The samples should be sent via overnight courier so they arrive while laboratory personnel are present and sufficient time is available to initiate the critical analyses immediately (unless special arrangements have been made with the laboratory). Always call to schedule a sample shipment and fax a confirmation of the sample shipping information. Always keep a copy of any sample identification sheets and send the originals (by mail, not in the coolers). Include a shipping list (and copy of appropriate sampling forms) in an envelope taped to the outside of the cooler.

Chain-of-Custody and Other Documentation

When the sample is collected, the bottle labels and chain-of-custody forms must be filled out. In many cases, additional field sheets containing site or sample information are also completed. Documentation of collection and analysis of samples requires all the information necessary to: (1) trace a sample from the field to the final result of analysis; (2) describe the sampling and analytical methodology; and (3) describe the QA/QC program (Mudroch and Azcue 1995; Keith et al. 1983).

Correct and complete field notes are absolutely necessary in any sampling program. Poor or incomplete documentation of sample collection can make analytical results impossible to interpret. The following items should be recorded at the time of sediment sampling (Mudroch and Azcue 1995):

1. Project or client number
2. Name of sampling site and sample number
3. Time and date of sample collection
4. Weather conditions (particularly wind strength and direction, air and water temperature)
5. Sample collection information
6. Type of vessel used (size, power, engine type)
7. Type of sampler used (grab, corer, automatic, etc.) and any modifications made to the sampler during sampling
8. Names of sampling personnel
9. Notes on any unusual events that occurred during sampling (e.g., problems with recovered samples or sampling equipment, observations of possible contamination)
10. Sample physical description including texture and consistency, color, odor, estimate of quantity of recovered samples by a grab sampler, length and appearance of recovered sediment cores
11. Notes on further processing of samples in the field, particularly subsampling methods, type of containers, and temperature used for sample storage
12. Record any measurements made in the field, such as pH and ORP

Bound notebooks are preferred to the loose-leaf type and should be kept in a room or container that will protect against fire or water damage. Whenever legal or regulatory objectives are involved, notebook data should be entered in ink, each page should be signed and witnessed, and all errors or changes should be struck through one time and initialed (Keith 1991).

When samples are transported to a laboratory, an inventory list of each individual sample should be included in the shipment, and a separate copy sent to the laboratory. The inventory list should indicate the required analyses for each enclosed sample. The transport container should be labeled properly, including a description of the contents, the destination, any special handling instructions, and phone numbers to call on arrival or in case of an emergency. It is highly recommended that laboratories receiving samples be alerted to their impending arrival, particularly if samples will arrive on a weekend or holiday, so that appropriate arrangements can be made for their receipt.

Samples collected for legal purposes typically require the use of strict chain-of-custody procedures during handling and transport. This includes preparing detailed documentation regarding sample collection, preparation, and handling. All transport containers must remain locked during transport to and from the sampling site. The name and signature of the person who collected the sample should be placed on each sample container and witnessed, and the label should be securely fastened to the container after the sample has been placed in it and the lid tightly secured.

Appropriate chain-of-custody forms must be filled out for each transport container, including a complete listing and description of the enclosed samples. Each transport should be locked during pickup, transit, and delivery and should have a tape seal to demonstrate that it has not been opened during transport. The chain-of-custody documentation must accompany the transport container, and every time the package changes hands, the transfer of responsibilities must be documented with names and signatures. A file of all documentation (e.g., signed package slips, waybills, chain-of-custody forms) should be established, and all samples must be kept in a locked area of the laboratory with restricted access. All documentation of the analytical procedures and results should be kept on file and in control of the laboratory and/or project QA/QC officer (EC 1994).

The typical information provided on a chain-of-custody form includes:

- The sampling location
- The sample identification number
- The type of test or analytical procedure
- The name of the person who relinquishes the samples
- The date and time of sample collection
- The date and time when samples are relinquished
- The name of the person who should receive the sampling results

Sample Preservation and Storage at the Laboratory

Once the samples arrive in the laboratory, they must be logged in, sorted for further processing, and filtered and preserved, as needed. In addition, the sample temperatures and the presence of ice in the coolers should be checked upon arrival in the laboratory to verify that the samples were kept below critical temperatures during shipping. A reading of pH and temperature is conducted as soon as the samples arrive, and bacteria analyses need to be started as soon as possible.

Within a day, chilled samples must be filtered. Glass filters used for suspended solids analyses typically contain large amounts of zinc that easily contaminates samples, therefore, membrane filters need to be used for filtered (dissolved) metal analyses. The filtered and unfiltered sample portions are then divided and preserved. The following is an example from the UAB environmental engineering laboratories:

- Unfiltered sample in two 250 mL amber glass bottles (Teflon-lined lids) (no preservatives) for total forms of toxicity, COD, and GC analyses (using MSD and ECD detectors)
- Filtered sample in one 250 mL amber glass bottle (Teflon-lined lids) (no preservative) for filtered forms of toxicity, COD, and GC analyses (using MSD and ECD detectors)
- Unfiltered sample in one 250 mL high-density polyethylene (no preservatives) for solids, turbidity, color, particle size, and conductivity
- Filtered sample in one 250 mL high-density polyethylene (no preservatives) for anion and cation analyses (using ion chromatography), hardness, dissolved solids, and alkalinity
- Unfiltered sample in one 250 mL high-density polyethylene (HNO_3 preservative to $pH < 2$) for total forms of heavy metal, using the graphite furnace atomic adsorption spectrophotometer
- Filtered sample in one 125 mL high-density polyethylene (HNO_3 preservative to $pH < 2$) for filtered forms of heavy metal, using the graphite furnace atomic adsorption spectrophotometer

All samples are chilled on ice or in a refrigerator at 4°C (except for the HNO_3-preserved samples for heavy metal analyses) and analyzed within the holding times shown below:

- Immediately after sample collection or upon arrival in the laboratory: pH and microorganisms
- Within 24 hours: toxicity, ions, color, and turbidity
- Within 7 days: GC extractions, solids, and conductivity
- Within 40 days: GC analyses
- Within 6 months: heavy metal digestions and analyses

Drying, freezing, and storage temperature all affect toxicity (ASTM 1991a). Significant changes in metal toxicity to cladocerans and microbial activity have been observed in stored sediments (Stemmer et al. 1990b). Recommended limits for storage of metal-spiked sediments have ranged from less than 2 to 5 days (Swartz et al. 1985), less than 2 weeks (ASTM 1991a; Nebeker et al. 1984), to 2 to 8 weeks (EPA 2000). Cadmium toxicity in sediments has been shown to be related to acid volatile sulfide (AVS) complexation (DiToro et al. 1991). AVS is a reactive solid phase sulfide pool that apparently binds some metals, thus reducing toxicity (DiToro et al. 1991). When anoxic sediments were exposed to air, AVS was volatilized. If a study intends to investigate metal toxicity and the sediment environment is anoxic, then exposure to air might reduce or increase toxicity due to oxidation and precipitation of the metal species or loss of AVS complexation. It is generally agreed that sediments used for toxicity testing should not be frozen (Schuytema et al. 1989; ASTM 1991), should be stored at 4°C with no air space or under nitrogen, and analyzed as soon as possible (Reynoldson 1987).

Samples should be handled and manipulated as little as possible to reduce artifact formation and constituent alteration. It is sometimes necessary to remove debris and predatory organisms from samples to be used for toxicity testing. As large a filter pore size as possible should be used to prevent removal of suspended solids, which affect toxicity. Dredge (grab) collected sediment samples (for toxicity testing) should be placed in wide-mouth containers which allow the sample to be gently stirred. The sediment should be stirred until it is a slurry or any overlying water is mixed into the sediment matrix. If necessary, the sample may be sieved to remove large debris and homogenize the particle size distribution. It may not be possible to remove all predatory or nontest organisms from whole sediment toxicity assays. Caution should be exercised when sieved samples are used for testing, as the particle size distribution, redox gradients, and other alterations have occurred which may affect toxicity responses and the accuracy of lab-to-field extrapolations. Sieving is recommended for macroinvertebrate analyses because it increases counting efficiency (see EPA 1990c for additional information).

Elutriate testing was developed by the U.S. Army Corps of Engineers to simulate a condition that occurs during a dredging operation. When dredging effects are a study objective, elutriate analysis should be included in the test design. Elutriate samples are prepared by mixing (shaking) a 1 to 4 ratio of sediment to water for 30 minutes. The mixture is allowed to settle for 1 hour, and the supernatant is used for testing. There are modified methods which mix for longer periods, mix by aeration, or filter the supernatant. It is important that the method used be consistent because any modification may alter the elutriate's characteristics. TCLP tests are also sometimes conducted to determine the leaching potential of sediments under more severe conditions.

Personnel Requirements

Personnel needed to carry out an effective monitoring program fall into several classifications. Obviously, project directors need to design the program to fulfill the project objectives while staying within the available resources. In many cases, a calculated monitoring program may be impossible to carry out because of insufficient monitoring opportunities (necessary length of monitoring period available, number of rain events expected, etc.). Obviously, the project personnel therefore need to understand the local conditions. The project directors also need a varied understanding of many components of the ecosystem being investigated (hydrology, biology, chemistry, land use, etc.). Project field staff must be able to collect samples in an efficient and safe manner and be capable of working under changing and uncomfortable conditions. In all cases, at least two people need to go into the field together. Selection of laboratory personnel depends on the analyses to be conducted, and candidates will likely need to have substantial wet-weather sample analysis experience. Statistical experts are also needed to assist in the project design and to help analyze the data. Some of this effort could be handled by volunteers, but most comprehensive monitoring programs will also require a substantial effort by highly trained

technical personnel. Obviously, volunteer support can be very successful from an economical and educational viewpoint. This is especially important in nonpoint source/watershed studies where local residents need to have a greater role in decision making and in taking responsibility for the watershed.

Uses of Monitoring Data and the Appropriate Use of Volunteers in Monitoring Programs

An increasingly common method to obtain water quality data in receiving waters affected by stormwater is through the use of volunteer programs. Typically, a group of interested people is recruited by a local environmental organization. These people are trained in the use of relatively simple field test kits and carry out relatively broad-based observations. Usually, these people obtain relatively frequent data from local waters that supplement regulatory agency monitoring efforts. Historically, the most common volunteer efforts have been conducted mostly by lake-shore property owners who take Secchi disk readings of lake water transparency. However, with decreasing budgets for regulatory agencies and decreasing formal monitoring efforts conducted by state agencies, volunteer monitoring programs are increasing. The objectives for the use of these data must still define the parameters to be measured and other aspects of the experimental designs (sampling locations, frequencies, etc.). All too often, volunteer monitoring programs are relatively unstructured and are restricted to parameters that are relatively simple to measure. They therefore cannot truly replace most professional monitoring programs, but can be good supplements. Recent evaluations of simple field test kits have also identified their limitations, along with their advantages (Day 1996).

Volunteer monitoring programs are currently being conducted by several hundred groups throughout the U.S. The following list shows the number of volunteer monitoring programs having specific objectives for the use of the data (EPA 1994):

Education	439
Problem identification	333
Local decisions	288
Research	226
Nonpoint source assessment	225
Watershed planning	213
Habitat restoration	160
Water classification and standards	127
Enforcement	120
Legislation	84
305b compliance	53

Most of these uses require accurate information, because the data may have profound effects on regulatory agency decisions. In many states, however, water quality monitoring data collected by anyone who is not an employee of the state regulatory agency is not admissible as evidence in court. The lack of adequate quality assurance and quality control plus legal chain-of-custody procedures (including proof that samples or observations were obtained where claimed) are the most obvious problems with volunteer collected data.

The users of volunteer-collected data are also varied. The following list indicates the numbers of volunteer monitoring programs collecting data used by various groups (EPA 1994):

State governments	319
Local governments	315
Advocacy groups	288
Federal government	156
University scientists	142

The types of data being collected by volunteer monitoring groups have greatly expanded since the early days of Secchi disk surveys. The following list shows the number of volunteer monitoring programs that are collecting specific information/data (EPA 1994):

Water temperature	377
pH	313
Dissolved oxygen	296
Macroinvertebrates	259
Debris cleanups	218
Habitat assessments	211
Nitrogen	205
Phosphorus	202
Turbidity	192
Coliform bacteria	184
Secchi disk transparency	177
Aquatic vegetation	173
Flow	157
Birds and wildlife	152
Fish	150
Watershed mapping	138
Rainfall	131
Photographic surveys	129
Salinity	101
Sediment assessments	100
Alkalinity	98
Pipe surveys	96
TSS/TDS	91
Construction site inspections	81
BOD	75
Hardness	71
Chlorides	62
Chlorophyll *a*	60
Metals	56
Pesticides	24
Other bacteria	24
Hydrocarbons	14

Many of these parameters are well suited for trained volunteers. They can conduct relatively low-cost observations, which require minimal sampling or analytical equipment costs, for temperature, salinity, debris cleanup, habitat assessments, Secchi disk transparency, watershed mapping, photographic surveys, pipe surveys, and construction site inspections. Most of the other parameters (including most of the chemical analyses) would require the use of analytical equipment.

Relatively simple field test kits have been marketed in the United States for the past 30 years that can evaluate many of these parameters. However, few of these kits are suitable substitutes for conventional laboratory procedures. With care, good "screening" observations can be obtained from many of these kits. The sample collector, kit user, and data user must be aware of the limitations and hazards associated with many of these kits. The main concerns include:

- Safety (safe and correctly labeled reagents and clear instructions, including disposal guidance)
- Adequate sensitivity for required use of data
- Problems with interferences
- Ease of use and level of training needed
- Cost

Tests recently conducted at the University of Alabama at Birmingham have evaluated numerous field test kits for these criteria (Day 1996). The results are summarized in Chapter 6.

RECEIVING WATER, POINT SOURCE DISCHARGE, AND SOURCE AREA SAMPLING

Samples can be collected by manual grab or automatic samplers, the latter being more expensive but often superior when conditions fluctuate rapidly or sporadically, or when available personnel are lacking. Automatic samplers are essential for the NPDES program when effluents are monitored for permit requirements. Many types of automatic samplers exist (e.g., see EPA 1982) and none is ideal for all situations. The following variables must be considered when selecting a sampler (EPA 1982):

- Water or effluent variation (flow and constituents)
- Suspended solids concentration, dissolved gases, and specific gravity of effluent
- Vertical lift required
- Maintenance

Commonly used water samplers are listed in Table 5.14 and are discussed later in this section.

Automatic Water Sampling Equipment

Automatic water samplers that are commonly used for stormwater monitoring are available from ISCO and American Sigma, among others (Figures 5.14 to 5.22). These manufactures have samplers that have very flexible programming capabilities specifically designed for stormwater sampling and designed for priority pollutant sampling. A simpler automatic sampler is the Masterflex self-contained composite sampler (from Forestry Suppliers, Inc., for about $1500). This sampler is restricted to composite sampling only on a time-increment basis, and there is little control over the sample volumes that can be obtained. However, it may be a worthwhile option for simple sampling needs.

The American Sigma (800-635-4567) samplers are an excellent example of a highly flexible automatic sampler (Figure 5.14). They have an integral flowmeter option and can directly connect to a liquid level actuator or a depth sensor. The depth sensor is placed in the storm drainage upstream of a flow monitoring device (such as a weir or flume, or any calibrated stage-discharge relationship can be used). The flow indicators can control sample initiation and/or sampling frequency. A rain gauge is also available that can be connected directly to the sampler. Rainfall data can therefore be logged by the sampler, along with flow information and sampling history. Rainfall can also be

Table 5.14 The Advantages and Disadvantages of Manual and Automatic Sampling

Type	Advantages	Disadvantages
Manual	Low capital cost Not a composite Point-in-time characterization Compensate for various situations Note unusual conditions No maintenance Can collect extra samples in short time when necessary	Probability of increased variability due to sample handling Inconsistency in collection High cost of labor[a] Repetitious and monotonous task for personnel
Automatic	Consistent samples Probability of decreased variability caused by sample handling Minimal labor requirement for sampling Has capability to collect multiple bottle samples for visual estimate of variability and analysis of individual bottles	Considerable maintenance for batteries and cleaning; susceptible to plugging by solids Restricted in size to the general specifications Inflexibility Sample contamination potential Subject to damage by vandals

[a] High cost of labor assumes that several samples are taken daily, large distances between sampling sites, and labor is used solely for sampling.

From EPA. *Handbook for Sampling and Sample Preservation of Water and Wastewater*, Environmental Monitoring and Support Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH, EPA 600/4-82/029. 1982.

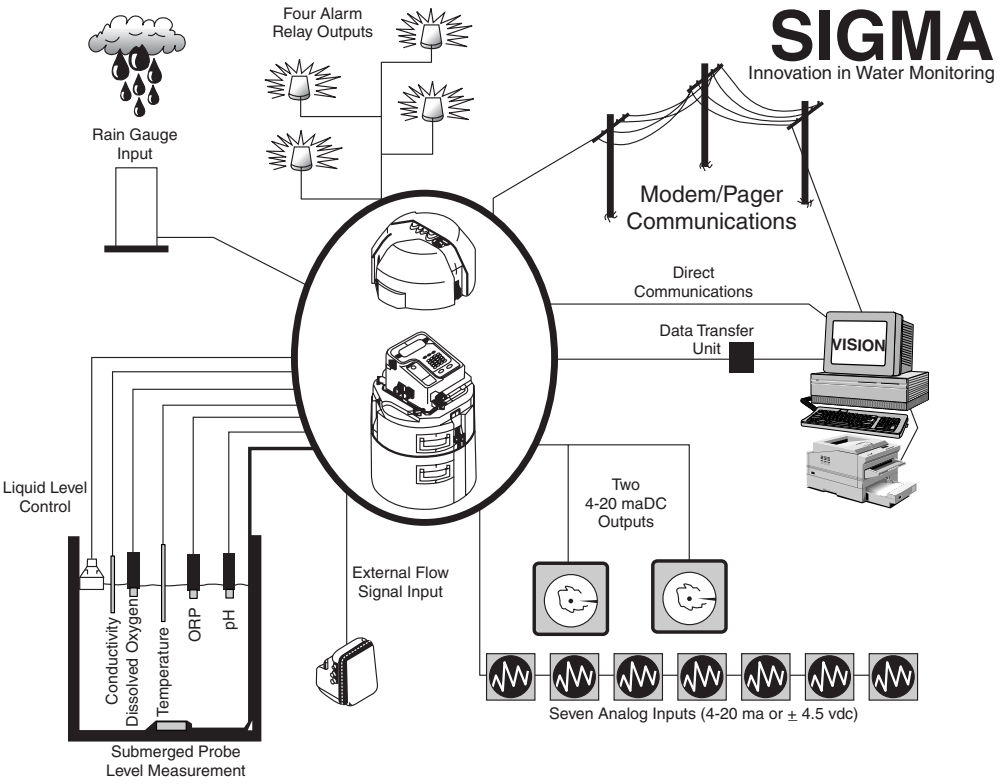

Figure 5.14 American Sigma connection options to ancillary equipment. (Used with permission.)

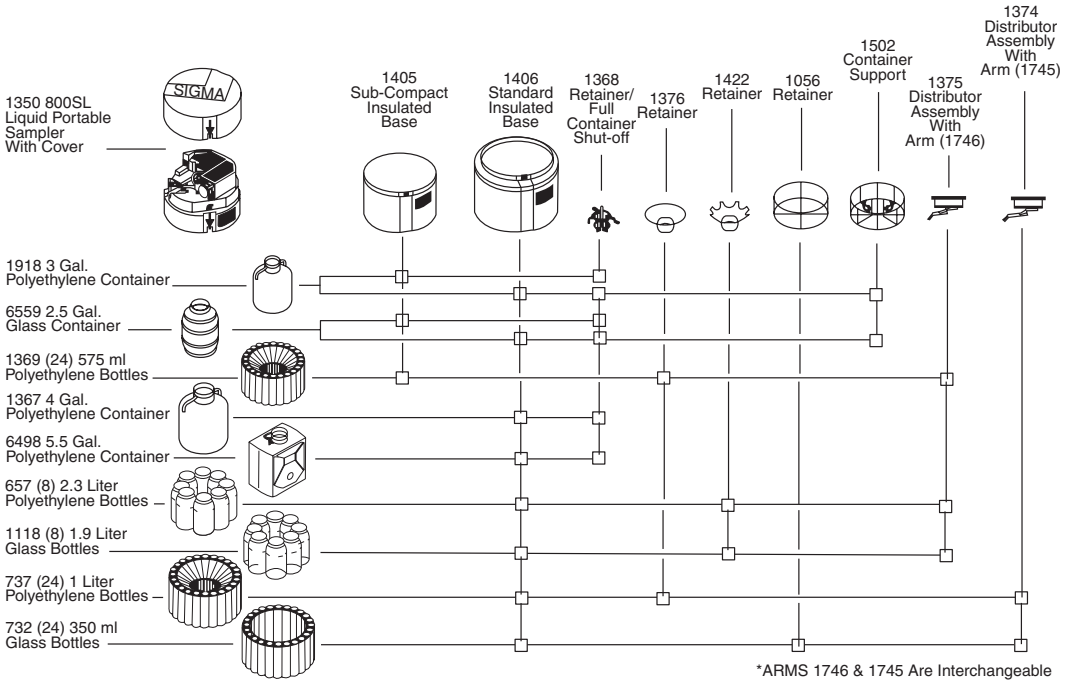

Figure 5.15 American Sigma sample bottle options. (Used with permission.)

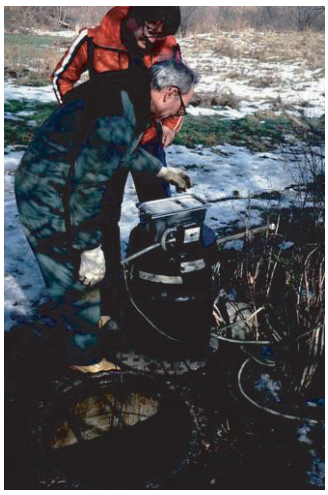

Figure 5.16 Automatic ISCO sampler used to monitor snowmelt in Toronto, Ontario, manhole.

Figure 5.17 ISCO sampler used in instrument shelter with flow monitoring and telemetry equipment in Madison, WI.

Figure 5.18 Intermittent stream monitoring in Austin, TX.

Figure 5.19 Refrigerated automatic sampler located at detention pond outfall in Madison, WI.

used to trigger sample initiation. A solar panel is also available to keep the sampler's battery charged. Several sample bases and sample bottle options are also available (Figure 5.15). Single bottle composite sample bases are available having glass or polyethylene bottles from 2.5 to 5.5 gallons in volume. Up to four 1 gallon glass or polyethylene bottles can also be used to obtain composite samples over segments of the runoff event. In addition, several 24 bottle options are also available, with 575 mL or 1 L polyethylene bottles, or 350 mL glass bottles. American Sigma also has several AC-powered samplers that are refrigerated.

ISCO (800-228-4373) also offers a complete line of automatic water samplers that have been used for stormwater sampling for many years. Flowmeter and rain gauge options are available, along with numerous sample base and sample bottle options. ISCO also has several AC-powered refrigerated samplers. The ISCO 6100 sampler (about $8000, with bladder pump and special bottle rack for 40 mL VOC bottles) is especially designed to obtain samples for volatile analyses. Samples are collected directly in capped 40 mL VOC vials in the sampler, with minimal loss of volatile compounds. Very few volatile hydrocarbons have ever been detected in stormwater, so this sampler

Figure 5.20 Refrigerated automatic sampler in Madison, WI, instrument shelter.

Figure 5.21 Discrete sample bottle base for ISCO automatic sampler.

(and VOC analyses) would probably be used only for specialized studies where VOCs are expected (such as in commercial areas with older dry cleaners or near gasoline stations).

Sigma and ISCO also have new automatic samplers that interface with continuously recording water quality probes that can be used to control sampling during critical periods, irrespective of time or flow. McCrone (1996) describes American Sigma's options for using numerous probes (such as conductivity, DO, temperature, ORP, and pH). The sampler can be programmed to collect a special sample when any of these monitored parameters meets a preset criterion. ISCO has a new sampler series that interfaces with the YSI 6000 water quality probes, allowing specific water quality conditions to also trigger sampling (similar to Sigma's list, plus turbidity).

If a refrigerated sampler cannot be used (due to lack of AC power), ice may be used if sample chilling is needed. Ice is placed in the central cavity surrounded by the sample bottles in the sampler base. The ice must be placed soon before an expected storm event, as it will generally melt within a day. The placement of any sampler in a cool location (such as a manhole) is much preferred over placement in a small shelter that may heat excessively in the summer. In most cases, chilling stormwater during sample collection is not done due to lack of AC power and the inconvenience of using ice. If the sampler is located in a cool location and the samples retrieved soon after the storm has ended, few problems are expected. Bacteria sampling, for example, requires manual sampling to ensure sterile equipment and to minimize storage problems. VOC analyses have previously required manual sampling, but the VOC sampler from ISCO can be used for automatic sample collection. The use of probes to measure pH, ORP, and temperature *in situ* also reduces the need for manual samples for these parameters. Therefore, it is possible to conduct a stormwater sampling program using automatic samplers that do not require AC-powered refrigerated

Figure 5.22 Composite sample bottle from Toronto snowmelt sampler.

samplers, if supplemented with manual sampling for microorganism determinations, and if the samples are retrieved soon after the event has ended. Some analyses may not be available using automatically collected samples, and other options may need to be used to supplement the automatic sampling. In all cases, special storage tests can be used to determine the likely errors associated with long storage in the samplers, with and without chilling.

Required Sample Line Velocities to Minimize Particle Sampling Errors

Typical sample lines are Teflon-lined polyethylene and are 10 mm in diameter. Table 5.15 shows the particle sizes that would be lost in vertical sampling lines at a pumping rate of 30 and 100 cm/s. The water velocity in sample lines is about 100 cm/s, enabling practically all sediment to be transported to the sample containers. A water velocity of 100 cm/s (about 3 ft/s) would result in very little loss of stormwater particles. Particles of 8 to 25 mm would not be lifted in the sample line at all at this velocity, but these particles would not fit through the openings of the intake or even fit in most sample lines. They are also not present in stormwater, but may be a component of bedload in a stream, or gravel in the bottom of a storm drain pipe, requiring special sampling. Very few particles larger than several hundred micrometers occur in stormwater and these should only have a loss rate of 10% at the most. Most particles in stormwater are between 1 and 100 μm in diameter and have a density of between 1.5 and 2.65 g/cm^3. Even at 30 cm/s, these particles should experience insignificant losses. A pumping rate of about 100 cm/s would add extra confidence in minimizing particle losses. ASTM (1995) in method D 4411 recommends that the sample velocity in the sampler line be at least 17 times the fall rate of the largest particle of interest. As an example, for the 100 cm/s example above, the ASTM recommended critical fall rate would be about 6 cm/s, enabling a particle of several hundred micrometers in diameter to be sampled with a loss rate of less than 10%. This is certainly adequate for most stormwater sampling needs.

Automatic Sampler Line Flushing

Automatic samplers generally go through three phases when activated to collect a sample. First, the sample line is back-flushed to minimize sample cross-over and to clear debris from the sample intake. Next, the sample is collected. Finally, the sample is back-flushed again before going into a sleep mode to await the next sampling instruction. It can require several minutes to cycle through this process. A volume of 1850 mL of water fills a 10 mm (3/8 in) diameter sample line that is 7.5 m (25 ft) long. If a sample volume of 350 mL is to be collected for each sample interval, the following total volume of water is pumped by the sampler for each sample instruction:

Back-flush line	1850 mL
Fill tube	1850 mL
Collect sample	350 mL
Back-flush line	1850 mL

Table 5.15 Losses of Particles in Sampling Lines

	30 cm/s Flow Rate		100 cm/s Flow Rate	
% Loss	Critical Settling Rate (cm/s)	Size range (μm, for ρ = 1.5 to 2.65 g/cm^3)	Critical Settling Rate (cm/s)	Size Range (μm, for ρ = 1.5 to 2.65 g/cm^3)
100	30	2000–5000	100	8000–25,000
50	15	800–1500	50	3000–10,000
25	7.5	300–800	25	1500–3000
10	3.7	200–300	10	350–900
1	0.37	50–150	1	100–200

This totals about 6000 mL of water to be pumped. Typical automatic samplers have a pumping rate of about 3500 mL/min for low head conditions (about 1 m). It would therefore require about 1.7 min to pump this water. With pump reversing and slower pumping speeds at typical pumping heads, this could easily extend to 2 min, or more. If the sampler collects 3 L of sample instead of 350 mL, then another minute can be added to this sampling time for one cycle.

This sampler cycle time necessitates various decisions when setting up and programming a sampler, especially for flow-weighted composite sampling. The most important decisions relate to selecting the sampling interval that can accommodate expected peak flows and the sample volume needed for the smallest events to be sampled. Sample storage in the samplers is limited, further complicating the issue. The samplers are generally programmed to sample every 15 min to 1 hour for time-compositing sampling, or for an appropriate sample volume increment for flow-weighted sampling. If each sample increment is 0.25 L, a total of 40 subsamples can accumulate in a 10 L composite sample container.

Time or Flow-Weighted Composite Sampling

Automatic samplers can operate in two sampling modes, based on either time or flow increments. The sample bases can generally hold up to 24 bottles, each 1 L in volume. A single sample bottle of up to about 20 L is generally available for compositing the sample into one container. These bottle choices and the cycle time requirements of automatic samplers restrict the range of rain conditions that can be represented in a single sampler program for flow-weighted sampling. It is important to include samples from small rains (at least as small as 0.1 to 0.2 in) in a stormwater sampling program because they are very frequent and commonly exceed numeric water quality criteria, especially for fecal coliform bacteria and heavy metals. Moderate-sized rains (from about 0.5 to 2 in) are very important because they represent the majority of flow (and pollutant mass) discharges. The largest rains (greater than about 3 in) are important from a drainage design perspective to minimize flooding problems. It is very difficult to collect a wide range of rain depths in an automatic sampler using flow-weighted sampling. Conflicts occur between needing to have enough subsamples during the smallest event desired (including obtaining enough sample volume for the chemical analyses) and the resulting sampling frequency during peak flows for the largest sampling event desired. As an example, consider the following problem:

- Desired minimum rain to be sampled: 0.15 in in depth, 4-hour runoff duration, having a 0.20 Rv (volumetric runoff coefficient)
- Largest rain desired to be sampled: 2.5 in in depth, 12-hour runoff duration, having a 0.50 Rv
- The watershed is 250 acres in size and 3 samples, at least, are needed during the smallest rain

The calculated total runoff is therefore:

- Minimum rain: 0.10 (0.15 in) (250 ac) (ft/12 in) (43,560 ft^2/ac) = 13,600 ft^3
- Maximum rain: 0.50 (2.5 in) (250 ac) (ft/12 in) (43,560 ft^2/ac) = 1,130,000 ft^3

The average runoff flow rates expected are roughly estimated to be:

- Minimum rain: (13,600 ft^3/4 hr) (hr/3600 s) = 0.95 ft^3/s
- Maximum rain: (1,130,000 ft^3/12 hr) (hr/3600 s) = 26 ft^3/s

Using a simple triangular hydrograph, the peak flows are estimated to be about twice these average flow rates:

- Minimum rain: 1.9 ft^3/s
- Maximum rain: 53 ft^3/s

Actual peak flow rates are obviously related to the watershed time of concentration and other factors of the watershed and drainage system, but this triangular hydrograph has been found to roughly estimate high flows during small and moderate rains. It is certainly not an adequate procedure for drainage design, however. As the smallest storm is to be sampled three times during the runoff period, the volume of flow per subsample is simply:

$$13{,}600 \text{ ft}^3/3 \cong 4500 \text{ ft}^3$$

Therefore, the total number of samples collected during the maximum rain would be:

$$1{,}130{,}000 \text{ ft}^3/4500 \text{ ft}^3 \cong 250 \text{ samples}$$

If the minimum sample volume required was 1 L, then each subsample could be as small as 350 mL. This would result in about 1 L of sample during the minimum storm, but result in about 90 L during the maximum storm (obviously much larger than the typical 10 to 20 L container). During the estimated high flow conditions of the largest storm, a subsample would be collected every:

$$4500 \text{ ft}^3 \text{ per sample}/53 \text{ ft}^3/\text{s} \cong 85 \text{ s}$$

If the sampler required 2 min to collect 350 mL, the sampler would not complete its cycle before it was signaled to collect another subsample. This would result in the sampler pump running continuously during this peak time. Since the peak flow period is not expected to have a long duration, this continuous pumping may not be a serious problem, especially considering that about 250 samples are being collected. The biggest problem with this setup is the large volume of sample collected during the large event.

This problem was solved during numerous stormwater monitoring projects (including Pitt and Shawley 1982 during the Castro Valley, CA, NURP project, and Pitt 1985 during the Bellevue, WA, NURP project) by substituting a large container for the standard sample base and installing the sampler in a small shelter. The large container can be a large steel drum (Teflon-lined), a stainless steel drum, or a large Nalgene™ container, depending on the sample bottle requirements. In order to minimize handling the large container during most of the events, a 10 L glass jar can be suspended inside to collect all of the subsamples for the majority of the events. The jar would overflow into the large container for the largest events. Glass bottles are used in the sampler when organics are to be analyzed, with the assumption that the short period of storage in the glass would not adversely affect the metal concentrations. The small shelter should be well vented to minimize extreme temperatures, as it is difficult to ice the large container. Obviously, the sampling stations need to be visited soon after a potential runoff event to verify sample collection, to collect and preserve the collected sample, and to clean the sampler to prepare it for the next event.

Alternatives to using a large sample base (Figure 5.23) in order to accommodate a wide range of runoff events include:

- Use time-compositing instead of flow-weighted sampling
- Use two samplers located at the same location, one optimized for small events, the other optimized for larger events (Figures 5.24 through 5.26)
- Visit the sampling station during the storm and reprogram the sampler, switch out the bottles, or manual sample

The most common option is the last one, which is expensive, uncertain, and somewhat dangerous. Few monitoring stations have ever used multiple samplers, but that may be the best all-around solution, but at an increased cost. The first option above, using time-compositing instead of flow-weighted sampling, should be considered.

Figure 5.23 . Automatic sampler with large base for monitoring wide range of flows, with large chest freezer USGS discrete sampler in background, at Bellevue, WA.

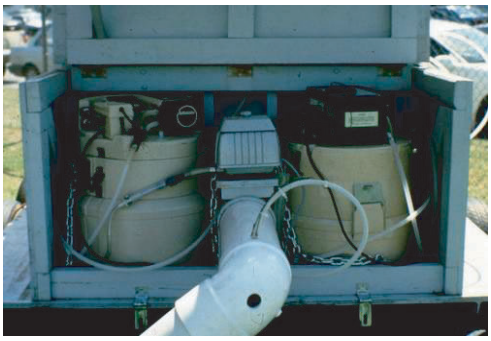

Figure 5.24 . Double monitor setup for simultaneously monitoring influent and effluent at small treatment device in Birmingham, AL.

Figure 5.25 . Double monitor setup for sampling over a wide range of flow conditions.

Figure 5.26 . Multiple flow monitor and sampler setup for simultaneously monitoring influent and effluent over wide range of flow conditions at a small treatment device in Madison, WI.

The Wisconsin Department of Natural Resources conducted a through evaluation of alternative sampling modes for stormwater sampling to determine the average pollutant concentrations for individual events (Roa-Espinosa and Bannerman 1994). Four sampling modes were compared at outfalls at five industrial sites, including flow-weighted composite sampling, time-discrete sampling, time-composite sampling, and "first-flush" sampling during the first 30 min of runoff. Based on many attributes, they concluded that time-composite sampling at outfalls is the best method due to simplicity, low cost, and good comparisons to flow-weighted composite sampling. The time-composite sampling cost was about $^1/_4$ of the cost of the time discrete and flow-weighted sampling schemes, for example (but was about three times the cost of the first-flush sampling only). The accuracy and reproducibility of the composite samples were all good, while these attributes for the first-flush samples were poor.

It is important to ensure that the time-weighted composite sampling include many subsamples. It would not be unusual to have the automatic samplers take samples every 10 min for the duration

of an event. If the minimum sample volume needed is 1 L and the shortest rain to be sampled is 30 min, then each subsample would need to be about 350 mL. The total volume collected would be about 50 L (144 samples) if a storm lasted 24 hours. The sampler would have to have an enlarged container (as in the above flow-weighted example), or the sampler would have to be visited about every 5 hours if a 10 L composite sample container was used.

Another important attribute of time-compositing sampling is that intermittent discharges and other short-term high concentration flows would be more readily detected. Flow-weighted composite sampling may allow very long periods to be unrepresented in the sample, while time-composite sampling can be adjusted to include relatively short sampling periods. Long periods between samplings could allow short-period episodes to be missed. However, sampling periods that are too short may result in almost continuous pumping activity that may exceed the continuous duty cycle of the sampler, resulting in frequent maintenance. Pump tubing should be carefully inspected and frequently replaced in any case, especially considering the gritty nature of stormwater. A new option is the use of *in situ* probes attached to the sampler that can be used to trigger sampling during unusual water quality shifts.

Automatic Sampler Initiation and the Use of Telemetry to Signal or Query Sampler Conditions

Automatic sampling equipment is typically located semipermanently in the field and is set to automatically begin sampling for a predetermined set of conditions. The most common method to start samplers is to use a stage indicator. This simple device, available from most sampler manufactures, may be a float switch (as from American Sigma) or an electronic sensor that shorts out when wet (ISCO). These devices plug into the sampler at the flow sensor connection. If flow monitoring is simultaneously being monitored, a Y connection is available to allow both connections. The stage sensor is typically placed slightly above the baseflow water elevation (in a pipe, open channel, or creek). It is difficult to sample small events that may not cause a large-enough stage elevation increase to trip the indicator. False alarms are also common when the sensor is placed too close to the baseflow water elevation or in areas of high humidity (for the moisture sensor). In addition, the baseflow water stage changes seasonally, requiring constant modifications in the sensor location. If the channel or pipe is normally dry, these problems are significantly reduced, as the sensor can be placed on the bottom of the drainage way or pipe. Flow-weighted sampling schemes can eliminate the use of sensors all together. In this case, some water may collect in the sample container during baseflow conditions, however. Frequent visits to the sampler are needed to empty and clean the sample container.

Another method used to initiate sampling is to trip the sampler using a rain gauge. Pitt and McLean (1986) used a rain gauge to initiate sampling at an industrial site in Toronto, while simultaneously monitoring flow. A tipping bucket rain gauge was used and three trips (about 0.03 in of rain) of the rain gauge within a few hours were usually used to initiate sampling.

In all cases, the use of telemetry (radio, telephone, or cellular phone) is extremely useful in minimizing false trips to a remote sampler by automatically signaling that samples have been collected (Figure 5.27). Campbell Scientific of

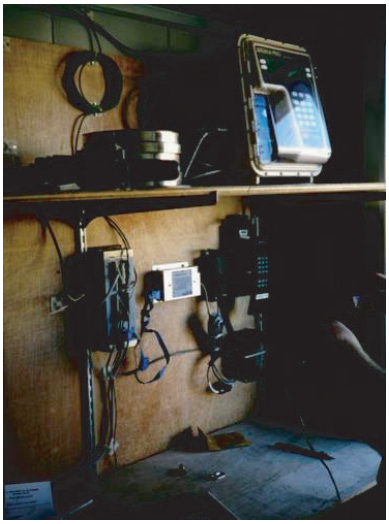

Figure 5.27 Telemetry equipment at USGS monitoring site in Madison, WI.

Figure 5.28 In-stream continuous probes at Dortmund, Germany, CSO monitoring site.

Figure 5.29 Automatic sampler connected to continuous probes and telemetry at Dortmund, Germany.

Logan, UT (801-753-2342), supplies many options allowing remote inquiring or automatic signaling to indicate sampler status. It is also possible to phone a monitoring station and immediately determine if a sampler is operating, and to download or observe instantaneous or compiled rain, flow, or continuous *in situ* water quality monitoring information. The use of telemetry is extremely important when many remote systems are being operated by a small group. It should be considered an integral part of all sampling and monitoring programs where high reliability and good quality data are needed. There are potential problems with RF interference between cellular phones and some monitoring equipment, so care must be taken to use an external antenna, to electronically shield the monitoring equipment, and to thoroughly test the setup.

An early example of an automatic stormwater monitoring program using telemetry to excellent advantage was the Champaign/Urbana NURP study conducted in the early 1980s (EPA 1983a). The Universität Gesamthochschule in Essen, Germany, has also used standard telemetry equipment components and specialized software in CSO monitoring in Dortmund, Germany, to inquire about monitoring station and flow status (Wolfgang Geiger, personal communication) (Figures 5.28 and 5.29). Numerous municipalities and state agencies in the United States have also installed telemetry-coupled monitoring stations using relatively inexpensive components, including cellular telephone service and solar-powered battery chargers. This has eliminated most of the concern about the availability of remote utility installations. Cooling collected samples still requires AC-powered chillers, or ice. For remote installations with a small sampling crew, it is impractical to ice the sampler in anticipation of a rain, but that is possible when the samplers are more accessible. It would be more important to recover the samples from the samplers as soon as possible after the event. This is made much more practical, especially with remote samplers, when telemetry is used to inquire about the sampler status.

Siphon Samplers

The USGS recently published a review of siphon samplers, compared to flow-weighted composite samplers for use along small streams (Graczyk et al. 2000). These are inexpensive units that can be utilized in many locations (Figure 5.30). They operate semiautomatically by starting to fill when the water level reaches level B (the top of the loop connected to the intake) in Figure 5.30. The sample

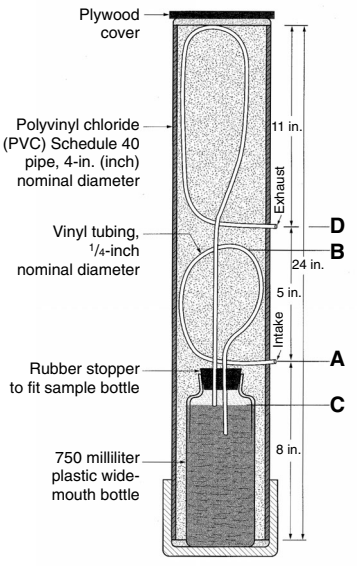

Figure 5.30 Siphon sampler. (From Graczyk, D.J. et al. *Comparison of Water Quality Samples Collected by Siphon Samplers and Automatic Samplers in Wisconsin*. USGS Fact Sheet FS-067-00. U.S. Geological Survey, Middleton, WI. July 2000.)

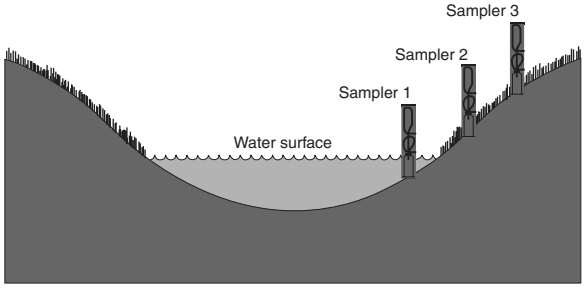

Figure 5.31 .Placement of siphon samplers along stream bank. (From Graczyk, D.J. et al. *Comparison of Water Quality Samples Collected by Siphon Samplers and Automatic Samplers in Wisconsin*. USGS Fact Sheet FS-067-00. U.S. Geological Survey, Middleton, WI. July 2000.)

bottle fills rapidly due to the hydraulic head (the elevation of the stream surface above the discharge end of the intake tube, level C, in the bottle). After the stream level reaches level D, an airlock is created in the top loop, stopping the filling. Therefore, the siphon collects a sample near the water surface when the stream stage is between levels B and D, which can be adjusted. Since they collect samples over narrow ranges of stream stages, several can be placed at different heights along a receiving water, as illustrated in Figure 5.31. Graczyk et al. (2000) compared sets of three siphon samplers, set at different elevations, along three streams that also had flow-weighted automatic samplers (ISCO) for comparison. They collected 40 to 50 pairs of samples and analyzed them for suspended solids, ammonia, and total phosphorus. Figure 5.32 illustrates the comparison for suspended solids. There was substantial scatter in the data, but the differences in the results averaged about 10% for suspended solids and ammonia,

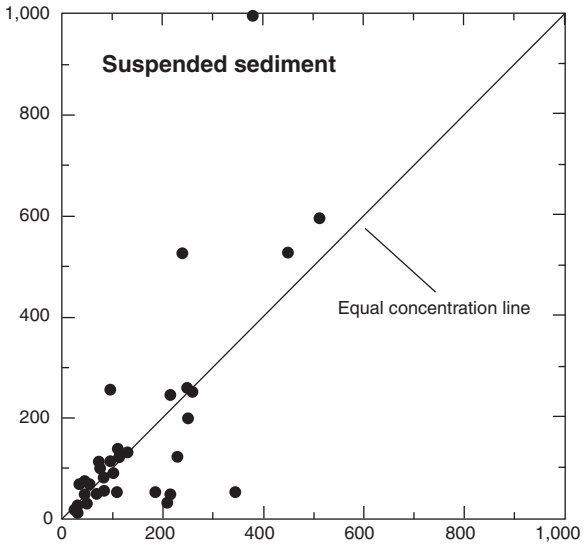

Figure 5.32 .Comparison of siphon sampler (y axis) and ISCO sampler (x axis) suspended solids observations. (From Graczyk, D.J. et al. *Comparison of Water Quality Samples Collected by Siphon Samplers and Automatic Samplers in Wisconsin*. USGS Fact Sheet FS-067-00. U.S. Geological Survey, Middleton, WI. July 2000.)

and about 25% for phosphate. However, the differences between individual pairs of samples were much greater. Some of the larger differences may reflect the siphon samplers only collecting samples at specific stage increments, while the automatic samplers collected samples at a single depth over longer periods of time. The siphon samplers may be useful when many samples can be collected and overall conditions are desired, in contrast to more accurate individual results. Their low cost and ability to sample for specific stage conditions makes them an interesting alternative to more expensive automatic samplers, or difficult manual sampling.

Retrieving Samples

Each sampler site will need to be visited soon after the runoff event to retrieve the sample for delivery to the laboratory. The storage time allowed in the sampler before collection should be determined from a special holding-time study conducted in conjunction with the analytical laboratory. Stormwater samples can usually withstand longer holding times than those implied from standard laboratory method descriptions without significant degradation. However, this will need to be verified by local tests. In all cases, the allowable holding times noted in Table 5.10 should be followed except in unusual situations and then only with specific tests. This is especially important when organizing sample deliveries to the laboratory after hours (which can happen frequently).

Manual Sampling Procedures

The following paragraphs summarize the procedures needed for manually collecting water and sediment samples from a creek or small stream.

1. Fill out the sample sheet and take photographs of the surrounding area and the sampling location. Conduct any *in situ* analyses (such as stream flow measurements, along with dissolved oxygen, pH, temperature, conductivity, and turbidity measurements in the water).
2. Use a dipper sampler to reach out into the flow of the stream to collect the sample. Slowly lower the sampler onto the water, gently rolling the top opening into the flow. Be careful not to disturb the bottom sediments. Submerge the sampler lip several inches into the water so floating debris are not collected. Lift out the sampler and pour the water into a compositing container (such as a churn sample splitter). Several samples should be collected in the area of concern and composited. In some cases, it may be useful to sample the water–air interface. This surficial layer is known to trap many types of organic chemicals (e.g., oils and surfactants) and have elevated microbial populations (e.g., pathogens).
3. Each water subsample can be poured into a large clean container during this sampling period. At the end of the sampling period, this composite sample is mixed and poured into the appropriate sample bottles (with preservatives) for delivery to the analytical laboratory.

Microbiological sampling requires special sampling techniques. ASTM (1995) in standard D 3370 describes the grab sampling procedures that must be used for collecting samples that will be analyzed for bacteria. The samples need to be glass and sterile. If the sample contains chlorine, then the sample bottle must contain sodium thiosulfate so any residual disinfection action will be destroyed. The bottle lid is removed and the bottle is placed under flowing water and filled to about $^3/_4$ of its capacity. Care must be taken when handling the bottle and lid (including not setting them down on any surface and not touching any part of the upper bottle portion) to minimize contamination. Do not rinse the bottle with the sample or submerge it under water.

Sampling sediment can be difficult (see also later discussion). The simplest method is to use a lake bottom sampler. Specifically, a small Ekman dredge sediment sampler, which is typically used for sand, silt, and mud sediments, is usually most useful. Corer samplers are generally not as successful for stream sediments. An exception is the freezing core sampler, where liquid CO_2 is pumped inside a stainless steel tube (with the bottom end sealed with a point) to freeze sediment

to the outside of the tube. Again, the sediment would have to be at least several inches deep. In all cases, multiple sediment samples would have to be obtained and composited. Any water samples should be obtained first, as the sediment sampling will create substantial disturbance and resuspension of sediment in the water column. All sampling equipment must also be constructed of noncontaminating materials. Stainless steel, polypropylene, or Teflon are the obvious choices.

Dipper Samplers

The simplest manual sampler is a dipper sampler (Figure 5.33). Markson (telephone: 800-858-2243) sells a dipper sampler that has a 1 L polyethylene beaker on the end of a two-piece, 4-m pole (catalog # MK34438 for about $60). They also sell units on 1- and 2-m poles and with 500 mL capacities. These samplers can only obtain samples from the surface of the water. If subsurface samples are needed, samplers with closure mechanisms need to be used, as described below. A dipper allows sampling of surface waters away from the immediate shoreline and from outfalls or sewerage pipes more conveniently than other types of samplers. Dippers are commonly used to sample small discharges from outfalls, where the flow is allowed to pour directly into the sampler. ASTM (1995) in standard D 5358 describes the correct stream water sampling procedure using a dipper sampler. The dipper needs to be slowly lowered into the water on its side to allow the water to flow into the sampler. The dipper is then rotated to capture the sample and is lifted from the water. Care must be taken to prevent splashing or disturbing the water. The sample is then poured directly into the sample bottles or into a larger container (preferably a churn sampler splitter, as previously described) for compositing several dipped samples.

Figure 5.33 Manual dipper sampler.

Submerged Water Samplers with Remotely Operated Closures

There are numerous historical and modern designs of samplers that can take water samples at specific depths. These all have a way to remotely operate closures in a sample container. The sampler capacities usually range from 0.5 to 3 L. Older designs include the Kemmerer and Van Dorn samplers, shown on Figure 5.34 (*Standard Methods* 1995). These samplers have a tube made of metal or plastic and end closures made of plastic or rubber. All Teflon units are available to minimize sample contamination. Newer designs commonly used for small lakes or streams are

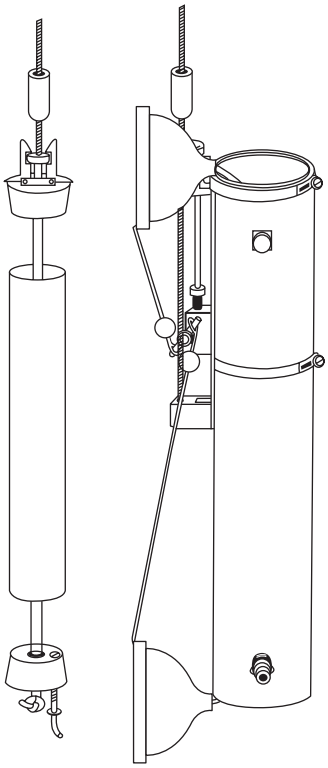

Figure 5.34 .Kemmerer and Van Dorn samplers. (From *Standard Methods for the Examination of Water and Wastewater.* 19th edition. Water Environment Federation. Washington, D.C. Copyright 1995 APHA. With permission.)

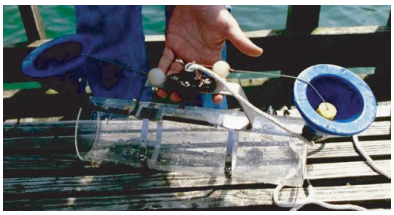

Figure 5.35 . Horizontal water sampler in open position before use.

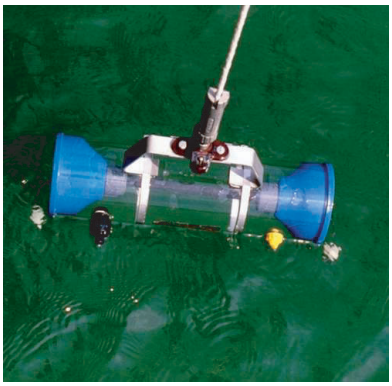

Figure 5.36 . Tripped horizontal water sampler being withdrawn from water with messenger resting on trigger mechanism.

Figure 5.37 . Open vertical water sampler being lowered into water, above a horizontal sampler on the same line.

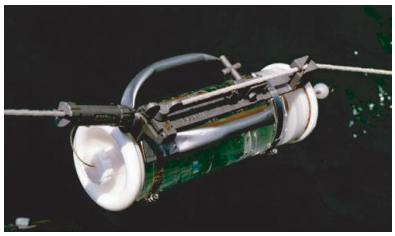

Figure 5.38 . Tripped vertical water sampler being withdrawn from water with messenger resting on trigger mechanism.

similar to the Van Dorn design (Figures 5.35 through 5.38). This design allows unhindered flow through the sample container before closure, enabling faster equilibrium with surrounding waters. These samplers are also available in horizontal models (for shallow water) or vertical models. Several of the vertical units can be used on a single line to obtain water samples from various depths simultaneously. A weighted messenger slides down the line that the samplers are attached to, striking a trigger mechanism that closes the end seals. If multiple samplers are used, the trigger releases another messenger that slides down to the next sampler to close that sampler and to release another messenger. A vertical alpha end-closure 2.2-L sampler (polyurethane end seals and transparent acrylic cylinder) is available from Forestry Suppliers, Inc. (800-647-5368) as catalog #77244, with messenger #77285, for a total cost of about $450. Several of these samplers can be installed on a line for simultaneous sampling at various depths. Forestry Suppliers, Inc., also sells a 1.2-L Teflon Kemmerer vertical bottle sampler (catalog #77190) for about $800. A water sample collected with this sampler only contacts Teflon.

Another surface operated design is a sampler that contains a 1-L glass bottle on the end of a long pole (such as catalog #53879 from Forestry Suppliers, Inc. at about $400). A stopper is spring loaded and is attached to a wire extending to the other end of the pole. The bottle end is lowered to the desired sampling depth and the wire is then pulled to fill the bottle. After a short period to allow the bottle to fill, the wire is released, resealing the bottle. This sampler was designed specifically for collecting water samples for Winkler titrations for DO analyses at sewage treatment plants. The bottle is initially full of air before the water enters and aeration may elevate the DO reading. If the bottle is prefilled with clean water, it is difficult to assume that the desired water sample will replace the water in the bottle. However, this sampler type might be useful for collecting subsurface samples for bacteriological analyses that should be collected in glass bottles with minimal handling.

Figure 5.39 Tube sampler.

Figure 5.40 .Grundfos Redi-Flo2 pump sampler with controller.

A newer alternative is a Teflon tube sampler that contains a wire-activated sealant mechanism and flow-through design (Figure 5.39). This overcomes the above limitations of the bottle sampler and still allows direct sampling at a specific depth. The AMS Cable Control Liquid Sampler is available from Forestry Suppliers, Inc. (catalog #77623), and costs about $550.

Manual Pump Samplers

A Grundfos Redi-Flo2 (Figure 5.40) pump and converter (designed and commonly used for well sampling) is available with a 300-foot polyurethane hose on a reel that can be used to deliver a water sample to a convenient location, especially useful when sampling wide and swift streams from a bridge. These pumps are available from Forestry Suppliers, Inc. (800-543-4203, catalog #76328 for pump, hose, and reel, and #76333 for voltage converter, for a total cost of about $4500). Hazco (800-332-0435) also sells (and rents) the Redi-Flo2 pump and converter for about $2100 without a hose (catalog #B-L020001 for converter and #B-L020005 for 150 motor lead and pump). A Teflon-lined polyethylene hose is available from Hazco for about $3.25 per foot, with support cable (catalog #A-N010041 and #C-L020009). This pump has an adjustable pumping rate of between 100 mL/min and 9 gal/min and can pump against a head of about 250 ft. However, this pump should be operated at least at 4.5 gal/min to meet the 100 cm/s criterion to minimize particulate settling in the 1 in ID hose. Low pumping rates from a submerged pump can also lead to "sand jamming," in addition to preventing an adequate sample from being obtained.

A less expensive alternative is the XP-100 pump, also available from Forestry Suppliers (#76216 for XP-060 pump and #76230 for control box, for a total cost of about $525). This is an adjustable rate pump and can deliver the needed 100 cm/s pump rate through a $^3/_8$-in tubing against a head of about 30 ft or less. This pump operates from a 12V DC power supply and has a limited service life, compared to the Grundfos pump. It may be useful for temporary installations having limited head, but needing several pumping locations across a stream. It is also useful for continuous sampling at different lake depths.

Depth-Integrated Samplers for Suspended Sediment

Suspended sediment is usually poorly distributed in both flowing and quiescent water bodies. The sediment is usually in greater concentrations near the bottom, as shown in Figure 5.41 (ASTM 1995). Larger and denser particles are also located predominantly in lower depths. Flowing water

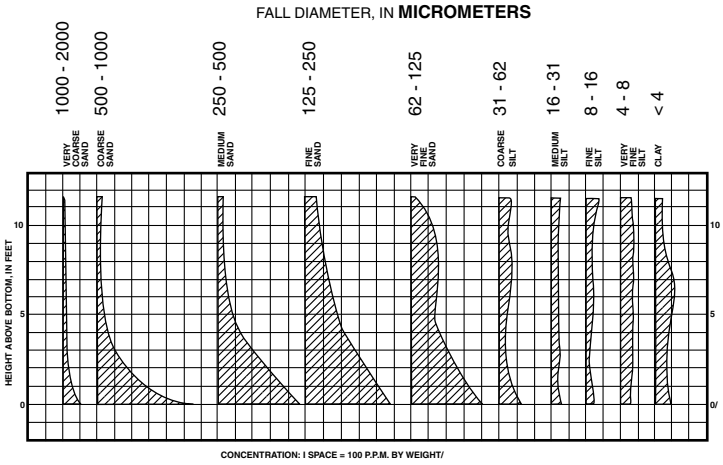

Figure 5.41 Sediment concentrations by depth and particle size, Missouri River, Kansas City, MO. (From American Society for Testing and Materials. *ASTM Standards on Environmental Sampling*. ASTM Pub Code No. 03-418095-38. ASTM, Philadelphia. 1995. Copyright ASTM. Reprinted with permission.)

in a sinuous stream also distributes the suspended sediment horizontally, as shown in Figure 5.42 (ASTM 1995), differently for large and small particles. Collecting representative samples in these situations for sediment analyses is therefore difficult. Because most of the pollutants in stormwater are associated with the particulates, this unequal distribution of sediment also affects the ability to collect representative samples of many pollutants. Depth-integrating sampling is commonly done in small upland streams. Sampling in smaller and more turbulent flows (such as in sewerage or at outfalls during moderate to large storms) is not as severely affected by sediment stratification.

Clay and silt-sized particles are generally well mixed with depth, depending mostly on water mixing conditions near discharges, etc., and not on gravity. ASTM (1995) states that the concentrations of particles smaller than about 60 μm in diameter will be uniform throughout the stream depth (Figure 5.41). However, larger particles will be more affected by gravitational forces and may not be represented well with typical sampling procedures. Conventional water samplers may be used to represent all of the sediment in flowing water (floating material, suspended sediment, and bedload), if the water is very turbulent and capable of mixing the sediment of interest. ASTM refers to these locations as "total-load" stations, allowing the collection of all sediment greater than about 2 mm in diameter. These are generally located at outfalls or other free-falling locations.

Automatic samplers (or any pumped sampler) may disproportionately collect particulates if the intake velocities vary significantly from the water velocity. Isokinetic sampling requires that

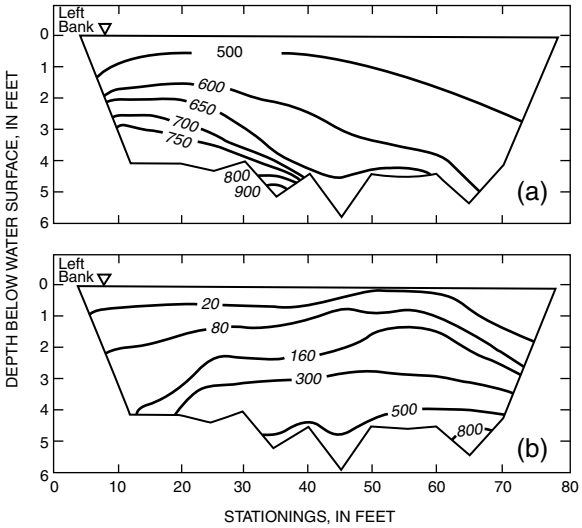

Figure 5.42 Suspended solids concentrations in the Rio Grande River, near Bernardo, NM, for different sediment sizes: (a) material between 62.5 and 125 mm; (b) material between 250 and 500 mm). (From American Society for Testing and Materials). *ASTM Standards on Environmental Sampling*. ASTM Pub Code No. 03-418095-38. ASTM, Philadelphia. 1995.Copyright ASTM. Reprinted with permission.)

Figure 5.43 . Depth-integrated sediment sampler parts.

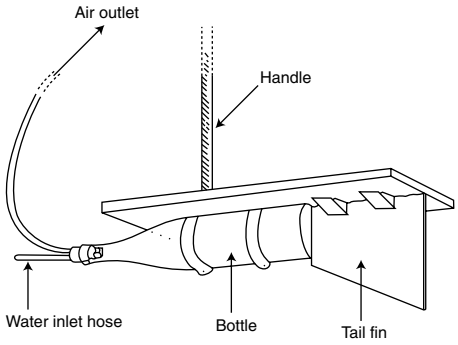

Figure 5.44 . Plan for a home-made depth integrated sampler. (Modified from Finlayson 1981.)

Figure 5.45 . Depth-integrated sediment sampler being readied for use.

the sampler intake be pointed directly into the flowing water and that the velocity in the intake be the same as the flowing water. The water and sediment streamlines will therefore be parallel in this situation and a sample representative of the flowing water will be obtained. If the sample intake velocity is greater than the water velocity, water will be drawn into the sampler, while heavier particles will tend to flow past. This effect is most evident for heavier particles (larger and denser) than for lighter particles. Berg (1982) reports that particles approaching 100 µm in diameter with densities of 2.65 g/cm^3 have less than a 20% sampling error when the velocities are not matched. Almost all stormwater and stream-suspended particulates are smaller and have a lighter density than this and would therefore generally follow the flow streamlines. These particles would therefore not be significantly affected by this possible problem.

Large-sized (larger than several hundred micrometers in diameter) suspended sediment measurements may be important for receiving water studies, especially in areas having flash flood flows in sandy soil regions (such as the southwest United States). The depth integrated sampler is designed to obtain a sample continuously as the sampler is lowered vertically through the water column at a constant velocity (Figures 5.43 through 5.45). These units vary significantly from commercial grab samplers that have remotely operated valves in that they have air vents to allow the air in the sample bottle to uniformly escape as the sample bottle fills with water. The home-made unit has a narrow-mouthed bottle mounted on a rod with stabilizing fins. The mouth of the bottle is fitted with a two-holed stopper. The top hole has a long flexible tube (which could extend above the water surface for most streams) to act as an air outlet, while the bottom hole has a rigid tube extending at least an inch to act as an intake. The intake nozzle should have a sharp front edge, with a narrow tubing thickness (less than $^1/_{16}$ in) and an inner

diameter of 5 to 6 mm ($^3/_{16}$ or $^1/_4$ in) (ASTM 1995, standard D 4411). These are available commercially from Forestry Suppliers, Inc. (800-543-4203) and in Canada from Halltech Environmental, Inc. (519-766-4568), or they can be constructed (Figure 5.44).

When collecting a depth-integrated sample, the sampler needs to stand to the side and downstream of the sampling area to minimize disturbance. The rod is lowered vertically through the water column at a constant rate of about 0.4 times the stream velocity. Detailed vertical sampling rates are presented by ASTM (1995) in standard D 4411 for the series of older depth-integrated samplers. The sampler is lowered at this constant rate from the surface of the stream to the stream bottom, and then reversed and brought back to the surface at the same rate. The sampler does not collect samples within several inches of the stream bottom. Moving sediment near the bottom is usually included in the bedload sample, which requires other sampling methods. The sample bottle should be between $^2/_3$ and $^3/_4$ full after sample collection. If it is full, then the sampler did not represent the complete stream depth and the sample should be discarded and collected again, at a faster vertical rate. If the sampler is less than $^2/_3$ full, another vertical sample pass can be collected. After the sample is collected, the sample is poured from the sampler into a sample bottle. It is possible to mount an appropriate sample bottle directly to the sampler, and sample transfer would therefore not be needed.

Several vertical samples will normally need to be collected across the stream, as the coarser suspended sediment is likely highly variable in both time and space (ASTM 1995). The location and number of sampling verticals required at a sampling site is dependent primarily on the degree of mixing at the cross section.

Settleable Solids Samplers

Sediment traps suspended in the water column can be used to capture settleable solids. Zeng and Vista (1997) describe the use of these samplers off San Diego to capture marine settleable solids for organic compound analyses in the water column at several off-shore locations. The sediment traps were located 1 and 5 m from the seafloor and were retrieved after 30 days. The traps were made of two parts, a glass centrifuge bottle at the bottom and a glass funnel positioned on the bottle through a Teflon-lined silicone rubber seal. When retrieved, the two parts of the traps were separated and water covering the particulates was carefully removed. The centrifuge bottles were then capped with Teflon-lined caps and brought to the laboratory for analysis.

Similar sediment traps were used in the Seattle area to investigate the amount and fate of CSO settleable solids in the receiving waters. These traps were generally similar to those described above but were located much closer to shore and in shallower water. Several were placed vertically on an anchored line in a grid pattern near and surrounding CSO discharge locations being investigated.

Sediment traps were also placed in Fresh Creek, New York City, at the Equi-Flow demonstration facility. These traps were placed within and outside the facility to quantify the amount of settleable material that was captured during the CSO storage operations before being pumped back to the treatment plant. This use of sediment traps was not very successful due to very dynamic flow conditions and the short exposure periods used in an attempt to obtain data during frequently occurring CSO events. Longer exposure periods would have enabled the capture of more measurable material, but would have blended together material from adjacent events.

Sediment traps can be useful sampling devices to capture and measure slowly settling solids *in situ* in the water column. This information is especially important when quantifying the effects of sediment-laden discharges into relatively large water bodies having slow to moderate currents. They may not be suitable for small streams, unless they can be miniaturized. Several traps should be suspended at one location at different depths, and redundant devices should be used to compensate for traps lost during the exposure period. Like the bedload samplers described next, the exposure periods should probably be long (several weeks). The sampler materials also need to be compatible with the constituents intended to be analyzed. A simple framework (made of

inert materials) should also be constructed to brace the assembled sediment trap and to allow easy attachment to the anchored line, but it should not extend above the funnel to minimize interference with settling materials.

Bedload Samplers

Bedload is the material that travels in almost continuous contact with the stream bed (ASTM 1995). The bedload material moves when hit by another moving particle, or when water forces overcome its resisting forces. Bedload is sampled by using a trapping sampler located on the stream bottom. The simplest bedload samplers are box or basket samplers which are containers having open ends facing upstream. Bedload material bounces and rolls into the sampler and is trapped. Other types of bedload samplers consist of containers set into the sediment with slot openings about flush with the sediment surface. The bedload material falls through a slot and is trapped. Slot widths and lengths can be varied to represent various fractions of the bedload actually moving in the stream. The errors associated with sampling bedload are greater than with sampling suspended sediment because the larger particles move more irregularly under the influence of gravitational forces and are not well mixed in the water.

Bedload may be important when characterizing stormwater sediment discharges. In northern areas where sands are used for ice control, relatively large amounts of sand can be transported along the drainage system as bedload. At the Monroe St. detention pond site in Madison, WI, the bedload accounted for about 10% of the total annual sediment loading. This fraction was much greater during the spring when most of the sand was flushed from the drainage area.

Conventional water samplers may not adequately collect bedload material. A slot sampler placed in a drilled hole in the bottom of a discharge pipe can effectively collect this material. However, the slot dimensions and placement exposure times must usually be determined by trial and error. In addition, several bedload samplers should be used in close proximity because of the varied nature of bedload transport. Bedload samplers that are full upon retrieval may not represent actual conditions. If full, then the slot widths should be reduced and/or the exposure time should be shortened. The slot length should be as long as possible for the container lid, as bouncing bedload particles may jump over openings that are too short. In addition, the slot widths should be at least $^1/_4$ in wide, as narrower slots will filter out large materials. Basket samplers are probably most applicable in streams, where the opening width is a small fraction of the stream width. Again, several samplers need to be used in close proximity, and the best exposure period needs to be determined by trial. For grab samples, both hand-held and cable suspended Helley Smith (Geological Survey) bedload samplers are available from Halltech Environmental, Inc. (519-766-4568).

Floatable Litter Sampling

One example of quantifying litter discharges during wet weather was described by Grey and Oliveri (1998). New York City has been involved in a comprehensive litter analysis and capture effectiveness program since the mid-1980s. As part of this investigation, it studied litter discharges from stormwater inlets using baskets that were inserted in manholes below catchbasins (Figure 5.46). The baskets were made of galvanized mesh and were 13 in square and 36 in high. The lower half of the baskets was made of $^1/_4$-in mesh, while the upper half was of $^1/_2$-in mesh. The baskets were positioned on a wooden platform just beneath the catchbasin outlet pipe and were held in place with ropes, allowing removal without requiring entry into the manholes. These baskets were installed at 38 locations throughout the city and were in place for 3 to 4 months. Most baskets were removed, emptied, and replaced every 2 weeks, although some were in place for only a week before emptying. The captured material was placed in sample bags, brought to the laboratory, sorted into 13 categories, counted, and weighed. The surface areas of the collected material were also measured.

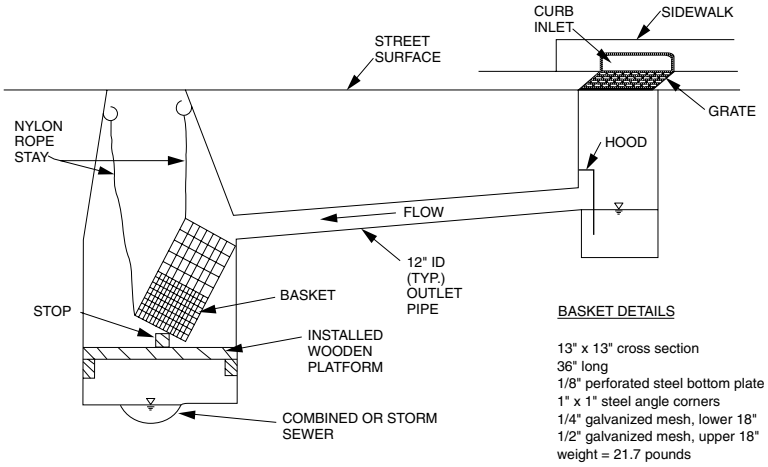

Figure 5.46 . New York City catchbasin litter sampling setup. (From HydroQual, Inc. *Floatables Pilot Program Final Report: Evaluation of Non-Structural Methods to Control Combined and Storm Sewer Floatable Materials*. City-Wide Floatables Study, Contract II. Prepared for New York City, Department of Environmental Protection, Bureau of Environmental Engineering, Division of Water Quality Improvement. NYDP2000. December 1995.)

In addition to characterizing the litter discharges, New York City also examined the effectiveness of the catchbasins in capturing this material. Grey and Oliveri (1998) also described these tests. They placed a known amount of litter (10 pieces each of 12 different floatable items, totaling about 1 ft^3 in volume of each material), including plastic bags, candy wrappers, straws, bottle caps, juice bottles, hard plastic pieces, glass vials, aluminum cans, polystyrene cups and pieces, cigarette butts, and medical syringes. They then opened a fire hydrant to produce a basic flow rate of about 75 gal/min (corresponding to a rain intensity of about 0.28 in/hour over a 40,000 ft^2 drainage area). They also ran tests at $^1/_3$ and 2× this flow. The flow was continued until no more items were transported to the sampling basket (usually about 5 to 10 min). The items remaining in the catchbasin were then retrieved and counted. This test was repeated five times for each test, and 10 tests in all were conducted (some with and some without catchbasin hoods).

Source Area Sampling

Much information can be obtained by collecting stormwater samples at source areas. Source areas are where the runoff originates before it is collected in the storm drainage system. Source area sampling also includes rainfall sampling for water quality analyses, conventionally done using a wet/dry-fall sampler. This sampler also collects dust fall during dry periods. This atmospheric contribution can have a significant affect on stormwater quality. However, very little of the dry-fall pollutants occurring over a watershed actually are washed off during rains.

This information can help identify the critical areas in the watershed where most of the problem pollutants may be originating and where control measures should be implemented (Pitt et al. 1995). These areas may include paved industrial storage areas, convenience store parking areas, vehicle maintenance areas, landscaped areas, roof runoff, etc. Conventional automatic samplers may not be efficiently used in these areas because of the small scale of the sampling areas and limited places where the samplers can be located that would only receive runoff from the area of concern. Three sampling methods have been used:

- Manual sheetflow samplers
- Semiautomatic samplers
- Special designs for automatic sample collection

Figure 5.47 .Sheetflow sampler operated by hand vacuum pump.

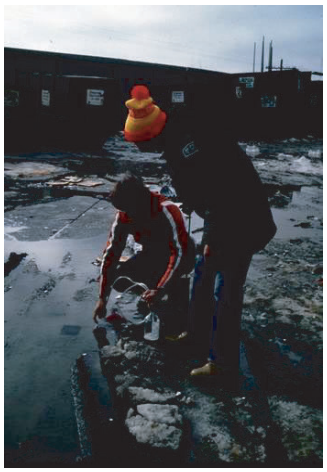

Figure 5.48 Sheetflow sampler being used to sample snowmelt.

Manual Sheetflow Samplers

Manual sheetflow samplers are usually used when collecting grab samples from many different sampling locations. A small team can visit many sampling sites during a single rain to obtain multiple grab samples for statistical comparisons (Figures 5.47 and 5.48). The main drawback is that the samples are not composited during the rain and only represent the conditions during the short sampling period. It is therefore very important to carefully document rain and flow conditions during the sampling period, and for the short time before the sample was obtained. Rain conditions up to the time of sampling can also have a significant effect on measured pollutant concentrations. In many cases, the ability to obtain many samples in a relatively short time is more important than obtaining flow-weighted composite samples. Roa-Espinosa and Bannerman (1994) found that many discrete samples (which could be composited before analysis) are just as useful in obtaining an event-mean concentration (EMC) as are more difficult to obtain flow-weighted composite samples.

Sheetflow samples should be obtained in areas where the sheetflow is originating from a homogeneous area, such as from a parking area, roof runoff, runoff from a landscaped area, etc. Sheetflow samples can be collected by collecting the flow directly into the sample containers, if the flow is deep enough. The flow may be "scooped" using a small container and by pouring the collected samples into the sample container. For shallow sheetflows, a hand-operated vacuum pump can be used to draw the sample into the sample container, as shown in Figure 5.47. A Teflon-lined lid that fits the sample containers can be fitted with two Teflon bulk-head connectors. One of the connectors has a Teflon tubing (about 18 in long and 1/4 in ID) attached that is used to draw the sample into the container. The other connector has a Tygon™ tube leading to a water trap (another bottle) that is in turn attached to a hand-operated vacuum pump (such as a Nalgene #6132-0020, at about $100). To collect a sample, the Teflon tubing is immersed in the sheetflow and the hand pump draws the water into the sample bottle. The pump should be operated slowly to prevent cavitation at the tubing inlet. The short lengths of Teflon tubing are inexpensive and can be replaced after each sample to prevent cross-contamination. Since the sample is drawn directly into the sample bottle, sample transfer is unnecessary.

An alternative to the hand-operated vacuum pump and water trap arrangement is to use a battery-operated peristaltic pump (such as a Masterflex L/S portable sampling pump, catalog #FE-07570-10, at about $850, with a Teflon tubing pump head, catalog #FE-77390-00, at about $400, available from Cole-Parmer, 800-323-4340). This battery-operated pump can be used to pump directly into the sample containers. The Teflon tubing used in this pump (catalog #FE-77390-60) costs about

$15 each and would therefore not likely be replaced after each sample. The tubing would therefore require field cleaning between each sample. Since the battery is built into this pump, and no water trap is needed, this sampling arrangement is relatively compact.

Semiautomatic Sheetflow Samplers

Source area samplers have been developed to semiautomatically collect composite stormwater samples from small drainages. Samplers (at $250 to $650) from the Vortox Company (909-621-3843) are an attractive option for some studies (Figure 5.49). These 0.8- to 5.5-gallon units (available Teflon lined) are completely passive and operate with a double ball closure system. They are installed in the bottom of intermittent flow paths, requiring a sump for installation. They have a screw closure to adjust the rate of filling. A top ball seals the inlet during dry conditions. When a flow occurs, this ball floats, opening the inlet. An inner ball on the underside of the inlet then seals the inlet when the sampler is full.

Figure 5.49 Vortox sampler.

Potential problems may occur with sediment clogging the very small inlet and fouling the ball seals. However, this sampler also collects bedload from the flowing stormwater (if the ball valve is opened sufficiently) that is not collected using conventional stormwater samplers. The sampler is somewhat awkward to clean. Another problem is the rapid time (less than 20 minutes for the 0.8-gal unit and less than 2 hours for the 5.5-gal unit) to completely fill the sampler. Sheetflows from homogeneous areas (especially small paved areas where these samplers are likely to be used) usually demonstrate strong "first-flush" conditions. The initial flows have much greater concentrations than the EMC, especially for relatively constant rain intensities. This would result in biased concentrations if only the first 20 min of the flow is represented in the sample.

Because of its low cost and passive operation, this sampler may be attractive in situations where many source areas are to be sampled with a small sampling crew. Again, caution must be expressed in interpreting the results, as the concentrations may be greater than the EMC values for source area flows. At outfalls, in complex drainage ways, or with highly variable rain intensities, the initial samples are not likely to be consistently different from the EMC. Frequent site visits will be necessary when runoff has been expected in order to retrieve samples. It may be desirable to have additional samplers so clean units can be substituted in the field for full samplers. The full samplers can then be brought to the laboratory to be emptied and cleaned.

Automatic Source Area Samplers

Problems associated with the above two sampling methods for source area sheetflows can be largely overcome using automatic samplers. Conventional automatic water samplers discussed earlier are probably the most flexible. However, they are expensive and large. Their size limits where they can be located and the size of flow they can sample. Their cost limits the number of units that can be simultaneously deployed. It is possible to rotate a relatively few samplers randomly between semipermanent sampling locations after every few storms. The samplers would be programmed for time-composite sampling (or time-discrete sampling) and automatically activated with

Figure 5.50 Prototype WI DNR/USGS automatic sheetflow sampler.

flow level sensors, or by rain gauge activity. As noted earlier, telemetry can be used to call the project personnel automatically when the sampler has been activated.

Roa-Espinosa and Bannerman (1994) describe a new automatic source area sheetflow sampler that the Wisconsin Department of Natural Resources and the Madison USGS office have jointly developed (Figure 5.50). Their initial source area sampler was similar to a slot bedload sampler and located in the flow path to be sampled. Like the Vortox unit, it usually filled quickly and did not represent the complete runoff event. This initial sampler consisted of a 10-in ID PVC pipe 12-in long. A 10-in PVC pipe coupling was cut in half and glued to the top of the pipe as a reinforcing collar. This pipe was then cemented in a drilled hole in the pavement (for pavement runoff sampling). A 1-in-thick PVC cap, having a $^5/_8$-in center hole, was fitted snugly in the coupling sleeve of the pipe section cemented in the pavement. The upper surface of this cap was flush with the pavement surface. A sample bottle lid was bolted to the underside of the removable cap, which also had a $^5/_8$-in hole matching the hole in the cap. A 2.5-L glass sample bottle was screwed into this lid and placed in the pipe cemented into the pavement when rain was expected. After the runoff ended, the bottles were retrieved and brought to the laboratory. As noted above, sample bottles commonly were full after the runoff ended, indicating that the samples did not represent the complete event. The sampling holes were reduced to reduce the inflow rate, but clogging was a concern and they still were frequently full. Investigators then developed a new sheetflow sampler that was electronically activated (Figure 5.50). A relatively large sample inlet was used to minimize clogging, but an electronically operated ball valve was added. It is possible to program the sampler to schedule the duration of the open and closed times. This enabled the complete runoff events to be represented in the sample. When commercially available, these samplers are likely to cost about $1000.

Source Area Soil Sampling

Soil sampling in urban areas usually involves collecting material from both paved and unpaved areas. Collecting particulates from paved areas (“street dirt”) is described in the following subsection and can be applied to many paved source areas, in addition to streets, the original area of most interest. Soil sampling from nonpaved areas involves more traditional soil sampling procedures and is discussed in any agricultural soils textbook. Generally, small trowels are used to collect surface soil samples for analyses, while small hand coring tools are used to collect subsurface samples down to about 1 ft in depth. Deeper soil samples can be best obtained from the walls of trenches that have been excavated using small backhoes.

If soil characteristics associated with particulates most likely to erode during rain events are of most interest, then care should be taken to emphasize the surface soils during sample collection. In this case, careful “scrapings” of surface dirt by a trowel or stiff brush into a sample container may be most efficient, as only very thin layers of most surface soils are typically eroded. If subsurface soil characteristics are needed, such as observing signs of seasonal high groundwater, then small trenches may be needed. Small soil cores should be used when measuring soil texture when soil infiltration studies are being conducted. Cores (or trenches) are also needed if soil chemical quality is needed for different soil depths.

Street Surface Particulate Sampling Procedures

The street dirt sampling procedures described in this section were developed by Pitt (1979) and were used extensively in many of the EPA's Nationwide Urban Runoff Program (NURP) projects (EPA 1983a) and other street cleaning performance studies and washoff studies (Pitt 1987). These procedures are flexible and more accurate indicators of street dirt loading conditions than previous sampling methods used during earlier studies (such as Sartor and Boyd 1972, for example). The procedures are described here in detail so that they can be used by those wishing to determine loading conditions, accumulation rates, washoff rates, and street cleaning effectiveness for their own locations.

Powerful dry vacuum sampling, as used in this sampling procedure, is capable of removing practically all of the particulates (>99%) from the street surface, compared to wet sampling. It can also remove most of the other major pollutants from the street surface (>80% for COD, phosphates, and metals, for example). Wet sampling, which would better remove some of these other constituents, is restricted to single area sampling, requires long periods of time, requires water (and usually fire hydrants, further restricting sample collection locations to areas that have no parked cars), and basically is poorly representative of the variable conditions present. Dry sampling can be used in many locations throughout an area; it is fast, and it can also be used to isolate specific sampling areas (such as driving lanes, areas with intensive parking, and even airport runways and freeways, if special safety precautions are used). It is especially useful when coupled with appropriate experimental design tools to enable suitable numbers of subsamples to be collected representing subareas, and finally, the collected dry samples can be readily separated into different particle sizes for discrete analyses.

Equipment Description

A small half-ton trailer can be used to carry the generator, two stainless steel industrial vacuum units, vacuum hose and wand, miscellaneous tools, and a fire extinguisher. This equipment can also be fitted in a pickup truck, but much time is then lost with frequent loading and unloading of equipment, especially considering the frequent sampling that is typically used for a study of this nature (sampling at least once a week, and sometimes twice a day before and after street cleaning or rains). A truck with a suitable hitch and signal light connections is needed to pull the trailer. The truck also requires warning lights, including a rooftop flasher unit. The truck is operated with its headlights and warning lights on during the entire period of sample collection. The sampler and hose tender both need to wear orange, high-visibility vests. The trailer also needs to be equipped with a caution sign on its tailgate. In addition, both the truck and the street cleaner used to clean the test area can be equipped with radios (CB radios are adequate), so that the sampling team can contact the street cleaner operator when necessary to verify location and schedule for specific test areas.

Experiments were conducted by Pitt (1979) to determine the most appropriate vacuum and filter bag combination. Two-horsepower (hp) industrial vacuum cleaners with one secondary filter and a primary dacron filter bag are recommended as the best combination. The vacuum units are heavy duty and made of stainless steel to reduce contamination of the samples. Two separate 2-hp vacuums are used together by joining their intakes with a Y connector. This combination extends the useful length of the 1.5-in vacuum hose to 35 ft and increases the suction so that it is adequate to remove all particles of interest from the street surface. Unfortunately, two vacuums need to be cleaned to recover the samples after the subsample collections. A wand and a "gobbler" attachment are also needed. The aluminum gobbler attaches to the end of the wand and is triangular in shape and about 6 in across. Since it was scraped across the street during sample collection, it wears out frequently and must be replaced. The generator needed to power the vacuum units must be of sufficient power

to handle the electrical current load drawn by the vacuum units, about 5000 watts for two 2-hp vacuums. Honda water-cooled generators are extremely quiet and reliable for this purpose. Finally, a secure, protected garage is needed to store the trailer and equipment near the study areas when they are not in use.

Sampling Procedure

Because the street surfaces are more likely to be dry during daylight hours (necessary for good sample collection), collection should not begin before sunrise nor continue after sunset. During extremely dry periods, sampling can be conducted during dark hours, but that requires additional personnel for traffic control. Two people are needed for sampling at all times, one acting as the sampler, the other acting as the vacuum hose tender and traffic controller. This lessens individual responsibility and enables both persons to be more aware of traffic conditions.

Before each day of sampling, the equipment is checked to make sure that the generator's oil and gasoline levels are adequate, and that vacuum hose, wand, and gobbler are in good condition. Dragging the vacuum hose across asphalt streets requires periodic hose repairs (usually made using gray duct tape). A check is also made to ensure that the vacuum units are clean, the electrical cords are securely attached to the generator, and the trailer lights and warning lights are operable. The generator requires about 3 to 5 min to warm up before the vacuum units are turned on one at a time (about 5 to 10 s apart to prevent excessive current loading on the generator). The amperage and voltage meters of the generator are also periodically checked. The generator and vacuums are left on during the complete subsampling period to lessen strain associated with multiple shutoffs and startups. Obviously, the sampling end of the vacuum hose needs to be carefully secured between subsamples to prevent contamination.

Figure 5.51 illustrates the general sampling procedure. Each subsample includes all of the street surface material that would be removed during a severe rain (including loose materials and caked-on mud in the gutter and street areas). The location of the subsample strip is carefully selected to ensure that it has no unusual loading conditions (e.g., a subsample should not be collected through the middle of a pile of leaves; rather, it is collected where the leaves are lying on the street in their normal distribution pattern). When possible, wet areas are avoided. If a sample is wet and the particles are caked around the intake nozzle, the caked mud from the gobbler is carefully scraped into the vacuum hose while the vacuum units are running. In addition, the hose needs to be struck against the ground at the end of the sampling period to knock loose any material stuck on the inside of the hose.

Subsamples are collected in a narrow strip about 6 in wide (the width of the gobbler) from one side of the street to the other (curb to curb). In heavily traveled streets where traffic is a problem, some subsamples consist of two separate one-half street strips (curb to crown). Traffic is not stopped for subsample collection; the operators wait for a suitable traffic break. On wide or busy roadways, a subsample is often collected from two strips several feet apart, halfway into the street. On busy roadways with no parking and good street surfaces, most particulates are found within a few feet of the curb, and a good subsample could be collected by vacuuming two strips adjacent to the curb

Figure 5.51 Street dirt subsample collection.

and as far into the traffic lanes as possible. Only a sufficient (and safe) break in traffic allows a subsample to be collected halfway across the street.

Subsamples taken in areas of heavy parking are collected between vehicles along the curb, as necessary. The sampling line across the street does not have to be a continuous line if a parked car blocks the most obvious and easiest subsample strip. A subsample can be collected in shorter (but very close) strips, provided the combined length of the strip is representative of different distances from the curb. Again, in all instances, each subsample must be representative of the overall curb-to-curb loading condition.

When sampling, the leading edge of the gobbler is slightly elevated above the street surface (0.125 in) to permit an adequate air flow and to collect pebbles and large particles. The gobbler is lifted further to accept larger material as necessary. If necessary, leaves in the subsample strip are manually removed and placed in the sample storage container to prevent the hose from clogging. If a noticeable decrease in sampling efficiency is observed, the vacuum hoses are cleaned immediately by disconnecting the hose lengths, cleaning out the connectors (placing the debris into the sample storage container), and reversing the air flows in the hoses (blowing them out by connecting the hose to the vacuum exhaust and directing the dislodged debris into the vacuum inlet). If any mud is caked on the street surface in the subsample strip, the sampler loosens it by scraping a shoe along the subsample path (being certain that street construction material is not removed from the subsample path unless it was very loose). Scraping caked-on mud is done after an initial vacuum pass. After scraping is completed, the strip is revacuumed. A rough street surface is sampled most easily by pulling (not pushing) the wand and gobbler toward the curb. Smooth and busy streets are usually sampled with a pushing action, away from the curb.

An important aspect of the sample collection is the speed at which the gobbler is moved across the street. A very rapid movement significantly decreases the amount of material collected; too slow a movement requires more time than is necessary. The correct movement rate depends on the roughness of the street and the amount of material on it. When sampling a street that has a heavy loading of particulates, or a rough surface, the wand needs to be pulled at a velocity of less than 1 ft/s. In areas of lower loading and smoother streets, the wand can be pushed at a velocity of 2 to 3 ft/s. The best indicators of the correct collection speed are achieved by visually examining how well the street is being cleaned in the sampling strip and by listening to the collected material rattle up the wand and through the vacuum hose. It is quite common to leave a visually cleaner strip on the street where the subsample was collected, even on streets that appeared to be clean before sampling.

In all cases, the hose tender must continuously watch traffic and alert the sampler of potentially hazardous conditions. In addition, the hose tender plays out the hose to the sampler as needed and keeps the hose as straight as possible to prevent kinking. If a kink develops, sampling is stopped until the hose tender straightens the hose. While working near the curb out of the traffic lane (typically an area of high loadings), the sampler visually monitors the performance of the vacuum sampler and periodically checks for vehicles. In the street, the sampler constantly watches traffic and monitors the collection process by listening to particles moving up the wand. A large break in traffic is required to collect dust and dirt from street cracks in the traffic lanes because the sampler has to watch the gobbler to make sure that all of the loose material in the cracks is removed.

When moving from one subsample location to another, the hose, wand, and gobbler need to be securely placed in the trailer. All subsamples are composited in the vacuums for each study area, and the hose must be placed away from the generator's hot muffler to prevent damage. The generator and vacuum units are left on and in the trailer during the entire subsample collection period. This helps dry damp samples and reduces the strain on the vacuum and generator motors.

The length of time it takes to collect all of the subsamples in an area varies with the number of subsamples and the test area road texture and traffic conditions. The number of subsamples required in each area can be determined using the experimental design sample effort equations described earlier in this chapter, with seasonal special sampling efforts to measure the variability

of street dirt loadings in each area. The variabilities can be measured using a single, small 1.5-hp industrial vacuum, with a short hose to make sample collection simpler. The vacuum needs to be emptied, the sample collected and placed in individual Ziploc™ baggies, and weighed (later in the lab) for each individual sample to enable the variability in loadings to be measured. As an example, during the first phase of the San Jose, CA, study (Pitt 1979), the test areas required the following sampling effort:

Test Area	No. of Subsamples	Sampling Duration, h
Downtown — poor (rough) asphalt street surface	14	0.5
Downtown — good (smooth) asphalt street surface	35	1
Keyes Street — oil and screens street surface	10	0.5–1
Keyes Street — good asphalt street surface	36	1
Tropicana — good asphalt street surface	16	0.5–1

In the oil and screens test area, the sampling procedure was slightly different because of the relatively large amount of pea gravel (screens) that was removed from the street surface. The gobbler attachment was drawn across the street more slowly (at a rate of about 3 s/ft). Each subsample was collected by a half pass (from the crown to the curb of the street) and therefore contained one half of the normal sample. Two curb-to-curb passes were made for each Tropicana subsample because of the relatively low particulate loadings in this area, as several hundred grams of sample material are needed for the laboratory tests. In addition, an "after" street cleaning subsample is not collected from exactly the same location as the "before" street cleaning subsample (they need to be taken from the same general area, but at least a few feet apart).

A field data record sheet kept for each sample contains:

- Subsample numbers
- Dates and time of the collection period
- Any unusual conditions or sampling techniques

Subsample numbers are crossed off as each subsample is collected. After cleaning, subsample numbers are marked if the street cleaner operated next to the curb at that location. This differentiation enables the effect of parked cars on street cleaning performance to be analyzed. In addition, photographs (and movies) are periodically made to document the methods and street loading conditions.

Sample Transfer

After all subsamples for a test area are collected, the hose and Y connections are cleaned by disconnecting the hose lengths, reversing them, and holding them in front of the vacuum intake. Leaves and rocks that may have become caught are carefully removed and placed in the vacuum can; the generator is then turned off. The vacuums are either emptied at the last station or at a more convenient location (especially in a sheltered location out of the wind and sun).

To empty the vacuums, the top motor units are removed and placed out of the way of traffic. The vacuum units are then disconnected from the trailer and lifted out. The secondary, coarse vacuum filters are removed from the vacuum can and are carefully brushed with a small stiff brush into a large funnel placed in the storage can. The primary dacron filter bags are kept in the vacuum can and shaken carefully to knock off most of the filtered material. The dust inside the can is allowed to settle for a few minutes, then the primary filter is removed and brushed carefully into the sample can with the brush. Any dirt from the top part of the bag where it is bent over the top of the vacuum is also carefully removed and placed into the sample can. Respirators and eye protection are necessary to minimize exposure to the fine dust.

After the filters are removed and cleaned, one person picks up the vacuum can and pours it into the large funnel on top of the sample can, while the other person carefully brushes the inside of the vacuum can with a soft 3- to 4-in paintbrush to remove the collected sample. In order to prevent excessive dust losses, the emptying and brushing is done in areas protected from the wind. To prevent inhaling the sample dust, both the sampler and the hose tender wear mouth and nose dust filters while removing the samples from the vacuums.

To reassemble the vacuum cans, the primary dacron filter bag is inserted into the top of the vacuum can with the filter's elastic edge bent over the top of the can. The secondary, coarse filter is placed into the can and assembled on the trailer. The motor heads are then carefully replaced on the vacuum cans, making sure that the filters are on correctly and the excess electrical cord is wrapped around the handles of the vacuum units. The vacuum hoses and wand are attached so that the unit is ready for the next sample collection.

The sample storage cans are labeled with the date, the test area's name, and an indication of whether the sample was taken before or after the street cleaning test, or if it was an accumulation (or other type) of sample. Finally, the lids of the sample cans are taped shut and transported to the laboratory for logging-in, storage, and analysis.

Measurements of Street Dirt Accumulation

The washoff of street dirt and the effectiveness of street cleaning as a stormwater control practice are highly dependent on the street dirt loading. Street dirt loadings are the result of deposition and removal rates, plus "permanent storage." The permanent storage component is a function of street texture and condition and is the quantity of street dust and dirt that cannot be removed naturally or by street cleaning equipment. It is literally trapped in the texture, or cracks, of the street. The street dirt loading at any time is this initial permanent loading plus the accumulation amount corresponding to the exposure period, minus the resuspended material removed by wind and traffic-induced turbulence. Removal of street dirt can occur naturally by winds and rain, or by human activity (by the turbulence of traffic or by street cleaning equipment). Very little removal occurs by any process when the street dirt loadings are small, but wind removal may be very large with larger loadings, especially for smooth streets (Pitt 1979).

It takes many and frequent samples to ascertain the accumulation characteristics of street dirt. The studies briefly described in the following paragraphs typically involved collecting many hundreds of composite street dirt samples during the course of the 1- to 3-year projects from each study area. With each composite sample made up of about 10 to 35 subsamples, a great number of subsamples were used to obtain the data. Without high resolution (and effective) sampling, it is not possible to identify the variations in loadings and effects of rains and street cleaning.

The most important factors affecting the initial loading and maximum loading values are street pavement texture and street pavement condition. When data from many locations are studied, it is apparent that smooth streets have substantially smaller street dirt loadings at any accumulation period compared to rough streets for the same land use. Very long accumulation periods relative to the rain frequency result in high street dirt loadings. During these conditions, the losses of street dirt to wind (as fugitive dust) may approximate the deposition rate, resulting in relatively constant street dirt loadings. At Bellevue, WA, typical inter-event rain periods average about 3 days. Relatively constant street dirt loadings were observed in Bellevue because the frequent rains kept the loadings low and very close to the initial storage value, with little observed increase in dirt accumulation over time (Pitt 1985). In Castro Valley, CA, the rain inter-event periods were much longer (ranging from about 20 to 100 days) and steady street dirt loadings were only observed after about 30 days when the loadings became very high and fugitive dust losses caused by the winds and traffic turbulence moderated the loadings (Pitt and Shawley 1982).

An example of the type of sampling needed to obtain accumulation rate values was conducted by Pitt and McLean (1986) in Toronto. They measured street dirt accumulation rates and the effects

of street cleaning as part of a comprehensive stormwater research project. An industrial street with heavy traffic and a residential street with light traffic were monitored about twice a week for 3 months. At the beginning of this period, intensive street cleaning (one pass per day for each of 3 consecutive days) was conducted to obtain reasonably clean streets. Street dirt loadings were then monitored every few days to measure the accumulation rates of street dirt. The street dirt sampling procedures previously described were used to clean many separate subsample strips across the roads, which were then combined for physical and chemical analyses.

In Toronto, the street dirt particulate loadings were quite high before the initial intensive street cleaning period and were reduced to their lowest observed levels immediately after the last street cleaning. After street cleaning, the loadings on the industrial street increased much faster than on the residential street. Right after intensive cleaning, the street dirt particle sizes were also similar for the two land uses. However, the loadings of larger particles on the industrial street increased at a much faster rate than on the residential street, indicating more erosion or tracking materials were deposited on the industrial street. The residential street dirt measurements did not indicate that any material was lost to the atmosphere as fugitive dust, likely due to the low street dirt accumulation rate and the short periods of time between rains. The street dirt loadings never had the opportunity to reach the high loading values needed before they could be blown from the streets by winds or by traffic-induced turbulence. The industrial street, in contrast, had a much greater street dirt accumulation rate and was able to reach the critical loading values needed for fugitive losses in the relatively short periods between the rains.

A street dirt sampling program must be conducted over a long enough period of time to obtain accumulation information. Infrequent observations hinder the analyses. It requires a continuous period of sampling, possibly with samples collected at least once a week, plus additional sampling close to the beginning and end of rains. Infrequent sampling, especially when interrupted by rains, does not allow changes in loadings to be determined. In addition, seasonal measurement periods are also likely needed because street dirt accumulation rates may change for different periods of the year. Infrequent and few samples may be useful to statistically describe the street dirt loading and to measure pollutant strengths associated with the samples, but they are not suitable for trend analyses. Chapter 7 presents statistical test procedures for identifying trends and should be consulted for different alternative methods to measure street dirt accumulation rates.

Small-Scale Washoff Tests

Washoff tests may be necessary to directly measure the energy available to dislodge and transport street dirt from paved areas to the drainage system. These tests are not usually conducted, as many rely on the process descriptions contained in commonly used stormwater models. Unfortunately, many of the process descriptions are in error due to improper interpretations of the test data. The following discussion therefore briefly describes these tests to encourage watershed researchers to obtain local data for accurate model calibration.

Observations of particulate washoff during controlled tests using actual streets and natural street dirt and debris are affected by street dirt distributions and armoring. The earliest controlled street dirt washoff experiments were conducted by Sartor and Boyd (1972) during the summer of 1970 in Bakersfield, CA. Their data were used in many stormwater models (including SWMM, Huber and Heaney 1981; STORM, COE 1975; and HSPF, Donigian and Crawford 1976) to estimate the percentage of the available particulates on the streets that would wash off during rains of different magnitudes. Sartor and Boyd used a rain simulator having many nozzles and a drop height of $1^1/_2$ to 2 m in street test areas of about 5 by 10 m. Tests were conducted on concrete, new asphalt, and old asphalt, using simulated rain intensities of about 5 and 20 mm/hour. They collected and analyzed runoff samples every 15 min for about 2 hours for each test. Sartor and Boyd fitted their data to an exponential curve, assuming that the rate of particle removal of a given size is proportional to the street dirt loading and the constant rain intensity:

$$dN/dt = krN$$

where: dN/dt = the change in street dirt loading per unit time
k = proportionality constant
r = rain intensity (in/hour)
N = street dirt loading (lb/curb-mile)

This equation, upon integration, becomes:

$$N = N_o e^{-krt}$$

where: N = residual street dirt load (after the rain)
N_o = initial street dirt load
t = rain duration

Street dirt washoff is therefore equal to N_o minus N. The variable combination rt, or rain intensity (in/h) times rain duration (h), is equal to total rain depth (R), in inches. This equation then further reduces to:

$$N = N_o e^{-kR}$$

Therefore, this equation is only sensitive to the total depth of the rain that has fallen since the beginning of the rain, and not rain intensity. Because of decreasing particulate supplies, the exponential washoff curve also predicts decreasing concentrations of particulates with time since the start of a constant rain (Alley 1980, 1981).

The proportionality constant, k, was found by Sartor and Boyd to be slightly dependent on street texture and condition, but was independent of rain intensity and particle size. The value of this constant is usually taken as 0.18/mm, assuming that 90% of the particulates will be washed from a paved surface in 1 hour during a 13 mm/hour rain. However, Alley (1981) fitted this model to watershed outfall runoff data and found that the constant varied for different storms and pollutants for a single study area. Novotny (as part of Bannerman et al. 1983) also examined "before" and "after" rain event street particulate loading data from the Milwaukee Nationwide Urban Runoff Program (NURP) project and found almost a threefold difference between the constant value of k for fine (<45 μm) and medium-sized particles (100 to 250 μm). The calculated values were 0.026/mm for the fine particles and 0.01/mm for the medium-sized particles, both much less than the "accepted" value of 0.18/mm. Jewell et al. (1980) also found large variations in outfall "fitted" constant values for different rains compared to the typical default value. Either the assumption of the high removal of particulates during the 13 mm/hour storm was incorrect or the equation cannot be fitted to outfall data (most likely, as this would require that all the particulates originate from homogeneous paved surfaces during all storm conditions).

This washoff equation has been used in many stormwater models, along with an expression for an availability factor. An availability factor is needed, as N_o is only the portion of the total street load available for washoff. This availability factor (the fraction of the total street dirt loading available for washoff) is generally used as 1.0 for all rain intensities greater than about 18 mm/hour and reduces to about 0.10 for rains of 1 mm/hour.

The Bellevue, WA, urban runoff project (Pitt 1985) included about 50 pairs of street dirt loading observations close to the beginnings and ends of rains. Very large reductions in street dirt loadings during rains were observed in Bellevue for the smallest particles, but the largest particles actually increased in loadings (due to deposited erosion materials originating from off-street areas). The particles were not source limited, but armor shielding may have been important. Most of the

particulates in the runoff were in the fine particle sizes (<63 μm). Very few particles greater than 1000 μm were found in the washoff water. Care must be taken to not confuse street dirt particle size distributions with stormwater runoff particle size distributions. The stormwater particle size distributions are much more biased toward the smaller sizes, as described later.

Washoff tests can be designed to investigate several important factors and interactions that may affect washoff of different sized particulates from impervious areas (Pitt 1987):

- Street texture
- Street dirt loading
- Rain intensity
- Rain duration
- Rain volume

Multiple parameters that may affect a process can be effectively evaluated using factorial tests as described by Box et al. (1978) and earlier in this chapter. As an example, the tests conducted by Pitt (1987) were arranged as an overlapping series of 2^3 factorial tests, one for each particle size and rain total, and were analyzed using factorial test procedures. Nonlinear analyses were also used to identify a set of equations to describe the resulting curve shapes. The differences between available and total loads were also related to the experimental factors. This experimental setup can be effectively repeated elsewhere, with possible adjustments in the levels used in the experiments to reflect local conditions.

All tests were conducted for about 2 hours, with total rain volumes ranging from about 5 to 25 mm. The test code explanations follow:

Test Code	Rain Intensity	Street Dirt Loading	Street Texture
HCR	High	Clean	Rough
HDR	High	Dirty	Rough
LCR	Light	Clean	Rough
LDR	Light	Dirty	Rough
HCS	High	Clean	Smooth
HDS	High	Dirty	Smooth
LCS	Light	Clean	Smooth
LDS	Light	Dirty	Smooth

Unfortunately, the streets during the LDS (light rain intensity; dirty street; smooth texture) test were not as dirty as anticipated and actually replicated the LCS tests. The experimental analyses were modified to indicate these unanticipated duplicate observations.

A simple artificial rain simulator was constructed using 12 lengths of "soaker" hose, suspended on a wooden framework about 1 m above the road surface (Figures 5.52 and 5.53). "Rain" was applied by connecting the hoses to a manifold having individual valves to adjust constant

Figure 5.52 Washoff test site in Toronto.

Figure 5.53. Runoff collection area for Toronto washoff tests.

Figure 5.54. Sprinklers at freeway washoff test site in Austin, TX.

Figure 5.55 Sampler and rain gauge location at Austin freeway washoff test site.

rain intensities for the different areas. The manifold was in turn connected to a fire hydrant. The flow rate needed for each test was calculated based on the desired rain intensity and the area covered. The flow rates were carefully monitored by using a series of ball flow gauges before the manifold. The distributions of the test rains over the study areas were also monitored by placing about 20 small graduated cylinders over the area during the rains. In order to keep the drop sizes representative of sizes found during natural rains, the surface tension of the water drops hanging on the plastic soaker hoses was reduced by applying a light coating of Teflon spray to the hoses.

A different washoff test site is shown in Figures 5.54 through 5.56, where large sprinklers were located along the side of a freeway in Austin, TX. The sprinklers rained water directly onto the freeway during traffic conditions to better represent the combined effect of rain and auto-induced turbulence. Unfortunately, in order to get "rain" over a substantial area of the freeway, the "rain intensity" was extremely high, supplying much more energy than was typical, even for extreme events. In addition, this setup, while useful in obtaining hard-to-get data, may also have imposed an unusually high accident risk to freeway users (although large amounts of publicity, signage, and available alternate routes were all used to reduce this risk). This semipermanent installation was also used to monitor runoff from natural rains for comparison.

It was difficult to obtain even distributions of rain during the light rain tests in Toronto using the manifold, so a single hose was used that was manually moved back and forth over the test area during the smaller rain tests (three people took 30-min shifts). To keep evaporation reasonable for the rain conditions, the test sites were also shaded during sunny days. Blank water samples were also obtained from the manifold for background residue analyses. The filterable residue of the "rain" water (about 185 mg/L) could cause substantial errors when calculating washoff.

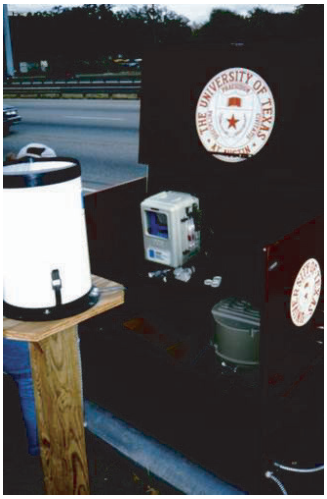

Figure 5.56. Sampler and flow monitoring equipment at Austin freeway washoff test site.

The areas studied were about 3 by 7 m each. The street side edges of the test areas were edged with plywood, about 30 cm in height and embedded in thick caulking, to direct the runoff toward the curbs with minimal leakage. All runoff was pumped continuously from downstream sumps (made of caulking and plastic sand bags) to graduated 1000-L Nalgene containers. The washoff samples were obtained from the pumped water going to the containers every 5 to 10 min at the beginning of the tests, and every 30 min near the end of the test. Final complete rinses of the test areas were also conducted (and sampled) at the tests' conclusions to determine total loadings of the monitored constituents.

The samples were analyzed for total residue, filtrate residue, and particulate residue. Runoff samples were also filtered through 0.4-μm filters and microscopically analyzed (using low power polarized light microscopes to differentiate between inorganic and organic debris) to determine particulate residue size distributions from about 1 to 500 μm. The runoff flow quantities were also carefully monitored to determine the magnitude of initial and total rainwater losses on impervious surfaces.

These tests are different from the important early Sartor and Boyd (1972) washoff experiments in the following ways:

- They were organized in overlapping factorial experimental designs to identify the most important main factors and interactions.
- Particle sizes were measured down to about 1 μm (in addition to particulate residue and filterable residue measurements).
- The precipitation intensities were lower in order to better represent actual rain conditions of the upper Midwest.
- Observations were made with more resolution at the beginning of the tests.
- Washoff flow rates were frequently measured.
- Emphasis was placed on total street loading, not just total available loading.
- Bacteria population measurements were also periodically obtained.

Sampling of Atmospheric Contributions

Atmospheric processes affecting urban runoff pollutants include dry dustfall and precipitation quality. These have been monitored in many urban and rural areas. In many instances, however, the samples were combined as a bulk precipitation sample before processing. Automatic precipitation sampling equipment can distinguish between dry periods of fallout and precipitation. These devices cover and uncover appropriate collection jars exposed to the atmosphere. Much of this information has been collected as part of the Nationwide Urban Runoff Program (NURP) and the Atmospheric Deposition Program, both sponsored by the U.S. Environmental Protection Agency (EPA 1983a).

One must be very careful in interpreting this information, however, because of the ability of many polluted dust and dirt particles to be resuspended and then redeposited within the urban area. In many cases, the atmospheric deposition measurements include material that previously resided and was measured in other urban runoff pollutant source areas. Also, only small amounts of the atmospheric deposition material would directly contribute to runoff. Rain is subjected to infiltration and the dry-fall particulates are most likely incorporated with surface soils and only small fractions are then eroded during rains. Therefore, mass balances and determinations of urban runoff deposition and accumulation from different source areas can be highly misleading, unless transfer of material between source areas and the effective yield of this material to the receiving water is considered. Depending on the land use, relatively little of the dustfall in urban areas likely contributes to stormwater discharges. The major exception would be dustfall directly on receiving waters.

Dustfall and precipitation affect all of the major urban runoff source areas in an urban area. Dustfall, is typically not a major pollutant source, but fugitive dust is mostly a mechanism for

pollutant transport. Most of the dustfall monitored in an urban area is resuspended particulate matter from street surfaces or wind erosion products from vacant areas (Pitt 1979). Point source pollutant emissions can also significantly contribute to dustfall pollution, especially in industrial areas. Transported dust from regional agricultural activities can also significantly affect urban stormwater.

Wind-transported materials are commonly called "dustfall." Dustfall is normally measured by collecting dry samples, excluding rainfall and snowfall. If rainout and washout are included, one has a measure of total atmospheric fallout. This total atmospheric fallout is sometimes called "bulk precipitation." Rainout removes contaminants from the atmosphere by condensation processes in clouds, while washout is the removal of contaminants by the falling rain. Therefore, precipitation can include natural contamination associated with condensation nuclei in addition to collecting atmospheric pollutants as the rain- or snowfalls. In some areas, the contaminant contribution by dry deposition is small, compared to the contribution by precipitation (Malmquist 1978). However, in heavily urbanized areas, dustfall can contribute more of an annual load than the wet precipitation, especially when dustfall includes resuspended materials.

Much of the monitored atmospheric dustfall and precipitation would not reach the urban runoff receiving waters. The percentage of dry atmospheric deposition retained in a rural watershed was extensively monitored and modeled in Oakridge, TN (Barkdoll et al. 1977). They found that about 98% of the lead in dry atmospheric deposits was retained in the watershed, along with about 95% of the cadmium, 85% of the copper, 60% of the chromium and magnesium, and 75% of the zinc and mercury. Therefore, if the dry deposition rates were added directly to the yields from other urban runoff pollutant sources, the resultant urban runoff loads would be very much overestimated.

Rubin (1976) stated that resuspended urban particulates are returned to the earth's surface and waters in four main ways: gravitational settling, impaction, precipitation, and washout. Gravitational settling, as dry deposition, returns most of the particles. This not only involves the settling of relatively large fly ash and soil particles, but also the settling of smaller particles that collide and coagulate. Rubin stated that particles that are less than 0.1 μm in diameter move randomly in the air and collide often with other particles. These small particles can grow rapidly by this coagulation process. They would soon be totally depleted in the air if they were not constantly replenished. Particles in the 0.1 to 1.0 μm range are also removed primarily by coagulation. These larger particles grow more slowly than the smaller particles because they move less rapidly in the air, are somewhat less numerous, and, therefore, collide less often with other particles. Particles with diameters larger than 1 μm have appreciable settling velocities. Those particles about 10 μm in diameter can settle rapidly, although they can be kept airborne for extended periods and for long distances by atmospheric turbulence.

The second important particulate removal process is impaction. Impaction of particles near the earth's surface can occur on vegetation, rocks, and building surfaces. The third form of particulate removal from the atmosphere is precipitation, in the form of rain and snow. This is caused by the rainout process in which the particulates are removed in the cloud-forming process. The fourth important removal process is washout of the particulates below the clouds during the precipitation event. Therefore, it is easy to see that reentrained particles (especially from street surfaces, other paved surfaces, rooftops, and from soil erosion) in urban areas can be readily redeposited through these various processes, either close to the points of origin, or some distance away.

Pitt (1979) monitored airborne concentrations of particulates near typical urban roads using Climat Particle Counters (Figure 5.57). He found that on a particle count basis, the downwind roadside particulate concentrations were about 10% greater than upwind conditions. About 80% of the concentration increases, by particle count, were associated with particles in the 0.5 to 1.0 μm range. However, about 90% of the particle concentration increases by weight were associated with particles greater than 10 μm. He found that the rate of particulate resuspension from street surfaces increases when the streets are dirty (cleaned infrequently) and varied widely for different street and traffic conditions. The resuspension rates were calculated based upon observed long-term accumulation conditions on street surfaces for many different study area conditions, and varied from about 0.30 to 3.6 kg/curb-km (1 to 12 lb/curb-mile) of street per day.

Figure 5.57 Hi-vol suspended particulate sampler, along with particle counters and wind velocity meters used to measure fugitive dust losses caused by traffic-induced turbulence and dirty roads in San Jose, CA, tests.

Murphy (1975) described a Chicago study in which airborne particulate material within the city was microscopically examined, along with street surface particulates. The particulates from both of these areas were found to be similar (mostly limestone and quartz) indicating that the airborne particulates were most likely resuspended street surface particulates, or were from the same source. PEDCo (1977) found that the reentrained portion of the traffic-related particulate emissions (by weight) is an order of magnitude greater than the direct emissions accounted for by vehicle exhaust and tire wear. They also found that particulate resuspensions from a street are directly proportional to the traffic volume and that the suspended particulate concentrations near the streets are associated with relatively large particle sizes. The medium particle size found, by weight, was about 15 μm, with about 22% of the particulates occurring at sizes greater than 30 μm. These relatively large particle sizes resulted in substantial particulate fallout near the road. They found that about 15% of the resuspended particulates fall out within 10 m, 25% within 20 m, and 35% within 30 m from the street (by weight). In a similar study Cowherd et al. (1977) reported a wind erosion threshold value of about 5.8 m/s (13 mph). At this wind speed, or greater, significant dust and dirt losses from the road surface could result, even in the absence of traffic-induced turbulence. Rolfe and Reinbold (1977) also found that most of the particulate lead from automobile emissions settled out within 100 m of roads. However, the automobile lead does widely disperse over a large area. They found, through multielemental analyses, that the settled outdoor dust collected at or near the curb was contaminated by automobile activity and originated from the streets.

The experimental design and interpretation of atmospheric contributions must therefore be done carefully. Measurements can be obtained using numerous procedures, as summarized below:

- Conventional air pollution monitoring equipment, especially hi-vol samplers for particulates. The captured particulates can be chemically analyzed for pollutants, especially heavy metals.
- Real-time air pollution monitoring equipment, such as nephelometers and particle counters (Figure 5.57). These are especially useful for short-term measurements of resuspended particulates from nearby pavements to indicate turbulence effects from vehicles or natural winds. They are also useful for fugitive dust measurements from construction sites and can also be used to indicate the effects of vehicular traffic and wind losses from construction roads, etc.
- Sticky paper fugitive dust samplers. These are simple upright cylinders about 10 cm in diameter and 20 cm in height that are carefully oriented to enable moderate- or long-term measurements of fugitive dust losses from specific directions. Simple measurements are made by comparing the color and tone of the exposed paper for different exposed directions to standards. The exposed

Figure 5.58 Wet-dry atmospheric deposition sampler in Bellevue, WA.

Figure 5.59 Large surface area used to capture sufficient rain for chemical analyses in early San Jose, CA, tests.

paper can also be examined under a microscope for more specific measurements and identification of particle characteristics.

- Wet- and dry-fall automatic samplers (Figure 5.58). These were commonly used during the EPA's NURP and Atmospheric Deposition Program and allow long-term sampling of dustfall during dry weather and rainwater during wet weather. A lid, connected to a moisture sensor, automatically moves to cover the appropriate sampling bucket. The collected samples are rinsed from the appropriate buckets after the desired exposure periods and chemically analyzed. If a single bucket sampler is used (without the automatic lid), then the dry dustfall and the rainwater samples are combined in one sample for a bulk precipitation analysis. Evaporation of the rainwater sample and obvious chemical transformations occur in these samplers during the typically long-term exposures. These samplers are therefore most useful for evaluations for stable compounds (such as suspended solids and most heavy metals) and are not very suitable for nutrient, bacteria, or organic analyses.
- Precipitation sampler. Because rainwater has little buffer capacity, short-term collections of rainwater are needed for many constituents (especially major ions, pH, and nutrients). However, in order to collect sufficient sample volume in a short period, a large collection area is needed. One simple solution is to construct a large collection area using a plastic tarp supported around its edges (Figure 5.59). The tarp is allowed to sag toward the center, where a weight surrounds a central hole that is located over an appropriate sample bottle. A tarp having about a 10 m^2 surface area can collect several liters of rainwater in a few minutes during a relatively light rainfall. Of course, potential contamination of the sample is possible through the use of the tarp. For a semipermanent installation, it would be possible to construct a relatively large collection area using a piece of glass (being careful of joint materials), or a Teflon-coated surface could be used with fewer interferences than a plastic surface. See the earlier discussion on sample contamination potential from various materials. Many laboratory suppliers sell Teflon-coated sticky paper that is used for covering laboratory benches. It may be possible to use this material to cover a simple seamless rigid platform, having a central trough for rainwater collection.

SEDIMENT AND PORE WATER SAMPLING

Sediment Sampling Procedures

As discussed previously, sediments act as sinks and sources of contaminants and have been implicated as the cause of beneficial use impairments, such as fish consumption advisories, at

numerous sites throughout North America. Sediments that should be targeted as potential problem sources during any receiving water assessment are the small-grained, depositional-type sediments in urban, industrial, and agricultural drainages. Stormwater discharges can cause metal and organic chemicals, nutrients, and pathogens to accumulate in depositional sediments. These contaminants then may enter groundwater or reenter surface waters for further transport, or contaminate resident organisms and the overlying food web (see also Chapter 6). Once stormwater flows subside, the influence of contaminated sediments on overlying water persists and even increases during low flow conditions. Even though the short-term BOD of stormwater is not very high (BOD_5 of about 25 mg/L), the long-term BOD (BOD_{90} of about 250 mg/L) is high and resulting accumulations of organic debris in urban streams create anaerobic sediment conditions (Pitt 1979). These depositional sediments will continue to degrade in quality as long as organic and contaminant loadings continue, resulting in replacement with pollution-tolerant benthic macroinvertebrates, such as midges and worms, and also degrade the fish community (Burton and Scott 1992). Assessing the role of sediments in beneficial use attainment and ecosystem health is a necessary aspect of a receiving water investigation. As noted previously, heavy metals and nutrient and organic toxicants are of most interest in urban stream sediments while nutrients and pesticides are of primary concern in agricultural waterways. Pathogens may be a problem in either urban or agricultural watersheds. Contaminated stream sediments likely impart the most important impairments to aquatic life in urban areas (after direct habitat destruction and frequent high flows) and may also in agricultural areas. Collecting and analyzing these sediments and their biota are therefore necessary to establish water quality and the sources of any degradation.

In many ways, sampling and evaluating the quality of sediments is more difficult than water quality sampling. Though sediments vary less than waters on a temporal basis, they exhibit greater variation spatially, in a complex, semisolid, three-dimensional structure. Understanding and preserving this structure has tremendous ramifications in the assessment process. The surficial sediment layers that interface with overlying waters are the most dynamic and recent sediments, subject to resuspension and downstream deposition, oxidation, and rapid changes in quality based on overlying water conditions. As sediment depth increases, the biological communities and chemical conditions may change orders of magnitude over a millimeter to centimeter scale. This has been observed in oxygen-redox vertical gradients (Carlton and Klug 1990) and toxicity (horizontally and vertically) (Stemmer et al. 1990b). In addition to the high degree of heterogeneity often observed, maintaining sediment structure integrity is crucial when attempting to characterize the sample based on physical (e.g., redox potential, percent fines), chemical (e.g., metal speciation, nutrient concentration and speciation, volatile components), biological (e.g., biotransformations, microbial-meiofaunal communities), and toxicity (e.g., contaminant bioavailability) characteristics (ASTM 1991b; Burton 1992b). Maintaining complete sediment integrity is nearly impossible since the very process of sample collection is disruptive (Figure 5.60). There are effective methods, however, by which to reduce this disruption (see also Chapter 6). The importance of maintaining sample integrity depends on the type of problem and the data quality objectives (DQOs) of the study. Several guidance documents exist that address sediment sampling in detail. The most comprehensive and current guidance documents to date include ASTM 1994 and EPA 2001.

Figure 5.60 The fine-grained and muddy nature of most urban sediments requires specific sediment sampling procedures.

Disrupting the sensitive sediment environment is a major concern when collecting samples for toxicity studies, since the bioavailability and resulting toxicity can change significantly when in-place sediments are disturbed. An additional major concern is that the sediment depth sampled and chemically analyzed matches that being assessed for organism exposure (indigenous organisms and/or toxicity and bioaccumulation using surrogate species). Too often sediment grab samples are collected at unknown sediment depths (0 to 30 cm). The sediments are homogenized and then subsampled for chemical and physical analyses. Contaminant peaks occurring near the surface or deeper in the sediments may be diluted via the mixing process and then compared to biological effects. Resident benthic organisms are likely not being exposed to the same chemicals or concentrations that result from this process. In addition, laboratory toxicity testing will yield results that may bear little resemblance to field conditions. Therefore, it is best to establish whether recent or historical contamination is a concern, sample the appropriate sediment depth, and match the chemical analyses with realistic organism exposures.

A number of sampling-related factors can contribute to loss of the sediment sample's original characteristics, including sampler-induced pressure waves, washout of fine-grained sediments during retrieval, compaction due to sampler wall friction, sampling vessel or person-induced disturbance of surficial layers, disruption during subsampling or transport, oxidation, and temperature alterations. While it is impossible to remove all of these factors from routine assessments, reducing their influence increases the certainty that the data generated and resulting weight-of-evidence conclusions will be reliable.

Choosing the most appropriate sediment sampler for a study will depend on the sediment's characteristics, the volume and efficiency required, and the study's objective (Tables 5.16 through 5.18; Figures 5.61 through 5.63). Numerous sediment samplers are available. Two general categories include core samplers (which can obtain samples that can be analyzed by depth) and surface grab samplers (which only collect surface sediment). ASTM (1995) standard 4823 contains much information concerning core sampling in unconsolidated sediments that is applicable to urban streams. ASTM standard E 1391 also presents additional useful information concerning the sampling of sediment for toxicological testing. The preferred sampling method is to use core samplers whenever possible. However, they collect relatively little sediment and represent only a very small area. In addition, it may be difficult to retain samples in the samplers for retrieval in some types of bottom conditions (especially sandy sediment).

Grab samplers only collect samples from the surface layers of the sediment (10 to 50 cm in depth, at maximum). They also greatly disturb the sediment that is being sampled. Common problems include shallow depth of penetration and presence of a shock wave that results in loss of the fine surface sediments. However, they are much easier to use than corers under a wide variety of conditions. A common grab sampler is the Ponar sampler (Figures 5.64 through 5.67). It comes in a standard size and a "petite" size that weighs substantially less and is more practical for urban streams. The Ponar sampler is useful for sand, silt, and clay sediments and can be used in relatively deep water or shallow waters. It has a flexible cover over a top screen that helps to minimize the loss of fines during sampling. Forestry Suppliers, Inc. (800-543-4203) sells a petite 6" × 6" Wildco Ponar bottom dredge (catalog #77250 for about $450) and a larger 9" × 9" Wildco Ponar bottom dredge (catalog #77249 for about $800). The Peterson grab sampler is similar to the Ponar, but doesn't have a screened top plate. It is heavy and is more suitable for deeper water and harder clay bottoms than the Ponar sampler. Because of its weight, it requires the use of a winch. Cole Parmer (800-323-4340) sells a Peterson dredge sampler (catalog #H-05472-00 for about $1000). An Ekman sampler is also commonly used in small urban streams and ponds, but is limited to sampling soft bottoms. Forestry Suppliers, Inc. sells a light 6" × 6" Wildco–Ekman bottom dredge (catalog #77251 for about $350, including line, messenger, and case). Cole Parmer also sells a larger 9" × 9" Ekman dredge (catalog #H-05470-10 for about $600).

Dredge samplers that quantitatively sample surface sediments have been described (Grizzle and Stegner 1985). The depth profile of the sample may be lost in the removal of the sample from the

Table 5.16 Popular Sediment Samplers: Strengths and Weaknesses

Sampler	Strengths	Weaknesses
	Core Samplers	
Hand and gravity corers 0–30 cm depth 0.1–1.5 L volume	Maintains sediment layering of inner core. Fine surficial sediments retained. Replicate samples efficiently obtained. Removable liners. Inert liners may be used. Quantitative sampling allowed.	Small sample volume. Liner removal required for repetitive sampling. Not suitable in large-grain or consolidated sediments. Spillage possible.
Freeze core sampler 0–1 m depth 1 L volume	Maintains sediment layering of core. Fine sediments retained. Replicates samples efficiently obtained. Can be made of inert materials.	Small sample volume. Freezing may disturb sediment. Uses liquid CO_2 or dry ice for collecting sample. Requires several minutes to obtain each sample. May not collect large material. Not suitable for consolidated sediments.
Box corer 0–50 cm depth 1–30 L volume	Maintains sediment layering of large volume of sediment. Surficial fines retained relatively well. Quantitative sampling allowed.	Size and weight require power winch, difficult to handle and transport. Not suitable in consolidated sediments.
Vibratory corers 3–6 m depth 6–13 L volume	Samples deep sediments for historical analyses. Samples consolidated sediments. Minimal disturbance. May be used on small vessels.	Expensive and requires winch. Outer core integrity slightly disrupted.
	Grab Samplers	
Ekman or box dredge 0–10 cm depth Up to 3.5 L volume	Relatively large volume may be obtained. May be subsampled through lid. Lid design reduces loss of surficial sediments as compared to many dredges. Usable in moderately compacted sediments of varying grain sizes.	Loss of fines may occur during sampling. Incomplete jaw closure occurs in large-grain sediments or with large debris. Sediment integrity disrupted. Not an inert surface.
Ponar 0–10 cm depth Up to 1 L volume (petite) Up to 7.5 volume (standard)	Commonly used. Large volume obtained. Adequate on most substrates. Weight allows use in deep waters.	Loss of fines and sediment integrity occurs. Incomplete jaw closure occurs occasionally. Not an inert surface.
Van Veen or Young Grab 0–30 cm depth Up to 75 L volume	Useful in deep waters and on most substrates. Young grab coated with inert polymer. Large volume obtained.	Loss of fines and sediment integrity occurs. Incomplete jaw closure possible. Van Veen has metal surface. Young is expensive. Both may require winch.
Peterson 0–30 cm depth Up to 9.5 L volume	Large volume obtained from most substrates in deep waters.	Loss of fines and sediment integrity. Not an inert surface. Incomplete jaw closure may occur. May require winch.
Orange-Peel 0–30 cm depth 10–20 L volume	Large volume obtained from most substrates. Efficient closure.	Loss of fines and sediment integrity. Not an inert surface. Requires winch.
Shipek 0–10 cm depth Up to 3 L volume	Adequate on most substrates.	Small volume. Loss of fines and sediment integrity. Not an inert surface.

Modified from ASTM (American Society for Testing and Materials). *Standard Guide for Collection, Storage, Characterization, and Manipulation of Sediments for Toxicological Testing*. American Society for Testing and Materials, Philadelphia, Standard E 1391. 1991.

Table 5.17 Sediment and Interstitial Water Sampler Selection Guidelines

1. Sediment grain size effects on sampler selection
   - Silt-clay = core, grab, or peeper*
   - Sand = grab or peeper
   - Cobble = peeper
2. Sediment compacted: powered core
3. Sediment vertical gradient must be maintained: core or peepers
4. Sediment volumes
   Large volumes over small vertical gradients: dredge
   Small to moderate volumes: dredge, core, or peeper
5. Optimal samplers, in order of maintaining original sediment characteristics:
   1. *In situ* peeper*
   2. *In situ* suction*
   3. Core
   4. Grab
   5. Dredge
6. Optimal methods of collecting interstitial water (in order of preference, see Table 5.18)
   1. *In situ* peepers
   2. *In situ* suction (airstone or core-port)
   3. Centrifugation @ 10,000 × *g* (4°C) (without subsequent filtration)
   4. Centrifugation @ lower speeds
   5. Basal cup
   6. Squeezing or pressurization
   7. Suction or filtration

* For interstitial water collection only.

sampler. Dredge sampling promotes loss of not only fine sediments, but also water-soluble compounds and volatile organic compounds present in the sediment (ASTM 1991a). A comparison of sampler precision for macrobenthic purposes showed the Van Veen sampler to be the least precise; the most precise were the corers and Ekman dredge (Figures 5.68 and 5.69). The Smith–McIntyre and Van Veen samplers are more commonly used in marine studies, due to their weight. Shipek samplers are also used in marine investigations but may lose the top 2 to 3 cm of sediment fines from washout (Mudroch and MacKnight 1991).

Many of the problems associated with dredge samplers are largely overcome with the corers. The best corers for most sediment studies are hand-held polytetrafluoroethylene plastic, high-density polyethylene, or glass corers (liners), or large box corers. Corer samplers can penetrate the sediment by several meters, but that is rarely necessary (or possible) in urban receiving water studies. Their most important advantage is that samples collected by corers can be separated by depth for analyses. However, conventional corer samplers are difficult to use in the highly variable bottom sediment conditions commonly found in urban streams. The freezing core samplers, described later, overcome many of the sample loss and disturbance problems associated with conventional corers.

If used correctly, box corers can maintain the integrity of the sediment surface while collecting a sufficient depth for most toxicity studies. Conventional gravity corers may compress the sediment as evidenced by altered pore water alkalinity gradients, and box coring was superior for studies of *in situ* gradients (Lebel et al. 1982). The box core can be subcored or sectioned at specific depth intervals, as required by the study. Unfortunately, the box corer is large and cumbersome; thus, it is difficult to use and usually requires a lift capacity of 2000 to 3000 kg. Box cores typically require fine-grained sediments of at least a 30 cm depth. Other coring devices that have been used successfully include the percussion corer (Gilbert and Glew 1985), vibratory corers (Imperato 1987; Figure 5.70), and freeze corers (Pitt 1979; Spliethoff and Hemond 1996; Figures 5.71 and 5.72).

When only chemical testing is to be conducted (that is, not toxicity testing), a useful type of corer sampler is the freezing core sampler. Sediments to be used for SOD, BOD, or toxicity

Table 5.18 Optimal Interstitial Water Collection Methods

Device	Sediment Depth (cm)	Volume (cm^3)	Advantages	Disadvantages
Peeper	0.2–10	1–500	Most accurate method, reduced artifacts, no lab processing; relatively free of temperature, oxidation, and pressure effects; inexpensive and easy to construct; some selectivity possible on nature of sample via specific membranes, wide range of membrane/mesh pore sizes, and/or internal solutes or substrates.	Deployment easiest by hand. in >0.6-m depth waters; allow hours to days for equilibration, which will vary with site and chamber; methods not standardized and used infrequently; some membranes such as dialysis/cellulose are subject to biofouling; must deoxygenate chamber and materials to prevent oxidation effects; some chambers only allow small sample volumes; care must be used on collection to prevent sample oxidation.
In situ suction	0.2–30	1–250	Reduced artifacts, gradient definition; shallow water (<60 m) air stone method ease; core method deployment may not require diving in deep water, rapid collection, no lab processing; closed system possible which prevents contamination; methods include air stone, syringes, probes, and cores.	Requires custom, nonstandard collection devices; small volumes; limited to softer sediments; core method may require diving for waters; methods used infrequently and by limited numbers of laboratories.
Centrifugation	—	Sampler dependent	Most accurate of lab processing methods; allows anoxic/cold processing; large volumes; commonly used.	Some chemical loss/alteration; results depend on centrifugation conditions; requires high-speed centrifuge; difficult with sandy sediments.
Suction	—	Sampler dependent	Use with all sediment types; may process in field; large volumes possible with some sediments; closed system possible.	Alteration of chemical characteristics may occur; increased loss of metals and organics; loss of vertical gradient resolution.
Squeezing	—	Sampler dependent	Use with all sediment types; may process in field; large volumes possible with some.	Alteration of chemical characteristics may occur; increased loss of metals and organics; loss of vertical gradient resolution sediments.

Note: Incorporation of filtration into any of the collection methods may result in loss of metal and organic compounds.

testing should not be frozen, as the bioavailability of nutrients and toxicants is altered. All of the freezing core samplers rely on CO_2 (either as a liquid or a solid — dry ice). The use of CO_2 must be carefully evaluated and minimized in consideration of its role as a greenhouse gas. Pitt (1979) devised a freezing core sampler to collect profiles in sandy deposits of catchbasins that would also work well in shallow streams. This sampler was a 19-mm-diameter stainless steel tube, with a stainless steel point attached to one end. This was pushed into the sediment. A length of flexible 6 mm copper tubing was then inserted into the free end of the stainless probe (which is above the water depth), extending to the bottom of the stainless probe. The other end of the copper tubing was attached to a high-pressure hose and to a valve on a CO_2 fire extinguisher. The fire extinguisher was modified with a valve in place of the standard squeeze release, and

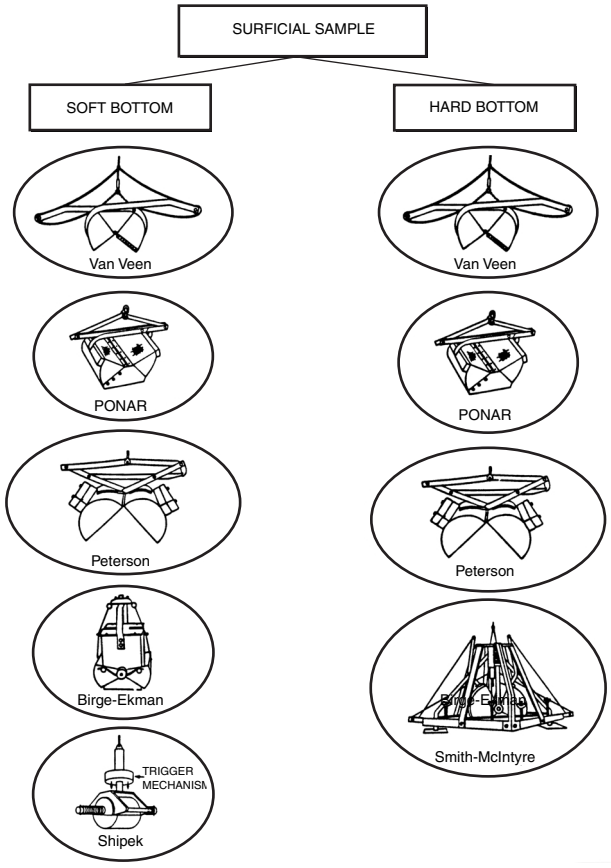

Figure 5.61 Some recommended devices for collecting surficial sediments. (From EPA. *Methods for Collection, Storage and Manipulation of Sediments for Chemical and Toxicological Analyses.* Office of Water. U.S. Environmental Protection Agency. Washington, D.C. In press.)

with an internal "delivery" tube that extended to the bottom of the fire extinguisher. This enabled liquid CO_2 to be delivered to the probe sampler, instead of gaseous CO_2 from the top of the fire extinguisher tank (the fire extinguisher is kept upright during operation). The valve was opened slightly and a continuous flow of CO_2 was delivered to the stainless steel probe (Figure 5.71). Care must be taken to turn off the flow of CO_2 at the fire extinguisher if it appears that a jam has occurred inside the probe (such as from ice forming due to water inside the probe sampler). The vaporization of the liquid CO_2 quickly chills the probe and freezes the sediment sample to the outside of the tube. In operation, the CO_2 is allowed to flow for about 1 min, but this can be changed depending on specific conditions and desired sample thickness. The probe is then removed from the sediment (with the sediment frozen to the outside) after the CO_2 flow is terminated and the copper tube is withdrawn. The probe with frozen sample is then laid on a stainless steel tray and the sample is removed by section and bottled separately, according to desired depth. A flame torch can be used to gently heat the probe uncovered by sample to allow the easier removal of the sample. It may be difficult to separate the sample into precise segments unless the sample is allowed to warm slightly first.

Another version of a freezing core sampler suitable for deeper water use was described by Spliethoff and Hemond (1996). They developed two versions of core samplers using dry ice within a probe that was used to measure the history of heavy metal contamination in an urban lake. One sampler (Figure 5.72) was made of a 96-cm length of 7.6-cm-diameter aluminum tubing. The bottom half of the tube was cut away lengthwise, and a flat aluminum plate was welded to act as a freezing surface. Stabilizing fins were also attached, along with weights to control penetration. PVC was also used to insulate the sampler where sample was not wanted. The sampler nose piece

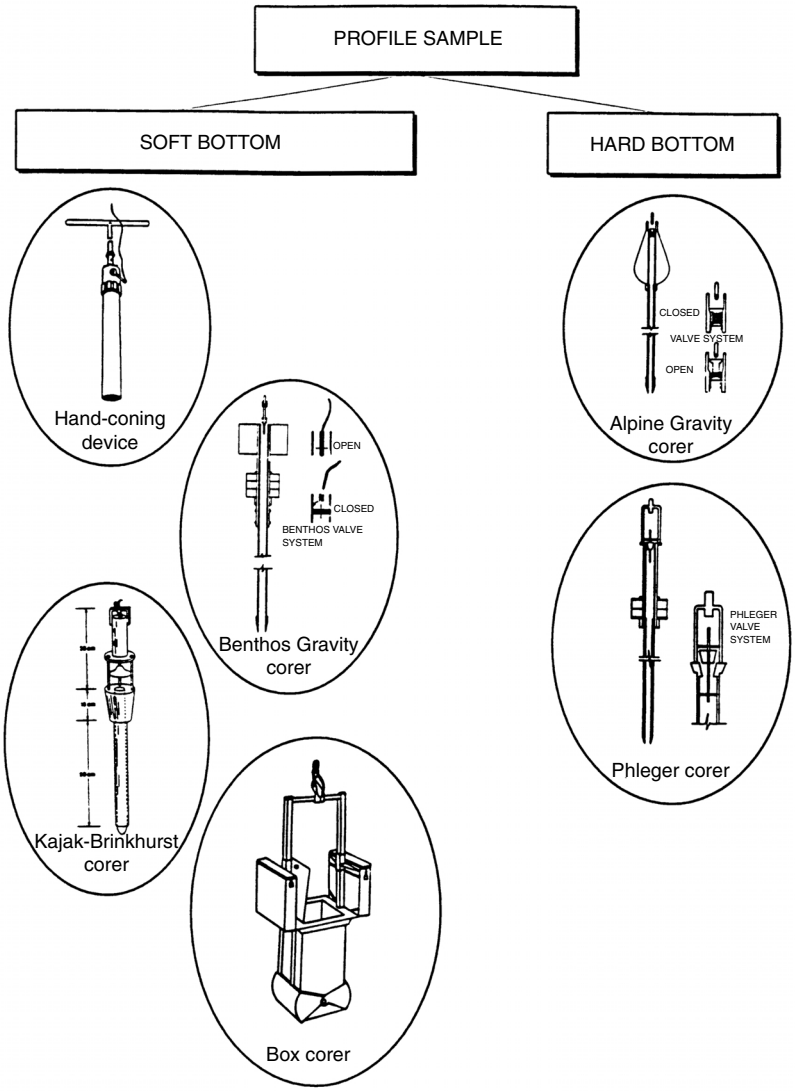

Figure 5.62- Some recommended devices for obtaining sediment profiles. (From EPA. *Methods for Collection, Storage and Manipulation of Sediments for Chemical and Toxicological Analyses*. Office of Water. U.S. Environmental Protection Agency. Washington, D.C. In press.)

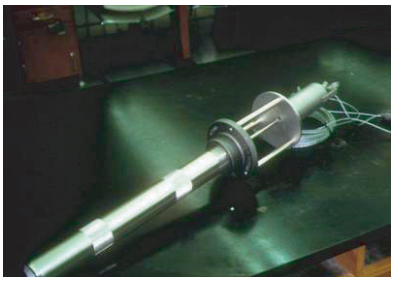

Figure 5.63 Gravity and hand corers.

Figure 5.64 Petite Ponar dredge.

Figure 5.65- Petite Ponar sediment dredge being lifted from water after sampling.

Figure 5.66- Emptying Ponar sample into stainless steel sample pan.

Figure 5.67 Winch with Ponar dredge.

Figure 5.68 Hand-held corer and Ekman dredge.

Figure 5.69 Collecting sediment with an Ekman dredge.

Figure 5.70 Shallow water vibratory core collection.

Figure 5.71- Freezing core sampler venting CO_2 used to sample catchbasin sediment in San Jose, CA.

was of solid aluminum. A screw cap was fitted to the other end which had a vent hole drilled in it. Another sampler was also constructed by Spliethoff and Hemond that allowed longer samples to be obtained (also in Figure 5.72). This sampler was made using a 125-cm length of 7.6-cm-square Extren tubing (a fiberglass reinforced resin). One side of the square tubing was machined off and an aluminum plate was attached to act as a freezing surface. A point-shaped lead weight was attached to one end and a cap with gas relief valve was attached to the other end. They used a slurry of dry ice and denatured ethanol to act as a coolant in both samplers. The samplers were dropped from the lake surface to test the penetration depth. The samplers were then retrieved, filled with the coolant mixture, and dropped again. After about 15 min, the CO_2 bubbles reaching the lake surface subsided, and the corers were retrieved. The samplers were then cleaned of unfrozen sediment and filled with warm lake water to help in releasing the frozen sample from the sampler. The frozen samples were sealed in plastic wrap and transported to the lab in dry ice filled coolers where they were separated into segments for analysis.

The above described freezing core samplers result in relatively undisturbed cores for analyses; plus they enable effective sampling in conditions where sample retention using conventional core samplers is difficult (unconsolidated coarse-textured sediment).

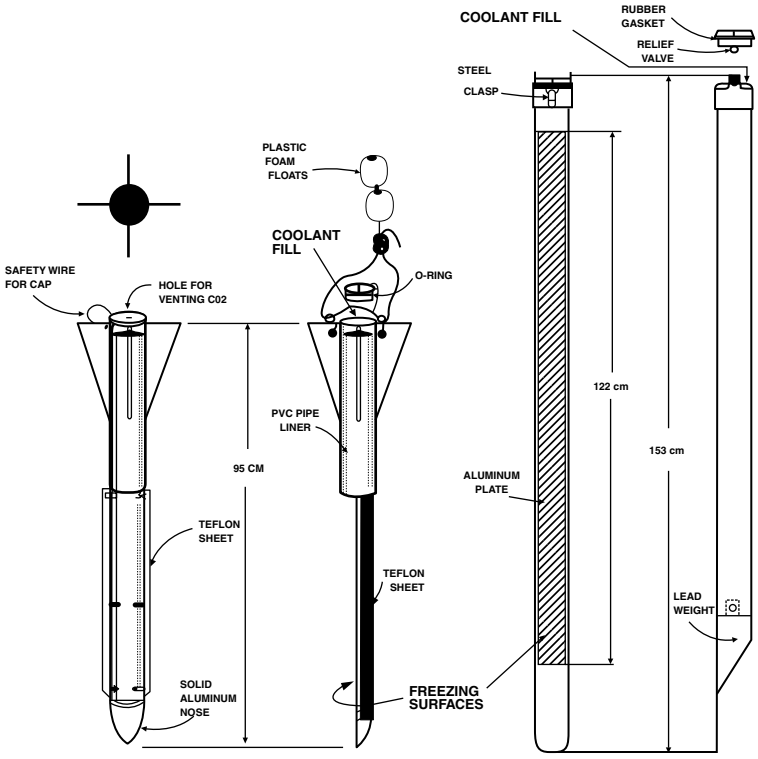

Figure 5.72 Freezing core samplers. (From Spliethoff, H.M. and H.F. Hemond. History of toxic metal discharge to surface waters of the Aberjona watershed. *Environ. Sci. Tech.*, 30(1): 121. January 1996. Copyright 1995 American Chemical Society. Reprinted with permission.)