Water Sampling Methods

10

Abstract

In order to determine influent and effluent contaminant loads or concentrations and treatment practice performance, assessment efforts often include stormwater runoff sampling. Depending on the water quality parameter of interest, sampling can be done in situ, by grab samples, or by automatic sampling devices. Samples can also be collected on a time-weighted basis (equal time between samples) or on a flow-weighted basis (equal volume of flow passing the sampling site between samples). This chapter discusses available sampling methods and when and how to implement a particular method, and discusses the number of sampled events required to achieve a desired confidence interval. Also included is a discussion of sample storage and handling is also included.

The effectiveness of a stormwater treatment practice at capturing a pollutant or pollutants can be assessed by comparing the amount of pollutant that enters the stormwater treatment practice to either the amount of pollutant that exits the stormwater treatment practice or to the amount that is retained. Pollutant quantities are measured in mass or concentration of pollutant, and these measurements can be collected using one of four methods. First, pollutants can be measured and recorded in situ, or in place, using pollutant sensors or probes placed directly in the stormwater runoff to collect near-continuous measurements with respect to time (in situ sampling). The measurements are later downloaded to a computer by an individual on site or via cell phone connection. Second, stormwater samples can be collected manually and analyzed on site with sensors, probes, or by other analytical methods (on-site sampling). Third, a sample can be collected manually in the field and transported back to a laboratory for analysis ("grab" sampling). Fourth, stormwater runoff can be collected with an automatic sampler, retrieved at a later time, and analyzed in a laboratory (automatic sampling). Some advantages and disadvantages of each method are given in Table 10.1. For more information on sampling methods, consult Standard Methods (APHA 1998b), "Urban Stormwater

A.J. Erickson et al., *Optimizing Stormwater Treatment Practices: A Handbook of Assessment and Maintenance*, DOI 10.1007/978-1-4614-4624-8_10,

Table 10.1 Comparison of in situ, on-site, grab, and automatic sampling methods

	Sampling approach			
Characteristic	In situ	On-site	Grab	Automatic
Sample of stormwater collected	No	Yes	Yes	Yes
Personnel required to collect sample	No	Yes	Yes	No
Sample transported	No	No	Yes	Yes
Relatively large setup costs	Yes	No	No	Yes
Possibility of equipment damage or theft	Yes	No	No	Yes
Parameters or pollutants that can be measured				
Suspended solids	No	No	Yes	Yes
Pathogens (i.e., coliforms)	No	No	Yes	No
Nutrients				
Phosphate	Yes	Yes	Yes	Yes
Nitrate	Yes	Yes	Yes	Yes
Ammonia	Yes	Yes	Yes	Yes
Specific organic chemicals[a]	No	No	Yes	Yes
Oxygen demand	No	No	Yes	No
Heavy Metals	No	No	Yes	Yes
Water quality indicators				
Dissolved oxygen	Yes	Yes	No	No
Temperature	Yes	Yes	No	No
pH	Yes	Yes	No	No
Conductivity	Yes	Yes	Yes	Yes
Turbidity (a surrogate for suspended solids)	Yes	Yes	Yes	Yes
Organic carbon	No	No	Yes	Yes

[a] Examples include petroleum hydrocarbons (e.g., benzene), pesticides, chlorinated solvents

BMP Performance Monitoring" (US EPA 2002), or "Wastewater sampling for process and quality control (Manual of practice)" (WEF 1996).

One advantage of in situ sampling is that data can be collected frequently, in small time steps, with the results available remotely (e.g., cellular phone connection) once the sampling equipment is installed. Another advantage of in situ sampling is that it can be used to measure some of the water quality parameters that are likely to change during sample storage or transport, such as pH and dissolved oxygen. Although personnel are not required to collect samples or perform the chemical analyses, someone must periodically (e.g., weekly) visit the site to maintain and recalibrate the equipment. Unfortunately, a different probe or sensor is required for each pollutant being measured, and not all pollutants can be measured with sensors or probes. For example, nutrient measurement technology is currently cumbersome, with potential improvements that are currently research topics (Arai et al. 2009). There are available, however, in situ bundles that include several common probes and sensors used in water quality assessment.

On-site sampling can also be used to measure water quality parameters that are likely to change during transport. Setup costs for on-site sampling are minimal because it does not require that any equipment remain in the field. Nevertheless, on-site sampling requires individuals to collect samples and perform the analysis on site.

Grab sampling works well for parameters that cannot be accurately or quickly measured in the field or in situ (e.g., phosphorus). Grab sampling also does not require any equipment to remain in the field, where it would be susceptible to damage from the weather or vandalism. Portable pumps and tubing may be used to collect samples from locations that are difficult to access, such as the bottom of an underground sedimentation device or the center of a wet pond. The primary advantage of grab sampling is that setup costs are small. Nevertheless, flow measurement equipment must be installed because pollutant removal efficiency and effluent pollutant loads cannot be determined without discharge measurements. The disadvantages of grab sampling include (1) inconvenience and cost of sending a crew to the site to collect samples during a storm event and (2) lack of an ability to perform flow-weighted sampling.

Automatic sampling requires someone to set up the sample collection system, periodically retrieve the samples from the sampler, and transport the samples to a laboratory for analysis. The time spent in the field for automatic sampling after sampler installation is minimal because samples collected automatically from a storm event can be retrieved and the automatic sampler reset within a few minutes. Automatic samplers are commonly used for stormwater monitoring operations because of the ability to accurately sample nutrients and metals. As will be discussed later, however, the accuracy of automatic samplers rapidly decreases when sampling suspended solids larger than 88 μm. This inaccuracy can affect the particulate or total phosphorus concentration because suspended solids can adsorb a significant amount of phosphorus.

Choosing from in situ, on-site, grab, and automatic sampling will depend on budget constraints, personnel availability, and the goals of the assessment program. The three levels of assessment, listed in order of increasing complexity are visual inspection (level 1), capacity testing (level 2a), synthetic runoff testing (level 2b), and monitoring (level 3). Visual inspection is the only level of assessment that does not require sampling. Capacity testing for saturated hydraulic conductivity (K_s) determination often requires samples for soil moisture measurements at each location (see Chap. 11). Some stormwater treatment practices for which synthetic runoff testing is applicable may require sampling of the influent or effluent synthetic runoff, or both. In these cases, the sampling methods for synthetic runoff testing are the same as the sampling methods for monitoring, which are discussed in the rest of this chapter.

The following five key questions should be considered when incorporating sampling into an assessment program:

1. How many storm events should be sampled to make statistically accurate estimates of performance?
2. How many samples should be collected per storm event?
3. When multiple samples are collected per storm event, should they be collected based on discharge amount, elapsed time, or a user-defined basis?

4. When multiple samples are collected per storm event, should they be collected in individual bottles (discrete samples) or combined into a single bottle (composite samples)?
5. Should stormwater runoff be sampled in situ, on-site, manually (i.e., grab), or automatically?

The next several sections provide discussion and recommendations for each of the above criteria, all of which should be thoroughly considered before sampling is included in any assessment program.

10.1 Representative Samples

Regardless of the type of samples collected (in situ, on-site, grab, or automatic), it is imperative that representative samples are measured or collected. A representative sample is a sample in which the measured parameter (e.g., phosphorus) is the same in the sample as in source from which the sample was measured or collected. In many cases, samples are only representative for a very short period of time and a small, specific location.

To make conclusions in an assessment program, it may be necessary to make assumptions about the dynamics of a system and to what degree a collected sample is representative. When planning a sampling program to include representative samples, the following should be considered:

1. How will sample contamination be prevented?
2. Does the measured parameter (e.g., phosphorus) change significantly in time or space?
3. Do conditions other than the measured parameter (e.g., discharge) change significantly in time or space?
4. Is the system poorly mixed or very large, such that a sample in one location is not representative of the entire system?

In order to measure or collect representative samples, it may be necessary to use a specific (or more than one) sampling method. Several examples for choosing sampling methods to ensure representative samples include:

- Measuring dissolved oxygen with on-site, grab, or automatic sampling in some situations requires careful sample collection, storage, handling, and analysis to prevent contamination. It may be more cost-effective to measure dissolved oxygen in situ.
- Some systems change quickly and capturing representative samples in these systems may require measuring or collecting several samples in a short period of time. On-site and grab sampling may be limited by the capacity of the personnel measuring or collecting the samples; therefore, in situ or automatic sampling may ensure more (temporally) representative samples.
- Some systems vary or change drastically in space, and capturing representative samples in these systems may require measuring or collecting samples in several

locations. It may be cost-prohibitive to install in situ or automatic samplers in several locations; therefore, it may be more cost-effective to measure or collect on-site or grab samples to ensure more (spatially) representative samples.

- Some systems vary or change drastically in time and space. Capturing representative samples in these systems may require measuring or collecting samples repeatedly in several locations simultaneously. On-site and grab sampling may be limited by the capacity of the personnel measuring or collecting the samples; therefore, in situ or automatic sampling may ensure representative samples. It may, however, be cost-prohibitive to install in situ or automatic samplers in several locations. In these situations, the best solution may be to choose a different (often simpler) assessment method or study site.

10.2 Number of Storm Events

The most important sampling consideration in an assessment program is the number of storm events to be sampled. The number of storm events sampled and the variance in the results from those storm events will determine assessment uncertainty. Assessment uncertainty must to be minimized so that comparisons to other stormwater treatment practices, comparisons to past assessments, predictions of future performance for Total Maximum Daily Load (TMDL) calculations, and maintenance scheduling are accurate and reliable. For example, suppose the event mean concentration (EMC) for a specific pollutant during a storm was reduced from an influent value of 100 mg/L to an effluent value of 40 mg/L in a stormwater treatment practice. It cannot be assumed that the stormwater treatment practice reduces the EMC by 60% for all storm events. Several storm events, representing a range of conditions (i.e., flow rate and pollutant concentration), need to be sampled and analyzed before predictions of treatment practice performance can be made. The rest of this section describes a process that can be used to select an appropriate range of assessment uncertainty, and subsequently determine the number of storm events that should be sampled.

To simplify the statistical analysis related to determining the number of storm events that should be sampled, several assumptions can be made. One assumption is that the percent removal data are normally distributed about a mean value and that one storm event does not influence other storm events. Another assumption is that there is no storm event bias (systematic uncertainty) in percent removal. Finally, the number of storms required will likely be fewer than 30 and the actual variance in the data is unknown. From these assumptions, the Student (Gosset 1908) *t*-distribution is used. The Student (Gosset 1908) *t*-distribution is a probability distribution used to estimate the mean of a normally distributed population from a sample of the population and is more accurate for small ($n < 30$) sample sizes than the similar *z*-distribution. For more information on distributions, consult a statistics text (e.g., MacBerthouex and Brown 1996; Moore and McCabe 2003).

The 95% confidence interval is recommended to adequately represent uncertainty in average pollutant removal efficiency because it indicates that there is a

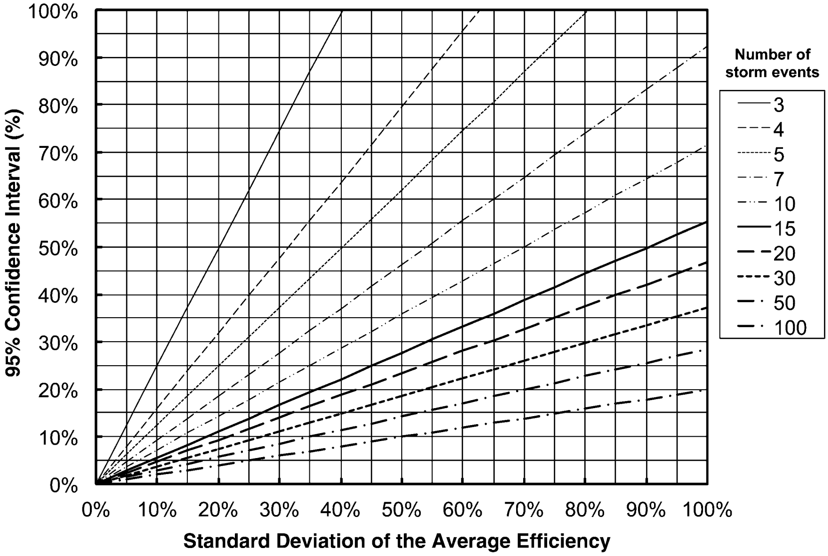

Fig. 10.1 Relationship between number of storm events and standard deviation for a 95% confidence interval

95% probability that the actual average performance will be within the confidence interval. For example, a stormwater treatment practice with an average pollutant capture rate of 72 ± 17% confidence interval ($\alpha = 0.05$) will have a 95% (19 out of 20) probability that the actual average pollutant capture rate is between 55 and 89%. The range of the confidence interval (in this case, ±17% for $\alpha = 0.05$) is dependent on the standard deviation and the number of monitored storm events. The relationship between standard deviation, number of storm events, and 95% confidence interval is shown in Fig. 10.1.

The process for determining the number of storm events can be performed in three steps, as illustrated in Example 10.1. This process should be performed during development of an assessment program to estimate the cost and effort associated with sampling multiple storm events based on the estimated uncertainty. As assessment results are gathered, this process should be performed again using actual assessment data to determine the actual uncertainty:

1. Compute the standard deviation of the percent removal values for storm events that have been sampled. If there are no storm event data, select a standard deviation; typical standard deviations for percent removal of stormwater treatment practices range from 20 to 40% (Weiss et al. 2005).
2. Select the desired range of the 95% confidence interval for the mean removal over all storms (10–15% is recommended).
3. Using the standard deviation (step 1) and the confidence interval (step 2), estimate the number of storm events required to achieve the desired range for the 95% confidence interval of the mean removal over all storms from Fig. 10.1.

Example 10.1: Determining the number of storm events required
Gina, an engineer in training (EIT) at a local consulting firm, is developing an assessment program that includes monitoring (level 3). She is tasked with determining how many storms will be required to attain 95% confidence that the average total suspended solids (TSSs) removal is within ±15%. From previous monitoring data, Gina finds that the stormwater treatment practice is expected to remove 72% (standard deviation = 27%) of TSS from any given storm. She then uses this information (standard deviation = 27%, 95% confidence interval = 15%) and Fig. 10.1 to determine that roughly 15 storm events are required, as shown in Fig. E10.1.

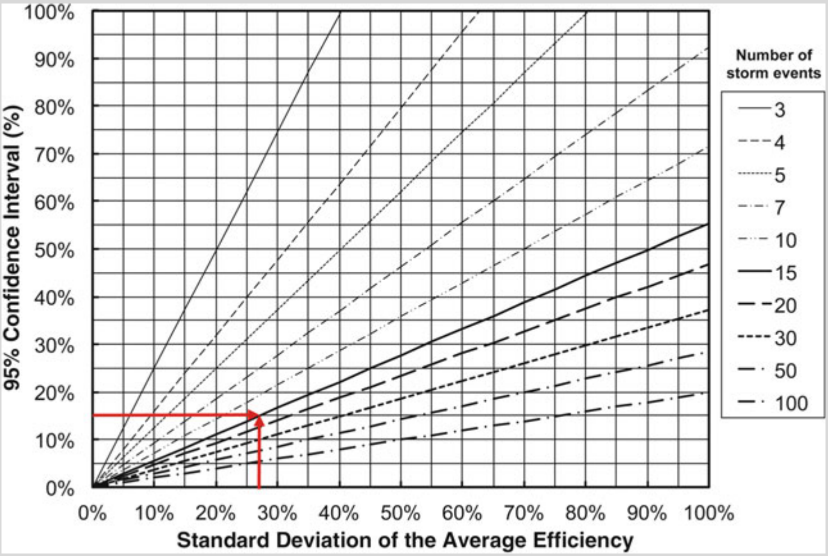

Fig. E10.1 Determining the number of storms required using Fig. 10.1

10.3 Samples Per Storm Events

The US EPA (2002) recommends that multiple samples be collected throughout a storm event to incorporate changes in concentration and discharge and therefore accurately represent the storm event. Choosing an appropriate number of samples per storm event will depend upon the basis on which the samples will be collected: discharge, time, or grab samples.

10.3.1 Flow-Weighted, Time-Weighted, and User-Defined Sampling

The frequency with which samples are typically collected can be defined by three approaches: (1) flow weighted, (2) time weighted, and (3) user defined. Any of these sampling approaches can be used to collect in situ, on-site, grab, or automatic samples. There are also two methods of sample storage: discrete and composite. Sample storage is not required for in situ samples and most in situ samples are time weighted. Samples are typically described by the method of collection and storage (e.g., flow-weighted discrete samples) but could be in situ, on-site, grab, automatic, or some combination thereof. The most common sampling programs are time-weighted in situ, flow-weighted discrete (automatic), flow-weighted composite (automatic), user-defined discrete (on-site), and user-defined discrete (grab). In all cases, influent and effluent discharge must be measured and recorded so that pollutant removal efficiency can be determined.

10.3.1.1 Flow-Weighted Sampling

Flow-weighted sampling involves collecting samples after a constant incremental volume of discharge (e.g., 5,000 gallons) passes the sampler. Each flow-weighted sample is assumed to represent the average pollutant concentration for the entire incremental volume of water to which it corresponds. If the pollutant concentration changes quickly, drastically, or both, the measured pollutant concentration may not represent the average pollutant concentration accurately for the incremental volume. Small incremental volumes may require collecting more samples than the automatic sampler can hold (typically 4–24 bottles, or 4–96 samples) or faster than grab samples can be collected, which could result in sampling only part of a storm event. The advantage of flow-weighted samples is that summation of loads and EMC calculations are simplified and presumed to be more accurate because the discharge volume is constant for each representative sample. The most common flow-weighted samples are discrete or composite samples that are collected automatically. The relationship between sampling accuracy and the number of samples collected is shown in Example 10.2.

Example 10.2: Error associated with number of samples

Gina, the EIT at a local consulting firm, has been contracted to assess the effectiveness of a dry pond that treats runoff from a Public Works facility. Preliminary monitoring determined the inflow and outflow hydrographs and pollutographs for total phosphorus (TP), as shown in Fig. E10.2. (1 cfs = 0.028 m^3/s)

(continued)

Example 10.2: (continued)

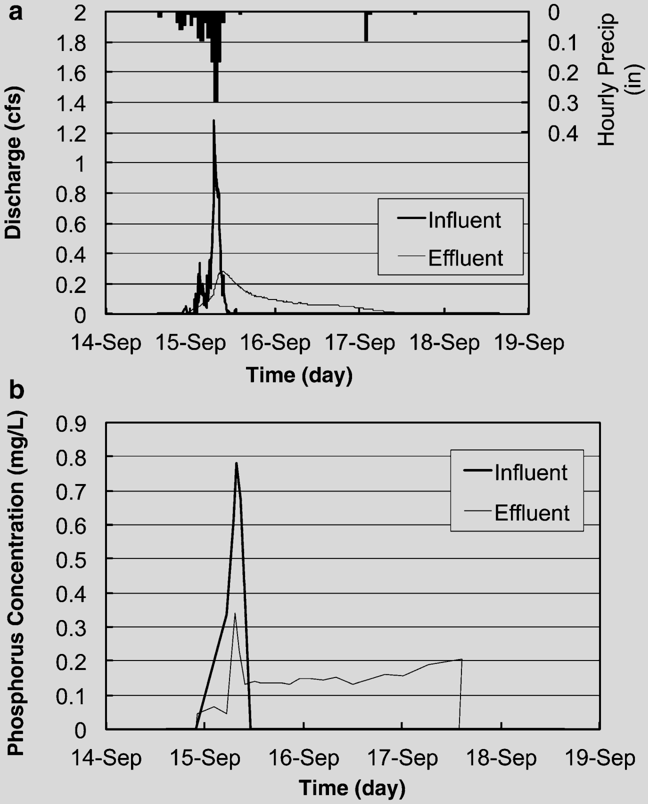

Fig. E10.2 Hydrograph (**a**) and pollutograph (**b**) for example storm event

Gina uses the hydrograph and pollutograph data to determine the error associated with the number of samples collected, assuming the sampled concentrations are correct. First she considers the effluent data, in which 23 individual samples were collected, and calculates the pollutant load, as shown in Table E10.1:

(continued)

Example 10.2: (continued)

Table E10.1 Storm event discharge, sample volume, pollutant concentration, and sum of pollutant mass (23 samples) (1 ft3 = 28.3 L)

Sample collected at (mm/dd hh:mm)	Discharge volume (ft3)	Incremental volume (L)	Concentration (mg/L)	Sum of mass load (g)
9/14 10:00 PM	0	0	0.047	0.0
9/15 2:22 AM	675	19,110	0.067	1.3
9/15 5:23 AM	1,566	25,233	0.045	2.4
9/15 7:16 AM	**2,573**	**28,506**	**0.342**	**12.2**
9/15 8:30 AM	3,710	32,197	0.232	19.6
9/15 9:39 AM	4,832	31,774	0.132	23.9
9/15 10:49 AM	5,934	31,226	0.136	28.1
9/15 12:04 PM	**6,976**	**29,481**	**0.141**	**32.3**
9/15 1:25 PM	7,965	28,006	0.137	36.1
9/15 2:54 PM	8,862	25,407	0.137	39.6
9/15 4:33 PM	9,749	25,128	0.138	43.1
9/15 6:28 PM	**10,631**	**24,973**	**0.138**	**46.5**
9/15 8:36 PM	11,505	24,754	0.131	49.7
9/15 11:03 PM	12,416	25,799	0.149	53.6
9/16 1:43 AM	13,293	24,813	0.149	57.3
9/16 4:46 AM	**14,167**	**24,757**	**0.146**	**60.9**
9/16 8:02 AM	15,018	24,102	0.151	64.5
9/16 11:49 AM	15,877	24,329	0.132	67.7
9/16 3:26 PM	16,682	22,792	0.144	71.0
9/16 7:40 PM	**17,527**	**23,931**	**0.162**	**74.9**
9/17 12:22 AM	18,267	20,948	0.156	78.2
9/17 6:23 AM	18,785	14,670	0.190	81.0
9/17 2:21 PM	**18,866**	**2,287**	**0.204**	**81.4**

Based on the calculations, the storm produced 18,866 ft^3 (534 m^3) of effluent discharge with 81.4 g (0.179 lb) of phosphorus load. The cost, however, to analyze 23 samples for each storm event could be expensive. Gina estimates the total load if there had been only six equally distributed samples collected during this same storm event in Table E10.2 (bold text from Table E10.1) (1 cubic foot = 28.3 L).

Table E10.2 Storm event discharge, sample volume, pollutant concentration, and sum of pollutant mass (six samples) (1 ft3 = 28.3 L)

Sample collected at (mm/dd hh:mm)	Discharge volume (ft3)	Incremental volume (L)	Concentration (mg/L)	Sum of mass load (g)
9/15 7:16 AM	2,573	72,849	0.342	24.9
9/15 12:04 PM	6,976	124,678	0.141	42.5
9/15 6:28 PM	10,631	103,514	0.138	56.8
9/16 4:46 AM	14,167	100,123	0.146	71.4
9/16 7:40 PM	17,527	95,154	0.162	86.9
9/17 2:21 PM	18,866	37,905	0.204	**94.6**

(continued)

Example 10.2: (continued)

Gina determines that if only six samples had been collected during the storm event, the pollutant load calculated using the same method above would be 94.6 g (0.209 lb), which is 16.2% more than the estimate resulting from 23 samples. If, however, the automatic sampler was programmed to collect 4 subsamples in each sample bottle, the same 23 bottles above would be collected in 6 composite samples and would result in a total phosphorus effluent load calculation of 78.7 g (3.3% error).

The number of samples collected depends on the influent discharge of each storm event and the incremental volume. Selecting the optimum volume increment depends on the size of the watershed, land cover, soil type, slopes, and expected rainfall intensity and discharge volume of the storm events. Due to the unpredictability of rainfall, the selection of a flow increment will always involve some uncertainty. An approach for selecting the incremental sampling volume is provided in Example 10.3.

Example 10.3: Determining the incremental volume for automatic sampling

Gina, the consulting EIT, realizes that storm event volumes will vary and therefore not every storm will produce exactly 24 samples. She therefore does an analysis of the variation of storm events to determine what incremental volume the samplers should be set at to capture the most storm events. Based on Gina uses the watershed area (A), runoff coefficient (C), and the previous season's rainfall (P), to estimate the inflow volume for each storm using $V = P \times C \times A$. The estimated inflow volumes for 12 storms are shown in Fig. E10.3.

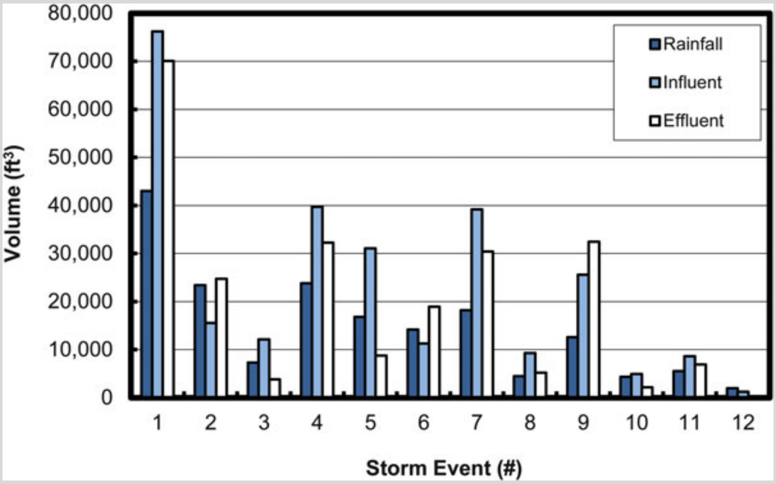

Fig. E10.3 Influent, rainfall, and effluent discharge volume for example storm event

(continued)

Example 10.3: (continued)

Based on the influent volumes, Gina calculates the relationship between incremental volume and number of samples for each storm event. She determines the number of samples by dividing the runoff volume by the incremental volume. She would like to capture as many storm events as possible, including the large storms, so the automatic samplers will be programmed to collect four small samples into each of the 24 sample bottles, allowing for 96 total samples.

Table E10.3 Number of samples required for each storm influent and effluent discharge volumes as a function of incremental volume (SE = Storm Event) (1 ft3 = 28.3 L)

		Incremental volume (ft^3)				
Influent	Volume (ft^3)	400	800	1,200	1,600	2,000
SE 1	76,182	>96	95	63	47	38
SE 2	15,586	38	19	12	9	7
SE 3	12,138	30	15	10	7	6
SE 4	39,752	>96	49	33	24	19
SE 5	31,075	77	38	25	19	15
SE 6	11,312	28	14	9	7	5
SE 7	39,181	>96	48	32	24	19
SE 8	9,280	23	11	7	5	4
SE 9	25,574	63	31	21	15	12
SE 10	4,980	12	6	4	3	2
SE 11	8,630	21	10	7	5	4
SE 12	1,247	3	1	1	None	None

		Incremental volume (ft^3)				
Effluent	Volume (ft^3)	500	750	1,000	1,250	1,500
SE 1	70,062	>96	93	70	56	46
SE 2	24,744	49	32	24	19	16
SE 3	3,837	7	5	3	3	2
SE 4	32,281	64	43	32	25	21
SE 5	8,796	17	11	8	7	5
SE 6	18,967	37	25	18	15	12
SE 7	30,420	60	40	30	24	20
SE 8	5,184	10	6	5	4	3
SE 9	32,470	64	43	32	25	21
SE 10	2,158	4	2	2	1	1
SE 11	6,926	13	9	6	5	4
SE 12	220	None	None	None	None	None

Gina determines that an inflow incremental volume between 800 and 1,200 ft^3 (22.65–33.98 m^3) would have allowed enough storage space to collect all samples from the largest storm and at least one sample from the smallest storm from the previous year. Similarly, an effluent incremental volume between 750 and 1,000 ft^3 (21.24–28.32 m^3) allows ample storage

(continued)

Example 10.3: (continued)
for the largest storm and several samples from the smallest storms, excluding the smallest storm from the previous year.

Gina realizes that this procedure should be revised and adjusted before each rainy season and sometimes during rainy seasons to ensure that the most storm events are sampled. To increase the accuracy of this procedure, rainfall data from more than one preceding year could be used to determine the appropriate incremental volume.

10.3.1.2 Time-Weighted Sampling

Time-weighted samples are collected at a user-specified, constant time interval (e.g., 30 min). Because the discharge of natural storm events is not constant, time-weighted samples do not represent constant volumes of flow with respect to time. Total discharge volume for each time interval must be calculated before calculation of summation of loads or event mean concentration (EMC). The time-weighted approach is common for in situ, on-site, and grab sampling.

The calculations for time-weighted samples can be more complicated than those for flow-weighted samples because each sample must be weighted by the corresponding discharge volume. In these cases, discharge volume for each time interval must be calculated by integrating the discharge vs. time curve.

Selection of the optimal time increment will depend on the duration of a "typical" storm event and the variation in storm event duration. It is also important to consider the amount of time required to collect in situ, on-site, and grab samples or the maximum number of samples the automatic sampler can collect, if applicable. Due to the unpredictability of rainfall events, however, the selection of a time increment will always involve some uncertainty.

10.3.1.3 User-Defined Sampling

User-defined samples are collected on a basis determined by the user which is commonly chosen based on the hydrology of the system being assessed. For example, some sampling programs may collect a specified number of grab samples during the rising and falling limbs of a storm event. The discharge and time increment between these samples will vary between samples and for each storm event. Similar to time-weighted sampling, total discharge volume for each interval between samples must be calculated before calculation of summation of loads or event mean concentration (EMC). User-defined sampling is most common for manually collected samples (i.e., on-site or grab samples).

10.3.2 Discrete and Composite Samples

Once it is determined how samples will be collected (flow-weighted, time-weighted, or user-defined), the next step is to determine whether to collect discrete (i.e., separate) samples or a composite sample(s). Discrete samples are collected in individual containers and the contents of each container are analyzed separately. Composite samples are collected in a single container and analyzed as a single sample representative of the entire sampling period.

Discrete samples can be collected manually for on-site or grab sample analysis, or with automatic samplers equipped with multiple sample containers. Most often, discrete sampling is only necessary when a record of temporal variation in pollutant concentration throughout a storm event (e.g., minimum, maximum) is desired. The main disadvantage of discrete sampling is that multiple samples must be analyzed for pollutant concentration for each storm event, which can increase the costs of an assessment program significantly.

Composite sampling combines all collected samples into one large storage container and should only be used in conjunction with flow-weighted sampling. Time-weighted composite samples cannot be used to determine pollutant loads or event mean concentration (EMC) because each time-weighted subsample does not represent equivalent volumes of discharge. Thus, if time-weighted sampling is used, samples should not be stored as composite samples.

Discrete and composite sampling can be used with on-site, grab, or automatic samples, but most automatic sampling equipment is designed specifically for one method or the other. Thus, in order to ensure compatibility between an assessment program and sampling equipment, the goals and details of the assessment program should be developed before purchasing sampling equipment.

It is important to note that flow-weighted samples can be collected either as discrete or composite samples because the volume increment is the same for each sample. Each sample added to a composite sample represents the same volume increment of stormwater and is therefore equally representative. Therefore, chemical analysis is considerably cheaper for flow-weighted composite samples compared to flow-weighted discrete samples, but only the event mean concentration (EMC) can be determined. If discrete samples are collected, the EMC and the concentration as a function of time over the runoff event can be determined.

Time-weighted samples, however, can only be collected as discrete samples because each sample represents a different volume of stormwater. It may be important to consider the parameters used by stormwater models (e.g., XP SWMM, and WinSLAMM, among others) when developing a sampling program because some models input sampling parameters (such as discrete samples) directly. Unless the goal is to measure pollutant removal performance as it changes with time throughout the runoff event, flow-weighted, composite sampling is recommended because of the cost savings of analyzing only one sample per storm event.

10.4 In Situ, On-Site, and Grab, and Automatic Sampling

Some pollutants can be measured in situ, on-site, or by analysis of grab or automatic samples. In situ, on-site, and grab sampling for assessment of stormwater treatment practices are cost-effective for some parameters that may be of interest. For example, capacity testing (level 2a) of a stormwater treatment practice for saturated hydraulic conductivity (K_s) requires measurement of soil moisture content. Soil moisture can be measured either by using a field soil moisture probe (in situ sampling) or by collecting a soil sample and analyzing it in the laboratory (grab sampling). Another example includes synthetic runoff testing of a wet pond for hydraulic performance using a conservative tracer. Rather than using grab or automatic sampling, a conductivity probe could be used in situ to measure salinity when sodium chloride (NaCl) is used as the conservative tracer. In this case, in situ sampling is simpler and cheaper than grab or automatic sampling, and therefore recommended.

In situ and on-site sampling for stormwater assessment are often limited by the availability of probes for many pollutants of concern. In addition, in situ probes may become fouled when they are not maintained as recommended by the manufacturer's instructions, which can produce erroneous measurements. It is also important to recognize may affect changes that occur over time in the stormwater treatment practice system, such as sediment collection in an inlet pipe or structure, that may affect in situ measurements. Some in situ probes such as pressure transducers or dissolved oxygen probes may require recalibration as conditions change. The following sections describe in situ, on-site, grab, and automatic sampling techniques as they apply to various stormwater pollutants.

10.4.1 Temperature

The temperature of stormwater runoff may be of interest depending on assessment goals and downstream conditions (e.g., temperature-sensitive trout streams). Unlike most water quality parameters such as phosphorus and suspended solids, temperature can be easily measured with in situ or on-site techniques. One method is to collect a stormwater sample and measure the temperature on-site with a thermometer immediately after the sample is collected. Another method is to use a probe or sensor in situ to collect near-continuous temperature data with a data storage device. There are two types of data storage devices that are used for in situ temperature measurement: devices that are integrated with temperature probes and devices that are externally attached to them (often called data loggers). Temperature must be measured either in situ or on-site because water temperature can change during transportation or storage.

For near-continuous in situ sampling using a data storage device, the probe or thermocouple must be submerged during a runoff event. The device will continually measure and record temperature at a user-specified time interval until the data storage capacity is exhausted. Most devices can be set such that the oldest data are overwritten with new data when storage capacity is exceeded. For data storage devices that are integrated with the probe, data are usually downloaded directly to a computer through a data transfer cable or infrared connection. For data storage devices connected to an external thermocouple, data are typically accessible via modem, cellular connection, or direct download (via serial cable) from the data storage device.

Some advantages of integrated and external data storage devices include:

Integrated data storage device advantages include
- Less expensive than data logger and thermocouple
- Data can be downloaded using infrared wireless connection
- Does not require protective cabinet to store data storage equipment

External data storage device advantages include
- Less expensive if a data logger is already in use
- Temporally synchronized with other measurements stored in the data logger (e.g., discharge, rainfall)
- Typically more storage capacity than an integrated device
- Thermocouples respond more quickly to temperature changes
- Data retrieval does not require disturbance of the thermocouple
- Data can be downloaded via modem or cellular connection

The US EPA (2002) notes that some pressure transducers have built-in thermometers so that water depth values can be corrected for temperature. Probes are available for different temperature ranges, depths, and prices.

Prior to monitoring, the temperature probes should be calibrated against a NIST (National Institute of Standards and Technology) traceable thermometer or against 0 °C (32 °F) temperature by placing the probe in a mix of ice and water. Probes should be placed in shaded areas of the sewer pipes or channels whenever possible, to avoid solar heating of the probe. It is recommended the probe be placed inside a PVC pipe anchored to the sewer to protect it from debris, as shown in Fig. 10.2.

To measure the water temperature in a stream or creek, the probe should be installed at least a few inches above the streambed and attached to stakes that are inserted securely into the streambed. The probe should not be installed directly on, or buried in, the sediment bed, because the sediment is often a different temperature than the stream water due to groundwater inputs. Most streams are well-mixed water bodies, and the temperature near or above the sediment surface is representative of the entire water column temperature. For shallow streams (less than 8 in. deep), the temperature probe should be installed in a shaded area of the stream channel to avoid direct solar radiation affecting the temperature measurement of the probe.

A measured difference in stream temperature between upstream and downstream locations may be due to atmospheric heating or surface inflow, not necessarily due to stormwater inflows. During hot summer days, solar radiation can heat the stream such that the water temperature at the downstream location becomes warmer than at the upstream location. The temperature difference varies diurnally and depends upon the solar radiation received, the distance between the upstream and downstream measurement locations, stream discharge, and stream geometry. During storm events and for several hours after, inflow of surface runoff directly into the stream may have a significant impact on the temperature difference between two locations. The thermal impact of surface inflow may be identified as transient change in the temperature difference (see Fig. 10.3).

Fig. 10.2 Installation of a temperature probe in a sewer pipe

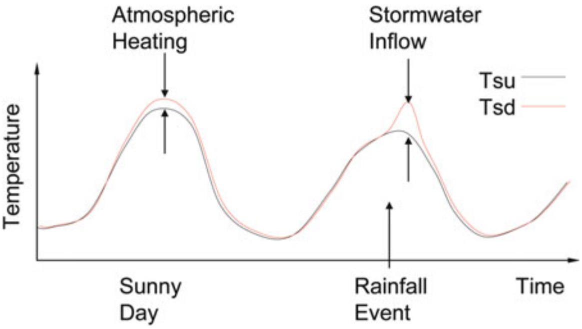

Fig. 10.3 Typical characteristics of stream temperature impacts due to atmospheric heating and stormwater inflows

10.4.2 pH or Hydrogen Ions

The acidity or basicity of water is indicated by pH, which is a function of the molar concentration of hydrogen ions in solution ($[H^+]$), $pH = -\log_{10} [H^+]$. Thus, for a water of pH 8, the hydrogen ion concentration is 10^{-8} moles/L. Acidic waters have relatively large hydrogen ion concentrations and therefore small pH values (< 7). Alkaline waters have relatively small hydrogen ion concentrations and large pH values (> 7) and neutral waters have pH values of approximately 7. USA federal and state regulations suggest that pH values remain between approximately 6.5 and 8.5 to ensure the quality of water for recreational use, aquatic life, and drinking water (MPCA 2003; US EPA 2004).

In situ or on-site sampling should be used to measure pH values. Grab samples for pH with subsequent analysis in a laboratory are permissible if the samples are transported on ice and analyzed within 2 h of collection; automatic sampling for pH measurement is not recommended. Probes should be calibrated weekly, after every 25 samples (US EPA 1997), or as recommended by the manufacturer to ensure accurate and consistent results.

10.4.3 Conductivity

Conductivity is an indirect measure of the ion concentration in water and is often measured with a probe or meter using in situ or on-site sampling techniques. Conductivity is often used as a surrogate for total dissolved solids (TDS) or salinity. Large concentrations of TDS can be toxic to aquatic life and can reduce habitat.

Conductivity is most often measured in situ or on-site but can also be measured using grab or automatic sampling techniques. Most "bundled" probes (multiple probes in one device) include a conductivity probe for in situ sampling. Grab or automatic samples transported to an analytical lab for conductivity measurements must be analyzed within 28 days of collection and should be kept on ice or refrigerated.

10.4.4 Turbidity

Turbidity is a measure of water clarity and can be measured in situ with a turbidity meter. Large turbidity values can block sunlight required for photosynthesis by aquatic vegetation and subsequently reduce aquatic life and diversity. Turbidity can be used as a surrogate for suspended solids concentration but requires calibration at each location and for different seasons to ensure accuracy (Stefan et al. 1983). Refer to the turbidity section in Standard Methods (e.g., APHA 1998b) for details about correlating turbidity and suspended solids.

Turbidity is most often measured in situ or on-site, but samples collected manually (i.e., grab) or by automatic samplers can also be transported to an analytical lab for analysis. Some "bundled" probes include a turbidity meter. Grab or automatic samples transported to an analytical lab for turbidity measurements must be analyzed within 24 h of collection and should be kept in the dark and on ice or refrigerated.

10.4.5 Dissolved Oxygen

Dissolved oxygen (DO) is the amount of oxygen dissolved in water. DO is necessary for the survival of aerobic aquatic organisms such as fish and invertebrates. Minimum dissolved oxygen concentrations for surface waters typically range from 5 to 7 mg/L depending on the use, class, and temperature of the water body, though values are rarely less than 5 mg/L (MPCA 2003; WDNR 2004; MDEQ 2006).

DO should be measured using in situ or on-site sampling techniques. Grab and automatic sampling for DO measurement is not recommended because DO concentrations can change during transport or storage. For on-site sampling, DO should be measured immediately after sample collection. Most DO probes require weekly cleaning and recalibration to ensure accuracy. Luminescent DO measurement techniques are available, but their accuracy and stability have not been thoroughly field tested.

10.4.6 Nutrients

Nutrients (e.g., phosphorus and nitrogen) support aquatic vegetation and organisms. Excess nutrients, however, can cause nuisance algae blooms that generate negative aesthetic and eutrophic conditions in receiving lakes and rivers (US EPA 1999a). In temperate fresh waters, dissolved phosphorus is typically the limiting nutrient (Schindler 1977; Aldridge and Ganf 2003).

Until recently, it was necessary to collect water samples by automatic or grab sampling techniques for subsequent analysis in a laboratory to determine nutrient levels. In situ probes, however, are now available for nitrate, ammonia, and phosphate. Nevertheless, the accuracy and stability of these probes have not been thoroughly demonstrated in the field.

10.5 Additional Considerations for Automatic Sampling

10.5.1 Automatic Sampling Equipment

Stormwater sampling equipment is designed to collect samples either manually when triggered by the user or automatically when predefined criteria are met, with the aid of data loggers and computer software. Available equipment is summarized herein and discussed in greater detail in “Urban Stormwater BMP Performance Monitoring” (US EPA 2002). Grab sampling equipment is also discussed in Stenstrom and Strecker (1993).

Automatic samplers, which collect and store water samples until they can be retrieved, are recommended for sampling suspended solids, phosphorus, nitrogen, salts, metals, and other pollutants that do not change or degrade rapidly. For pollutants that may undergo rapid transformation, such as temperature, fecal coliforms, and organic chemicals, it may not be possible to retrieve and analyze the samples before transformation compromises the sample integrity. For such pollutants, in situ or on-site measurement, grab samples, or rapid retrieval of automatically collected samples followed by prompt analysis are recommended to ensure accurate representation of the pollutant concentration. Alternatively, sample refrigeration or chemical preservatives can be used to reduce the rate at which pollutant transformation occurs. Consult an analytical methods manual (e.g., APHA 1998b) to determine if refrigeration or preservatives will reduce transformation of pollutants and whether addition of preservatives will interfere with analysis of other pollutants of concern.

Automatic samplers do not require anyone to be present for sample collection; they can be programmed to begin sampling when a user-specified rainfall amount or intensity occurs (electronic rain gauge required), after a predefined depth or quantity of flow occurs, or after some combination of conditions is met. They can also be programmed to collect varying sample sizes, collect samples at user-specified time intervals (i.e., time-weighted) or flow volume increments (i.e., flow-weighted), or collect samples over an entire runoff event that lasts 2 days or more.

Some automatic samplers are powered from an external 120-V AC power source. Many locations, however, do not have an external power source and therefore most monitoring applications use automatic samplers that are powered by one or more deep-cycle, 12-V battery. Solar panels are also available to recharge the batteries, provided that adequate sunlight is available and the solar panel is free from obstructions (e.g., snow and leaves, among others). Another option is to use an additional battery as backup to the power supply.

Automatic samplers are available to collect discrete samples or composite samples. The sampling portion of an assessment program should be planned before sampling equipment is purchased to ensure the appropriate equipment is available and does not exceed the budget of the program. Automatic samplers with refrigerated sample storage compartments can be used to preserve the integrity of samples that degrade. For example, sample storage for dissolved phosphorus determination recommends refrigeration to reduce the transformation of dissolved phosphorus to particulate phosphorus, or vice versa (APHA 1998a). Refrigeration units, however, require an AC power supply.

While samples must always be manually retrieved from the storage unit for analysis, some samplers and data loggers have modem or cellular connections that allow measurement data such as flow rate, water depth, and rainfall intensity to be retrieved without physically visiting the sampling location. Some systems also allow users to remotely determine whether samples have been collected.

10.5.2 Equipment Placement and Maintenance

Placement of sampling equipment is site specific and depends on a number of factors, including equipment type, amount of equipment, availability of protective cabinets, and type and design of stormwater treatment practice. As described in Chap. 9, influent (or effluent) flow measurement and sampling is simplified if all

Fig. 10.4 Pressure probe for flow measurement and sampling tube for pneumatic sample collection placed at a weir to measure stormwater inflow

stormwater inflow (or outflow) is routed to a single location. Placing sampling equipment near flow measurement equipment is advantageous because sampling is typically triggered by flow measurement equipment and all instrumentation can be housed in the same enclosure. An example of flow measurement and sampling equipment in the same location is shown in Fig. 10.4, and a protective cabinet housing automatic sampling equipment is shown in Fig. 10.5.

Automatic sampling equipment that remains in the field for long periods of time should be maintained at weekly intervals. Sampling equipment maintenance will vary, but manufacturer's recommendations are typically provided and should be followed. Additional sampling bottles are available for purchase, and it is recommended to have at least two sets of sample bottles (one for the sampler and one for transporting samples to the analytical lab). More sets of sample bottles may be required, depending on the frequency of storm events and the processing time of the analytical lab.

It is important to recognize that some pollutants adsorb to the surface of collection bottles (organic compounds), degrade over time (coliforms), or may volatilize (dissolved gases). These confounding processes can be minimized by choosing sample bottle material properly (e.g., plastic or glass) and cleaning sample bottles appropriately. Consult Standard Methods (e.g., APHA 1998b) or the analytical lab performing the water quality analysis to determine whether the pollutants of interest for the assessment program will adsorb or degrade and which bottle material or preservation technique is recommended. If analyte degradation is a

Fig. 10.5 Protective cabinet housing automatic sampling equipment

concern, then sample preservation (e.g., refrigeration), collection followed by rapid analysis, or both may be necessary.

Care and cleaning of sampling equipment and bottles will prolong proper functionality and reduce analytical error. Sample bottles should be cleaned according to Standard Methods (e.g., APHA 1998b). Depending on the pollutant, special procedures may be required to prepare the bottles for sampling. For example, sample bottles for metals or phosphorus should be acid washed, and sample bottles for coliforms should be sterilized (e.g., autoclaved). Refer to the analytical procedure for pollutants of interest, Chap. 11, or the analytical lab that will process the samples for more information.

10.5.3 Winter Sampling in Cold Climates

Stormwater treatment practices may function differently during the winter than during the summer. For example, a layer of ice in a wet pond can reduce the effective volume of the pond and cause short-circuiting, which will reduce hydraulic residence times and lower sediment removal rates. Some of the largest concentrations of pollutants in stormwater are found in late winter/early spring runoff (i.e., snowmelt). Unfortunately, winter runoff and snowmelt events are not commonly monitored, most likely due to the inherent challenges imposed by the weather.

One winter challenge that must be overcome is the formation of ice in and around sampling lines and bubbler lines that are used for water depth measurement at weirs (see Sect. 9.2 in Chap. 9). Ice formation in sampling lines can prevent samples from being collected. Ice formation over bubbler tubes will result in erroneously large pressure readings and inaccurate depth measurements. In addition, if an automatic sampler is installed to collect samples when the water depth exceeds a certain value, then a false pressure reading could trigger a sampling sequence when insufficient water depth is available. Because of this possibility, a pressure transducer is recommended to measure water depth. Caution must be exercised, however, because the flexible diaphragm inside a pressure transducer can be damaged by ice formation. In one monitoring attempt in Minnesota, USA, the bubble tube developed ice over the discharge end, which prevented air from being pushed out of the tube. Although the resistance to air flow and large pressure that developed was due to the ice, the monitoring equipment registered an inaccurately large value of water depth and attempted to collect water samples when no water was present.

It is possible to maintain a charge on the batteries used to power the sampling and flow monitoring equipment during winter months with solar panels (Hussain et al. 2006). Solar panels should be faced toward the south and angled steeply (near vertical) to capture the most sunlight and to remain free of snow accumulation. Because of the potential problems of winter sampling, grab sampling is advised in conjunction with automatic sampling to ensure that appropriate samples are collected.

10.5.4 Automatic Sampling of Water Containing Suspended Solids

The accuracy of automatic sampling of water that contains suspended solids has been documented (Reed 1981), and research conducted at the University of Minnesota's St. Anthony Falls Laboratory to investigate the limits of sampling suspended solids and particulates and to improve sampling methods for automatic samplers has shown that large errors can exist when using automatic samplers to collect water for analysis of suspended solids.

Research conducted on an ISCO 3700 automatic sampler at the St. Anthony Falls Laboratory has shown that samples collected by automatic samplers may not accurately represent the suspended solids concentration in stormwater runoff (Gettel et al. 2011). A sediment feeder was installed at the upstream end of an 18-in. (45.7-cm) diameter pipe and sediment and water were fed into the pipe. Suspended solids were sampled 34.8 ft (10.6 m) downstream of the feed point. Discharge through the pipe was measured using a V-notch weir downstream of the pipe. The tests were conducted using five sediment size distributions.

1. Silts and clays with a median diameter of 25 μm and a maximum diameter of 88 μm
2. Silts of size 44–88 μm
3. Sands with size range of 125–180 μm
4. Sands with size range of 180–250 μm
5. Sands with size range of 250–355 μm

Table 10.2 Experimental results for sampled and feed suspended sediment concentration for conventional sampling methods when sampling intake without strainer (tube only) was mounted at the bottom of pipe and facing upstream or downstream of the flow

Particle size (μm)	Water discharge (cms)	Water surface slope (%)	Mean feed conc. (mg/L)	Mean sampled conc. (mg/L)[a]	Mean relative conc. (%)[b]	95% Confidence interval (± around mean %)
Sampling tube only facing downstream						
Silt ($D_{50} = 20$ μm)	0.095	0.90%	199.5	253.4 (8)	126.9%	12.7%
44–88	0.095	1.55%	122.8	187.2 (21)	148.6%	7.8%
125–180	0.092	N/A	210.1	1049.9 (13)	499.7%	59.4%
180–250	0.091	0.65%	220.4	1396.1 (14)	1396.0%	142.4%
250–355	0.092	0.65%	201.6	2420.9 (7)	1200.8%	107.7%
Sampling tube only facing upstream						
Silt ($D_{50} = 20$ μm)	0.089	1.00%	143.1	154.9 (19)	106.4%	3.6%
44–88	0.089	1.55%	221.5	524.0 (16)	246.9%	5.3%
125–180	0.084	N/A	247.6	2093.5 (21)	1011.1%	11.5%
180–250	0.092	0.65%	135.1	5405.6 (21)	2907.0%	10.3%
250–355	0.088	0.45%	218.5	14826.8 (20)	6583.5%	7.3%

Depth of flow was set at 0.23 m (Gettel et al. 2011)

[a] The value in parentheses indicates the number of samples per test

[b] Relative concentration is based on the sample-weighted average concentration

Four automatic intake configurations were tested:

1. Sampling tube oriented parallel to the flow and facing upstream
2. Sampling tube oriented parallel to the flow and facing downstream
3. A commercially available intake manifold attached to the end of the sampling tube and to the bottom of the pipe
4. A commercially available intake manifold attached to the end of a sampling tube and only the tube attached to the side of the pipe so that the manifold was able to move freely in the flow

The results given in Tables 10.2 and 10.3 show that the automatic sampler overestimated the concentration of the suspended sediment by up to 6,600% for large particle sizes. Silts and clays are typically sampled more accurately. The configuration in which the manifold was allowed to move freely in the flow yielded the most accurate results. For TSS concentration, if the size distribution is not too large, automatic sampling with the manifold free to move laterally will collect samples with concentrations within 25% of the actual concentration. The sampling of large sand particles in this configuration, however, resulted in errors of approximately 200%. This indicates that size distributions will be skewed toward larger sizes by the use of an automatic sampler.

Table 10.3 Experimental results for sampled and feed suspended sediment concentration for conventional sampling methods when the sampling intake with strainer position is fixed or flexible

Particle size (μm)	Water discharge (cms)	Water surface slope (%)	Mean feed conc. (mg/L)	Mean sampled conc. (mg/L)[a]	Mean relative conc. (%)[b]	95% Confidence interval (± around mean %)
Sampling intake strainer in fixed position						
Silt ($D_{50} = 20$ μm)	0.095	0.84%	140.4	143.9 (13)	101.0%	9.0%
44–88	0.089	0.90%	107.8	137.1 (21)	127.2%	5.0%
125–180	0.089	0.84%	211.2	541.0 (20)	258.7%	5.6%
180–250	0.089	0.77%	225.6	543.0 (19)	303.0%	11.9%
250–355	0.089	0.77%	216.9	338.4 (23)	169.3%	8.6%
Sampling intake strainer in flexible position						
Silt ($D_{50} = 20$ μm)	0.089	0.71%	142.5	142.7 (12)	100.1%	4.0%
44–88	0.090	1.48%	113.6	124.2 (20)	109.3%	2.7%
125–180	0.088	1.42%	219.8	438.6 (9)	199.6%	18.5%
180–250	0.087	1.36%	230.2	471.4 (14)	204.8%	18.8%
250–355	0.089	1.42%	211.7	277.5 (14)	131.0%	22.6%

Depth of flow was set at 0.23 m (Gettel et al. 2011)

[a] The value in parentheses indicates the number of samples per test

[b] Relative concentration is based on the sample-weighted average concentration

Solids suspension is a function of flow characteristics and particle size, density, and shape. Sampling suspended solids concentration is strongly influenced by the location of the intake within the depth of the flow. For a typical stormwater conduit, concentrations larger than the mean concentration are found at lower relative depths for most particle sizes (> 10 μm). Intakes of automatic samplers are typically placed at the base of conduits, which can result in suspended solids concentrations containing larger particles being overestimated.

As depicted by the dotted line in Fig. 10.6, if a sampler intake is located at 10% of the total depth ($y/d = 0.1$), the resulting sampled concentration for 250-μm sand particles will be approximately 2.1 times the mean concentration for the given flow condition. Similarly, at that same relative depth and flow condition, 100-μm fine sand/silt and 11-μm clay particles are sampled at approximate concentrations of 1.3 and 1.0 times the mean concentration, respectively. For this conduit, only clay particles can be sampled accurately. Suggestions have been made to place the sampler intakes at a depth above the bed, but in this configuration the automatic sampler is unable to collect samples below the intake depth.

Developed from equations given in Rouse (1937), Fig. 10.7 represents a limiting particle size for a measured flow condition to ensure a sample concentration within 20% of the mean. Figure 10.7 assumes that the flow is fully developed, i.e., does not

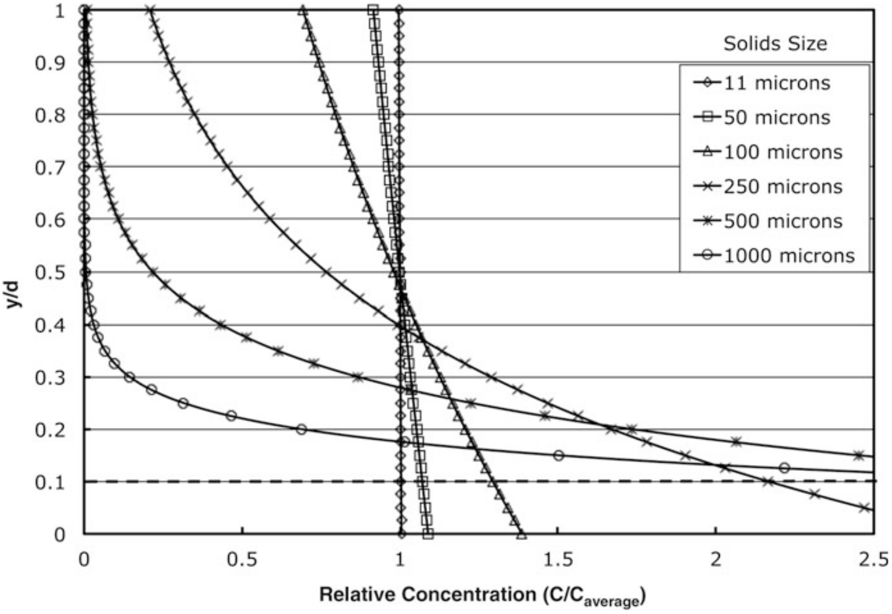

Fig. 10.6 Suspended solids concentration in a given flow condition (slope = 0.02) as a function of depth (Rouse 1937) where C = actual concentration, C_{average} = mean concentration, y = distance up from the bed, and d = depth of flow. Uniform flow in a wide open channel with particle density of sand is assumed

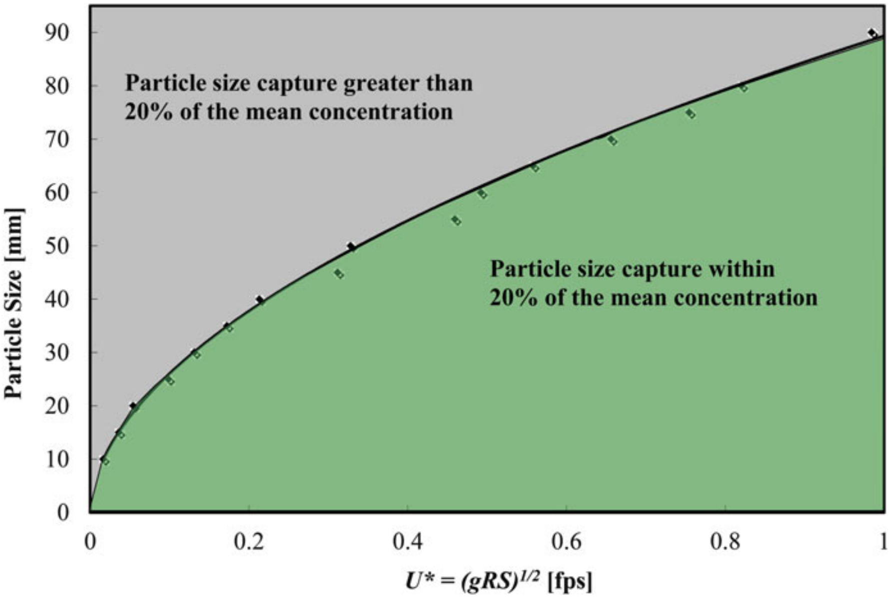

Fig. 10.7 Particle size capture (density of sand) is considered within 20% of the mean concentration under a measured flow condition typical of stormwater culverts. U^* = shear velocity (the square root of wall shear divided by liquid density), g = gravitational acceleration, R = hydraulic radius (A/P, where A = cross-sectional area and P = wetted perimeter), and S = water surface slope, assumed equal to the culvert slope

depend upon upstream entrance conditions. When sampling solids concentrations with automatic samplers, the sample is within 20% of the mean when the maximum particle size is at or below the limiting line depicted in Fig. 10.7.

Example 10.4: Accuracy of automatic sampling of water containing suspended solids

Gina, the consulting EIT, wants to determine the solid size of sand density particles that will be captured within 20% of the mean concentration of that particle size in an 18-in. (46 cm) inside diameter culvert is oriented at a 2% slope and with 6 in. (15 cm) of water depth. To use Fig. 10.7, Gina needs to calculate the shear velocity of the flow, which is the shear stress on the culvert wall divided by the density of stormwater. The hydraulic radius is also needed for the calculation, but Gina can find it in books on fluid mechanics. In this case, Gina determines that $R = 0.31$ ft (9.4 cm). Then she can determine the shear velocity using (E10.1):

$$U^* = \sqrt{gRS} = \sqrt{32.2\frac{\text{ft}}{\text{s}^2} \times 0.31\ \text{ft} \times 0.02\frac{\text{ft}}{\text{ft}}} = 0.45\frac{\text{ft}}{\text{s}} \qquad \text{(E10.1)}$$

where

U^* = shear velocity (ft/s)
g = gravitational acceleration (ft/s^2)
R = hydraulic radius
$R = A/P_w$ (ft)
S = energy grade line slope, assumed to be equal to pipe slope (ft/ft)

Now Gina can use Fig. 10.7 to determine that particles less than or equal to 60 μm in equivalent diameter (i.e., silts and clays) will be measured within 20% of their true mean concentration. From Fig. 10.7, Gina knows that sand-like particles greater than 60 μm, such as fine sand and larger, will not be measured within 20% because of their vertical distribution in the flowing stormwater.

A second challenge is the velocity with which the sample is drawn. Automatic samplers are equipped with pumps to draw samples, which create velocities different from localized streamflow velocities at the intake. When the intake velocity is equal to the streamline velocity (i.e., localized streamflow velocity), the sampled suspended solids concentration equals the mean suspended solids concentration. This is referred to as isokinetic sampling. With varying flow velocities and fixed intake velocities, automatic samplers rarely sample isokinetically.

Research on non-isokinetic samplers (FISP 1941) found significant errors for particle sizes greater than 60 μm silt. Errors associated with non-isokinetic

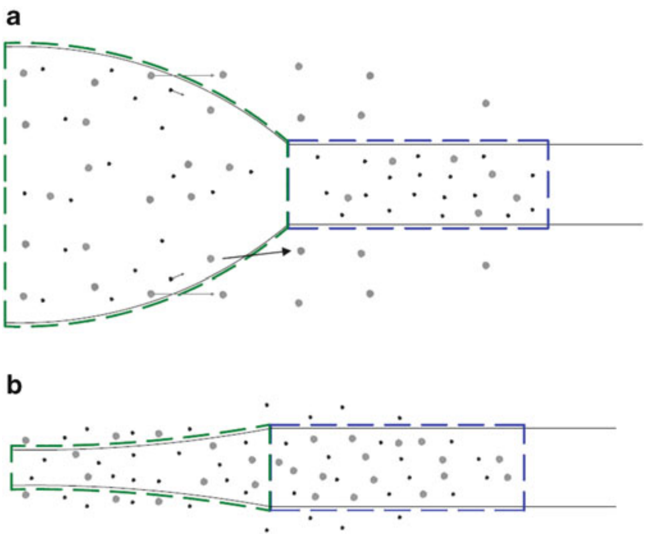

Fig. 10.8 Examples of non-isokinetic sampling (*arrows* indicate larger particles crossing streamlines). (**a**) The intake velocity is greater than the flow velocity; (**b**) the intake velocity is less than the flow velocity

sampling are due to inertial effects of the particles. The larger particles have a significant mass, which corresponds to inertial forces that can result in particles not following curved flow streamlines coming into a non-isokinetic sampling port. Dividing flow streamlines are indicated in Fig. 10.8a, b as illustrations of non-isokinetic sampling. Figure 10.8a is an example of when the intake velocity is greater than the flow velocity. Figure 10.8b is an example of when the intake velocity is less than the flow velocity. The green dashed line is an initial capture control volume upstream of the intake, and the blue dashed line is the corresponding capture control volume of the intake. Both figures contain two particle sizes, one significantly larger than the other. The small particles have minimal inertial forces and have less of a tendency to cross streamlines. The larger particles have enough inertia to move in a horizontal direction and can cross the streamlines. For the case in Fig. 10.8a, a portion of the larger particles leaves the flow streamlines and is not captured by the intake, resulting in a measured concentration smaller than the true mean. When the flow velocity is greater than the intake velocity, as in Fig. 10.8b, the larger particles cross into the streamlines, resulting in a larger measured concentration than the true mean.

For most stormwater conditions, the sampling of fine sand and sand will not be sufficiently accurate. This does create additional challenges in sampling chemicals that are attached to particles, such as particulate phosphorus and many metals and organic chemicals. Currently, the only means of ensuring accurate solids sampling is to capture all of the solids over a known length of time and discharge (Sansalone et al. 1998). Then, suspended solids concentration may be computed from (10.1), noting that each side of the equation must have equivalent units:

$$C = M \times \frac{t}{Q} \tag{10.1}$$

where

C = solids concentration (mg/L)
M = mass of solids collected (mg)
t = time of collection (s)
Q = stormwater discharge (L)

Designing sedimentation practices from inaccurate sampling of suspended solids can lead to practices that are significantly larger than required and therefore more expensive to construct and maintain.

10.6 Sample Handling

Proper sample handing is essential for representative samples. Some constituents undergo rapid reaction, such as degradation (e.g., BOD), degassing (e.g., oxygen), adsorption to the walls of bottles (many metals and organics), and coagulation (e.g., fine suspended sediment). Without proper handling, sample contamination can occur and result in inaccurate results for some analyses, most notably phosphorus and some metals. It is also important that sample handing procedures are documented and that personnel collecting samples are properly trained.

Prior to sampling, sample bottles, filtration apparatuses, filters, and other equipment must be cleaned properly. Bottles used for collection and storage of samples containing nutrient or metals often need to be cleaned with special detergents and acid rinses. Details are provided in Standard Methods (APHA 1998b).

Some analyses require that samples undergo some process prior or during storage, such as filtration and preservation. An extensive list of sample handing requirements is presented in Table 1060.1 in Standard Methods (APHA 1998b). For example, samples to be analyzed for dissolved constituents should be filtered within a few hours of collection.

Some dissolved gases (e.g., dissolved oxygen and total dissolved gas) are readily measured in situ, using field instruments. If laboratory analysis is necessary, samples must be analyzed within a few minutes or collected in sample bottles that are filled completely with water (i.e., no gas bubbles) and sealed tightly to avoid contamination by gas exchange.

Many types of samples require preservation, such as refrigeration, acidification, or reaction to form stable samples for storage. Even with preservation, acceptable holding times vary from a few hours to a few months. Analysis requirements for storage containers, cleaning, filtration, and preservation vary significantly;

therefore, it is possible for several samples to be collected at one time, or for samples to be split into many subsamples, for each type of analysis.

10.7 Recommendations for Water Sampling Methods

Sampling methods will vary based on the goals and budget of the assessment program. In the case of synthetic runoff testing or monitoring, the number of storm events sampled and the number of samples collected during storm events (synthetic or natural) will also vary depending on the assessment goals. For most assessment programs that use synthetic runoff testing or monitoring to assess pollutant removal effectiveness, however, it is generally recommended that:

1. In situ pollutant sensors be used whenever possible
2. Grab samples or automatic samples be collected promptly for pollutants or characteristics that change rapidly (e.g., temperature, bacteria, DO)
3. Flow-weighted composite samples be collected by automatic samplers, unless there is a specific need to measure pollutant concentration over time
4. Proper sample collection and handling techniques be followed to ensure representative samples and avoid contamination