conservative: as noted previously a larger l and hence larger l/m gives a smaller V/V_i for given t_r/t_c and Q^*/I_p. In some cases an adequate value of l may be found by regression analysis of the actual storage-elevation relationship, and in other cases a conservative value of l may be selected based on that relationship. See Section 10.4.

A unique outflow-elevation relationship exists for a particular outlet geometry. When the outlets are computationally determinable and mathematically simple, the outflow-elevation relationship can be programmed into appropriate design software. See Section 10.5.

When the outlets are of moderate hydraulic complexity (e.g., unsubmerged culverts), an efficient procedure is to initially generate outflow-elevation points. That avoids the computation of a great deal of wasted information in the form of many outflow-elevation points that are not saved for subsequent use. Computationally, the outflow-elevation relationship can then take the form of a two-column two-dimensional array with flow in one column and corresponding basin water surface elevation values in the other. Having set up the array, values of outflow and headwater can be calculated during routing by simple interpolation as part of the solution algorithm to which the array is input (e.g., Graber 1999). Interpolation can also be used when the outflow-elevation relationship is based on measured data points.

In some cases, a variable tailwater affects the basin discharge, such that the outflow is a function not only of the storage elevation (and conversely), but also of the tailwater elevation. An example is a detention basin for which the downstream water body creates a varying hydraulic control for the outlet, by submerging the free-discharge hydraulic control that would otherwise occur at the outlet. In such cases the tailwater elevation (and hence outflow) is in turn a function of basin outflow. For more detailed technical understanding of one method of incorporating such tailwater variations, see Graber and Elkerton (1999) which expresses the outflow in terms of the following functional relationship:

$$Q = \Psi[y - y_t(Q)] \tag{10-6}$$

In such a case, an array giving the tailwater elevation-flow relationship can first be computed. Then the basin outflow-elevation array can be developed as follows. For each value of flow, the tailwater can be calculated by interpolation from the tailwater-elevation flow array. Knowing the tailwater and flow, the basin elevation can then be computed. A basin elevation-flow array can thus be developed that takes tailwater into account. Again, having set up that array, values of flow and basin elevation can be calculated by simple interpolation as part of the solution algorithm (e.g., Graber 1999).

Commercially available (or free in some cases) routing software, such as HydroCAD, XPSWMM, HECRAS, HEC-HMS, and TR-20, is capable of handling many of the previously discussed procedures.

10.9 PRACTICAL APPLICATIONS

The following provides some practical design examples, drawn from actual practice, of some of the methods discussed.

10.9.1 Successive Trapezoidal Hydrographs. Table 10-2 gives an example from actual practice using successive trapezoidal hydrographs and the numerical method previously discussed for a project reviewed and modified (based on review) in Randolph, Massachusetts. An existing detention pond outlet control structure was to be modified in conjunction with upstream improvements to attenuate post-development peak flows to pre-development peaks downstream of the impoundment without increasing flood levels upstream of the impoundment. The outlet control structure consists of a tapered box culvert operating under inlet control [similar to Chow's (1959) Type 6] over the flow range of interest, with a rectangular slot upstream of the culvert and emergency overflows. The data in Table 10-2 are for post-development conditions with the 100-year storm and a 6-minute time of concentration. As shown in Table 10-2, for each return period runs for different storm durations were performed to determine the duration giving the largest outflow. The peak outflow occurs with storm duration equal to 270 minutes, and is 3.7 times the peak outflow computed with storm duration equal to time of concentration. The 0.240 m^3/s (8.47 cfs) peak outflow compares with a 0.537 m^3/s (10.5 cfs) peak outflow estimated by the proponent under the same conditions but using the TR-55 tabular method and its associated 24-hour storm (SCS 1986); that 0.537 m^3/s (10.5 cfs) peak outflow is acceptably below the predevelopment peak flow and indicates the conservatism of the TR-55 method in this case (however, not necessarily for others). A tabulation similar to Table 10-2 for a rooftop impoundment is given as Table 2 in Graber (2009b).

Table 10-2. Detention Basin Design Example

Storm Duration t_r, minutes	Rainfall Intensity, i		Peak Inflow, I_p		Peak Outflow, Q_p	
	mm/hour	in./hour	m^3/s	cfs	m^3/s	cfs
6 (t_c)	188.0	7.4	2.8879	102	0.0648	2.29
30	96.5	3.8	1.4836	52.4	0.1418	5.01
60	63.0	2.48	0.9683	34.2	0.1775	6.27
120	41.9	1.65	0.6427	22.7	0.2155	7.61
180	31.2	1.23	0.4799	16.95	0.2220	7.84
225	28.7	1.13	0.4388	15.5	0.2387	8.43
270	25.9	1.02	**0.3964**	14	**0.2398**	**8.47**
315	23.1	0.91	0.3539	12.5	0.2356	8.32
360	20.3	0.8	0.3114	11	0.2231	7.88

For the case discussed in the previous paragraph, the complexity of the outlet was such that case-by-case routing analyses were performed. For a project in Boxborough, Massachusetts, however, with a freely discharging rectangular-culvert outlet, nonuniform backwater conditions yielded a relationship of the form of Eq. (10-3), with the same datum as the storage-elevation relationship. In that case, generalized curves of the type discussed previously apply exactly. For a 25-year storm, the time of concentration was 40 minutes and critical storm duration was 200 minutes. As another example of the use of the generalized curves, for a project in Sudbury, Massachusetts, for a 50-year storm with a pond controlled by a three-barreled culvert functioning with inlet control [similar to Chow's (1959) Type 6], the critical storm duration was equal to the 15-minute time of concentration. A similar application is discussed in Graber (2011b), which provides additional exemplification of the use of the generalized curves and its relation to other methods.

A detention basin reviewed in Topsfield, Massachusetts, had a 21-minute time of concentration and a culvert outlet predicted to function with flow types [similar to Chow's (1959) classifications] changing as flow increases from Type 6, to Type 5, to Type 5 with full upstream end, to Type 2. The critical storm duration was found, by difference formulation using successive trapezoidal hydrographs, to be 60 minutes for the 10-year storm and 120 minutes for the 100-year storm.

For a project in Wellesley, Massachusetts, the regulatory agency required that back-to-back identical storms, the second one within 24 hours of the first, be considered. The analysis for the first storm in such a case can proceed in the customary manner, and the analysis for the second storm then begins with the detention basin water level calculated at the end of the first storm.

Graber (2009b) gives numerous additional examples of the use of successive trapezoidal hydrographs focusing on roof storage specifically and utilizing numerical, generalized, and analytical solutions. The examples again demonstrate the importance of considering storm duration on a case-by-case basis for proper determination of the maximum depth, storage, and outflow. A critical duration at which the greatest water depth and outflow occur must be found in each case. Large differences in the basin depth, volume requirements, and flow attenuation can result from failure to do so (see Table 10-1).

Commercial software packages are available to perform analyses similar to those discussed. Results obtained utilizing HydroCAD's Modified Rational Method capability with automatic duration analysis are close to those given in Table 10-1, which were obtained using the method described in Section 10.2. The small differences are attributed primarily to the use of a smaller time step and smaller error limit for Table 10-1 vs. the minimum time step and error limit available in HydroCAD. The most important results, namely outflow and depth of water on the roof, differ by amounts of no practical significance.

In more complex cases, such as with detention basins in series, a succession of rectangular (constant-intensity) rainfall hyetographs can be used to find the critical storm duration. Software packages capable of using such input hyetographs include HEC-HMS, HydroCAD, and others listed by the Metropolitan Milwaukee Sanitary District (MMSD undated). Other methods given in Chapter 8 can also be used.

10.9.2 Locus-of-Maxima Method. For preliminary design or review purposes, rather than considering various storm durations each corresponding conceptually to a single simulated storm event, one can consider the locus of maximum values obtained from a series of trapezoidal hydrographs. That approach is analytically simpler in that only a single hydrograph is considered rather than considering a series of hydrographs to determine which is most critical. That "locus-of-maxima" hydrograph is conservative and may be substantially so if the critical storm duration corresponded to a large multiple of the time of concentration. The conservatism in volume of water can be visualized as the area under the locus curve (Ci in which C is Rational Method runoff coefficient and i is rainfall intensity) and the trapezoidal hydrograph for a particular storm duration [see Fig. 2 of Graber (2009b)], and most particularly for the critical storm duration. The conservatism would be small if the critical storm duration is fairly close to the time of concentration. A simpler version of this method, attributed to the U.S. Federal Aviation Administration, is discussed by Mays (2011, p. 653).

For some projects reviewed using the locus-of-maxima method, such as the original submittal of the Randolph, Massachusetts, project mentioned previously, the method has indicated the need for substantial revisions by the proponent. However, for a project reviewed in Rockport, Massachusetts, for a 100-year storm and 8-minute time of concentration with an unsubmerged circular culvert outlet [similar to Chow's (1959) Type 5 at lower flows and Type 2 at higher flows], the locus-of-maxima method gave a peak post-development outflow only 5% above that estimated by the proponent using the SCS (1986) 24-hour storm (TR-20 method).

10.9.3 SCS/NRDC Method. Despite the shortcomings discussed in Sections 8.0 and 10.3, the SCS/NRDC TR-20 method (USDA 2009), with its commercial implementations, remains one of the simplest and most ubiquitous methods in use. Fig. 10-1 is based on application of this method to an actual design case. In addition to the information given on Fig. 10-1, the Type III, 24-hour storm was used for a 100-year return period.

10.10 MORE SOPHISTICATED METHODS

The emphasis up to this point in this chapter has been on event-based methods and systems in which only detention or retention basin storage is considered. Two more sophisticated methods are considered here, one consisting of continuous simulation and the other considering storage in additional system features. These methods require considerable expertise.

In concept, the most accurate way to analyze a stormwater impoundment would be to simulate the performance of the impoundment configuration (storage and outflow characteristics) with historic rainfall and calculated runoff to estimate basin discharge over a period that is long relative to the return periods of interest and perform a statistical analysis on basin discharge. The basin discharge corresponding to the return periods could then be determined, the basin configuration revised as necessary, and the process repeated until the design objective is achieved. Similar methods have been used for simulating reservoir performance using rainfall and evaporation data together with actual and synthesized streamflow data, or such data alone to simulate reservoir, pond, and lake releases to downstream streams (e.g., Graber 2001). Such analyses are generally reserved for more major structures, with stormwater impoundments customarily analyzed for single rainfall events of prescribed characteristics. However, the recent use of continuous simulation for stormwater impoundment design, e.g., by Pandit and Youn (2005), Rajan and Roesner (2005), and Rohrer et al. (2005), is noteworthy. The last two of these references used the Storm Water Management Model SWMM (USEPA 2004) for their implementation. As discussed in Section 8.3.5, commercially available implementations of SWMM also exist. The Hydrologic Simulation Program-Fortran (HSPF), discussed in Section 8.3.4, is another continuous-simulation model. The dearth of continuous-simulation analyses for stormwater impoundments is due in part to the complexity of such long-term simulations and in part because adequate rainfall data may be lacking, particularly for cases with small times of concentration (e.g., less than the 15-minute interval between measurements at "continuously-recording" stations).

Storage of stormwater in pipes or conduits, streets, and drainage ways can be beneficially considered in the design of drainage systems. Such storage can attenuate peak flows, affect the timing and the magnitude of flow, and decrease the required size of storms sewers to less than would be required if such storage was neglected. Conjunctive modeling of surface and conveyance systems can be accomplished. One of the most commonly used models for such purposes is the SWMM model. Originally developed to analyze single-event combined sewer overflows, the model has evolved and can now evaluate most components of stormwater systems using dynamic wave routing. The dual model DORA based on a double-order approximation enables flow and storage in streets to be taken into account by considering the streets to form an upper channel network, connected to the sewer system by vertical links corresponding to the pipes connecting the inlet basins to the storm sewer (Noto and Tucciarelli 2001; Nasello and Tucciarelli 2005). Another recent model with similar capabilities combines SWMM and a two-dimensional noninertia overland-flow model (Seyoum et al. 2012).

10.11 FIELD MONITORING AND THE USE OF MODELS

Field monitoring to achieve calibration and gain insight into the processes involved is always worthwhile and desirable where possible. Several inexpensive monitoring devices are available that allow for continuous water-level monitoring. Technologies include visual staff gauges, mechanical float devices with strip-chart recorders, pressure transducers with data loggers, and remote radar sensors with data loggers. Many of these technologies can also be telemetered to cell phone, telephone, radio, or Wi-Fi connection for uploading data through peer-to-peer communication or web-based data logging and processing. Sometimes these are installed permanently to provide high-water-level alarms and/or used in flood forecasting. When installing a unit, considerations for maintenance and service access, prevention from flood damage or vandalism, power source, precision, wave action, sensor fouling, freezing etc., need to be taken into account.

Time and cost can, of course, often be constraints when considering monitoring. However, any amount of field data that allows one to check the models against "real" data is always helpful and can add credibility. Even a storm well below the design storms in magnitude can provide useful insight, and even short-term monitoring can capture a significant storm. Field information should be used to inform the models whenever possible.

It is also worth concluding with a caution about the use of computer models. Users should develop their own models or select available models judiciously, understand the models thoroughly, and avoid the uncritical acceptance of answers from such models.

CHAPTER 11
WATER QUALITY

Urban land development increases the pollutant loading in stormwater runoff. It introduces new sources of stormwater pollutants and creates impervious surfaces that accumulate pollutants between storms. Structural stormwater collection and conveyance systems allow stormwater pollutants to quickly wash off during storm or snowmelt events and discharge to downstream receiving waters. By contrast, in undeveloped areas natural hydrologic processes such as infiltration, interception, depression storage, filtration by vegetation, and evaporation can not only reduce the quantity of stormwater runoff but also reduce pollutants through physical, chemical, and biological processes. Impervious areas decrease the natural stormwater treatment functions of watersheds and increase the potential for water quality impacts in receiving waters (CDEP 2004).

The primary focus here, in keeping with Chapter 1, Scope, and regulatory requirements discussed in Sections 5.2.2.1, 5.2.3.2, and 5.2.3.3, is on the case where the impoundment is the stormwater control measure (SCM) and provides water quality and flow control at the outlet to a downstream receiving water. The term SCM has been selected over the term BMP (Best Management Practice) to be consistent with the new WEF Manual of Practice No. 23 (WEF/ASCE 2012) and the 2008 NRC report (NRC 2008), as it reflects a broader sense of managing both stormwater quality and runoff volume. However, because this term is somewhat transitory, for the purposes of the paper, the terms are interchangeable.

For the case in which the impoundment is the SCM, numerous design standards and guidelines have been adopted by jurisdictions throughout the United States. From a water quality perspective wet ponds, wet detention ponds, extended detention ponds, etc., are designed specifically for the purpose of meeting water quality, flow control, volume control, or a combination of these (UDFCD 2010). Design methods for these types of impoundments are discussed in Sections 11.2 and 11.3. More comprehensive discussion of the methods and types of SCMs available is outlined in the WEF Manual of Practice No. 23 (WEF/ASCE 2012).

Another perspective is viewing the impoundment as the receiving water, for example a recreational pond where water quality within the pond is needed. In that case, having an acceptable level of water quality from the contributing watershed is desirable, and SCMs would be taken upstream to provide for water quality and volume control. Such SCMs are discussed in Section 11.3. Such measures can also be in lieu of a detention basin or augment a detention basin to improve water quality in the ultimate receiving water and in the detention basin.

A third perspective is viewing the aspects of design that affect water quality within the impoundment, in some cases without respect to the water quality from the upstream watershed. Factors such as water depth, turnover, water temperature, infiltration, exfiltration, vegetation, and biota affect the water quality, somewhat independently of the water quality of the influent. These considerations are also discussed in the following.

11.1 STORMWATER POLLUTANTS

Stormwater runoff generates and transports many pollutants in a watershed. This section describes the common pollutants found in urban stormwater runoff, typical pollutant sources, related impacts to receiving waters, and factors that influence pollutant reduction. Some of these pollutants occur in a dissolved or soluble form, which has important implications for the selection and design of SCMs.

11.1.1 Nutrients. Urban stormwater runoff typically contains elevated concentrations of nitrogen and phosphorus that are commonly derived from natural sources and anthropogenic sources. Natural sources include decomposition of parent material in soils; aerosols composed of pollen, dust, and fine particulate material; decomposition of organic matter such as deciduous leaves; flower shatter; and animal waste from birds and other wildlife. Anthropogenic sources include lawn fertilizers from residential and commercial landscaping, urban nurseries, and improperly stored materials. Other sources include detergents from vehicle washing, building and deck washing, windshield detergents, etc. Within urban areas domestic animals, leaking septic systems and occasional cross-connections, illicit discharge of recreational vehicle waste tanks, and discarded disposable diapers contribute waste products. Anthropogenic activities also generate nutrients that are subject to atmospheric deposition. These are products of combustion, aerosol applications of chemicals, and industrial processes. Organic matter includes trash and debris, food waste, and mixed yard debris from landscaping activities.

Both nitrogen and phosphorus are transported in different forms and can transition from one to the other depending on pH, dissolved oxygen, and biological activity. Forms include solid and dissolved phases. Solid phases can be particulate-bound N or P as part of an organic structure such as dead cells or components of living microorganisms residing on solid surfaces. Dissolved forms can be uptake-available phosphate (PO-4), nitrate N, nitrite N, and ammonia. Nutrients can also be associated with solids or microorganisms that pass through the filters used in the analytical procedures.

Nutrient concentrations in urban runoff are similar to those found in secondary wastewater effluents (American Public Works Association and Texas Natural Resource Conservation Commission 1998). Elevated nutrient concentrations in stormwater runoff can result in excessive growth of vegetation or algae in streams, ponds, lakes, reservoirs, and estuaries, a process known as accelerated eutrophication. Phosphorus is typically the growth-limiting nutrient in freshwater systems, while nitrogen is growth-limiting in marine systems, and both can be growth-limiting in brackish waters such as estuaries. The growth-limiting forms are the ones stimulating algal growth in these respective bodies of water.

Excessive nutrients in runoff are a major source of degradation in receiving waters or impoundments, which are susceptible to eutrophication from nutrient loadings. Excessive nutrients cause detrimental growths of phytoplankton (algae), submerged aquatic vegetation, and zooplankton. Increased amounts of phytoplankton and zooplankton in the water column decrease available light. Excess nutrients can also favor the growth of macroalgae, which can dominate and displace submerged aquatic vegetation, such as eelgrass beds (CDEP 2004), that supports the aquatic community. The presence of excessive vegetation and algae can also cause dramatic and rapid changes in dissolved oxygen and pH. For example, high algae concentrations respire during the night and use the oxygen in the water, dropping the dissolved oxygen (DO) to a level where many aquatic species of fish and other higher-order fauna cannot survive. The simultaneous generation of massive amounts of CO_2 also acidifies the water column.

11.1.2 Sediment. Sediment loading to water bodies occurs from washoff of particles that are deposited on impervious surfaces such as roads and parking lots, soil erosion associated with construction activities, and streambank erosion. Although some erosion and sedimentation is natural, excessive sediment loads can be detrimental to aquatic life including phytoplankton, algae, benthic invertebrates, and fish, by interfering with photosynthesis, respiration, growth, and reproduction. Solids can either remain in suspension or settle to the bottom of the water body. Suspended solids can make the water cloudy or turbid; decrease the aesthetic and recreational value of a water body; and harm submerged aquatic vegetation, finfish, and shellfish. Sediment transported in stormwater runoff can be deposited in a stream or other water body or wetland and can adversely affect fish and wildlife habitat by smothering bottom-dwelling aquatic life and changing the bottom substrate. Sediment deposition in water bodies can result in the loss of flood storage volume and deep-water habitat and can affect navigation, often necessitating dredging. Sediment transported in stormwater runoff can also carry other pollutants such as nutrients, metals, pathogens, and hydrocarbons.

Typically sediment loads in stormwater runoff are measured as total suspended solids (TSS) (Roesner et al. 2007), however this is typically a fraction of what is actually transported in stormwater runoff. Many solids are large and saltate through the drainage system where they are deposited into calmer water columns such as those generated by impoundments. Though frequently used to regulate the approvals for water quality stormwater control measures, the measurement of TSS in stormwater is fraught with sampling and analytical error.

11.1.3 Pathogens. Pathogens are bacteria, protozoa, and viruses that can cause disease in humans. The presence of bacteria such as fecal coliform or enterococci is used as an indicator of pathogens and of potential risk to human health (CDEP 1995). Pathogen concentrations in urban runoff routinely exceed public health standards for water contact recreation and shellfishing. Sources of pathogens in stormwater runoff include animal waste from pets, wildlife, and waterfowl; combined sewers; failing septic systems; and illegal sanitary sewer cross-connections. High levels of indicator bacteria in stormwater have commonly led to the closure of beaches along the Great Lakes, East Coast and West Coast beaches, and numerous lakes used for recreational purposes.

In many cases the construction of water quality ponds in urban developments attracts permanent populations of geese, which are not only a source of bacteria but a significant source of nutrients as well. Research also indicates that in some cases many of the indicator bacteria can reproduce in the outside environment, confounding accurate testing to indicate the presence and concentration of pathogenic organisms (Olivieri et al. 2008).

11.1.4 Oxygen-Demanding Organic Materials. Oxygen-demanding organic materials such as grass clippings, leaves, animal waste, and street litter are commonly found in stormwater. The decomposition of such substances in the water column can deplete oxygen from the water. Organic matter is of primary concern in water bodies where oxygen is not easily replenished, such as slower-moving streams, lakes, and estuaries. The organic materials carried by stormwater runoff can also settle to the bottom of water bodies, which contributes to sediment oxygen demand (SOD). The SOD can cause anaerobic conditions resulting in the release of noxious gases caused by the presence of anaerobic organisms. The annual turnover of these ponds and lakes is an important function to restore balance. Shallow lakes and ponds will not turn over and will begin to transition to wetlands and bogs.

11.1.5 Petroleum Hydrocarbons. Urban stormwater runoff contains a wide array of petroleum hydrocarbon compounds, some of which are toxic to aquatic organisms at low concentrations. The primary sources of hydrocarbons in urban runoff are automotive. Source areas of hydrocarbons in stormwater runoff include roads and parking lots. So-called hot spots include service stations, maintenance facilities, bulk petroleum storage facilities, and in many cases illicit discharges from motor oil and transmission fluid changing. Other sources of heavy chain hydrocarbons include asphalt particles and tire dust.

Oils and grease tend to be weathered and not very mobile in the environment and tend to adhere to solids in the sediment. Free oils and fuels from hotspots are transported as free oils on the water surface and as solubilized oils created by the constant maceration by high-speed vehicle tires. Frequently the oils can be attached with surfactants such as windshield wiper fluids.

Other hydrocarbons include glycol from radiator fluids and deicing activities. Data also indicate that certain coal-tar-based asphalt sealers contain high levels of polychlorinated aromatic hydrocarbons (PAHs), a recognized carcinogen (Crane 2010).

11.1.6 Metals. Metals such as copper, lead, zinc, mercury, and cadmium are commonly found in urban stormwater runoff. Chromium and nickel are also frequently present. Metals are transported in the water column in both solid and dissolved phases. Frequently bound to fine organic particles or in a dissolved state (<0.45 μm), metals such as copper have been shown to cause chemosensory deprivation in salmon (Sandhal 2007).

The primary sources of these metals in stormwater runoff are vehicular exhaust residue, copper brake rivets, fossil fuel combustion, corrosion of galvanized and chrome-plated products, roof runoff, stormwater runoff from industrial sites, and the application of deicing agents. Other sources include vehicle brake linings, tires, and other automotive parts. Architectural copper associated with building roofs, flashing, gutters, and downspouts has been shown to be a source of copper in stormwater runoff in many areas of the country. Copper is often used in fungicides and incorporated in or applied to roofing materials and lawns as a mossicide.

11.1.7 Organic Compounds. Synthetic organic chemicals can also be present at low concentrations in urban stormwater. Pesticides, phenols, polychlorinated biphenyls (PCBs), and polynuclear or polycyclic aromatic hydrocarbons are the compounds most frequently found in stormwater runoff. Such chemicals can exert varying degrees of toxicity on aquatic organisms and can bioaccumulate in fish and shellfish. Toxic organic pollutants are most commonly found in stormwater runoff from industrial areas. Pesticides are commonly found in runoff from urban lawns and rights-of-way. A review of monitoring data on stormwater runoff quality from industrial facilities has shown that PAHs are the most common organic toxicants found in roof runoff, parking area runoff, and vehicle service area runoff (Pitt et al. 1995). Recent research also shows that coal-tar-based sealcoats are significant sources of PAHs (Mahler 2005).

11.1.8 Deicing Chemicals and Other Cold-Weather Sources. Salting of roads, parking lots, driveways, and sidewalks during winter months and snowmelt during the early spring result in the discharge of sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride (MgCl), and potassium chloride (KCl), and other deicing compounds to surface waters via stormwater runoff. Sufficient concentrations of chlorides may prove toxic to certain aquatic species and vegetation exposed to high concentrations in runoff. Other deicing compounds may contain nitrogen, phosphorus, and oxygen-demanding substances. Excess nitrogen in drinking water can lead to health problems in infants ("blue baby syndrome") and individuals on low-sodium diets. Antifreeze from automobiles is a source of phosphates, chromium, copper, nickel, and cadmium. Other pollutants such as sediment, nutrients, and hydrocarbons are released from the snowpack in high concentrations during the spring snowmelt season and during winter rain-on-snow events. The pollutant loading during snowmelt can be significant and can vary considerably during the course of the melt event (NYDEC 2001).

Another source of cold-weather pollutants is increased volumes of solids from road-sanding activity. Sand or sometimes cinders used to provide tire traction are ground up by traffic and can be transported as fine solids or transported to receiving waters en masse by energetic storms. Frequently, snowplowing activities and stockpiling of polluted snow directly into water quality facilities, wetlands, and streams accentuates the problem.

The use of metal-studded tires, chains, or cables also contributes to elevated iron and aluminum concentrations in runoff. In addition the abrasion of pavement contributes more solids and heavy hydrocarbons and other pollutants that have been abraded from the pavement surfaces.

11.1.9 Trash and Debris. Trash and debris are washed off the land surface by stormwater runoff and can accumulate in storm drainage systems and receiving waters. Litter detracts from the aesthetic value of water bodies and can harm birds and aquatic life either directly (by being mistaken for food) or indirectly (by habitat modification). Sources of trash and debris in urban stormwater runoff include residential yard waste, commercial parking lots, street refuse, combined sewers, illegal dumping, and industrial refuse.

Although not always viewed as trash and debris, large volumes of leaves are problematic. In natural systems leaves fall to the ground and most remain in place when decay and other natural process provide for forest "duff" nutrient enrichment and recycling. A relatively small fraction finds its way to streams, where decay materials provide organic carbon to microorganisms and tannins and lignins that bind with metals as organic ligands and increase the water hardness. However, in situations where forests have been cleared, or street trees, for example, drop massive quantities of leaves into street gutters where they are washed into the drainage system, they can overload the streams. In addition, leaves mechanically block gutters, pipes, control outlets, etc.

11.1.10 Other Issues. Sometimes the construction of an impoundment can affect water quality in a negative way and needs to be considered. The construction of a pond will frequently increase thermal loading. Exposing the surface of a pond to sunlight will cause it to heat. When a storm occurs, this warmer water can be displaced to streams where cool water is needed to support fish habitat. Increased temperature can also affect the lifecycle timing of aquatic biota, which provide food for migrating and spawning fish.

Impoundments often attract permanent populations of water fowl such as geese, which can contribute a significant load of nutrients by defecating in the water or the immediate surrounds.

Impoundments can also attract wildlife and domestic animals. Constructed water bodies can attract vermin, or be "redesigned" by beavers. The water will attract wild birds, which can be preyed upon by domestic cats. In some cases, large populations of frogs create noise issues. Larger animals such as snakes and alligators can inhabit a pond and pose a danger to people and domestic animals.

Impoundments can provide a habitat for mosquitoes, especially impoundments that are poorly maintained and collect trash and produce emergent wetland vegetation such as cattails (Hunt et al. 2006). Detailed discussion is provided in Section 7.2.

Part of the pond system includes the zone along the banks. Sometimes that zone becomes a source of seed and propagules of noxious weeds and plants, which can spread to downstream waterways. Riparian vegetation management needs to be part of the pond maintenance plan.

Possible adverse effects on quality of groundwater and nearby surface waters due to infiltration from impoundments should be considered, as discussed in Section 4.2.

11.2 WATER QUALITY CONSIDERATIONS IN URBAN IMPOUNDMENT DESIGN

Through careful design, stormwater impoundments can be effective in reducing urban stormwater pollutants through several different physical, chemical, and biological mechanisms. Treatment is primarily achieved by the sedimentation process where suspended particles and pollutants settle to the bottom of the pond. Relatively high-velocity water entering an impoundment will immediately begin to slow and start the process. Heavier solids will settle first followed by finer solids in areas that are either more quiescent or farther away from the inlet. This frequently creates a sorting of the solids with finer solids toward the outlet. When feasible, impoundments can be designed with a forebay where the gross solids can be captured and removed by maintenance activities. In highly urbanized areas hydrodynamic separators are frequently used at the inlet to reduce the impoundment footprint and reduce long-term maintenance costs.

Many ponds also have designs to manage floating materials. Trash and debris, leaves, and oil and grease can be trapped by inverted elbows, skimmers, and trash racks. When larger volumes of trash are expected, the impoundment should be designed such that any of these appurtenances can be accessed during a storm to facilitate trash removal.

Sometimes impoundments can collect oils and greases on the surface. Evidenced by a sheen, these oils and greases tend to be lighter, short-chain hydrocarbons such as fuels, motor oils, etc. In cases of heavy concentrations, oil adsorbent booms are installed near the inlet(s) to facilitate removal. Lower concentrations are removed through volatilization, photodegradation, biological decomposition, sorption to solids, or a combination of these.

Stormwater impoundment can also potentially reduce soluble pollutants in stormwater discharges by adsorption to sediment, bacterial decomposition, and the biological processes of aquatic and fringe wetland vegetation. The key to maximizing the pollutant reduction effectiveness of stormwater impoundments is maintaining a permanent pool. To achieve this, wet ponds typically require a large contributing watershed with either an impermeable liner or an elevated water table without a liner. Incoming water mixes with the existing pool and undergoes treatment through sedimentation and other processes. To the extent that the pond acts as a plug flow system (which it generally only does imperfectly), a portion of the "new" polluted runoff is retained as the "old" treated water is discharged from the pond, thereby allowing extended treatment of the water quality volume (WQV). The WQV is defined as the volume of incoming stormwater that the pond is designed to retain during the storm event. Mixing and plug flow efficiencies are a function of the pond geometry and flow rates (Persson 1999).

For example, when sized to store the WQV, an impoundment system will retain all of the water from storms that generate runoff less than or equal to the WQV and result in a significantly increased period of time available for treatment. For storms that generate runoff greater than the WQV, wet ponds still provide a reduced level of treatment through conventional settling for the additional runoff volume that is conveyed through the pond. The pond volume should be greater than or equal to the WQV to achieve adequate retention time (24-hour retention time is recommended) within the pond. When properly designed, the permanent pool reduces the velocity of incoming water to prevent resuspension of particles and promote settling of newly introduced suspended solids. The energy-dissipating and treatment properties of the permanent pool are enhanced by aquatic vegetation, which is an essential part of the stormwater pond design.

Chemical process are varied and complex, being largely dependent on the water chemistry, temperature, pH, hardness, dissolved oxygen (DO), and other parameters associated with aqueous chemistry. For the purposes of this discussion understanding that changes in chemistry and hence pollutant forms are dynamic is important. For example DO will affect the partitioning of metals and nutrients, and solids can dissolve in water or can precipitate based on pH and DO.

Photochemical reactions are also important for photosynthesis and the volatilization of organics. Photochemical processes also degrade lighter-chain hydrocarbons into heavier, less mobile hydrocarbons. Natural UV radiation will kill pathogens.

Biochemical processes also affect water quality in impoundments. Bacteria and macrophytes will provide for the uptake and transformation of nutrients. Processes of nitrification and denitrification are common, depending on DO.

Aquatic plants and riparian plants, often limited by bioavailable phosphorus, will provide for the uptake of nutrients and the cycling of nutrients on a seasonal basis.

Most critical to the health of an impoundment is maintaining a balance within the system. High pollutant concentrations can exceed the assimilative capacity of the water body and cause it to fail or convert to an unintended outcome. For example a pond converts to a wetland to a bog as part of the eutrophication process.

11.2.1 Configuration of Stormwater Impoundments. Wet ponds typically consist of two general components: a forebay and a permanent wet pool. The forebay provides pretreatment by capturing coarse sediment particles to minimize the need to reduce the sediments from the primary wet pool. The wet pool serves as the primary treatment mechanism and is where much of the retention capacity exists. Wet ponds can be sized for a wide range of watershed sizes, if adequate space exists. For example, a variation on the conventional wet pond, sometimes referred to as a "pocket pond," is intended to serve relatively somewhat small drainage areas, between 1 and 5 acres (0.4 and 2 ha), with little or no baseflow available to maintain water elevations; it relies on groundwater to maintain a permanent pool. Because of these smaller drainage areas and the resulting lower hydraulic loads of pocket ponds, outlet structures can be simplified and often do not have safety features such as emergency spillways and low level drains. Fig. 11-1 depicts a typical schematic design of a conventional impoundment for stormwater treatment.

Maintaining a sufficient permanent pool depth is important to prevent the resuspension of trapped sediments. Conversely, thermal stratification and anoxic conditions in the bottom layer might develop if permanent pool depths are too great. Stratification and anoxic conditions may decrease biological activity and may also increase the potential for the release of phosphorus and heavy metals from the pond sediments. These factors dictate that the permanent pool depth should not exceed 6 m (20 ft). The optimal depth ranges between 1 and 3 m (3 and 9 ft) for most regions (EPA 1999a).

Average annual removal efficiencies of wet ponds can be estimated using continuous simulation. Youn and Pandit (2012) discuss a Natural Resources Conservation Service (NRCS) simulation model that they suggest gives more realistic and more conservative results than a USEPA planning-level model.

Inlet and outlet design are discussed in Chapter 9, Hydraulic Design. Two additional considerations are mentioned here. First, in some areas the inlets (and outlets) may require protection from beaver activity, which can create maintenance and safety issues. One design approach is the Clemson beaver pond leveler (Clemson University 1994), which is designed to prevent beaver activity near inlets and outlets with flowing water. Second, several types of floating outlets provide for constant discharge rates. This allows for the reduction in pond volume because the device can start the maximum allowable design flow vs. waiting for the head to build up in the pond. This approach can reduce the size of the pond and associated costs. However, the impacts of the sustained "square wave" higher flows at the outlet need to be considered relative to the downstream channel conditions. These devices also provide the benefit of skimming floatables on the surface.

11.2.2 Water Quality Volume. WQV is the storage needed to capture and treat the runoff generated by a design storm event. In numerical terms, it is equivalent to the rainfall depth in inches multiplied by the volumetric runoff coefficient (R_v) for the site and the site drainage area. The specific rainfall depth to be used can be tailored to the local and/or regional rainfall for the specific project site. The depth can be determined based on a statistical analysis of the long-term rainfall records. The typical design rainfall depth to be used for determining the WQV is in the range of 0.5–1.5 in. (1.3–3.8 cm). In the Midwest of the United States, the rainfalls within this range equal about 90% of the 1-year 24-hour rainfall. The following equation is used to determine the water quality volume in customary units:

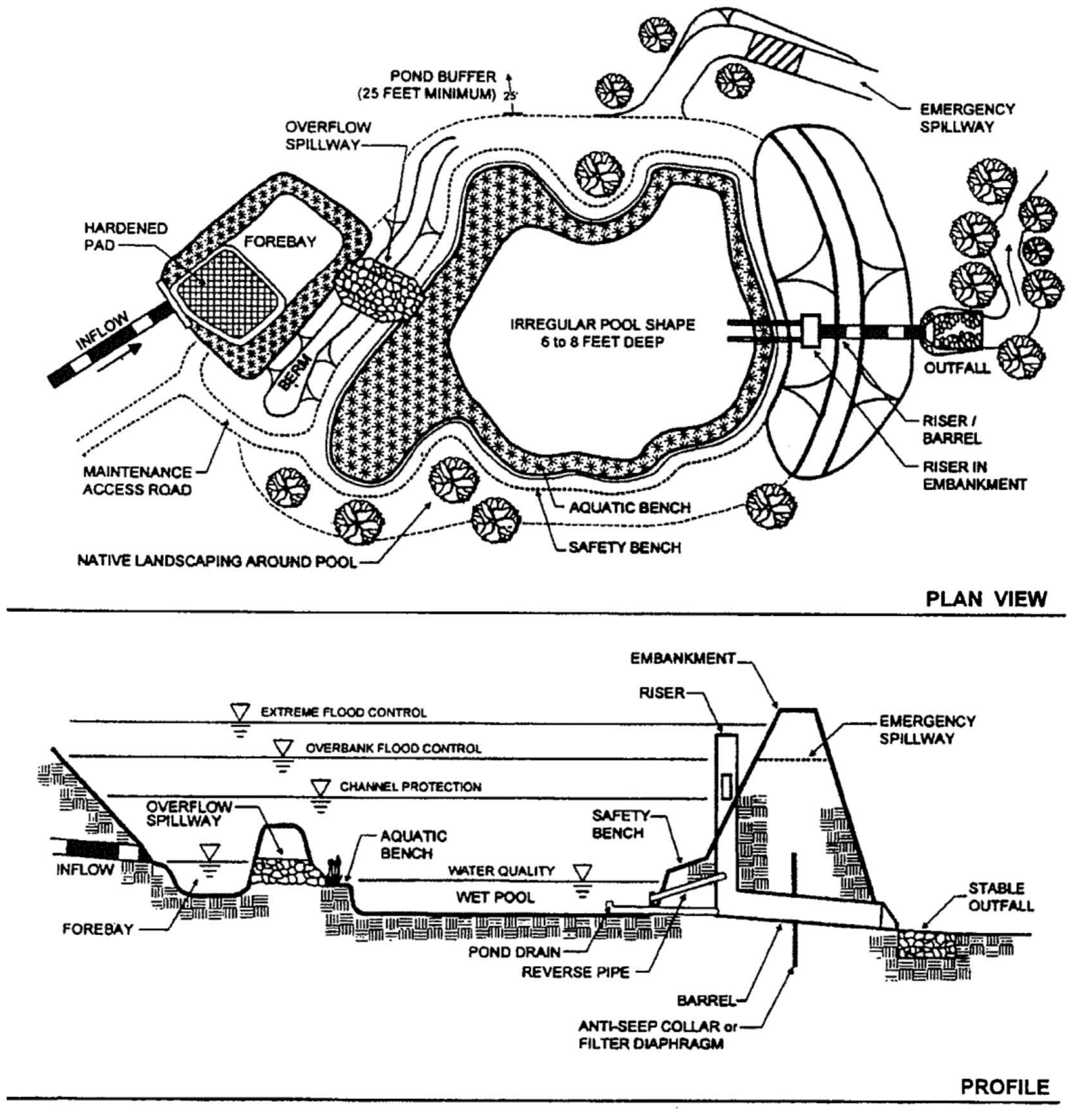

FIGURE 11-1. Schematic Design of Conventional Impoundment for Water Quality Treatment
Source: NYDEC (2001); reproduced with permission from New York Department of Environmental Conservation.

$$\mathrm{WQV} = P \times (R_v) \times A/12 \qquad (11\text{-}1a)$$

where

WQV = water quality volume (acre-ft),
P = rainfall depth of design storm (in.),
R_v = runoff coefficient, and
A = area (acres).

The metric form of the equation is as follows:

$$\mathrm{WQV} = P \times (R_v) \times A \times 100{,}000 \qquad (11\text{-}1b)$$

where

WQV = water quality volume (m^3),
P = rainfall depth of design storm (mm),
R_v = runoff coefficient, and
A = area (km^2).

Runoff coefficient can be defined in different ways. One example is as follows:

$$R_v = 0.15(1 - I) + 0.9(I) \qquad (11\text{-}2)$$

where

I = imperviousness fraction.

Also see Section 5.2.1.1 for other design criteria.

11.3 STORMWATER CONTROL MEASURES (BEST MANAGEMENT PRACTICES)

Urbanized areas generate large quantities of pollutants during storm events. The various pollutant sources in urbanized areas contribute large quantities of pollutants that accumulate on streets, rooftops, and other surfaces. During rainfall or snowmelt, these pollutants are mobilized and transported from the streets and rooftops into the storm drain system, where they are conveyed and ultimately discharged to waterways.

To reduce the impacts to receiving waters from the high concentrations of pollutants contained in the runoff, BMPs can be implemented to reduce these pollutants. In the Clean Water Act (CWA), the USEPA defines BMPs as schedules of activities, prohibition of practices, maintenance procedures, and other management practices to prevent or reduce the pollution of waters of the United States. BMPs also include treatment requirements, operation procedures, and practices to control runoff from construction or industrial sites and spills or leaks (USEPA 1993).

Stormwater management BMPs are control measures taken to mitigate changes to both quantity and quality of urban runoff caused through changes to land use. Generally, BMPs focus on water quality problems caused by increased impervious surfaces from land development. BMPs are designed to reduce stormwater volume, peak flows, and/or nonpoint source pollution through evapotranspiration, infiltration, detention, and filtration or biological and chemical actions. Stormwater BMPs can be classified as "structural" (i.e., devices installed or constructed on a site) or "nonstructural" (procedures, such as public education programs). Various BMPs are available, depending on pollutant-removal capabilities. A list of BMPs can be found at the EPA National Menu of Stormwater BMPs (USEPA 2012b).

Properly designed, constructed, and maintained structural BMPs can effectively reduce a wide range of pollutants from urban runoff. Pollutant reduction in stormwater BMPs can be accomplished through several physical and biochemical processes. The efficiency of a given BMP in reducing pollutants is dependent upon a number of site-specific variables, including the size, type, and design of the BMP; the soil types and characteristics; the geology and topography of the site; the intensity and duration of the rainfall; the length of antecedent dry periods; climatological factors such as temperature, solar radiation, and wind; the size and characteristics of the contributing watershed; and the properties and characteristics of the various pollutants (USEPA 1999a). The following sections provide the description of various SCMs. The detailed design guidance can be found in "Design of Urban Stormwater Control" (WEF/ASCE 2012).

Note, however, that BMPs are sometimes assumed to be more effective than they actually are, and methods for quantifying their effectiveness are important. The following are cited in this regard: Schneider and McCuen (2006), Emerson and Traver (2008), Lee et al. (2010), and Young et al. (2011).

Though utilized for many years, the approaches to managing stormwater quality and volume are continuously changing. More recent approaches use green infrastructure or LID to reduce runoff volume and retain and treat pollutants closer to the sources vs. "end-of-pipe" treatment.

11.3.1 Infiltration Systems. Infiltration systems include infiltration basins, porous pavement systems, and infiltration trenches or wells. An infiltration SCM is designed to capture a volume of stormwater runoff, retain it, and infiltrate that volume into the ground. Infiltration of stormwater has several advantages and disadvantages. The advantages of infiltration include both water quantity control and water quality control. Water quantity control can occur by taking surface runoff and infiltrating this water into the underlying soil. This reduces the volume of water that is discharged to receiving streams, thereby reducing some of the potential impacts caused by an excess flow and increased pollutant concentrations in the receiving stream. Infiltration systems can be designed to capture a volume of stormwater and infiltrate this water into the ground over a period of several hours or even days, thereby maximizing the infiltrative capacity of the SCM.

Infiltration can have many secondary benefits such as increasing recharge of underlying aquifers and increasing baseflow levels of nearby streams. Infiltration SCMs can also provide water quality treatment. Pollutant reduction can occur as water percolates through the various soil layers. As the water moves through the soil, particles can be filtered out. In addition, microorganisms in the soil can degrade organic pollutants that are contained in the infiltrated stormwater.

Although infiltration of stormwater has many benefits, it also has some drawbacks. First, infiltration may not be appropriate in areas where groundwater is a source of drinking water due to the potential for contaminant migration. This is especially true if the runoff is from a commercial or industrial area where the potential for contamination by organics or metals is present. Also, the performance of infiltration SCMs is limited in areas with poorly permeable soils. In addition, infiltration SCMs can undergo reduced infiltrative capacity and even clogging due to excessive sediment accumulation. Frequent maintenance may be required to restore the infiltrative capacity of the system. Care must also be taken during construction to limit compaction of the soil layers underlying the SCM. Excessive compaction due to construction equipment may cause a reduced infiltrative capacity of the system. Plus, excessive sediment generation during construction and site grading/stabilization may cause premature clogging of the system. Infiltration systems should not be placed into service until disturbed areas in the drainage have been stabilized by dense vegetation or grasses.

In addition to detriment to groundwater uses, infiltration can adversely affect nearby surface water bodies (Fischer et al. 2003).

11.3.2 Detention Systems. Detention systems are SCMs that are designed to intercept a volume of stormwater runoff and temporarily impound the water for gradual release to the receiving stream or storm sewer system. Detention systems are designed to completely empty out between runoff events and therefore provide mainly water quantity control as opposed to water quality control. Detention basins can provide limited settling of particulate matter, but much of this material can be resuspended by subsequent runoff events. Detention facilities should be considered mainly as practices used to reduce the peak discharge of stormwater to receiving streams to limit downstream flooding and to provide some degree of channel protection. Several types of detention facilities are used to manage stormwater runoff, including detention basins and underground vaults, pipes, and tanks. Design of detention systems is discussed by Takamatsu et al. (2012) and references given therein.

As mentioned in Section 11.2.1, in some cases floating outlets and other devices have been used to create a "square wave" outlet hydrograph to effectively reduce the total detention volume of the pond or vessel.

More recent developments include so-called "smart detention" where the outlets are operated by valves that are microprocessor-controlled. Examples include systems where the microprocessor interacts with a rain gauge to simulate a hydrograph similar to predeveloped conditions, while the remainder of the runoff is directed to infiltration or even rainwater harvesting.

Other systems will retain water for reuse such as irrigation, but based on rainfall prediction will prerelease water at a low rate to make room for the incoming storm (Quigley and Brown 2014).

11.3.3 Retention Systems. Retention systems include wet ponds and other retention systems such as underground pipes or tanks. Retention systems are designed to lose water only through infiltration or evaporation. They typically do not have an outlet, and sometimes a requirement exists to provide for what is termed a channel protection volume. They are designed to capture a volume of runoff and retain that volume until it is displaced in part or in total by the next runoff event. Retention systems can provide both water quantity and quality control. The volume available for storage, termed the water quality volume, is provided above the permanent pool level of the system. The main pollutant reduction mechanism in retention systems is sedimentation. By retaining a permanent pool of water, retention systems can benefit from the added biological and biochemical pollutant reduction mechanisms provided by aquatic plants and microorganisms, mimicking a natural pond or lake ecosystem. Also, sediments that accumulate in the pond are less likely to be resuspended and washed out due to the presence of a permanent pool of water. In addition to sedimentation, other pollutant reduction mechanisms in retention systems include filtration of suspended solids by vegetation, infiltration, biological uptake of nutrients by aquatic plants and algae, volatilization of organic compounds, uptake of metals by plant tissue, and biological conversion of organic compounds.

A retention variant that is becoming more prevalent is rainwater harvesting tanks or cisterns. Depending on water rights and beneficial use, many jurisdictions approve or even require their use. In this case the stored water is pretreated to a high degree, and the water for beneficial use is treated to various standards, including high-level filtration, disinfection, and chlorination.

11.3.4 Wetlands. Constructed wetland systems incorporate the natural functions of wetlands to aid in pollutant reduction from stormwater. Constructed wetlands can also enable quantity control of stormwater by providing a significant volume of ponded water above the permanent pool elevation. Constructed wetland systems have limits to their application. A water balance must be performed to determine the availability of water to sustain the aquatic vegetation between runoff events and during dry periods. In addition, a sediment forebay or some other pretreatment provision should be incorporated into the wetland system design to allow for the reduction of coarse sediments that can degrade the performance of the system. Also, construction sediment should be prevented from entering constructed wetlands, as the resulting sediment loading can severely degrade the performance of the system. Constructed wetlands are particularly appropriate where groundwater levels are close to the surface because groundwater can supply the water necessary to sustain the wetland system.

Stormwater runoff should not be intentionally routed to natural wetlands without pretreatment due to the potentially damaging effects runoff can have on natural wetland systems. In addition, natural wetlands that receive stormwater runoff should be evaluated to determine if the runoff is causing degradation of the wetland, and if so measures should be taken to protect the wetland from further degradation and to repair any damage that has been done. In addition, local permitting authorities should be consulted prior to designing and maintaining constructed wetland systems to determine if any local regulations apply to their use or maintenance.

11.3.5 Filtration Systems. A filtration system is a device that uses media such as sand, gravel, peat or compost, or an engineered media to reduce a fraction of the constituents found in stormwater. A wide variety of filter types are in use. Various proprietary designs also use specialized filter media made from materials such as pelletized leaf compost. Filters are primarily a water quality control device designed to reduce particulate pollutants. Quantity control can be included by providing additional storage volume in a pond or basin, by providing vertical storage volume above the filter bed, or by allowing water to temporarily pond in parking lots or other areas before being discharged to the filter. Media filters are commonly used to treat runoff from small sites such as parking lots and small developments, in areas with high pollution potential such as industrial areas, or in highly urbanized areas where land availability, costs, or both preclude the use of other BMP types. Filters should be placed off-line (i.e., a portion of the runoff volume, called the water quality volume, is diverted to the SCM, while any flows in excess of this volume are bypassed) and are sometimes designed to intercept and treat only the first 0.5–1 in. (1.3–2.5 cm) of runoff and bypass larger stormwater flows. A benefit of using filters in highly urbanized areas is that the filter can be placed under parking lots or in building basements, limiting or eliminating costly land requirements.

However, placing filters “out of sight” may have implications for continued maintenance and performance without a proactive operation and maintenance (O&M) program. Media filters should use a forebay or pre-settling chamber to reduce a portion of the settleable solids prior to filtration. This helps to extend the life of the filter run and reduce clogging of the filter media by removing a portion of the coarse sediment. Also, care must be taken to prevent construction site sediments and debris such as fines washed off of newly paved areas from entering the filter, as these can cause premature clogging of the filter.

11.3.6 Vegetated Systems (Biofilters). Vegetated systems such as grass filter strips and vegetated swales are used for conveying and treating stormwater flows. These BMPs are commonly referred to as biofilters, because the grasses and vegetation “filter” the stormwater as it flows. Open channel vegetated systems are alternatives to traditional curb-and-gutter and storm sewer conveyance systems. By conveying stormwater runoff in vegetated systems, some degree of treatment, storage, and infiltration can be provided prior to discharge to the storm sewer system. This can help to reduce the overall volume of stormwater runoff that is generated from a particular drainage area.

Other approaches of vegetated systems include green roofs (also see Chapter 10 for limitations, etc.), which provide for detention of runoff from rooftops and significant evapotranspiration (ET). Many municipalities are also looking at street trees to increase ET and reduce runoff though rainfall interception.

11.3.7 Impoundment Aeration. DO is critical for plant and animal respiration, and problems develop when the DO level is low in the impoundment. Oxygen enters into impoundment water through diffusion of air at the water surface and from green plants through photosynthesis. Diffusion at the water/air interface is greatly increased by moving water, ripples, and splashing. Most oxygen supplied by plants comes from microscopic plankton, filamentous algae, and submerged rooted plants growing in shallow water. Aeration is often used as a BMP to replenish DO in the water. The widely used aeration methods include surface aerators, fountain aerators, and compressed air supplied through diffusers. Aquaculture applications include paddlewheel aerators, direct oxygen diffusers, surface aspirators, and venturi air injectors. Other special applications require pumped waterfalls, underwater circulators, air injected into deep “U” tubes, ozone injection, and many other developing technologies.

In some urban ponds, especially when nutrient concentrations cause issues with eutrophication, the dissolved oxygen drops below levels that support aquatic life. Anaerobic digestion of bottom sediments can cause foul odors and extremely acidic conditions. Aeration can help manage this issue by maintaining the DO at acceptable levels. Design guidelines are available from several sources including equipment manufacturers. Criteria such as water temperature, BOD (biochemical oxygen demand), power requirements, gas transfer efficiency, etc., need to be reviewed (MPCA 2009).