Price current meters can be ordered with instantaneous- or average-velocity readouts. The averaging meter is most common, and comes with a counter that registers bucket-wheel revolutions over any selected period. The averaging velocity is then read off a standard rating chart, or can be computed by a formula (Fig. 6).

For calibration of open channels in regular-shaped conduits, the use of a two-point method at 20% and 80% of the channel depth is preferable to use of a single 62%-of-depth velocity measurement. Multiple measurements are generally made across a channel of appreciable width, and unless the channel is exceptionally wide,





Simple composite samplers

Fig. 7

the velocity measurements should not be farther apart than 3 ft. For very high precision, or irregularly shaped conduits, the channel should be divided into a number of equal areas, and velocity measurements should be made at the centroid of each area [*1,14*].

A well-designed flowmetering installation that uses a V-notch weir will have the average approach velocities to the weir generally less than 0.5 ft/s (near the minimum of the reliable range of a Price current-meter). To calibrate such a weir one must use dilution or other techniques.

Marsh-McBirney [*15*] and others manufacture hand-held electromagnetic flowmeters that are reported to accurately measure velocities as low as 0.05 ft/s. This equipment is more expensive than a Price-type current meter, but its accuracy and applicability may be considerably greater. Since the velocity head correction on a weir at approach velocities of 0.05 ft/s is less than 4×10^{-5} ft, the use of a Marsh-McBirney meter to calibrate the weir may extend the lower range of flow measurement almost 75% below the calibration range of a Price or Pygmy-type meter.

According to its sales literature, Marsh-McBirney is manufacturing a device that will simultaneously compute the channel cross-section and determine the average velocity of a location (for a predetermined channel shape). The company claims an accurate determination of the flowrate in the channel to within 10%, before calibration. This equipment is, however, only available for permanent installations.

Dilution techniques

If direct techniques are not available for velocity measurement and flowmeter calibration, highly reliable indirect techniques may be used to provide reasonably good answers. These techniques are commonly known as dye or tracer studies.

The tracer solutions most commonly used are rhodamine dyes, salts (especially NaCl), and radioactive tracers. Any of these, if properly used, will provide good results. The salt-solution tracer study is often more difficult to run because background salt concentrations may interfere with the measurements.

Tracer studies are generally run on either a batch- or a continuous-injection basis. With the development of fluorescent dyes and highly sensitive fluorometers, or the equally sensitive radiation-detection equipment, the selection of the tracer system becomes a matter of personal preference. The principal requirement for conducting tracer studies is that complete mixing must occur between the point of tracer injection and the point at which the dilution ratio is measured. Quiescent-flow locations are generally not suitable for tracer studies.

Turner Designs publishes a good technical description of how to conduct a dye test in "Fluorometric Facts" [*16*]. Turner and others also manufacture fluorometers that can be used for field or laboratory calibration of effluent flowmeters, or for determining other flowrates.

A word of caution about determining a calibration curve for a flowmeter installation: Do not attempt to determine a flowrate for other than instantaneous flow conditions (use of a composite sampler to find average rates may lead to erroneous results).

Sampling and samplers

At the beginning of this article we indicated that attempting to collect an accurate, representative sample from an effluent is analogous to having to know most of the answer in order to be able to ask a particular question. In this section, we'll attempt to examine sampling theory, and equipment, and see how the errors in sampling may be the most significant—especially under certain circumstances.

Collection of accurate data from a sampling program requires planning and effort. Sampling is an important part of a monitoring system and must be planned with regard to the operations and production schedules of the plant. As mentioned earlier, we need to consider *how* we will sample and *how much* sample we need as well as *what* we will sample. We also need to know what may cause interferences or inaccuracies in the sampling program, as well as how to analyze the sample. We need to look at the sampling theory, sampling equipment, and sample-handling techniques—all with regard to the plant operations.

Sampling equipment collects either discrete, composite, or continuous samples. Continuous samplers are generally used with continuous analyzers but can be used for collection of composite or discrete samples. Discrete samplers, which collect individual samples of the effluent over a finite time period, are most widely used. When individual discrete or grab samples are mixed with other discrete samples in a predetermined order, the mixture is called a composite sample, and is more nearly a true representation of the composition.

Some composite samples are alleged to be more representative of the effluent flow than is a single discrete sample. The degree of representativeness of the composite sample is a question that needs to be examined.

There is only one way of absolutely determining the total quantity of what a plant is discharging, and that is to analyze the entire volume of the discharge. Since that is an impossible or impracticable task, we must determine what a good composite sample is and how to go about taking such a sample.

There are as many different definitions of composite samples as there are persons collecting samples. The U.S. EPA uses a very broad definition in its "NPDES Compliance Sampling Inspection Manual" [*17*] to differentiate composite samples from grab samples. Since EPA makes the rules for determining permit compliance, we will use its definitions:

"A grab sample is defined as an individual sample [aliquot of the flow*] collected over a period of time *not exceeding fifteen minutes.*"

"A composite sample should contain a minimum of eight discrete samples taken [collected] at equal time intervals over the compositing period or proportional to the flow rate over the compositing period."

EPA describes six methods for collecting samples—two continuous methods and four composite methods. These are presented in Table III. EPA further suggests that if the maximum or minimum flow is greater than

*Italics and words in brackets added.

15% above or below the average flow during the sampling period, a flow-proportional sampling method should be used to collect a composite sample. (Note: Ref. 17 is an excellent indication of EPA thoughts on compliance monitoring and enforcement activities, and chain of custody procedures, etc., but better information is available on the subject of flowmetering).

Sampling equipment

Many types of sampling equipment, using various levels of sophistication and differing sampling techniques, are currently available. Generally speaking there are single- and multiple-container samplers. The simplicity or sophistication of the sampling equipment used depends primarily upon the amount of money to be spent, the type of analyses to be performed, and the amount of information being sought about the effluent.

Dippers, Trebler samplers and other similar devices are among the simplest sampling devices available (Fig. 7). These generally collect samples at predetermined intervals, and deposit them, by gravity, into a single container. The equipment is very reliable for collecting samples of floating materials and sediments. The Trebler sampler is generally limited to areas where the installation, including the sample container, is not subject to flooding. Other dippers are limited only by the length of the sampling drive-chain.

The next level of sampler sophistication is timer-activated units that will provide either a single composite sample, or will operate trip releases on sequentially arranged evacuated sample containers. The sampler manufactured by Sirco relies on a timer to release a hose clamp on an evacuated sample container (which draws the sample into the sample container). Brailsford, N-Con, ProTech and a number of other manufacturers all sell a simple pump on a timer system that will collect a single composite sample. All of these are quite reliable and may be acceptable for many sampling purposes. This equipment generally relies on a small sampling tube or sampling head immersed in the water and is limited to sites where the sampler is less than 20 feet above the waste stream.

The highest level of sampling equipment technology is represented by multiple-bottle samplers with programming options that permit the collection of flow-proportional grab samples in single or multiple containers. Such equipment is manufactured by Isco, N-Con, ProTech, Quality Control Equipment Co., and a number of others. The equipment is available with refrigeration, submersible pumps (for sample transport), sample container indexing (up to 24 containers), automatic or preprogrammed sequencing, and the ability to accept flowmeter signals and to collect grab and composite samples on a time-constant or flow-constant basis.

Most of the sampling equipment commercially available is designed to be portable, and self-contained, including space to hold both the sample and ice for refrigeration. Most equipment will successfully collect samples of sewage, and perform satisfactorily under a variety of conditions. However, much of the commercially available sampling equipment contains design features (limits) that may affect the overall quality or composition of the sample. Design limits include very small sampling lines (usually 1/4 to 3/8-in. I.D.), small collection capacity; improper sampling probe entrance conditions, low sample-line transport velocities; and sample-handling conditions that may permit cross contamination. Careful equipment selection and good practices in installation engineering can overcome most of these limitations.

Simulation of composite sampling techniques Table IV

Ratio of composite sample concentration for various sampling methods to theoretical average concentration

Change of flow with time, t		Change of concentration with time, t: $1-t$	$1-\frac{t}{2}$	$\cos\frac{\pi t}{2}$	e^{-t}	$\sin \pi t$
	a)	0.90	0.97	0.92	0.95	0.99
	b)	0.90	0.97	0.92	0.95	0.99
	c)	0.90	0.97	0.92	0.95	0.99
	d)	0.90	0.97	0.92	0.95	0.99
t	a)	1.35	1.09	1.26	1.14	0.99
	b)	0.90	0.97	0.90	0.97	0.90
	c)	0.86	0.96	0.87	0.95	0.89
	d)	0.87	0.96	0.89	0.95	0.97
$1-t$	a)	0.68	0.87	0.72	0.82	0.99
	b)	0.95	0.98	0.98	0.96	1.12
	c)	0.92	0.97	0.95	0.95	1.09
	d)	0.92	0.97	0.93	0.95	0.97
$\sin \pi t$	a)	0.90	0.97	0.88	0.97	0.80
	b)	1.01	1.00	1.00	1.00	1.01
	c)	0.90	0.97	0.92	0.95	0.98
	d)	0.90	0.97	0.92	0.95	0.97

Tabulated values are ratios for sampling methods
Line a) Time interval and aliquot volume constant
Line b) Time interval constant, aliquot volume flow proportional
Line c) Time interval constant, aliquot volume proportional to flow since last sample
Line d) Aliquot volume constant, time interval flow proportional
Source: Ref. 19

What sampler to use?

EPA has surveyed and used several types of samplers, and in Ref. 18 and 19 it indicates the relative advantages of one type of equipment design, but falls short of a specific recommendation. Ref. 19, in particular, surveys a large cross section of the sampling equipment available in 1975, and includes an evaluation of the equipment with respect to ability to collect samples from municipal sewage. Much of this equipment is still commercially available, with the same design features and limitations. The survey report indicates that certain types of equipment may perform more satisfactorily than others but provides no support for those allegations. Ref. 18 has similarly been used (or misused) by manufacturers to indicate equipment reliability and equipment superiority. Sampling equipment will have individual features that may make one model best suited for a particular installation. However, in most situations encountered, more than one type of equipment will satisfactorily sample and store the effluent.

How representative is the sample?

Most effluent permits express discharge limitations in a daily mass rate. This rate is determined by measuring and time-integrating fluctuations in flow and in chemical concentration in the effluent stream. We measure the flow as accurately as possible and then hope that our sampling equipment is obtaining a representative composite sample of the fluctuations in chemical concentrations. For particular sampling techniques and flow and concentration variations, a mathematical model indicates that results may be between 114% and 68% of the actual average mass discharge rate. This information is contained in Table IV [*19*]. A further indication of how different sampling schemes using similar equipment can produce variant results is given in Table V [*18*].

From the information presented thus far, it can be seen that one can actually obtain almost any desired result by selecting the manner in which one monitors the effluent.

Comparison of COD sampling data and sample collection techniques on a biological wastewater treatment plant — Table V

All figures are daily ratios of different composite sample data, compared with manually flow-composited grab samples collected every four hours.

Sample type	Ratio of COD values			Comments
Sewage treatment plant influent data				
2-hour flow composite	1.18	0.740	1.21	Different samplers used for each sampling method.
15-minute time composite	2.10	1.74	2.08	
Mean of all 4-hour grab samples	1.27	0.793	0.937	
Final effluent data				
2-hour flow composite	1.12	0.96	1.22	Different samplers used for each sampling method.
4-minute time composite	1.07	0.89	1.28	
Mean of all 4-hour grab samples	1.07	0.82	1.05	

Data collected on Richards-Gebaur Sewage Treatment Plant for the period May 21-24, 1973, as reported in Ref. 18.

What is "good practice"?

Owing to process operations, in-plant spills, upsets, equipment cleaning, shift changes, manufacturing campaigns, etc., the chemical composition and strength of an effluent stream may vary quite widely. Careful planning of a sampling program must address all these variables.

One method of determining the minimum sampling frequency for compliance purposes is by use of a powerful technique called spectral analysis. This type of analysis generally requires a relatively large amount of data, but can determine the frequency of the major and minor events that contribute to high variability in effluent data. A good discussion of the use of spectral analysis in effluent monitoring is contained in Ref. 20.

A useful rule from spectral analysis can be applied to our data analysis activities without resort to a computer. This rule states that if we attempt to observe a periodic phenomenon, we must sample the effluent at an interval greater than twice the frequency of the event to be observed. If, for example, we wish to include the events that occur within one hour, we must sample *at least* every half-hour (more frequently if possible).

Fortunately, many of the events that occur in a chemical plant are not random, but scheduled. If we are attempting to determine how frequently to sample the effluent either during the day or during the month, we need to look at the production and shift schedules, and plan our program accordingly.

The difference in sampling frequency and number of samples collected can be quite important (Table V). The samplers that operated with greater frequencies generally gave higher composite sample concentrations than did manual sampling conducted at four-hour intervals. This indicates that there may be no one best frequency or pattern for collecting samples, but that there is a broad spectrum of sampling techniques suitable to a particular effluent, depending also upon the sampling equipment being used.

At present there is no good method for *in situ* calibration of the entire monitoring system. The optimum result of good monitoring program planning is identification and minimization of various types of errors, including those arising from flow-measurement and sampling errors.

Other statistical considerations

At the time of permit negotiation or renegotiation, the regulatory agency will seek to impose limits on what can be discharged; most permits have a limit on total suspended solids (TSS). In order to determine the number of samples needed to measure compliance with the limit, use:

$$n = \frac{(Z_a + Z_b)^2}{(\Delta/\sigma)^2} \qquad (3)$$

Where: Z_a and Z_b are the interval for acceptance at the upper and lower bounds of an assumed distribution—i.e., where the acceptance level is 95%, $Z = 1.65$; Δ is the difference being sought between the standard and the data mean; σ is the standard deviation of the data, including all sources of error; n is the number of samples required.

If the permit limit is determined on a net basis, the value obtained must be doubled. An example of this type of analysis is worked out in the box on this page.

This method of analyzing data can also be used to indicate how frequently one should sample the effluent, or how many pairs of samples may be needed to detect a certain permit value.

You may find it helpful to measure the variance on each permit pollutant, as the permit limits are absolute and the interferences are not. The permit limits may sometimes be within the variance of the parameter being measured [*11*].

Sampling suspended solids

The collection of representative samples of suspended solids (TSS) from an effluent stream is a difficult task. Almost every NPDES permit has either a TSS limit or a

TSS monitoring requirement, even though there is no analytical standard for TSS and there is no way to determine what a certain TSS value means. Moreover, a controversy has developed over the number of washings permitted in the analytical technique for determining TSS, and the current analytical procedure may be changed.

Suspended solids have a large size range, and the particles range in density from 1.01 to over 2.65. The location, orientation, and intake velocity of the sampling probe and the transport velocity of the sample-collection line may all affect the concentration of TSS in the sample container. Tests run at a number of locations suggest that, where possible, the sampler inlet should be mounted in the side or bottom of the stream with an orientation parallel to the flow. The preferred practice is to orient the sampling probe intake to face the flow.

Sample-intake velocities should preferably be above 3 ft/s, and sample-transport line velocities, especially in vertical runs, should be above 2 ft/s, and above the settling velocity of the largest particle sampled [*19*]. A sampling study showed that even when all the above recommendations on sampling were followed, segregation of the sample occurred, with subsequent poor capture of sand particles whose diameter was 0.6 mm or more.

Suspended solids are best sampled at locations of high velocity and turbulence—not upstream of a well-designed flowmeter installation, where quiescent flow conditions are needed.

Sampling toxic pollutants

EPA analytical procedures for sample collection, storage and analysis must be followed in monitoring for toxic pollutants in the effluents. The protocols are tricky, the results are of questionable reliability at current reporting levels (10 parts per billion), and the analysis is very expensive (about $2,000 per sample for all of the 129 toxic pollutants that are analyzed by gas-chromatograph/mass-spectrograph techniques).

EPA would recommend that the sampling equipment used consist of Teflon, or that the sample contact only Teflon. Other materials of construction, however, may be used in the sampling location and in the equipment if they have been in place sufficiently long enough to reach equilibrium with the chemicals in the effluent.

Do not collect a sample in polyethylene if you plan to perform low-level organic analyses on it—polyethylene is a sponge for organic chemicals, from which they cannot practically be desorbed.

Another problem frequently encountered is accidental sample contamination. This problem is made more difficult by the extreme sensitivity of the analytical equipment currently in use. Contamination may occur due to improper or inadequate cleaning of the sample containers, or failure to remove residues from sample collection lines, as well as by physical cross-mixing of the samples.

Summary

The biggest sources of monitoring-data uncertainties generally are found in flow-measurement and sampling procedures; these uncertainties are much larger than the limits of analytical accuracy in the laboratory. Careful equipment selection, careful installation of equipment, and comprehensive planning of a sampling program can increase the reliability and accuracy of the data collected. Finally, the sampling of suspended solids and of toxic pollutants are two types that may pose unusual difficulty for the person collecting the sample: suspended solids sampling poses difficulty because of the physical characteristics of the materials and the lack of approved analytical techniques; toxic-pollutant sampling poses difficulty because of the special materials and contamination-control procedures required.

Roy V. Hughson, Editor

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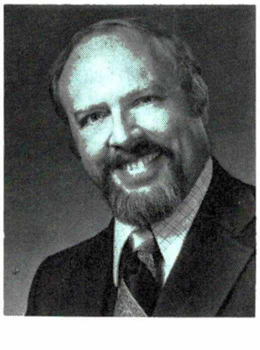
The author



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