Chapter 3
HYDROLOGIC AND HYDRAULIC MONITORING

The accurate collection and analysis of hydrologic and hydraulic data is one of the most important components of a Best Management Practice (BMP) monitoring study and is essential for Low Impact Development (LID) techniques and sites. To begin with, precipitation and other meteorological data are key components of watershed water balances needed to evaluate LID sites. Accurate flow measurements are also required to complete water balance computations and are critical for estimating BMP capture and bypass volumes, as well as volume losses. These flow rate measurements also affect the estimates of event mean concentrations (EMCs) and pollutant loads (see Chapter 4). **LID studies without well designed and implemented hydrologic and hydraulic monitoring components are of little value to the technical community.**

Hydrologic and hydraulic data can be collected using a variety of methods and equipment; the choice of which directly affects the usability of the data. This chapter discusses some of the methods and considerations for monitoring hydrologic and hydraulic phenomena and summarizes the equipment that can be used to collect data relevant to the evaluation of BMP performance. Additionally, practical considerations such as the critical importance of proper calibration of equipment and challenges associated with flow monitoring for LID studies are also discussed. For detailed discussion of water measurement practices, researchers are encouraged to see the U.S. Bureau of Reclamation (2001) *Water Measurement Manual*, which can be downloaded from http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/, along with other references in Exhibit 3-1.

Exhibit 3-1. Supplemental Hydrologic Monitoring References

U.S. Bureau of Reclamation. 2001. *Water Measurement Manual*. http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/

Granato et al. 2003. National *Highway Runoff Water-Quality Data and Methodology Synthesis, Volume I --Technical issues for monitoring highway runoff and urban stormwater*. FHWA-EP-03-054, 479 p. http://ma.water.usgs.gov/fhwa/fhwaep.htm

Caltrans. 2003. *Caltrans Comprehensive Monitoring Protocols Guidance Manual*. CTSW-RT-03-105.51.42. http://www.dot.ca.gov/hq/env/stormwater/special/newsetup/index.htm

U.S. Geological Survey (USGS). 1982. *Measurement and Computation of Streamflow*, Volumes. 1 and 2. USGS WSP-2175. http://pubs.usgs.gov/wsp/wsp2175/

U.S. Geological Survey (USGS). (various dates). *Techniques of Water-Resources Investigations Reports*. Multiple Chapters. http://pubs.usgs.gov/twri/

Sauer and Meyer. 1992. *Determination of error in individual discharge measurements.* USGS Open-File Report 92-144. 21 p. http://water.usgs.gov/admin/memo/SW/sw93.14.html

3.1 Meteorological Data Collection

3.1.1 Precipitation

Precipitation monitoring is an essential component of any effective monitoring study. Precipitation data may help determine when to start sampling, as well as provide information to identify storm characteristics such as precipitation depth, duration, and intensities. Precipitation data are also important in terms of identifying when a storm begins and ends, which can be unclear in some climates. When combined with tributary area and land use characteristics, precipitation data can provide a "reality check" on flow data (e.g., was the reported flow physically possible for this storm event?). Accurate high resolution precipitation data are relatively inexpensive to collect, so the benefits of having such data typically outweigh the costs. Considerations related to the type and quantity of precipitation gages needed for study are identified below.

3.1.1.1 Types of Precipitation Gages

Standard Rain Gage

Standard rain gages (SRGs) are plastic or metal cylinders that are placed vertically in the ground to collect rainwater. These devices are typically read manually on a daily basis. The National Weather Service, for example, uses the 8-inch non-recording SRG as the primary rainfall measuring device at Cooperative Weather Stations.

A SRG consists of four major components: (1) measuring tube; (2) collector funnel; (3) measuring stick; and (4) overflow can. When it rains, an 8-inch collector funnel in the SRG directs rainfall into a measuring tube, which can range in capacity from 0.5 to 2 inches. The amount of water in the tube is measured using a measuring stick in the device, which is typically marked every one hundredth of an inch. When rainfall during an observation period exceeds the 2-inch capacity of the measuring tube, water spills from it into the overflow can. The capacity of the overflow can ranges from 7 to 20 inches. When using this device, it is important to manually read rainfall amounts promptly after an event to prevent underestimation due to evaporation from the SRG.

Exhibit 3-2. Standard Rain Gage
(http://www.crh.noaa.gov/ind/?n=standardgage)

Tipping Bucket

A tipping bucket rain gage consists of a funnel that directs rainfall to one of two small "buckets." Once a given amount of rain falls into the funnel, usually 0.01 inches, a rocker mechanism empties the filled bucket and moves the empty bucket underneath the funnel. A recorder in the gage records each tip and the time in which the tip occurred. A tipping bucket gage may not be an effective option in some circumstances. For example, it cannot be used in freezing weather because the rocker mechanism can freeze and/or the funnel hole can become blocked with ice. The rocker mechanism may also fail or double tip during intense storm events. These devices can, however, be fitted with wind shields and antifreeze overflow devices. Additionally, precipitation can go undetected during extremely light and short events if the fixed amount of rainfall required to tip the bucket does not accumulate during the event. In all cases, rain intensity monitoring devices, such as that tipping bucket rain gage, need to have concurrent standard rain gage measurements to minimize these errors. In addition, they need to be calibrated at least twice a year. Tipping buckets can also be effectively used to trigger samplers (usually after about three tips to start the sampler; this is much more reliable than relying on flow alone to start the sampler in the presence of base flows).

Exhibit 3-3. Tipping Bucket Rain Gage
(http://www.arm.gov/instruments/instrument.php?id=rain)

Weighing Gage

A weighing precipitation gage collects precipitation data by directing precipitation into a container. At a prescribed time interval (typically every few minutes), a recorder attached to the scale records the weight of the bucket contents. Unlike the tipping bucket gage, this gage does not usually underestimate intense rain events because it has an attachment that fits around the device to create a vacuum that reduces the effects of wind and allows the gage to catch more precipitation. Another advantage of a weighing gage is that it can collect measurements of hail and snow simply by filling the collection bucket with a pre-weighed volume of antifreeze. Weighing gages are more expensive and require more maintenance than tipping bucket gages.

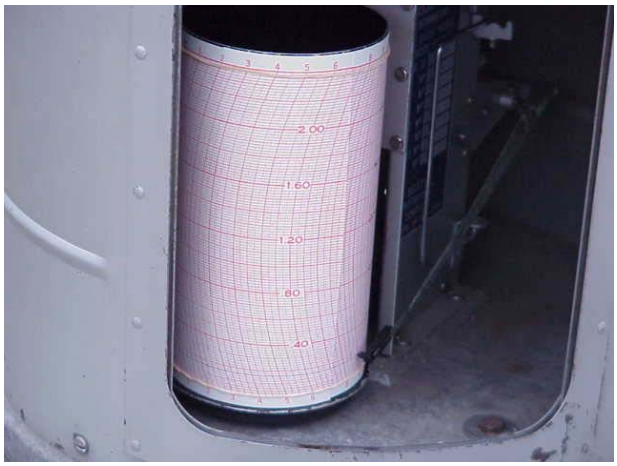

Exhibit 3-4. Universal Weighing Rain Gage
(http://www.erh.noaa.gov/aly/COOP/Equipment/UWG.htm)

Optical Rain Gage

Optical rain gages are a relatively new technology compared to the standard, tipping bucket, and weighing rain gages described above. These gages measure precipitation by using a laser and

phototransistor detector along with an array of collection funnels. When water falls into an optical rain gage, it passes through a laser beam and causes the beam to scatter. These light scatterings are then counted and recorded by the phototransistor detector and converted into rainfall measurements. As long as the collection funnels are heated to melt frozen precipitation, optical gages can operate in freezing conditions. On minute to minute and daily timescales, Ritsche et al. (2008) reported good agreement between tipping bucket and optical rain gages. Ritsche et al. also noted that on an annual basis, tipping bucket gages may underestimate precipitation due to mechanical limitations during periods of intense rainfall. Optical rain gages may overcome the types of mechanical issues associated with tipping buckets.

Exhibit 3-5. Optical Rain Gage
(http://www.arm.gov/instruments/instrument.php?id=org)

3.1.1.2 Site Proximity

In many regions, precipitation can vary significantly within a small geographic area because of orographic effects (i.e., weather effects of mountains), elevation, and proximity to water bodies. Therefore, it is important to position precipitation gages within or as close as possible to the drainage area tributary to the BMP. It may also be possible to use real-time data available over the Internet from rain gages operated by the U.S. Geological Survey (USGS), the National Weather Service, and/or the nearby municipalities. These established stations are convenient to use if they are in close proximity to the monitoring site, or as a general estimate of precipitation if they are located further from the monitoring site.

Precipitation gages typically need to be installed at the study site to obtain accurate precipitation data, unless another established gage is in adequately close proximity. Proper installation and maintenance of a rain gage is important and is relatively straightforward when manufacturers' guidelines are followed. The main concerns during installation are:

- Leveling the device.

- Making sure that vegetation (trees) or structures are not obstructing precipitation. A general rule of thumb is to place the device twice as far from the obstruction as the obstruction is tall.
- Providing enough height above the ground to prevent vandalism.
- Discouraging use as a perch by birds (e.g., install a bird wire).
- Being aware of possible influence of wind patterns around buildings in urban areas (e.g., make sure gage location conditions are comparable to area tributary to BMP).
- Positioning the rain gage in close proximity to other monitoring equipment to provide required connections for recording of precipitation depths and/or representative records.

3.1.1.3 Number of Gages

The number of precipitation gages installed in a study area directly affects the quality of storm event analyses and correlation of observed flow rates. Generally, more precipitation gages provide better estimates of precipitation characteristics. Locating a gage at each study site for small catchments is imperative because local variations in total precipitation and precipitation intensity can significantly impact the runoff for small watersheds. Nearby offsite locations (typically if over a mile away or at a different elevation) may not be useful in estimating precipitation at the actual site as a result of the variations which occur in precipitation over geographic areas.

In addition to the network of rain gages accessed for monitoring, it is also useful to install inexpensive manual rain gages at the monitoring site to check the accuracy, consistency, and proper functioning among the different gages. Variation between gage measurements can occur because of gage location (i.e., elevation or microclimate) or they can be erroneous for other reasons (e.g., improper installation or placement or natural interferences such as birds resting on the gage or tree shadows). When significant variation is observed, it is important to identify the cause and correct it. Calibration about twice a year is important.

3.1.2 Collection of Other Meteorological Data

In addition to precipitation, other meteorological data such as temperature, humidity, wind speed, barometric pressure, and evapotranspiration may be desired to assess site conditions and BMP performance. These data are especially important for LID sites where water balance computations are needed to estimate watershed-wide effects (see Chapter 8). For infiltration oriented BMPs, temperature (and hence, frozen subsurface conditions) is important to document. This section briefly discusses some of the equipment that can be used to collect meteorological data in addition to rainfall.

3.1.2.1 Atmometers

The evapotranspiration of reference crops (ET_o) can be estimated using an atmometer. This device consists of a reservoir that supplies distilled water to a porous ceramic plate covered with

a canvas material. The ceramic plate and canvas mimic the stomatal resistance of either alfalfa or turfgrass. The canvas, typically colored green, additionally mimics the albedo of vegetation covered land. As a wick draws water from the reservoir to the plate and canvas to be evaporated, the water level is measured with time to determine the rate of evaporation.

3.1.2.2 Weather Stations

Complete weather stations are commercially available as complete units that typically monitor the following meteorological parameters:

- precipitation
- temperature
- humidity
- wind speed and direction
- barometric pressure

As with rain gages, the placement of weather stations is critical for the collection of representative and accurate data. Ideally, weather stations should be located in the open and away from buildings, trees, or other objects that may affect measurements. The various sensors may need to be placed in different locations. For example, temperature and humidity, measured with thermometers and hygrometers, should be measured in the shade to avoid being biased by direct solar radiation, but away from vegetation. Conversely, anemometers (wind speed) and rain gages should be placed out in the open, away from obstructions that can block wind and prevent significant portions of rain from being collected by a rain gage.

In lieu of a full weather station, relatively inexpensive Thermochron “iButtons” or comparable devices can be attached to various locations to record temperature. These can be taped to telephone poles, weighted and placed in ponds and so on. As previously noted, temperature can affect infiltration and is important to document in many LID studies.

3.2 Flow Measurement Methods

Natural channels, engineered open channels, and pipes are used as stormwater conveyances. In each case, hydraulic considerations dictate the mathematical relationships that can be used to describe the flow rate at a given point in time. One of the primary hydraulic considerations is whether the flow configuration represents an “open” or “closed” channel. For example, open channel flow has a free water surface that varies with depth because the flow is driven by gravity. Closed channel flow, in which the flow fills a conduit, is caused by and increases with the hydraulic pressure gradient. Some stormwater conveyance system pipes may function as open channels during periods of low storm runoff and as closed channels when the runoff volume becomes sufficiently large or when water is backed up due to downstream flow conditions (e.g., tide, river flooding). Under such surcharged flow conditions, discharge velocities typically are greater than open channel flow due to the hydraulic gradient. Surcharged sewers have been known to pop manholes.

In general, the flow rate in an open channel depends on the depth of flow along with several other factors (Chow 1959) including:

- Geometric shape and changes in shape and slope along the length of the channel (affects potential for development of turbulence and/or varied flow and therefore the choice of methods and instruments used for measurement of flow).

- Hydraulic roughness of the conveyance surface, whether natural or manmade (affects the energy losses of the flow).

- Rate at which the depth of flow changes over time (steady versus unsteady flow).

- Spatial scale over which the flow rate changes (uniform versus varied flow).

The measurement of the flow rate in an open channel is more difficult to obtain than that of a full pipe, because the free surface will change with respect to time. Typically, stormwater flow through BMPs can fit the open channel flow configuration. However, some BMPs are drained by pipe systems, which may flow full at times. Therefore, methods used to measure flow in full pipes are also discussed below.

Exhibit 3-6 summarizes available flow measurement methods, the requirements for their use, typical BMP use, and required equipment. Each of these methods is discussed in more detail in the following sections.

Exhibit 3-6. Flow Measurement Methods

Method	Major Requirements For Use	Typical BMP Use	Required Equipment
Stage-Based Weir/Flume	▪ Open flow ▪ Constraint will not cause flooding	▪ Manual or automatic sampling	▪ Weir/flume and depth measurer
Velocity-Based	▪ Entrained air or sediments (Doppler-based velocity devices)	▪ Automatic sampling	▪ Depth measurer and velocity meter
Volume-Based Direct Measurement Methods	▪ Low flow rates	▪ Calibrating equipment ▪ Manual sampling	▪ Container and stopwatch
Tracer Dilution	▪ Adequate turbulence and mixing length	▪ Typically used for calibrating equipment	▪ Tracer and concentration meter
Pump-Discharge	▪ All runoff into one pond	▪ Not typically used for BMPs	▪ Pump
Stage-Based Variable Gate Meter	▪ 4-, 6-, or 8-inch pipes only	▪ Not typically used for BMPs	▪ ISCO variable gate meter
Stage-Based Empirical Equations	▪ Open flow ▪ Known channel/pipe slope ▪ Channel slope, geometry, roughness consistent upstream	▪ Manual or automatic sampling	▪ Depth measurer

The most common flow measurements methods for BMP studies include: (1) Stage-Discharge; (2) Area-Velocity; (3) Direct Flow Measurement; (4) Dilution; and (5) Pumped Discharge.

3.2.1 Primary Flow Measurement Devices

This section provides an overview of the process of selecting a primary flow measurement device. Because of the broad range of storm flows experienced at many BMP studies, it is important that measurement devices be able to accurately monitor a broad range of runoff events, including small, frequently-occurring storms that account for the majority of runoff and pollutant loads in urban areas, as well as larger storms. The USBR (2001) identifies key factors influencing the selection of a flow measurement device. These include:

- Accuracy requirements
- Cost

- Legal constraints
- Range of flow rates
- Head loss
- Adaptability to site conditions
- Adaptability to variable operating conditions
- Type of measurements and records needed
- Operating requirements
- Ability to pass sediment and debris
- Longevity of device for given environment
- Maintenance requirements
- Construction and installation requirements
- Device standardization and calibration
- Field verification, troubleshooting, and repair
- User acceptance of new methods
- Vandalism potential
- Impact on environment

Primary flow measurement devices fall into two general categories, flumes and weirs. These devices allow for accurate measurement of discharge rates by creating a channel geometry in which the hydraulics are controlled (a "control section"). Using a known empirical equation, primary devices are calibrated (i.e., in the laboratory or by the manufacturer) to relate the stage at a predetermined point in the control section to the discharge rate. (For examples, see Granato et al. 2003.) These types of measurement devices are called depth-based (or stage-based) methods because the discharge through the device is directly related to the depth (stage or head) of the flow. The relationship between the depth of flow and the discharge is called the "rating." Tables referred to as rating curves are available for all standard flumes and weirs and are easily accessible from multiple sources such as the USBR Water Measurement Manual (http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/).

Exhibit 3-7. U.S. Bureau of Reclamation Water Measurement Manual Water Measurement Device Selection Guidelines

(USBR, 2001. Table 4-2. http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/)

[Symbol Notes: "+": advantageous aspects; "-" negative features; "0": neutral. These symbols are relative indicators comparing application of water measurement devices to the listed criteria."v" denotes device suitability varies widely, "na" denotes not applicable to criteria.]

Device	Accur-acy	Cost	Flows >150 ft^3/s	Flows <10 ft^3/s	Flow span	Head loss	Site conditions			
							Lined canal	Unlined canal	Short full pipe	Closed conduit
Sharp-crested weirs	0	0	-	+	0	-	-	0	na	na
Broad-crested weirs	0	+	+	+	+	0	+	0	na	na
Long-throated flumes	0	0	+	+	+	0	+	0	na	na
Short-throated flumes	0	-	-	0	0	-	-	0	na	na
Submerged orifices (in channels)	0	0	-	+	-	-	0	0	na	na
Current metering	-	-	+	-	-	+	0	-	na	na
Acoustic velocity meters in open channel	-	0	0	-	0	+	0	0	na	na
Radial and sluice gates	-	+	0	0	-	-	+	+	+	na
Propeller meters at pipe exit	-	+	-	0	0	+	0	0	+	+
Differential head meters for pipe[1]	+	-	-	+	-	V	na	na	0	+
Mechanical velocity meters for pipe[2]	0	+	-	0	0	+	na	na	0	+
Magnetic meters for pipe	0	0	-	0	0	+	na	na	-	+
Acoustic Doppler ultrasonic meters for pipe	-	0	-	-	-	+	na	na	-	+
Acoustic flowmeter pipe (single path)	0	-	0	0	0	+	na	na	-	+
Acoustic flowmeter pipe (multipath)	+	-	+	0	+	+	na	na	-	+

[1] Venturi, orifice, pitot tube, shunt meters, etc.
[2] Propeller meters, turbine meters, paddle wheel meters, etc.

Additional Consider-ations	Measure-ments		Sediment/ Debris Pass.		Longevity		Mainte-nance	Constr-uction	Field verifi-cation	Standard-ization
	Rate	Vol-ume	Sedi ment	Debris	Moving parts	Elec tricity needs				
Sharp-crested weirs	+	-	-	-	+	+	0	-	0	+
Broad-crested weirs	+	-	0	+	+	+	+	+	+	0
Long-throated flumes	+	-	0	+	+	+	+	0	+	0
Short-throated flumes	+	-	0	+	+	+	+	-	-	+
Sub-merged orifices (in channel)	+	-	-	-	+	+	+	0	+	0
Current metering	+	-	+	+	0	0	0	+	0	+
Acoustic velocity meters in open channel	+	0	+	+	0	-	-	+	-	-
Radial and sluice gates	+	-	0	-	+	0	+	+	-	-
Propeller meters at pipe exit	0	+	0	-	-	0	-	+	0	0
Differential head meters for pipe[1]	+	-	-	v	+	0	0	0	+	+
Mechanical velocity meters for pipe[2]	v	v	-	-	-	0	-	0	0	0
Magnetic meters (pipe)	+	0	0	0	0	-	-	0	-	0
Acoustic Doppler ultrasonic meters (pipe)	+	0	0	0	0	-	-	0	-	-
Acoustic flow meter pipe (single path)	0	+	0	0	0	-	-	-	-	0
Acoustic flow meter pipe (multipath)	+	+	0	0	0	-	-	-	-	+

[1] Venturi, orifice, pitot tube, shunt meters, etc.
[2] Propeller meters, turbine meters, paddle wheel meters, etc.

3.2.1.1 Weirs

A weir is a designed obstruction (usually a vertical plane) built or placed across an open channel or within a pipe under open channel flow so that water flows over the weir's top edge or through a well-defined opening in the plane. Many types of weirs can be used to measure discharge. The three most common weirs are: the rectangular; trapezoidal (or Cipolletti weir); and triangular weirs. The weir opening (i.e., the rectangular, trapezoidal, or triangular opening) is called the "notch." Each type of weir has a specific discharge equation for determining the flow rate through the weir.

Compared to flumes, weirs are generally low in cost, easy to install, and can be quite accurate when used correctly. A weir can be used to regulate flow in a natural channel with irregular geometry—a situation where Manning's Equation, for example, would not provide reliable estimates for the flow rate. Weirs are generally used for flow measurements with relatively large head available to establish free-flow conditions over the weir. While a weir can be used to regulate flow, it creates a partial dam causing backwater. During large storm events, the backwater may cause or exacerbate flooding upstream, particularly in a closed conduit. Some jurisdictions prohibit the use of weirs for this reason.

When evaluating the suitability of a monitoring site for a weir, it is important to determine whether the system was "over designed." That is, will the conveyance be able to move the design capacity after weir installation? In the case where the downstream depth of flow is greater than the crest of the weir (i.e., the weir is submerged), a different stage-flow relationship for the weir will apply.

Weirs are often not a good choice where representative suspended sediment samples are desired because larger sediment particles tend to settle above the weir, particularly during low flow conditions. Sediments and debris that accumulate behind a weir can also alter the hydraulic conditions, changing the empirical relationship between flow depth and discharge rate. Weirs should be inspected regularly to remove accumulated sediment or debris. If high amounts of sediment or debris occur in the flow, then use of a flume may be more appropriate as flumes generally avoid sedimentation problems.

3.2.1.2 Flumes

A flume is a specially built channel (most often a prefabricated insert) with a converging entrance section, a throat section, and diverging exit section.

Because the velocity of water accelerates as it passes through a flume, the problem of sedimentation associated with weirs as described above is avoided; however, problems with debris accumulation in a flume can still occur. Flumes reduce the backwater effect by introducing a lower headloss than weirs. A flume may be more expensive and difficult to install than a weir because of its more complex design; however, where applicable, flumes can provide accurate results and significantly reduce maintenance issues.

The most common types of flumes are the Palmer-Bowlus, the HS, H, and HL flumes, and the trapezoidal flume. Parshall flumes have also been commonly used historically, but long-throated flumes are now recommended instead of Parshall flumes (USBR 2001).

Exhibit 3-8. Thel-Mar Weir (Parson Environmental)

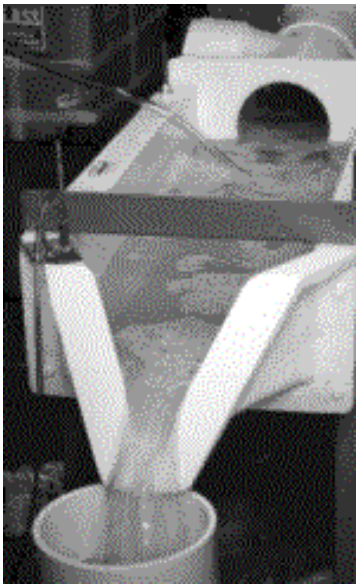

Exhibit 3-9. H-flume (Tracom Inc.)

3.2.1.3 Selection Considerations

There are many factors to consider when selecting a primary flow measurement device as summarized in Exhibit 3-10. These factors may include range of flows, accuracy, cost, head loss and flow characteristics, sediment and debris, and construction requirements, all of which are investigated below.

Range of Flows

Many measurement devices have a limited range of flow conditions for which they are applicable. This range is usually related to the need for certain prescribed flow conditions which are assumed in the development of calibrations. Large errors in measurement can occur when the flow is outside this range (USBR 2001). Several examples include:

- Thel-Mar weirs: These are composite weirs that provide measurement over a large range of flows from low to high. A V-notch is used for accurate low flow measurements and a broad-crested weir for high flow measurements. A challenge associated with this weir is that it uses less than 50 percent of the cross-sectional area of the pipe in which it is installed, limiting accurate measurement of pipe-full flows.

- Triangular thin-plate weirs: These weirs have a large range in their ability to measure flows because of the 2.5-power relationship between flow depth and flow rate. That is, relative to other devices, flow increases quite rapidly as a function of head. The range of flow rates that can be measured accurately can vary by a factor (ratio of largest flow to smallest flow rate) of 200 for fully contracted weirs to a factor of around 600 for partially contracted 90° notches that utilize the allowable range of head (ASTM 1995).

- Rectangular thin-plate weirs: The range of measurement for these weirs typically varies from a factor of about 90 to about 110 for full-width weirs. These ranges depend somewhat on the crest length to channel width ratio. These results are based on a minimum head of 0.1 ft (0.03 m) and a suggested (although not absolute) maximum head of 2 ft (0.6 m). However, the range of measurement of smaller rectangular weirs can be significantly less (ASTM 1995).

- Parshall flumes: Although Parshall flumes are in extensive use in many western irrigation projects, they are no longer generally recommended because of the advantages of long-throated flumes and some significant disadvantages of Parshall flumes. Designing and setting Parshall flumes for submerged flow measurement is not usually recommended because less expensive, long-throated flumes can be designed that approach or exceed 90 percent submergence limits with a single upstream head measurement. Moreover, the absolute required drop in water surface is usually less for the long-throated flumes, particularly the modified broad-crested weir styles (USBR 2001). (See http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/chap08_10.html for more information.)

- Palmer-Bowlus and other long-throated flumes: The range of measurement for these flumes depends on the shape of the throat cross-section. The range increases as the shape varies from rectangular toward triangular. For typical Palmer-Bowlus flumes of trapezoidal section, the range of flow rates that can be measured accurately generally varies by a factor of 30. The USGS has also developed and tested a modified Palmer-Bowlus flume (USGS 1985) for use in circular pipes that carry highway stormwater runoff. Flow can occur under either open or pressurized flow. These flumes measure the discharge under pressurized flow by using two bubbler sensors, which detect the hydraulic pressure change between upstream and downstream locations on the flume. This system was found to be one of the most accurate after calibration was performed. However the range between low and high flows that can be measured accurately using a Palmer-Bowlus flume is not as large as some other types of devices.

- H, HS or HL flumes: The use of H, HS, or HL flumes should be considered when measuring extreme flow ranges along with sediment transport capabilities, as is often the case for stormwater runoff. The range of flows that can be measured accurately using all

varieties of H-type flumes can exceed three orders of magnitude; for example, a 3 ft H-flume can measure flows between 0.0347 cfs at 0.10 ft of head to 29.40 cfs at 2.95 ft of head.

- Nested Flumes: For some cases when low flows are expected to occur for an extended period but will ultimately be superseded by much larger flow rates, the interim use of removable small flumes inserted inside larger flumes can provide a method for accurate measurement of the range of flows.

In summary, small and moderate flows are generally best measured with thin-plate weirs, with the triangular notches most appropriate for the smallest flows (ASTM 1995). Small Palmer-Bowlus flumes are also useful in measuring low flows. While these flumes do not have issues related to sediment passage and head loss as do thin-plated weirs, they have the potential to be less accurate (ASTM 1995). Flumes and broad-crested weirs are generally the best choices for the measurement of large discharges.

Accuracy

When selecting a primary flow measurement device, it is important to consider the accuracy. Weirs are generally recognized as more accurate than flumes (Grant and Dawson 1997). A properly installed weir can typically achieve accuracies of 2 to 5 percent of the rate of flow, while flumes can typically achieve accuracies of 3 to 10 percent (Spitzer 1996). However, ASTM cites lower errors for weirs ranging from about 1 to 3 percent and Palmer-Bowlus flumes with typical accuracies around 5 percent.

The overall accuracy of the flow measurement system depends on a number of factors, including proper installation, proper location for head measurement, regular maintenance, the accuracy of the method employed to measure the flow depth, approach velocities (when using weirs), and turbulence in the flow channel (when using flumes). The largest source of error in flow measurement of stormwater typically results from inaccuracies related to low flow or unsteady flow; however, significant measurement errors are also caused by improper construction, installation, or lack of maintenance. A silted weir or inaccurately constructed flume can have associated errors of ±5 to 10 percent or more (Grant and Dawson 1997). Circumstances present in many stormwater monitoring locations can result in errors well in excess of 100 percent.

Potential inaccuracies in the method used to measure the depth of flow tend to increase the error in flow measurement as the flow depth approaches the minimum head. For primary devices operating near minimum head, even a modest error can have a significant effect on the measured flow rate. Therefore, it is important to select sizes or combinations of primary devices that avoid prolonged operation near minimum head (Spitzer 1997). It is also important to understand the limitations of the stated accuracy of flow measurement devices. A device that states an accuracy of 1 to 2 percent at optimal operating conditions may have a much poorer accuracy for flow conditions that are less than optimal (e.g., low flow/shallow depths).

One possible approach to reducing inherent error associated with each flow measurement device is to use the same type of device at each location associated with the study in an effort

to balance errors. This may be a realistic option at some studies where comparable conditions exist for inflows and outflows, but at locations where inflow and outflow characteristics differ significantly, it is more important to select a device expected to have the highest accuracy for the expected flow conditions.

In situ calibration of meters and other equipment can also help to reduce errors.

Cost

It is important to consider the manufacturing, installation, and operational costs when selecting a primary flow measuring device. Weirs are often considerably less expensive to fabricate than flumes due to simpler design and material requirements (Grant and Dawson 1997). Weirs are also usually easier and less expensive to install, although installation of flumes designed for insertion into a pipe (e.g., Palmer-Bowlus and Leopold-Lagco) are generally straightforward. Despite the higher initial costs of flumes, the relatively low maintenance requirements may outweigh those costs with time (Grant and Dawson 1997). Consideration should be given to the expected sediment loads in the flow to be measured for likely accumulation and maintenance requirements for weir installations.

Head Loss and Flow Characteristics

The head difference that is required for a weir or flume to operate properly can also be an important selection criterion. Examples include cases where the elevation difference is not adequate to maintain the minimum required flow or where the upstream channel cannot contain the backwater. Under comparable flow conditions, thin plate weirs typically require the largest head difference, and the long-throated flumes require the least amount of head (ASTM 1995). Parshall flumes require an intermediate amount of head, but are no longer recommended for use.

Weirs are typically gravity fed and must be operated within the available head of the system. Flumes also require a certain head range in which the flow level is low enough so that it does not exert back pressure on the water in the throat of the flume. If a flume does not have sufficient head range, it will be in a submerged condition thus requiring two head measurements to accurately determine the flow rate.

Operation of a weir is sensitive to the approach velocity, often necessitating a stilling basin or pond upstream of the weir to reduce the fluid velocity. Operation of a flume is sensitive to turbulence or waves upstream from the entrance to the flume, which can require a section of straight channel upstream of the flume.

Sediment and Debris

Sediment and debris is another factor to consider when choosing a primary flow measurement device. Flumes tend to be self-cleaning because of the high flow velocity and the lack of any obstruction across the channel (Spitzer 1997). Therefore, a flume is generally more suited to flow channels carrying solids than is a weir.

Debris accumulation is likely to occur behind a weir, especially when a stilling basin is present to reduce flow velocities to an acceptable rate. Debris accumulation behind a weir can affect flow measurement and may even interfere with water quality measurements. This

requires periodic inspection and maintenance to remove debris. To allow periodic removal of deposits, it is recommended that the weir bulkhead be constructed with an opening beneath the notch to sluice accumulated sediments (Spitzer 1997).

Flumes, while typically not susceptible to problems due to sedimentation, can have debris accumulate in the throat portion of the flume and require periodic maintenance. This maintenance is generally required less frequently than it is for weirs.

Construction Requirements

When selecting a primary flow measuring device, it is important to consider construction requirements as each differs in shape and complexity. The Parshall flume is usually the most difficult device to construct due to the relatively complex shape and the possible need to excavate the channel floor to accommodate the sharp downward slope of the throat. Because flumes are empirical devices, it is necessary to closely follow the design specifications (ASTM 1995). The discharge coefficients for long-throated flumes can be obtained theoretically which allows for some departure from the prescribed dimensions. Many types of flumes are available in prefabricated sizes up to several feet in width.

Weirs are generally easier to construct than flumes due to their more simplistic design. The most difficult task when constructing a weir is the fabrication of the notch edges, which require a sharp edge so the nappe is free flowing.

3.2.2 Secondary Flow Measurement Devices

A variety of instruments can be used to measure water depth. Because some techniques are relatively cumbersome, they are more useful for calibrating equipment than for routine or continuous data collection during storm events. The equipment required for each technique and the associated advantages and disadvantages for sampling runoff at BMP sites are described below. Exhibit 3-10 summarizes the equipment available for measuring depth of flow, important requirements for use of this equipment, and how this equipment is typically used within a BMP monitoring program. When selecting measurement devices, it is important to carefully consider practical factors such as site conditions and instrument and cable housing. For example, some types of cable housing do not function for long-term continuous monitoring and can be damaged if placed in the sampling stream for extended periods of time. Teflon® cable housing can be used to extend life span. Additional discussion on several methods follows. Regardless of the method used, the importance of proper calibration procedures and frequencies cannot be overstated.

Exhibit 3-10. Equipment for Measuring Depth of Flow

Method	Major Requirements For Use	Typical Use in a BMP Monitoring Program
Visual Observations	Small number of sites and events to be sampled. No significant health and safety concerns.	Manual sampling
Float Gage	Stilling well required.	Manual or automatic sampling
Bubbler Tube	Open channel flow. No velocities greater than 5 ft/sec.	Automatic sampling
Pressure Transducer	Less "drift" if remains submerged between events.	Automatic sampling
Ultrasonic Depth Sensor	Open channel flow. No significant wind, loud noises, turbulence, foam, steam, or floating oil and grease.	Automatic sampling
Ultrasonic Uplooking	No sediments or obstructions likely to cause errors in measurement.	Automatic sampling
Radar/Microwave	Similar to Ultrasonic Depth Sensor but can see through mist and foam.	Automatic sampling
3-D Point Measurement	Highly controlled systems. Typically not useful in the field.	Automatic sampling
Pressure Probe	Open channel flow. No organic solvents or inorganic acids and bases.	Automatic sampling

3.2.2.1 Float Gage

A float gage is used to measure changes in water surface elevation to determine flow rates. A float gage consists of a float that is free to move up and down in response to the rising and falling water surface in a channel. Prior to an actual stormwater sampling event, the site is calibrated to establish an initial reference depth. During the storm, the float rises and falls with changes in water surface elevation, and a device attached to the float records the magnitude of these changes. The changes in water surface elevation are converted to depth of flow by the float gage. A data logger can then record the depth of flow, and if capable of performing mathematical equations, determine the flow rate. If the data logger does not have the capability to do these types of calculations, data can be inputted into appropriate software to compute the flow rate.

In some applications, the use of a float gage requires a stilling well. A stilling well is a reservoir of water connected to the side of the conveyance that isolates the float and counterweight from turbulence in the main body of the flow. Retrofitting an existing channel or conduit with a stilling well can be a potentially expensive and time-consuming process and a principal drawback of this technique. However, this method can be useful if sampling is conducted at a site where a float gage and stilling well have been previously installed.

3.2.2.2 Bubbler Tube

Bubbler tubes are used by some types of automated flow meters to measure the depth of flow. Compressed air (or gas) is forced through a submerged tube attached to the channel invert (i.e., bottom of the channel). A pressure transducer measures the pressure needed to force a bubble out of the tube. This pressure, in turn, is linearly related to the depth of the overlying water:

$$P = \rho h \qquad \textbf{Equation 3-1}$$

Where:

P: hydrostatic pressure, N/m^2 (lb/ft^2)
ρ: specific weight of water, N/m^3 (lb/ft^3)
h: depth of water, m (ft)

Bubbler tubes are commonly integrated with a flow meter, or a data logger that is capable of performing mathematical calculations. This approach allows the measurement of depth to be immediately converted to a flow. These real-time inputs, along with a program that tracks accumulated flow volumes, can be used to trigger the collection of samples for flow-weighted compositing by an automated sampler.

Exhibit 3-11. Bubbler Flow Meter (ISCO)

Bubbler tubes are simple to use and are not usually affected by wind, turbulence, foam, steam, or air-temperature gradients. Accuracy is not lost under dry conditions in a conveyance between runoff events (some other types of probes must remain submerged). Although they are generally reliable, bubblers are susceptible to error under high velocity flow. That is, as flow velocity increases to over 1.5 to 1.8 m/s (5-6 ft/sec), a low pressure zone is induced around the mouth of the bubbler tube, interpreted by the flow meter as a drop in flow rate. These instruments, therefore, should not be used in channels where the slope of the bottom exceeds 5 to 7 percent. Sediments and organic material can also plug bubbler tubes. Some units are periodically purged with compressed air or gas to prevent this problem, but visual inspection and periodic maintenance are recommended for any unit installed in the field. Bubblers can be problematic for winter monitoring if the bubbler is pressurized through a diaphragm, which can become brittle and break at below freezing temperatures. Bubblers are commonly available in integrated systems, such as those manufactured by ISCO and American Sigma, but are also sold as independent devices.

3.2.2.3 Ultrasonic Depth Sensor

An ultrasonic depth sensor consists of a sonar-like device mounted above the surface of the water at a known distance above the bottom of the channel. A transducer emits a sound wave and measures the period of time taken for the wave to travel to the surface of the water and back to a receiver. This time period is converted to a distance and then converted to a depth of flow, based on measurements of the site configuration. As with bubbler tubes, an ultrasonic sensor can be integrated into a flow meter or interfaced with a data logger. An ultrasonic depth sensor and data logger can provide the real-time flow data necessary to trigger an automated sampler to collect a stormwater sample for flow-weighted compositing.

Exhibit 3-12. Ultrasonic-Depth Sensor Module (ISCO)

Some manufacturers have built redundancy into their ultrasonic depth-measuring instruments. Redundancy helps to ensure that useful data can be collected even if some of the sensors in the array become fouled with grease, surface-active materials, or organisms. Experience has shown that this type of fouling can occur during storm events. Because an ultrasonic sensor is mounted above the predicted surface of the water, it is not exposed to contaminants in the runoff unless the depth is greater than anticipated or it is installed in a pipe that reaches fully pressurized flow. While this device is not generally affected by contaminants, ultrasonic signals can be adversely affected by wind conditions, loud noises, turbulence, foam, and steam. Ultrasonic signals can also be affected by changes in density associated with air temperature gradients; however, some manufacturers do build a compensation routine into their instruments. Because of these potential problems, periodic inspection and maintenance of these instruments is recommended.

Background noise can interfere with a sensor's ability to accurately measure water depth. For example, an ultrasonic sensor was used in Portland, Oregon to measure the depth of flow at an urban stormwater sampling site located in a manhole in which runoff from an arterial pipe splashed down into the main conveyance. To dampen the effect of the interfering signal, the ultrasonic sensor was retrofitted with a flexible noise guard.

3.2.2.4 Pressure Probe

A pressure probe consists of a transducer, mounted at the bottom of the channel that measures the hydrostatic pressure of the overlying water. This hydrostatic pressure is converted to a depth

of flow. When selecting probes, it is important to select devices that are rated for hydrostatic pressures expected at the monitoring location. Additionally, some pressure probes have a built-in thermometer to measure the temperature of the water thus allowing for temperature compensation in the depth of flow calculation, which is important for accurate measurements. As with bubblers and ultrasonic probes, the pressure probe can be integrated into a flow meter or interfaced with a data logger to provide real-time inputs into an automated sampler. If the instrument is fitted with a thermometer, it is also possible for temperature data to be collected and stored for future use.

Exhibit 3-13. Pressure Transducers (In-Situ Inc.)

Submerged probes are not adversely affected by wind, turbulence, foam, steam, or air temperature gradients. However, because contaminants in the water may interfere with or damage the probe, periodic inspection and maintenance is recommended. Dry conditions between storms can affect the accuracy of the probe, as can sudden changes in temperature. Installation of a simple staff gage can also be useful in calibrating pressure probes.

3.2.2.5 Ultrasonic "Uplooking"

This depth-of-flow sensor is mounted at or near the bottom of the channel or pipe. It uses ultrasonic signals to determine the depth of the flow. Some vendors report that this equipment is not recommended for stormwater BMP influent because the sensor is likely to become covered by sediments and debris. This then interferes with the signal and does not allow the sensor to work properly. These sensors have, however, been successfully used to monitor BMP effluent.

3.2.2.6 Radar/Microwave

A variation of the ultrasonic method is a non-water contacting instrument that emits and reprocesses electromagnetic waves in the radar/microwave spectrum. By altering the wavelength of the electromagnetic signal, problems associated with foam, mist, and rapid changes in air temperature and pressure are eliminated or significantly reduced. A radar/microwave sensor is used in the same manner as an ultrasonic "downlooking" sensor for measuring fluid levels in tanks. Based on experience, this device does not present a significant advantage over other methods of level measurement, since foam and mist are not typically a large concern during stormwater monitoring. Radar/microwave sensors have not been extensively tested by

manufacturers for this type of application, and there is no existing literature that shows them being used for stormwater monitoring.

3.2.3 Velocity-Based Methods

The continuity method is a velocity-based technique for estimating flow rate. Each determination requires the simultaneous measurement of velocity and depth of flow. Flow rate is calculated as the sum of the products of the velocity and the cross-sectional area of the flow at various points across the width of the channel:

$$Q = A_i * V_i \qquad \textbf{Equation 3-2}$$

Where:

Q: flow, m^3/s (ft^3/sec)
A_i: cross-sectional area of the flow at planar section *i*, m^2 (ft^2)
V_i: mean velocity of the flow at section *i*, m/s (ft/sec)

In stormwater runoff applications, the conveyance is small enough that a single cross-sectional area and estimate of average velocity can typically be used to estimate flow rate. That is, it is not necessary to segment the cross-sectional area of the flow. The accuracy of this method depends on the ability of a sensor to measure velocity over a range of flow.

Although this method is useful for calibrating equipment, it is more sophisticated and expensive than the stage-flow relationships previously discussed. In addition, this method is suitable only for conditions of steady flow. That is, the water level must remain essentially constant over the period required for obtaining velocity measurements. This is not generally a problem in small conveyance systems when instruments that make measurements rapidly are employed.

Additionally, the Darcy-Weisbach equation can be used in systems where pressurized flow (i.e., pipes flowing full; no free water surface) is present and can be found in Gupta (1989).

Use of the continuity equation for measuring flow requires the estimation of average velocity as well as depth. The velocity of flow can be measured using visual methods (i.e., the float-and-stopwatch or the deflection/drag-body methods), tracer studies, the use of instruments such as rotating-element current meters and pressure, acoustic, ultrasonic (Doppler), and electromagnetic sensors. Electromagnetic sensors have been found to be the most accurate. Among these methods, many are more useful for the calibration of automated equipment than for continuous data collection. Only the ultrasonic and electromagnetic methods are recommended for measuring velocity during a storm.

When using any type of velocity meter over a range of flows, it is important to be aware of their limitations. For example, area-velocity (A-V) meters that will be used for low flow measurement will require installation of a structure to create a backwater condition. A-V meters require both a minimum depth for the depth measurement (~0.5 inch) and several inches for velocity measurement. A backwater condition is needed to ensure that both the depth and velocity instruments have minimum depth requirements.

3.2.3.1 Ultrasonic (Doppler) Sensors

An ultrasonic sensor applies the Doppler principle to estimate mean velocity. A sound wave, emitted into the water, reflects off particles and air bubbles in the flow. The shift in frequency of waves returning to the sensor is a measure of the velocity of the particles and bubbles in the flow stream. The instrument computes an average from the reflected frequencies, which is then converted to an estimate of the average velocity of the flow stream.

Exhibit 3-14. Area Velocity Sensors Module (ISCO)

The sensor is mounted at the bottom of the channel. However, because the ultrasonic signal bounces off suspended particles, the signal may be dampened and not able to reach portions of the flow stream when suspended particle concentrations are high. The sensor can also be mounted on the side of the channel, slightly above the invert to help reduce the impacts of bed load and solids accumulation on the sensor. Combined with the appropriate hardware and software, the sensor can filter out background signals associated with turbulence in the flow. Conversely, in ultra-clean water, the signal may "drop out" when there are not enough particles to reflect the signal.

Ultrasonic Doppler sensors can be used under conditions of either open channel or pressurized flow. When properly calibrated and combined with the hardware and software required for real-time flow measurement, data logging, and automated sampling, this system is capable of greater accuracy than systems that rely on a stage-flow (i.e., Manning's Equation) relationship. The ultrasonic sensor-based system can be more expensive but the additional expense may be justified by program objectives. Routine maintenance of ultrasonic sensors is recommended to prevent inaccuracies from fouling by surface-active materials and organisms.

3.2.3.2 Electromagnetic Sensors

Electromagnetic sensors work under the principle stated in Faraday's Law of electromagnetic induction: a conductor (i.e., water) moving through an electromagnetic field generates a voltage proportional to its velocity. The sensor is mounted at or near the channel bottom where it generates an electromagnetic field and measures the voltage inducted by the flow. Although velocity is measured at only a single point, that measurement is used to estimate the average velocity of the flow stream.

Electromagnetic sensors can be pre-calibrated for many types of site configurations. While the sensor is usually mounted at the channel invert, it can be mounted on the side of a channel, slightly above the invert, if high solids loadings are expected. A built-in conductivity probe senses when there is no flow in the conveyance.

Electromagnetic instruments are not sensitive to air bubbles in the water or changing particle concentrations like the ultrasonic sensors, but they can be affected by extraneous electrical "noise." As with the ultrasonic system, when an electromagnetic sensor is properly calibrated and combined with the hardware and software required for real-time flow measurement, data logging, and automated sampling, it is capable of greater accuracy in specific circumstances than a system relying on a stage-discharge relationship. The electromagnetic sensor-based system can be more expensive, but the additional expense may be justified by program objectives.

3.2.3.3 Acoustic Path

These sensors are used to determine the mean velocity of streams and rivers, and where they are applicable, they have been found to be one of the most accurate flow measurement systems. The method consists of an array of sensor elements that are installed at an even elevation across the channel. The number of sensor elements used is dictated by the channel width (i.e., larger channels require more sensors). Due to the sensor array's height above the channel bottom, its use is generally limited to larger channels that have a base flow present. These sensors have been successfully used in backwater and tidal conditions where the multi-layer sensors were able to measure layers of water moving in different directions in large outfalls (Personal Communication with Robert Pitt, University of Alabama, 2009). It is not a practical method to use for smaller diameter conveyances with no base flow, which may be found at a BMP site. Additionally, stormwater conduits for BMP runoff can be small enough that a single point measurement for velocity provides a reasonable estimate for the average velocity. For these reasons, acoustic path sensors are rarely applicable to BMP monitoring situations.

3.2.3.4 Rotating-Element Current Meters

A current meter or current meter array can be used to measure the velocity at various points throughout a flow stream. The measured point velocities can be combined to estimate a mean velocity for the flow. As with the deflection or drag-body method, if employed for longer periods, a current meter inserted into the flow can accumulate debris causing it to malfunction and possibly break away. Therefore, this method should only be used for short-term measurements such as during equipment calibration or to develop a rating curve. Two types of readily available instruments that meet USGS standards are the type AA Price and Pigmy current meters.

3.2.3.5 Pressure Sensors

A pressure sensor or transducer measures the dynamic pressure head at a given point in the flow. The dynamic pressure is a measure of the point velocity and can be used to estimate the mean velocity of the flow. A common example of a pressure sensor is the Pitot tube used on an airplane or on some boat speedometers.

The same caution described for bubbler tubes must be applied to pressure sensors as well. That is, as the velocity of the flow increases above 1.5 to 1.8 m/s (5-6 ft/sec), a low pressure zone is

induced across the sensor and interpreted by the flow meter as a drop in flow rate. These instruments should not be used in channels where the slope of the bottom exceeds 5 to 7 percent.

3.2.3.6 Acoustical Sensors

An acoustical sensor emits a sound wave under water across a channel and measures the time required for the signal's return. Transit time is correlated with channel width. The relative positions of the emitting and receiving sensors are used to estimate velocity. A minimum depth of flow is required to use this sensor effectively. Also, this type of sensor can only be used at sites with sufficient base flow to provide the medium in which the sound wave travels. If there is no base flow, the lower portions of the rising and falling limbs of the hydrograph are lost.

3.2.3.7 Float-and-Stopwatch Method

In this method, the time it takes for a float to move a known distance downstream is determined. Velocity is calculated as the distance traversed divided by the travel time. The characteristics of a good float are: an object that floats such that it is partially submerged, allowing some averaging of velocity above and below the surface of the water; an object that is easily observed and tracked; an object that is not easily affected by wind; and an object that does not cause problems if not recovered. Citrus fruits such as oranges, limes, or lemons are commonly used as floats. Ping-pong and styrofoam balls float well but are too light and are easily blown by the wind; they can also pose environmental problems if not recovered.

One variation of this method is the use of a vertical float with a weighted end. The vertical float provides a better measure of mean velocity over the depth of the water column than a float moving primarily at the surface. In addition, this type of float can be designed to minimize bias due to wind.

In most cases, the float-and-stopwatch method is not accurate enough to be of significant use in stormwater monitoring studies. It is also particularly inaccurate for very deep systems and where there is a significant difference in velocity across the water surface (e.g., natural channels).

3.2.3.8 Head Stick Estimated Flow

For approximate flow measurement using minimum equipment, the “head stick” method can be used by following these steps:

1) Place a ruler in the flowline of the channel so that the edge of the ruler is paralleled to the flow line. The ruler should be more or less streamlined. Record the depth measured on the ruler (d_1).

2) Rotate the ruler 90 degrees so that the flat surface of the ruler is perpendicular to flow. Record the depth (d_2). The difference between d_2 and d_1 is the velocity head.

3) Calculate the velocity (V) as follows:

$$\Delta h = d_2 - d_1 = \frac{V^2}{2g}$$

$$V^2 = (d_2 - d_1) \cdot 2g$$

$$V = \sqrt{(d_2 - d_1) \cdot 2g}$$

Equation 3-3

Where:

V: velocity (ft)
G: gravitational acceleration (32.2 ft/s^2)
d_2, d_1: recorded depths (ft). (Note: If depth in inches, convert to feet.)

4) Flow can be calculated using the velocity estimate and cross sectional area of flow.

3.2.3.9 Deflection (or Drag-Body) Method

In this method, the deflection or drag induced by the current on a vane or sphere is used to measure the flow velocity. This method is only practical for short-term, real-time measurements, such as equipment calibration, because an object of this size inserted into the flow can accumulate debris, causing it to change the hydraulic form, provide inconsistent data, and potentially break away.

3.2.3.10 Tracer Studies

Tracer methods have been developed to measure flow velocity under uniform flow (USGS 1980). For Total Recovery Tracer studies, as described in the flow measurement methods section, a discrete slug of tracer is injected into the flow. Concentration-time curves are then constructed at two downstream locations. By determining the time for the peak concentration of the dye plume to pass the known distance between these two locations, one can estimate the mean velocity of the flow. This method is not practical for continuous flow measurement, but is useful for site calibration. As previously noted, this method is not appropriate for areas affected by combined sewer overflows (CSOs).

3.2.3.11 Methods Suitable for Calibration

The most important aspect of any calibration method is its ability to obtain accurate results with a high degree of certainty and repeatability. Proper calibration of equipment is essential in reducing flow measurement errors. A variety of methods have been employed in the past. The most common methods are described in this section. Exhibit 3-15 summarizes the available methods.

Exhibit 3-15. Velocity Measurement Methods Suitable for Calibration

Method	Comments
Tracer Studies	Although one of the best calibration methods, it is often not practical. Requires complete mixing of tracer with flows.
Rotating-Element Current Meters	Useful for larger flows that do not rapidly vary with time. Typically useful for large systems with appreciable flows. Low flows are difficult to monitor.
Pressure Sensors	Not useful for velocities above 1.5-1.8 m/sec or in pipes with steep slopes (>5%).
Acoustical Sensors	Not applicable to most monitoring locations. Large flow rates are typically required. Base flow required to observe complete storm hydrograph. Typically applicable only to large channels.
Float and Stopwatch	Rarely accurate enough for calibration purposes. Not recommended for most situations
Bucket and Stopwatch	Although not a velocity method, this approach can work very well for determining flow rates and may be a very useful tool for flow rate calibration.
Deflection (or Drag-Body) Method	Rarely accurate enough for calibration purposes. Not recommended for most situations.

3.2.4 Data Loggers

Where automated data collection is desired over time, secondary devices typically are attached to data loggers. Data loggers are devices that monitor signals from instruments and store the impulses that they generate. When data loggers are combined with software to measure and route signals between instruments and analyze data, they are referred to as “data acquisition systems” and are often used as the execution center of a monitoring station. Most data loggers have multiple input ports and can accommodate a variety of sensory devices, such as temperature probes, rainfall gages, or pressure transducers.

Some vendors provide automated water quality sampling and/or weather station “monitoring systems” that have intrinsic data loggers that will accommodate inputs from the typical sensors that would be associated with the type of monitoring that the system is designed to accomplish and a central processing unit (CPU) with limited programming and data processing capabilities. Often, these “monitoring systems” are adequate for standard BMP monitoring applications and can greatly simplify monitoring station setup.

One drawback of these “monitoring systems” is that often times they can only support sensors from the same vendor that provided the system. Before choosing a “monitoring system” over a stand-alone data logger, it is important to make sure that the programming options, data storage capacity, and sensor specifications (e.g., resolution, accuracy, design configuration, construction

materials, power consumption) of the system are compatible with the proposed application and data needs

Data loggers suitable for stormwater monitoring applications are typically constructed of weather-resistant materials capable of protecting their internal circuitry from water and dust hazards. They are designed to operate at extreme temperatures, from as low as -55°C to as high as 85°C (-67°F to 185°F). However, be aware that some common data loggers and auto-sampler heads do not function at subfreezing temperatures without retrofit. After-market heaters and thermostats can be purchased to enable year round continuous monitoring in cold climates. In addition, most models can be securely mounted in remote locations, providing protection from wind and rain, wildlife, and vandalism.

Exhibit 3-16. Data Logger with Weatherproof Housing (Handar)

A typical data logger for field use may consist of the following components: a weatherproof external housing or a "case"; a CPU or microprocessor; memory (RAM and/or Flash) for storing data and programs; data input ports; data output ports; one or more communications ports (remote access via cell, wireless broadband, land line, or radio frequency modem is available for some data loggers); and at least one power source.

Most data loggers provide for user interface so that they can be field programmed and interrogated. The user interface can be a touch screen on the data logger or part of another device (e.g., PC, PDA) connected to the communications port on the logger. Data stored Memory may be retrieved by downloading to personal computers (PCs) or personal digital assistants (PDAs), data transfer units (DTU), or via remote access (modem).

Systems that rely on volatile memory (i.e., RAM) for data storage require a backup power source such as a lithium battery to prevent data loss in the event the primary power fails.

Exhibit 3-17. Data Logger Without Housing (Campbell Scientific)

Data loggers vary in size from 0.2 to 9 kilograms (0.5 to 20 pounds) or more. Both portable and fixed data logging systems are available. For long-term, unattended monitoring projects, a fixed instrument capable of serving as a remote transmitting unit may be preferable to a portable one. Manufacturers of data loggers suitable for stormwater monitoring can be easiliy obtained through simple internet searches.

3.2.4.1 Programmability

Some data loggers can be programmed to convert the signals they receive directly into useful information such as velocity, flow, or rainfall depth. These data loggers can be programmed to interrogate a sensor at user-selected data recording time intervals. Once the intervals are set, the data logger can collect the information and record the output (e.g., the voltage or resistance output from a pressure transducer sensor), or it can record an "exception" if the sensor output goes outside a defined range (e.g., break in signal when a rainfall gage bucket tips). The data logger can then develop simple statistics based on the input they receive.

Less expensive models can be pre-programmed at the factory to collect data at a defined interval or to count exceptions. In this case, the user must post-process the downloaded information to create meaningful data.

Many vendors offer data loggers with the capability of remote manipulation via modem and PC, however, the user-friendliness of the various models can vary greatly between vendors. These data loggers require vendor-developed software packages and an IBM-compatible PC with Windows™ to run the packages. Therefore, this additional cost should be considered when evaluating a particular model. Another point of consideration is the format in which a particular model logs the data it receives. Some models log data in a format that can be converted from ASCII files to any of several commonly available spreadsheet or word processing files, while others require the use of their particular vendor-developed software for data analysis and manipulation.

3.2.4.2 Data Capacity

Memory type and capacity vary greatly between instruments. Standard capacity varies between models and vendors from less than 8 Kilobytes to several gigabytes with removable flash memory. In general, one data point uses 2 bytes of information; therefore, a data logger with 64K of memory can be expected to have a maximum data point capacity of 32,000 data points before downloading data or requiring more memory to be added. Some types of sensor inputs require as much as 4 bytes of memory per data point; these would require data loggers with more

memory capacity. It should also be noted that when recording sets of data related to storm events, memory can be exhausted more quickly than expected.

Most data loggers use a non-volatile Flash type of memory for data storage. That means that no power is required to store data once it is recorded. However, some data loggers store programs and data on volatile RAM-type memory. All information stored on volatile RAM is lost if the power is cut off. For these data loggers, an automatically activated backup power source is recommended. Backup power is usually a lithium battery that requires frequent monitoring and replacement every 1 to 10 years.

Most models are programmed to stop recording data upon exhaustion of available memory. However, some models are equipped with wraparound or rotary memory, which rewrites over the oldest data when available memory becomes exhausted. When using rotary memory, it is important to realize that data can be lost if it is not downloaded before it is written over.

Systems with data loggers that are separate from water quality samplers are more flexible than combined data/samplers because they are more programmable. Memory capacity is often an issue (even with the current inexpensive memory) and requires that careful attention be paid to downloading data before it is overwritten.

3.2.4.3 Communications

Models vary in their ability to accept input from more than one source. Significant advances have been made in recent years in this regard. Some data loggers are designed with a single analog input channel, while others are designed with up to 16 channels. In addition, some of the newer models accept digital input data. The choice of a particular model should be based upon the number of sensors or probes from which the instrument will be required to accept data.

Data loggers can accept information from many different types of sensors and transducers. This allows for versatile use of most data logging systems. Some vendors offer probes and transducers with built-in data loggers; however, these systems typically cannot accept input data from other sensory devices, and their ability to communicate output data is often limited.

With regard to output communications, most data loggers interface with the standard RS-232 interface type, and some possess the capability to communicate with other interface types. In most cases, data can be downloaded on-site to a laptop PC or transported to a lab or office so that the data can be downloaded to a desktop PC. As indicated earlier, data loggers can be equipped with an internal modem for telecommunications, allowing a user to download data from a remote host PC without having to visit the field site.

In most cases, use of a telephone modem requires an IBM-compatible PC as the host as well as the vendor's software. Typically, baud rates can be selected by the user. However, some models are capable of only a few baud rates, a limitation that should be considered when choosing a specific model. Some machines also possess the capability to transmit data via line-of-sight, UHF/VHF or satellite radio. These options also allow for remote manipulation of programming and downloading of data.

With rapidly occurring changes in communication technology, this is a constantly improving component of stormwater monitoring. Advances in recent years include cellular modems, sattelite technologies and other emerging communication technologies.

3.2.4.4 Power Requirements

In general, data loggers are energy efficient devices. Most are powered by an internal battery, with the option of using external electrical power, if available. Because power is lost during some storms, batteries should be the primary power source, although they can be recharged from other sources. Many devices are also equipped to use solar power. Data loggers can also be powered by internal batteries. In this case, there is often a choice of cell type. While some models offer the choice of rechargeable cells or standard 12-volt alkaline cells, others offer alkaline lithium batteries. The power source and model selected generally depends upon several factors, including site accessibility, distance from the nearest point on the electric power grid, and amount of data to be recorded.

When evaluating power options, the battery replacement and disposal costs should be considered along with the estimated life of the battery. For example, alkaline cells are less expensive than lithium or rechargeable batteries, but they have a shorter life and must be replaced more often. While alkaline cells offer a potential power life of several months, lithium cells offer a potential power life of several years. However, since lithium batteries are considered a hazardous material, data loggers using lithium batteries are subject to more stringent shipping requirements than models using standard alkaline cells. In addition, since alkaline batteries must be replaced and discarded frequently, the use of alkaline batteries may actually be more expensive than using rechargeable batteries. Although rechargeable batteries offer less battery waste and potential cost savings, the time and cost required to recharge the batteries should be considered when evaluating power options.

Operating temperature range is another important factor to consider when choosing a power supply. Lithium expands both the minimum and maximum temperatures at which power can be used by the data logger. Under extreme conditions, it may not be feasible to use a data logger powered by alkaline batteries.

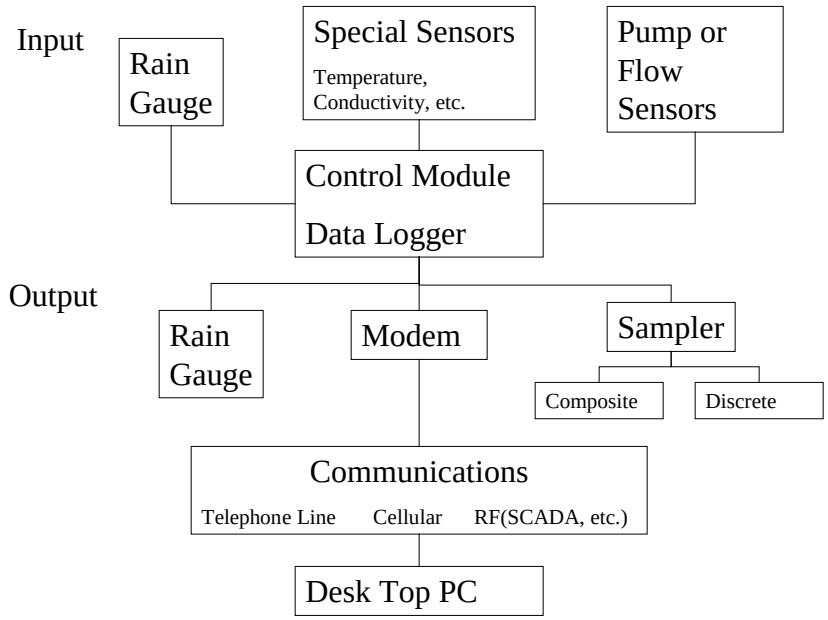

Exhibit 3-18. Data Logger Summary

3.2.5 Other Flow Measurement Methods

In addition to the primarily automated flow monitoring methods previously described, other methods also exist that may be appropriate and useful in various situations. These include direct measurement methods, tracer dilution methods, pump discharge methods, and stage-based equations, as described in the following sections.

3.2.5.1 Direct Measurement Methods

Flow rate can be directly measured by estimating the time it takes to fill a receptacle of known volume or the time it takes to drain a storage basin with a known volume based on the relationship described in Equation 3-4:

$$Q = V/T \qquad \textbf{Equation 3-4}$$

Where:

Q: flow in m^3/s (ft^3/s)
V: volume, m^3 (ft^3)
T: time in seconds.

This method is easy to understand, requires relatively simple equipment, and can be very accurate at low rates of flow. Simply use a bucket with known capacity at predetermined level to capture water and a stopwatch to measure the time it takes to capture that volume. Typically, multiple measurements are made and the results are averaged.

This method requires the complete capture of the flow stream during the measurement interval and is most often used for conducting limited research and for calibrating equipment. However, this method can also be used to obtain estimates of average discharge rates from a treatment facility, provided that the flow is fairly uniform.

3.2.5.2 Tracer Dilution Methods

Tracer dilution methods can be used where the flow stream turbulence and the mixing length are sufficient to ensure that an injected tracer is completely mixed throughout the flow stream (USGS 1980; Gupta 1989). Tracers are chosen so that they can be distinguished from other substances in the flow. For example, chloride ion can be injected into fresh water, and dyes or fluorescent material can be used if turbidity is not too high. Dye calibration does not work well where CSOs are present.

Dilution studies are well suited for short-term measurements of turbulent flow in natural channels and in many manmade structures such as pipes and canals. However, these methods are better suited to equipment calibration than to continuous monitoring during a storm event. Two dilution methods can be used to determine flow rate, including:

- Constant Injection Rate Tracer Dilution Studies: In this study, a known concentration of tracer is injected at a constant rate into a channel. The concentration of the tracer in the flow is measured at a downstream point over time. Flow is calculated from the initial tracer concentration, the tracer injection rate, and the steady-state downstream concentration. The changes in concentration of the dye reflect changes in flow, which makes this method especially useful during an actual runoff event with highly varying flows. Use a downstream sampler to collect discrete samples that are taken to a lab for fluorescence determinations and compare with calibration curve made from injection dye stock and upgradient water. Create several sets of calibration curves for different times to compensate for potential changes in interferences.

- Total Recovery Tracer Dilution Studies: In this study, a discrete slug of tracer is injected into the channel. Near-continuous measurements of tracer concentration in the flow are taken at a downstream point until the plume has entirely passed. Flow is calculated from the volume and concentration of injected tracer and the total area under the concentration-time curve.

3.2.5.3 Pump Discharge Method

In some cases, the overall discharge rate for a catchment can be measured as the volume of water that is pumped out of a basin per unit time while holding the water level in the basin constant. This method can be applied at sites where flow runs into a natural or manmade basin from several directions or as overland flow. If the pump is already calibrated, then the number of revolutions per minute, or the electrical energy needed to pump a given volume, can be used as a surrogate to measure the pumped volume during a stormwater runoff event.

A considerable amount of knowledge about the installed pump's performance is required to implement this method. While the pump discharge method is one option available to measure the

runoff volumes, it is not typically used in the field because other methods are often easier to implement and are more accurate; therefore, pumps are not discussed further in this manual.

3.2.5.4 Stage-Based Variable Gate Meters

ISCO produces a Variable Gate Metering Insert. In this device, discharge flows through the insert and under a pivoting gate, which creates an elevated upstream level that is measured with a bubbler system. The meter uses an empirical relationship to calculate the discharge rate based on the angle of the gate and the depth of flow upstream of the gate. This approach can be used only under conditions of open channel flow in circular pipes. Currently the system is only available for pipe diameters of 10.16, 15.24, and 20.32 cm (4, 6, and 8 inches).

The Variable Gate Metering Insert is designed to measure the flow rate under fluctuating flows and can be effective at both very high and very low flow rates. Its main limitation is the size of the conveyance for which it is designed. The insert may be useful for sampling very small catchment areas; however, debris accumulation can occur, causing problems with the meter.

3.2.5.5 Stage-Based Equations

In cases where measurement of flows is not possible, mathematical equations such as Manning's and Chezy's Equations may be used to estimate flows. If used, it is critically important that those using the equations understand their proper use and associated limitations.

Manning's Equation

The most commonly used empirical relationship, the Manning Equation, is appropriate for open channels with steady-state and uniform flow conditions. In other words, it is used in locations where the flow rate does not vary rapidly over time and the depth of flow does not vary over the length of the channel (Gupta 1989). The Manning Equation (Equations 3-5 and 3-6) requires data for these variables: the slope of the energy grade line, which is usually assumed to be the slope of the channel bottom; the cross-sectional area of the flow; the wetted perimeter; and an empirical roughness coefficient, which accounts for channel material, age, and physical condition.

$Q = \frac{1}{n} AR^{2/3}S^{1/2}$	$Q = \frac{1.486}{n} AR^{2/3}S^{1/2}$
Equation 3-5	**Equation 3-6**
Where: Q: flow, m^3/s n: Manning roughness coefficient (dimensionless) A: cross sectional area, m^2 R: hydraulic radius, m (area per wetted perimeter) S: slope of the channel, m/m	Where: Q: flow, ft^3/s n: Manning roughness coefficient (dimensionless) A: cross sectional area, ft^2 R: hydraulic radius, m (area per wetted perimeter) S: slope of the channel, ft/ft

While the Manning Equation only truly applies to steady and uniform flow, it can provide a fairly accurate estimate of flow rates if certain conditions are met. For example, the channel slope and cross-sectional geometry must be constant for some distance upstream of the site, the exact distance varying with overall system hydraulics. As a rule of thumb, the distance used is the length of twenty channel diameters, or forty hydraulic radii upstream. In addition, flow conditions at the site should not be affected by downstream features (i.e., no backwater effects). Additional information on applicability and values for Manning's roughness coefficients for common channel types are provided in most hydraulics texts (Chow 1959; Gupta 1989). Researchers should be aware, however, that these roughness coefficients are intended for design purposes and, at times, are larger than roughness values based on back-calculation from field-measured flows. Additionally, they can very greatly with depth of flow, debris, and other factors.

Use of the Manning Equation assumes that the slope of the channel bottom is accurately known. Monitoring studies using this technique to estimate flow rates often rely on as-built drawings to determine channel slope. Because these drawings vary in accuracy, direct measurement of the slope of the channel bottom and verification of hydraulic conditions is recommended.

The flow rate of stormwater runoff tends to be unsteady. This is due to changes in the intensity of precipitation and the dynamic nature of overland flow, which can cause the flow rate to vary gradually or rapidly with time. Depending on the frequency with which the depth of flow is measured, rapid fluctuations in flow rate can be missed and the total runoff volume from a storm event can be miscalculated. It is important to calibrate use of the equation with site conditions based on continuous stage measurements and dye injection, or another calibration method.

Chézy Equation

Another empirical relationship used to estimate flow is the Chézy Equation (Gupta, 1989):

$$\frac{Q}{A} = C\sqrt{RS}$$ **Equation 3-7**

Where:

Q: flow, m^3/s (ft^3/s)
A: cross-sectional area, m^2 (ft^2)
R: hydraulic radius, m (ft)
S: slope of the energy grade line, m/m (ft/ft)
C: flow coefficient, $m^{1/2}/s$ ($ft^{1/2}/s$)

Under open channel flow, the coefficient "C" can be defined as:

$$C = \frac{R^{1/6}}{n}$$ **Equation 3-8**

Where:

n: Manning's Roughness Coefficient

When "C" is substituted into Chézy's Equation, the resulting equation is identical to the Manning Equation.

A limitation of both the Manning and Chézy Equations is that they imply that the Manning "n" value is constant for a given channel. However, it is known that for natural channels "n" may vary greatly with respect to flow (Ponce 1989). Therefore, when considering applying these equations to a natural channel, one should first evaluate the alluvial material in the channel and the magnitude of flows expected. It may be desirable to select another flow measurement approach for natural channels with highly varied surfaces and flow rates.

3.2.6 QA/QC of Flow Measurements

Quality assurance and quality control programs (QA/QC) need to be established at the beginning of a project to ensure that precipitation and stormwater flow measurements are accurate and representative of the flow system investigated. Granato et al. (2003) recommend that an effective QA/QC program for stormwater flow data collection activities should include:

- Frequent and routine site visits by trained/experienced field personnel.
- Redundant methods for measuring precipitation and stormwater flow.
- Technical training for project personnel.
- Frequent review by project personnel of precipitation and stormwater-flow data collected.
- Quality audits, in the form of periodic internal reviews.
- Quality audits, in the form of periodic external reviews.

For specific procedures to determine probe accuracy, precision and drift, and to QA/QC-associated discharge measurements, see the references listed in Exhibit 3-1 of this chapter, as well as manufacturer user's guides associated with monitoring equipment.

3.2.7 Infiltration Estimates

Methods to estimate and measure infiltration are discussed in more detail in Chapter 8 in the context of LID; however, estimates of infiltration are valuable for all BMPs, providing a check on the accuracy of hydrology measurements and providing a basis of comparison of hydrologic benefits from LID to conventional BMPs.

3.2.8 Common Flow Monitoring Challenges for LID Techniques

Because most LID techniques are intentionally designed to disperse flows (avoid concentration) and infiltrate runoff, flow monitoring can be challenging, but is likely the most important aspect of performance monitoring for LID. Chapter 8 discusses LID monitoring strategies in more detail; nonetheless, the discussion below provides some practical tips on monitoring common LID practices.

- Pervious Pavements: When monitoring pervious pavements, careful experimental design is needed for both influent and effluent. Influent monitoring presents the unique challenge of not having any runoff to monitor unless there is run-on to the pavement surface from adjacent impervious areas. Influent flow monitoring can be done by either monitoring precipitation at the site and converting it to flow, or by monitoring flow from a nearby location and then scaling the flow proportionally to the areas. For influent water quality monitoring, an adjacent area should be selected with land use and proximity as close as possible. Ideally, this would be an area immediately adjacent with comparable traffic usage. Effluent monitoring is typically done through subdrains, as is the case for many LID techniques. Effluent subdrain monitoring should consider the amount of storage, if any, provided in a subbase reservoir below the subdrain. Groundwater monitoring wells can provide important monitoring data with respect to migration of subsurface contaminants, groundwater mounding, and seasonal high water levels. Catch basins and common surface grading are commonly present at pervious pavement sites as a redundancy measure and can be used for monitoring bypassed flows. Bypass monitoring is more important for failing pavements, but may not be needed for functional sites (Personal Communication with Rob Roseen, University of New Hampshire, 2009).

- Calculating (Modeling) Flows as an Alternative to Flow Measurement: Because LID designs inherently seek to disperse flow, rather than concentrate it, inflow measurement for BMPs can be challenging. However, if other parameters are accurately measured, it may be possible to calculate or model inflow. For example, at a bioinfiltration site monitored by the Villanova Urban Stormwater Partnership (VUSP), inflows cannot be monitored, but water depth in the infiltration "bowl", rainfall and overflow can be measured. VUSP has developed and calibrated a hydrologic model to calculate inflows.

3.3 Conclusions

A wide range of hydrologic and hydraulic monitoring approaches are available for urban stormwater BMP monitoring. Selection of equipment is based on site-specific conditions, budget, and desired accuracy. Defensible hydrologic monitoring is fundamental to BMP performance analysis, particularly as many communities are placing increased emphasis on techniques that promote volume reduction.

3.4 References

American Society for Testing and Materials (ASTM). 1995. *Standard Guide for Selection of Weirs and Flumes for Open-Channel Flow Measurement of Water (D5640).* American Society for Testing and Materials, West Conshohocken, PA.

Caltrans. 2003. *Caltrans Comprehensive Monitoring Protocols Guidance Manual*. CTSW-RT-03-105.51.42. http://www.dot.ca.gov/hq/env/stormwater/special/newsetup/index.htm

Chow, V.T. 1959. *Open-Channel Hydraulics*. McGraw-Hill, New York, NY.

Gupta, R.S. 1989. *Hydrology and Hydraulic Systems*. Prentice Hall, NJ.

Granato, G.E., Zenone, C., and P.A. Cazenas (eds.). 2002. *National Highway Runoff Water-Quality Data and Methodology Synthesis, Volume I --Technical issues for monitoring highway runoff and urban stormwater.* U.S. Department of Transportation, Federal Highway Administration FHWA-EP-03-054. 479 p. http://ma.water.usgs.gov/fhwa/fhwaep.htm

Grant, D.M. and B.D. Dawson. 1997. *ISCO Open Channel Flow Measurement Handbook.* ISCO Environmental Division. Lincoln, NE.

Pitt, R. 2009. University of Alabama. Personal communication.

Ponce, V.M. 1989. *Engineering Hydrology Principles and Practices*. Prentice Hall, Englewood Cliffs, NJ.

Ritsche M.T., Holdridge D.J., Deieso A., Kanta, A., and J. Prell. 2008. *Optical Rain Gage and Tipping Bucket Rain Gauge Comparisons at the ARM Climate Research Facility TWP Sites*. Environmental Science Division, Argonne National Laboratory, Argonne, IL and Department of Geography, Northern Illinois University, DeKalb, IL.

Roseen, R. 2009. University of New Hampshire. Personal communication.

Sauer, V.B. and R.W. Meyer. 1992. *Determination of error in individual discharge measurements*. U.S. Geological Survey Open-File Report 92-144. 21 p. http://water.usgs.gov/admin/memo/SW/sw93.14.html

Spitzer, D.W. (ed.). 1996. *Flow Measurement Practical Guides for Measurement and Control*. Instrument Society of America, NC.

U.S. Department of the Interior Bureau of Reclamation. 2001. *Water Measurement Manual*. http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/

U.S. Geological Survey (USGS). 1980. *National Handbook of Recommended Methods for Water-Data Acquisition.* U.S. Geological Survey, Reston, VA.

U.S. Geological Survey (USGS). 1982. *Measurement and Computation of Streamflow*. Volumes 1 and 2. USGS WSP-2175. http://pubs.usgs.gov/wsp/wsp2175/

U.S. Geological Survey (USGS). 1985. *Development and Testing of Highway Storm-Sewer Flow Measurement and Recording System*. Water-Resources Investigations Report 85-4111. U.S. Geological Survey, Reston, VA.

U.S. Geological Survey (USGS). 2001. *A Synopsis of Technical Issues for Monitoring Sediment in Highway and Urban Runoff*. Open-File Report 00-497. U.S. Geological Survey, Northborough, MA.

U.S. Geological Survey (USGS). (various dates). *Techniques of Water-Resources Investigations Reports*. Multiple Chapters. http://pubs.usgs.gov/twri/