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Emerging Stormwater Controls for Critical Source Areas

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Overview of Design Objectives and General Approach in the Selection of Stormwater Controls

Introduction

An extensive literature review and survey of past and current drainage design practices during a recent EPA-funded research project found that design standards have not changed significantly during the past 25 years, but that there has been a shift towards the use of more sophisticated design tools (Pitt, *et al*. 1999). Unfortunately, current practices were identified as inadequately addressing water quality issues, even though almost all survey respondents recognized the significance of wet weather flow impacts. The use of long-term continuous simulation and addressing small storms that can be responsible for important receiving water quality problems is a recommended improvement in current design practices. Important changes in urban water management will also be needed in coming years to balance the needs for both water quality and quantity control in developing areas.

This recent EPA research, along with many other current literature sources, found that it is possible and best to develop stormwater management design guidelines based on local rain conditions. Small events, making up the majority of rain events, commonly exceed bacteria and metal criteria, but are relatively easy to control through simple infiltration or on-site reuse of the stormwater. Moderate sized rains, however, are responsible for the majority of the runoff volumes and pollutant discharges. The runoff from these events can also be significantly reduced, but certainly not eliminated, through infiltration, but larger flows will have to be treated to reduce pollutant concentrations and excessive discharge rates. Large rains that approach and may exceed the capacities of the drainage system produce little of the annual flows and are rare. In addition, significant pollutant concentration reductions during these large events would be difficult and very expensive because of the very large flows involved. However, runoff flow rates should be reduced to produce instream flowrate distributions less than critical values in order to protect in-stream habitat.

Numerous researchers have found that receiving waters degrade sharply after the impervious area in the watershed exceeds about 5 to 10%. It may be possible in many cases, especially for newly developing areas, to determine the appropriate level of stormwater control to compensate for impervious areas greater than these critical values. In addition, researchers have found that critical flow rates may be identified that define stable streambed conditions. If excessive flows are discharged at levels below this critical value, much less damage may occur than if the frequency of flows above this critical value is increased.

Many stormwater problems can be reduced or eliminated using relatively simple changes in development practices. Stormwater from numerous, small, events can be effectively eliminated from surface runoff. Runoff from moderate sized storms can be significantly reduced and larger flows that cannot be eliminated can be treated. Runoff from large storms need to be safely conveyed to minimize property damage and safety issues, and to have the flow rate distribution modified to minimize habitat problems in the receiving water. However, these benefits can only be realized with significant runoff volume reductions that are much easier to implement at the time of development. Implementing appropriate stormwater controls at the time of development is much more cost effective and will provide much more effective levels of control than if only retrofitting is used. Extensive retro-fitting may only result in low to moderate levels of stormwater control (generally about 25% reductions over the whole watershed), while implementation of a broad set of appropriate controls (using both sedimentation and infiltration) at the time of development could result in control levels approaching 75%, or more.

Different drainage design criteria and receiving water use objectives often require the examination of different types of rains for the design of urban drainage systems. These different (and often conflicting) objectives of a stormwater drainage system can be addressed by using distinct portions of the long-term rainfall record. Several historical examinations (including Heaney, *et al*. 1977) have also considered the need for the examination of a wide range of rain events for drainage design. However, the lack of efficient computer resources severely restricted long-term analyses in the past. Currently, computer resources are much more available and are capable of much more comprehensive investigations (Gregory and James 1996). In addition to having more efficient computational resources, it is also necessary to re-examine some of the fundamental urban hydrology modeling assumptions (Pitt

1987). Most of the urban hydrology methods currently used for drainage design have been successfully used for large "design" storms. Obviously, this approach (providing urban areas safe from excessive flooding and associated flood related damages) is the most critical objective of urban drainage. However, it is now possible (and legally required in many areas) to provide urban drainage systems that also minimizes other problems associated with urban stormwater. This broader set of urban drainage objectives requires a broader approach to drainage design, and the use of hydrology methods with different assumptions and simplifications.

Stormwater treatment at critical source areas is usually quite different from treatment at other areas. The control of small critical area contributions to urban runoff may be the most cost-effective approach for treatment/reduction of stormwater toxicants. The general features of the critical source areas appear to be large paved areas, heavy vehicular traffic (especially frequent and large numbers of vehicle starts, such as at convenience stores) and outdoor use or storage of problem pollutants. Most of these areas are quite small, being small commercial establishments. However, large areas of continuous pavement (such as at shopping malls) are also critical sources. Runoff from these larger areas can usually be controlled through the use of preferred wet detention ponds, but runoff control for small areas usually requires special applications.

Design Approach Affected by Runoff and Pollutant Yields for Different Rain Categories

The basics for developing appropriate stormwater controls is understanding that specific receiving water problems are associated with specific rain depth categories. In order to identify which rain categories are important for which receiving water problems, long-term evaluations are needed. Long-term continuous simulations using Atlanta, GA, rain data were made using SLAMM, the Source Loading and Management Model (Pitt 1986; Pitt and Voorhees 1995). These simulations were based on 8 years of rainfall records for the years from 1985 through 1992, containing about 1000 individual rains. The rainfall records were from certified NOAA weather stations and were obtained from CD-ROMs distributed by EarthInfo of Boulder, CO. Hourly rainfall depths for the indicated periods were downloaded from the CD-ROMs into an Excel spreadsheet. This file was then read by an utility program included in the SLAMM software package. This rainfall file utility combined adjacent hourly rainfall values into individual rains, based on user selections (at least 6 hrs of no rain was used to separate adjacent rain events and all rain depths were used, with the exception of the "trace" values: similar analyses were made using inter-event definitions ranging from 3 to 24 hours, with little differences in the conclusions.). These rain files were then used in SLAMM for typical medium density and strip commercial developments. The outputs of these computer runs for Atlanta were plotted on Figure 1. The following summaries these evaluations:

- <0.3 inch. These rains account for most of the events (about 60%), but little of the runoff volume (5 to 9%), and are therefore easiest to control. They produce much less pollutant mass discharges and probably have less receiving water effects than other rains. However, the runoff pollutant concentrations likely exceed regulatory standards for several categories of critical pollutants, especially bacteria and some total recoverable metals. They also cause large numbers of overflow events in uncontrolled combined sewers. These rains are very common, occurring once or twice a week. Rains less than about 0.1 inches would not produce noticeable runoff.

- 0.3 to 4 inches. These rains account for the majority of the runoff volume (about 85%) and produce moderate to high flows. They account for about 40% of the annual rain events. These rains occur on the average about every two weeks and subject the receiving waters to frequent high pollutant loads and moderate to high flows.

- >4 inches. These rains probably produce the most damaging flows, from a habitat destruction standpoint, and occur every several months (at least once or twice a year). These recurring high flows establish the energy gradient of the stream and cause unstable streambanks. Less than 2 percent of the rains are in this category and they are responsible for about 5 to 9 percent of the annual runoff and pollutant discharges.

- very large rains. This category is rarely represented in field studies due to the rarity of these large events and the typically short duration of most field observations. These rains occur only rarely (every several decades, or less frequently) and produce extremely large flows. For example, the 8-year monitoring period (1985 through 1992) had a large rain of about 7 inches (less than a 1% probability of occurring in any one year, if it had a duration of about 1 day). These extreme rains only produce a very small fraction of the annual average discharges. However, when they do occur, great property and receiving water damage results. The receiving water damage (mostly associated with habitat destruction, sediment scouring, and the flushing of organisms great distances downstream and out of the system) can conceivably naturally recover to before-storm conditions within a few years.

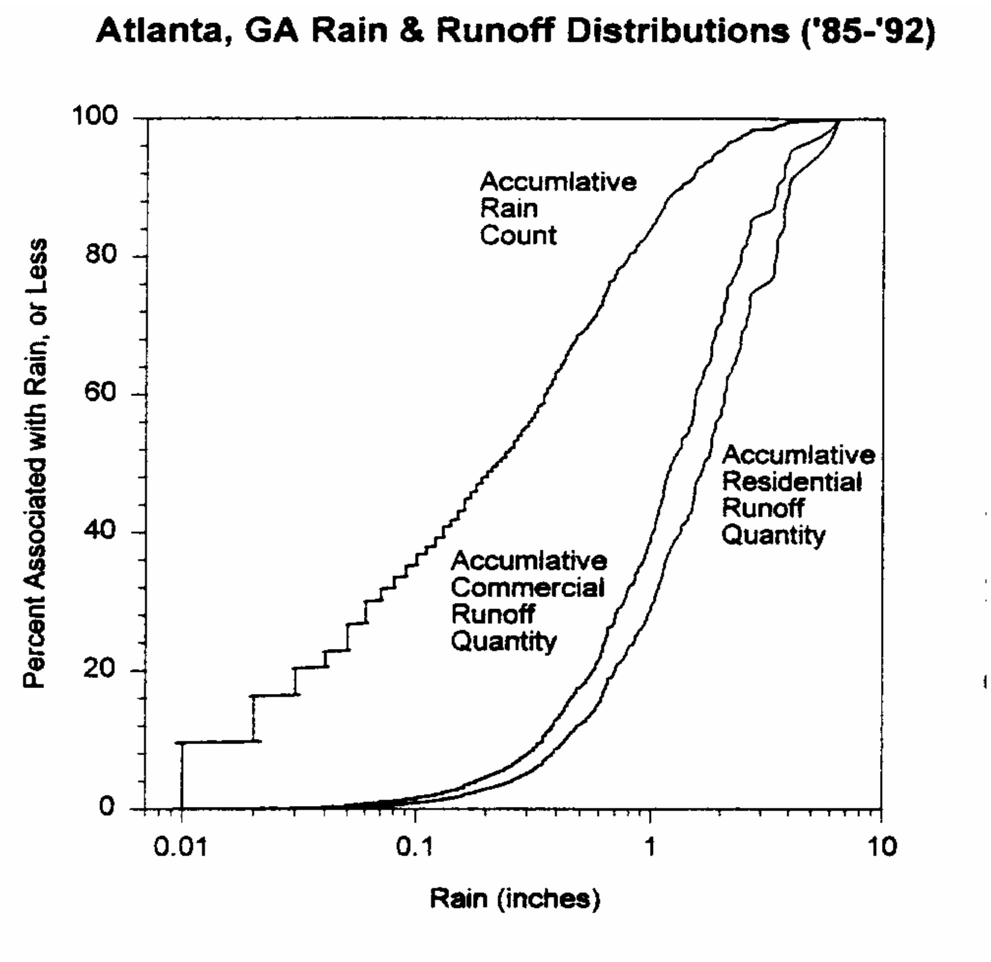

Figure 1. Modeled rainfall and runoff cumulative probability density functions (CDFs).

Candidate Scenarios for Urban Drainage

It is much more difficult to achieve significant stormwater improvements by retro-fitting controls in existing areas compared to establishing controls in newly developing areas. However, it is unlikely that stormwater controls can ever maintain pre-development receiving water conditions except for the most optimal conditions. Stormwater management should therefore be considered necessary to reduce the rate and extent of degradation of receiving waters, but not to preserve pre-development conditions.

From a retro-fit perspective, the control of gross litter and garbage, plus CSO control is of primary concern. Control of toxicants is unreasonable and not very critical in the presence of gross contamination of waterways. Even acceptable litter and floatable control may likely be beyond reasonable financial means in many existing areas. However, many stormwater controls can be implemented at the time of development in a cost-effective manner that can have significant benefits to the receiving waters.

Stormwater Controls Suitable for Retro-fitting in Existing Areas

The ability to construct new stormwater controls in existing areas is severely limited to both a limited number of controls suitable and to the extent of control that may be accomplished. In addition, retro-fitted controls are always much more costly than if the same control was used at the time of development. Retro-fitting stormwater controls is generally limited to the practices shown on the following list. In general, items near the top of this list are more popular for implementation, although they may not be the least expensive or the most effective.

- Public Works Practices (may be implemented by Municipal Streets Department, Parks and Recreation Department, Engineering Department, Sanitation District, etc.)
    - enhanced street cleaning
    - increased catchbasin cleaning
    - repairs of trash hoods in catchbasins
    - installation of catchbasin inserts
    - re-building of inlets to create catchbasins
    - litter control campaign, with increased availability/pickup of trash receptacles
    - public environmental education campaign
    - dog waste control enforcement
    - household toxicant collection
    - enhanced enforcement of erosion control requirements
    - modifications to public place landscaping maintenance

- Infiltration Practices at Source Areas
    - rooftop drain disconnections towards pervious areas
    - amend soils with compost
    - modify residential and commercial landscaping (such as constructing small bioretention areas)
    - french drains for roof runoff in areas with little pervious areas
    - replacement of pavement with porous paver blocks

- Outfall Wet Detention Ponds
    - modify existing dry detention ponds for enhanced pollution control
    - enhance performance at existing wet ponds (modify outlet structure, construct forebay, provide post treatment using media filtration or wetland treatment)
    - construct new wet detention ponds in available areas

- Control Runoff at Critical Source Areas (such as vehicle service facilities, scrap yards, etc.)
    - sand perimeter filters
    - underground sedimentation/filtration units

- Other Controls
    - replace exposed galvanized metal with non-polluting material
    - provide new regional stormwater controls downstream of existing developed areas

Recommended Controls for New Developments

Stormwater controls established at the time of development can take advantage of simple grading and site layout options that can have significant stormwater benefits with little cost. In addition, the design of the storm drainage system can be easily modified for pollution control objectives, while still meeting drainage objectives. Most importantly, regional stormwater control facilities can be effectively located and sized with little interference with existing development. The following list indicates some likely effective wastewater collection scenarios for several different conditions for new developments (Pitt, *et al*. 1999):

- low and very low density residential developments (<2 acre lot sizes). Sanitary wastewater should be treated on site using septic tanks and advanced on-site treatment options. Domestic water conservation to reduce sanitary wastewater flows should be an important component of these systems. Most stormwater should be infiltrated on site by directing runoff from paved and roof areas to small bio-retention areas. Disturbed soil areas should use compost-amended soils and should otherwise be constructed to minimize soil compaction. Roads should have grass swale drainage to accommodate moderate to large storms.

- medium density developments (¼ to 2 acre lot sizes). Separate sanitary wastewater and stormwater drainage systems should be used. Sanitary wastewater collection systems must be constructed and maintained to eliminate I/I, or use vacuum or pressurized conveyance systems. Again, most stormwater should be infiltrated on site by directing runoff from paved and roof areas to small bio-retention areas. Paved areas should be minimized and the use of porous pavements and paver blocks should be used for walkways, driveways, overflow parking areas, etc. Disturbed soil areas should use compost-amended soils and should otherwise be constructed to minimize soil compaction. Grass swale drainages should be encouraged to accommodate moderate to large storms for the excess runoff in residential areas, depending on slope, soil types, and other features affecting swale stability. Commercial and industrial areas should also use grass swales, depending on groundwater contamination potential and available space. Wet detention ponds should be used for controlling runoff from commercial and industrial areas. Special controls should be used at critical source areas that have excessive pollution generating potential.

- high density developments. Combined sewer systems could be effectively used in these areas. On-site infiltration of the least contaminated stormwater (such as from roofs and landscaped areas) is needed to minimize wet weather flows. On-site storage of sanitary wastewaters during wet weather (Preul 1996), plus extensive use of in-line and off-line storage, and the use of effective high-rate treatment systems would minimize the damage associated with any CSOs. The treatment of the wet weather flows at the wastewater treatment facility would likely result in less pollutant discharges in these areas than if conventional separate wastewater collection systems were used.

The following sections review selected control practices that can be used at critical source areas to control runoff from these areas typically having the highest unit area pollutant discharges. As such, they are important supplements to the general stormwater controls outlined above. These critical source area controls are represented by some traditional "public works" practices commonly carried out by municipalities, in addition to other specialized controls that are more likely to produce significant reductions in pollutant discharges.

Public Works Activities Historically used for Stormwater Control at Critical Areas

Public works control practices are commonly used in critical source areas and at "ultra-urban" locations, because of the difficulty and cost of retro-fitting alternative stormwater controls in these small and intensively built-up areas. This section describes typical expected performance of catchbasins, oil and water separators, street cleaning, and describes investigations to identify and correct inappropriate discharges to storm drainage systems. Most of these public works stormwater control practices have been used for some time and can be effective in controlling litter and other floatable material and other gross contamination. However, these practices have limited pollutant removal capabilities for most cases, but the control of floatable materials in wet weather flows is a fundamental goal that should be achieved in all areas.

Catchbasins and other Floatable and Grit Traps

Storm drainage system inlet structures can be separated into three general categories. The first category is a simple inlet that is comprised of a grating at the curb and a box, with the discharge located at the bottom of the box which connects directly to the main storm drainage or combined sewerage. This inlet simply directs the runoff to the drainage system and contains no attributes that would improve water quality. However, large debris (several cm in size) may accumulate (if present in the stormwater, which is unlikely). The second type of inlet is similar to the simple inlet, but it contains a sump that typically extends 0.5 to 1 m below the bottom of the outlet. This is termed a catchbasin in the U.S., or a gully pot in the U.K., and has been shown to trap appreciable portions of the course sediment. The third category is also similar to the simple inlet, but contains some type of screening to trap debris. These include small cast iron perforated buckets placed under the street grating, as used in Germany, large perforated and lipped stainless steel plates placed under the street grating, as used in Austin, Texas, and a number of proprietary devices incorporating filter fabric or other types of screening placed to intercept the stormwater flow.

Over the past 85 years, there has been extensive use of catchbasins for coarse material removal from stormwater runoff (Lager, *et al.* 1977), mainly to reduce sedimentation problems in the storm drainage system. Catchbasins have also been utilized in Europe for over a century. The purpose of catchbasins historically has been to prevent the clogging of sewer lines with sediment and organic debris, and to prevent odors from escaping from the sewers by creating a water seal. Over the years, many different styles of catchbasins have been used, and many different enhancement devices have been added to increase their effectiveness. According to Lager, *et al.* (1977), catchbasins were considered marginal in performance as early as the turn of the century. They felt that the use of catchbasins may be more of a tradition for most municipalities rather than a practice based on performance. Sartor and Boyd (1972) suggested that all catchbasins should be filled in, citing their ineffectiveness at removal of pollutants and the threat of slug pollution of the scoured material. Grottker (1990) was more positive. He reports of an inlet design in Germany that is modified with sumps and a primary filter to screen out the larger debris. He recommended the modified device as a cost-saving practice that improves water quality.

Catchbasin performance has been investigated for some time in the U.S. Sartor and Boyd (1972) conducted controlled field tests of a catchbasin in San Francisco, using simulated sediment in fire hydrant water flows. They sampled water flowing into and out of a catchbasin for sediment and basic pollutant analyses. Lager, *et al.* (1977) was the first EPA funded research effort that included a theoretical laboratory investigation to evaluate sedimentation in catchbasins and to develop effective designs.

The mobility of catchbasin sediments was investigated by Pitt (1979). Long-duration tests were conducted using an "idealized" catchbasin (based on Lager, *et al.*'s 1977 design), retro-fitted in San Jose, CA. The research focused on re-suspension of sediment from a full catchbasin over an extended time period. It was concluded that the amount of catchbasin and sewerage sediment was very large in comparison with storm runoff yields, but was not very mobile. Cleaning catchbasins would enable them to continue to trap sediment, instead of reaching a steady-state loading and allowing subsequent stormwater flows to pass through untreated.

Pitt (1985) statistically compared catchbasin supernatant with outfall water quality and did not detect any significant differences. However, Butler, *et al.* (1995) investigated gully pot supernatant water and found that it may contribute to the more greatly polluted first flush of stormwater reported for some locations. Specific problems have been associated with the anaerobic conditions that rapidly form in the supernatant water during dry weather, causing the release of oxygen demanding material, ammonium, and possible sulfides. These anaerobic conditions also affect the bioavailability of the heavy metals in the flushed water.

Catchbasins, simple inlets, man-holes, and sewerage sediment accumulations were monitored at more than 200 locations in Bellevue, Washington, in two mixed residential and commercial study areas (Pitt 1985). These locations were studied over three years to monitor accumulation of sediment and sediment quality. The sediment in the catchbasins and the sewerage was found to be the largest particles that were washed from the streets. The sewerage and catchbasin sediments had a much smaller median particle size than the street dirt and were therefore more potentially polluting than the particulates that can be removed by street cleaning. Cleaning catchbasins twice a year was found to allow the catchbasins to capture particulates most effectively. This cleaning schedule was found to reduce the total residue and lead urban runoff yields by between 10 and 25 percent, and COD, total Kjeldahl nitrogen, total phosphorus, and zinc by between 5 and 10 percent (Pitt and Shawley 1982).

Catchbasins have been found to be effective in removing pollutants associated with coarser runoff solids (Pitt 1985). High reductions in total and suspended solids (up to 45% reduction for low gutter flows) were indicated by a number of prior studies (such as Pitt 1979, Aronson, *et al.* 1983, and Pitt 1985). However, relatively few pollutants are associated with these coarser solids (Pitt 1979 and Pitt 1985). Pitt (1985) found that catchbasins will accumulate sediments until the sediments reach about 60% of the total sump capacity (or to about 0.3 m under the catchbasin outlet). After that level, the sediment is at an equilibrium, with scour balancing new deposition. Earlier EPA research (Lager, *et al.* 1977) found that an optimal catchbasin design should have the following dimensions: if the outlet pipe is D in diameter, its bottom should be located about 2.5D below the street level and 4D from the bottom of the catchbasin sump. The overall height of the catchbasin should therefore be 6.5D, with a diameter of 4D.

Butler, *et al.* (1995) found that the median particle size of the sump particles was between about 300 and 3000 µm, with less than 10% of the particles smaller than 100 µm, near the typical upper limit of particles found in stormwater. Catchbasin sumps therefore trap the largest particles that are flowing in the water, and allow the more contaminated finer particles to flow through the inlet structure. Butler, *et al.* (1995) and Butler and Karunaratne

(1995) present sediment trapping equations for sediment in gully pots, based on detailed laboratory tests. The sediment trapping performance was found to be dependent on the flow rate passing through the gully pot, and to the particle sizes of the sediment. The depth of sediment in the gully pot had a lesser effect on the capture performance. In all cases, decreased flows substantially increased the trapping efficiency and larger particles had substantially greater trapping efficiency than smaller particles, as expected.

Three storm drain inlet devices were evaluated in Stafford Township, New Jersey, by Pitt and Field (1998) as part of an EPA-funded study. An optimally designed catchbasin with a sump and two representative designs that used filter material. The inlet devices were located in a residential area. The monitoring program included 12 inlet and effluent samples from these devices over several different storms. Complete organic and metallic toxicant analyses, in addition to conventional pollutants, were included in the analytical program. In addition to these field tests, controlled tests were also conducted in the laboratory to further evaluate filter fabrics used in some inlet devices.

Samples were analyzed for a wide range of toxicants using very low detection limits (about 1 to 10 µg/L). The constituents analyzed include heavy metals and organics (phenols, PAHs, phthalate esters, and chlorinated pesticides). Particle size distributions, using a Coulter Multi-Sizer II, were also made, in addition to conventional analyses for COD, major ions, nutrients, suspended and dissolved solids, turbidity, color, pH, and conductivity. All samples were also partitioned into filterable and non-filterable components before COD and toxicant analyses to better estimate fate and treatability. All samples were also screened using the Microtox toxicity test to measure relative reductions in toxicity associated with the inlet devices.

Conventional Catchbasin with Sump. A sump was installed in the bottom of an existing storm drain inlet by digging out the bottom and placing a section of 36 inch concrete pipe on end. The outlet pipe was reduced to 8 inches and the sump depth was 36 inches. Inlet water was sampled before entering the catchbasin, while outlet water was sampled after passing through the unit.

Filter Fabric Unit. A filter fabric unit, having a set of dual horizontal trays, each containing about 0.1 m^2 of filter fabric, was retro-fitted into one of the existing inlets for testing. When the filter fabric clogs on the upper tray, the stormwater overflows a small rectangular weir, onto another similar tray located beneath the upper tray. Again, paired samples were obtained above and under the unit for analyses. According to the manufacturer, this system can handle up to 300 gallons per minute. The unit tested has been replaced by the manufacture with a new type of catchbasin filter that also includes a selection of filtering media.

Coarse Filter Unit. A coarse filter was also retro-fitted into an existing stormdrain inlet. This unit uses a relatively coarse foam material (about 1mm cell diameter and 8 mm thick) that is sandwiched between two pieces of galvanized screening for support. This unit was fitted in the inlet, sealed along the bottom and sides on the outlet side, forcing any water through the unit before it is discharged. The filter was placed in front of the catchbasin outlet in a near vertical position. Its main purpose is to filter debris, including leaves and grass clippings, from stormwater. As with the other units, the inlet and outlet water was simultaneously sampled for analyses.

The catchbasin with the sump was the only device that showed important and significant removals for several pollutants:

total solids (0 to 50%, average 22%).
suspended solids (0 to 55%, average 32%).
turbidity (0 to 65%, average 38%).
color (0 to 50%, average 24%).

The coarse screen unit showed consistent washout of material, while both the coarse screen unit and the catchbasin showed slight increases for several major ions, most likely associated with contact with concrete and other drainage system materials. None of the other parameters or inlet devices demonstrated significant differences between the influent and effluent water (at the 95% confidence level, or better), except for the filter fabric unit which showed a small removal for nitrate. Several significant and large increases in major ion concentrations were noted for the catchbasin (bicarbonate, magnesium, and calcium) and for the coarse screen unit (bicarbonate, and potassium).

These increases, which are not believed to be very important, may have been due to the runoff water being affected by the concrete in the inlet devices. These increases are likely part of the general process where runoff water increases its alkalinity and buffer capacity as it flows through urban areas.

The significant and large increases in total solids, suspended solids, volatile solids, and conductivity for the coarse screen unit imply washout of decomposing collected organic solids (mostly leaves). The coarse screen unit traps large debris, including decomposable organic material, behind the screen. Stormwater then flows through this material as it passes through the screen, as in most inlet screening/filtering devices. If not frequently removed, this organic material may decompose and wash through the screen in subsequent storms. The large debris was not represented in the influent water samples, but after partial decomposition, this material could have added to the solids concentrations in the effluent samples. The catchbasin did not exhibit this increase in solids concentrations likely because the collected material is trapped in the sump and not subjected to water passing through the material. Previous catchbasin tests found that catchbasin supernatant water quality is not significantly different from runoff water quality, nor is the collected debris easily or commonly scoured from the sump. The filter fabric unit did not exhibit this increase in solids, possibly because it trapped relatively small amounts of debris, and the overflow weirs allowed the subsequent stormwater to flow over the trapped debris instead of being forced through the debris.

Suggestions for Optimal Storm Drainage Inlet Use

The best catchbasin configuration for a specific location would be dependent on site conditions and would probably incorporate a combination of features from several different inlet designs. The primary design should incorporate a catchbasin with a sump, as described by Lager, *et al.* (1977), with an inverted (hooded) outlet. If large enough, catchbasins with sumps have been shown to provide a moderate level of suspended solids reductions in stormwater under a wide range of conditions in many studies in the U.S. and Europe. The use of filter fabrics in catchbasins is not likely to be beneficial because of their rapid clogging from retained sediment and trash. The use of coarser screens in catchbasin inlets is also not likely to result in water quality improvements, based on conventional water pollutant analyses. However, well designed and maintained screens can result in substantial trash and litter reductions. It is important that the screen not trap organic material in the flow path of the stormwater. Prior research (Pitt 1979 and 1985) has shown that if most of the trapped material is contained in the catchbasin sump, it is out of the direct flow path and unlikely to be scoured during high flows, or to degrade overlying supernatant water. Storm drainage inlet devices also should not be considered as leaf control options, or used in areas having very heavy trash loadings, unless they can be cleaned after practically every storm.

The goal is a storm drainage inlet device that:

- does not cause flooding when it clogs with debris,
- does not force stormwater through the captured material,
- does not have adverse hydraulic head loss properties,
- maximizes pollutant reductions, and
- requires inexpensive and infrequent maintenance.

The following suggestions and design guidelines should meet some of these criteria. Catchbasins in newly developing areas could be more optimally designed than the suggestions below, especially by enlarging the sumps and by providing large and separate offset litter traps.

The basic catchbasin (having an appropriately sized sump with a hooded outlet) should be used in most areas. This is the most robust configuration. In almost all full-scale field investigations, this design has been shown to withstand extreme flows with little scouring losses, no significant differences between supernatant water quality and runoff quality, and minimal insect problems. It will trap the bed-load from the stormwater (especially important in areas using sand for traction control) and will trap a low to moderate amount of suspended solids (about 30 to 45% of the annual loadings). The largest fraction of the sediment in the flowing stormwater will be trapped, in preference to the finer material that has greater amounts of associated pollutants. Their hydraulic capacities are designed using conventional procedures (grating and outlet dimensions), while the sump is designed based on the desired cleaning frequency. Figure 2 is this basic recommended configuration, based on Lager, *et al.* (1977).

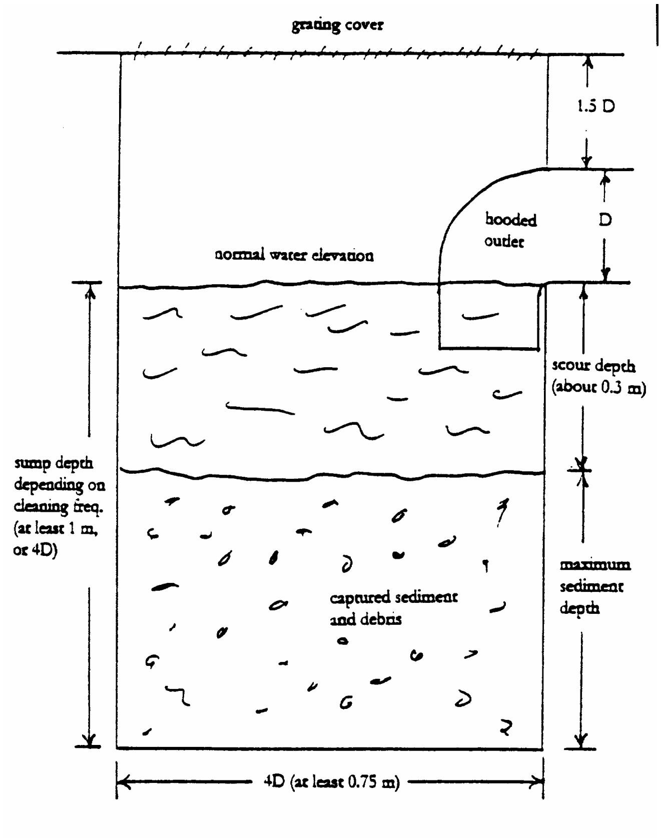

Figure 2. Basic catchbasin design, based on Lager, *et al.* (1977).

The use of filter fabrics or other fine screens as an integral part of a storm drain inlet is not recommended unless shown to have minimal problem potential. Pitt and Field (1998) showed that filter fabric screens may provide important reductions (about 50%) in suspended solids and COD. However, the filter fabrics can only withstand about 1 to 2 mm accumulation of sediment before they clog. This is about 4 kg of sediment per square meter of fabric. If runoff had a suspended solids concentration of 100 mg/L, the maximum loading of stormwater tolerated would be about 40 meters. For a typical application (1 ha paved drainage area to a 1 m^2 filter fabric in an inlet box), only about 5 to 10 mm of runoff could be filtered before absolute clogging.

Grit Traps

Several proprietary stormwater treatment devices are being marketed throughout North America. These devices can be located underground. Unfortunately, comprehensive testing with actual stormwater is not available for most of these devices. The designs and demonstrations are mostly based on reduction of relatively large particles that rarely occur in stormwater. The suspended solids in stormwater is mostly in the range of 1 to 100 µm, with only a small fraction of the mass (usually <10%) associated with particles greater than 100 µm. These devices are designed to capture particle sizes that have typically been found on streets, not in the runoff water (Pitt 1987). These devices are excellent grit chambers (and can probably capture floating oils) and can be used to prevent sand-sized particles from accumulating in sewerage. Very little scour of the captured grit material is also likely with these devices. However, they are not likely to provide important reductions of most stormwater pollutants, especially the toxicants. If a site is grossly contaminated with oils or grit, then a proprietary oil/water separator or grit chamber is needed, but further treatment will also likely be necessary, such as with a media filter.

Oil/Water Separators

This section (summarized from Pitt, *et al*. 1999) briefly examines oil/water separators and their expected ability to treat stormwater. These devices are extensively used to treat industrial wastewaters and have been shown to be effective in those applications for which they were designed. These units perform best at very high levels of oil contamination, such as may be found at some industrial locations (API 1990). Generally, they obtain about 90% reductions in oil if the influent oil concentrations are greater than about 10,000 mg/L. Reductions of about 50% would occur at influent oil concentrations of about 200 mg/L. Very little reduction is expected at levels less than about 100 mg/L. Little information is available demonstrating their effectiveness in treating stormwater, which usually has oil contamination levels of much less than 100 mg/L.

Factors Relevant to Oil/Water Separator Performance

Many factors affect separator performance, including: the quantity of oil, oil density, water temperature and other wastestream characteristics. The most important characteristic affecting oil removal performance is oil droplet size, from which the critical rise rate can be determined. After determining the rise rate, design flow rate, and effective horizontal separation area, the separator can be appropriately sized.

Oil/water mixtures are usually divided into four categories:

- free-floating oil, with oil droplet sizes of 250 µm or more, is evidenced by an oil slick or film on the water surface. In this case, the oil has separated from the water.
- oil droplets and globules ranging in size from 10-300 µm. This range is the most important range when dealing with oil/water separation.
- emulsions, which have sizes in the 1-30 µm range, and
- “dissolved” oil with diameters of less than 10 µm.

The largest oil droplets are easily separated from water using a basic spill trap or separation device. Smaller droplets cause wide ranging differences in performance from different separation devices. Emulsions are of two types: stable and unstable. Stable emulsions are usually the result of surfactants (i.e. soaps and detergents) which hold the droplets in solution. This type of emulsion is often present in cleaning operations and can often be very difficult to remove. Unstable emulsions are created by shearing forces present in mixing: the oil is held in suspension when the interfacial tension of the drops’ surface is equal to the force acting on the drops. These will generally separate by physical methods such as extended settling times or filtration methods. Oil/water separators are not able to treat stable emulsions or dissolved oil.

Gravity Separation

Gravity separation relies on the density differences between oil and water. Oil will rise to the water surface unless some other contributing factor such as a solvent or detergent interferes with the process. For gravity units, this density difference is the only mechanism by which separation occurs. Other technologies, such as air flotation, coalescing plates, and impingement coalescing filters, enhance the separation process by mechanical means.

Gravity separators are the most basic type of separator and are the most widely used. They have few, if any, moving parts and require little maintenance with regard to the structure or operation of the device. Usually, separators are designed to meet the criteria of the American Petroleum Institute (API), and are fitted with other devices such as coalescing plate interceptors (CPI) and filters. Even though these separators are effective in removing free and unstable oil emulsions, they are ineffective in removing most emulsions and soluble oil fractions (Ford 1978). Furthermore, it is important to remember that no gravity oil/water separation device will have a significant impact on many of the other important stormwater pollutants, requiring additional treatment (Highland Tank).

<u>Conventional American Petroleum Institute (API) Oil/Water Separator</u>

The conventional API oil/water separator consists of a large chamber divided by baffles into three sections. The first chamber acts as an equalization chamber where grit and larger solids settle and turbulent flow slows before entering the main separation chamber. Often, manufacturers suggest the use of a catchbasin or interceptor tank as a pretreatment device so that coarse material will be kept from entering the oil/water separation tank. After entering the main chamber, solids settle to the bottom and oil rises to the top, according to Stokes' law. Larger API oil/water separators contain a sludge scraper which continually removes the captured settled solids into a sludge pit. The oil is also removed by an oil skimmer operating on the water surface. At the end of the separation chamber, all oil particles having a diameter of larger than the critical size have theoretically risen to the surface and have been removed by an oil skimmer. Small API units usually do not contain an oil skimmer, sludge scrapper, or sludge pit. While they are less costly due to the absence of moving parts, they require more frequent cleaning and maintenance. These smaller units have been shown to be as effective as the larger more expensive units, if they receive proper maintenance at regular intervals.

The API (1990) stipulates that if their design criteria are met, then the separator will remove all oil droplets greater than about 150 µm in diameter. The API reports that retention times are usually greater than the actual design values since actual flows are usually smaller than design flows, hence smaller droplets are removed most of the time. This finding is confirmed by Ruperd (1993) in a study of an oil/water separator treatment device in the community of Velizy, France. Also, API tanks are known to effectively remove large amounts of oil, including slugs of pure oil, and will not be overwhelmed (Tramier 1983). Studies have also shown that these separators can produce effluents down to 30 ppm (Delaine 1995), routinely at 30-150 ppm, with occasional concentrations above 150 ppm, depending upon the flow rate, and hence the retention times (Ford 1978).

The API has stated that very few separators with ratios of surface area to flow within the API design range achieved effluent oil concentrations lower that 100 ppm (API 1990). Therefore, the API separator is a recommended system for the removal of solids and gross oil as a pretreatment device upstream of another treatment system, if additional pollutants of concern are present, or if more stringent effluent standards are to be met.

Maintenance of Oil/Water Separators

Problems with oil/water separators can be attributed largely to poor maintenance by allowing waste materials to accumulate in the system to levels that hinder performance and to levels that can be readily scoured during intermittent high flows. When excess oil accumulates, it will be forced around the oil retention baffle and make its way into the discharge stream. Also, sludge buildup is a major reason for failure. As waste builds up, the volume in the chamber above the sludge layer is reduced and therefore the retention time is also reduced, allowing oil to be discharged. Therefore, the efficiency of oil/water separators in trapping and retaining solids and hydrocarbons depends largely upon how they are maintained. They must be designed for ease of maintenance and be frequently maintained. Apparently, few oil/water separators built for stormwater control are adequately maintained.

Ease of maintenance must be considered when designing separators, including providing easy access. Maintenance on these devices is accomplished by using suction equipment, such as a truck mounted vacuum utilized by personnel trained to handle potentially hazardous waste. The vacuum is used to skim off the top oil layer and the device is then drained. In larger devices, the corrugated plates are left in place, but otherwise, they are lifted out along with any other filter devices that are present. The sludge is then vacuumed out or shoveled out and any remaining solids are loosened by spraying hot water at normal pressure.

Performance of Oil/Water Separators for Treating Stormwater

Manufacturers state that efficiencies observed during testing of oil/water separators are on the order of 97 – 99% for the removal of oil from wastewater. The test method typically applies oil to a paved washpad, with water added via a sprinkler system to simulate rainfall. Oil is of a specified density (typically 0.72 – 0.95). These synthetic events are necessary to evaluate the performance of a separator but do not necessarily reflect the processes which occur during actual rainfall conditions where rapidly changing flows rates, unknown oil mixtures, and other pollutants are present. Published research is difficult to find on how these units actually perform once placed in operation.

Interception of solid particles through settling, and flotation of oils and other floatables are processes occurring within an oil/water separator. French studies have shown that the average suspended solids removal efficiency of separators is about 50% (Aires and Tabuchi 1995). Oil/water separation requires an ascending speed of about 8 m/h, while the settling velocity of solids require descending velocities on the order of 1 to 3 m/h. At rates of 20% of the design flow rate, about 80% of the solids are removed; at 30% of the design flow rate, about 50% of the solids are removed. Negative removals also occur as the result of resuspension of previously settled material (Legrand, *et al*. 1994).

When the concentration of the oil in the wastewater is high, the oil removal efficiency increases. In Velizy, France, Ruperd (1993) found that oil/water separators fitted with cross current separators had removal efficiencies ranging from zero to 90%, with an average of 47%. Low efficiencies were associated with low influent levels and greater efficiencies were associated with higher influent levels. This finding supports those of Tramier (1983), stated earlier, that separators are effective in removing large amounts of oil when the oil concentrations are elevated.

The Metropolitan Washington Council of Governments (Washington, D.C.) has conducted a survey of 109 separator vaults in suburban Maryland and subsequently examined 17 in detail to determine their long-term effectiveness (Schueler and Shepp 1993). These separators were used for controlling runoff from areas associated with automobile usage. These separators were either pre-cast or poured in place concrete structures consisting of one, two or three chambers. The results of this study revealed that the amount of trapped sediments within separators varied from month to month and that the contained waters were commonly completely displaced during even minor storms (Shepp and Cole 1992). Of the original 109 separators that were observed in the survey, devices less than one year old were effective in trapping sediments. Devices older than one year appeared to lose as much sediment than they retained. Not one of these separators had received maintenance since their installation. Survey observations suggested no net accumulation of sediment over time, in part because they received strong variations in flow. Of the 109 separators surveyed in this suburban Maryland study, 100% had received no maintenance, 1% needed structural repair, 6% were observed to have clogged trash racks, 84% contained high oil concentrations in the sediments trapped in their first chamber, 77% contained high oil concentrations in the sediments trapped in their second chambers, 27% contained high oil and floatables loading in their first chambers, and 23% contained high oil and floatables loading in their second chambers.

Numerous manufacturers have developed small prefabricated separators to remove oils and solids from runoff. These separators are rarely specifically designed and sized for stormwater discharges, but usually consist of modified oil/water separators. Solids are intended to settle and oils are intended to rise within these separators, either by free fall/rise or by counter-current or cross-current lamella separation. Many of these separators have been installed in France, especially along highways (Rupperd 1993). Despite the number of installations, few studies have been carried out in order to assess their efficiency (Aires and Tabuchi 1995).

The historical use of oil/water separators to treat stormwater has been shown to be ineffective for various reasons, especially lack of maintenance and poor design for the relatively low levels of oils present in most stormwaters (Schueler 1994). Stormwater treatment test results from Fourage (1992), Rupperd (1993) and Legrand, *et al*. (1994) show that these devices are usually greatly under-sized. They may possibly work reasonably well at flow rates between 20 and 30% of their published design hydraulic capacities. For higher flow rates, the flow is very turbulent (the Reynolds numbers can be higher than 6000), and improvements in settling by using lamella plates is very poor. These devices need to be cleaned very frequently. If they are not cleaned, the deposits are scoured during storm events, with negative efficiencies. However, the cleaning is usually manually conducted, and expensive. In addition, the maintenance job is not very easy because the separators are very small. Some new devices are equipped with automatic sediment extraction pumps which should be a significant improvement. Currently, these researchers have found that the cleaning frequencies are very insufficient and the stormwater quality benefits from using oil/water separators are very limited.

The Multi-Chambered Treatment Train (MCTT), described later in this chapter, was developed to specifically address many of the stated problems found for oil/ water separators used for stormwater treatment at critical source areas (Pitt, *et al*. 1999). It was developed and tested with specific stormwater conditions in mind, plus it has been tested at several sizes for the reduction of stormwater pollutants of concern. The MCTT is intended to reduce organic and metallic toxicants, plus suspended solids, in the stormwater. Oil/water separators are intended to reduce very large concentrations of floating oils that may be present in industrial wastewaters . The extremely high concentrations of oils that the oil/water separators are most effective in removing are very rare in stormwater, even from critical source areas. If a site has these high levels, then an oil/water separator may be needed, in addition to other controls to reduce the other critical pollutants likely present. The MCTT can remove the typically highest levels of oils that may be present in stormwater from most critical source areas, plus also provide control of the trace toxicants present.

Street Cleaning

Street cleaning was extensively studied during early EPA-funded research projects. It was thought to be an effective runoff water quality control practice because of the large quantities of pollutants found on streets during early stormwater research in the U.S. (Sartor and Boyd 1972). Because streets were assumed to contribute most of the urban runoff flows and pollutants, street cleaning was assumed to be a potentially effective practice. Unfortunately, few data have shown street cleaning to be effective because of the different sized particles that street cleaners remove compared to the particles that are mostly removed by rains. Furthermore, in many areas, rains are relatively frequent and keep the streets cleaner than typical threshold values that most street cleaners can remove. However, in the arid west of the U.S., rains are very infrequent, allowing streets to become quite dirty during the late summer and fall. Extensive street cleaning during this time has been shown to result in important suspended solids and heavy metal reductions in runoff (Pitt 1979, Pitt and Shawley 1982). In other areas of the U.S., especially in the wet southeast where large and frequent rains occur, street cleaning is likely to have much less direct water quality benefits, beyond possible important litter and floatable control. Obviously, street cleaning is most effective in areas having large fractions of pavement in good condition that can be assessed by street cleaners. Many critical source areas (especially large parking areas, paved equipment storage yards, etc.) could likely benefit with more frequent cleaning, especially with new equipment designed for better removal of fine particulates.

Street cleaning plays an important role in most public works departments as an aesthetic and safety control measure. Street cleaning is also important to reduce massive dirt and debris buildups present in the spring in northern regions. Leaf cleanup by street cleaning is also necessary in most areas in the fall.

Factors significantly affecting street cleaning performance include street dirt loadings, street texture, litter and moisture, parked car conditions, and equipment operating conditions (Pitt 1979). If the 500-1000 µm particle loadings are less than about 75 kg/curb-km for smooth asphalt streets, conventional street cleaning does little good. As the loadings increase, the removals also increase: with loadings of about 10 kg/curb-km, less than 25 percent removals can be expected, while removals of up to about 50 percent can be expected if the initial loadings are as high as 40 kg/curb-km for this particle size. The removal performance decreases substantially for smaller particles, including those that are most readily washed off the street during rains and contribute to stormwater pollution.

Particles of different sizes “behave” quite differently on streets. Typical street dirt total solids loadings show a “saw-tooth” pattern with time between street cleaning or rain washoff events. The patterns for the separate particle sizes vary considerably for different particle sizes. Typical mechanical street cleaners remove much (about 70 percent) of the coarse particles in the path of the street cleaner, but they remove very little of the finer particles (Sartor and Boyd 1972; Pitt 1979). Rains, however, remove very little of the large particles, but can remove large amounts (about 50 percent) of the fine particles (Bannerman, *et al*. 1983; Pitt 1985; Pitt 1987). The intermediate particle sizes show reduced removals by both street cleaners and rain. Conventional street cleaning therefore does not have a very positive effect on stormwater quality because conventional street cleaners preferentially remove the large particles, and the smaller particles from the street that are most effectively removed during rains. Valiron (1992) confirmed the many earlier U.S. studies by showing that street cleaners only remove about 15% of the finest particles (less than 40 µm), while close to 80% of the largest particles (>2,000 µm) are removed.

Enhanced street cleaner performance was obtained with a modified regenerative-air street cleaner, especially at low loadings during tests in Bellevue, WA (Pitt 1985). The improved performance was much greater for the fine particle sizes, where the mechanical street cleaner did not remove any significant quantities of material. The larger particles were removed with about the same effectiveness for both street cleaner types. Other tests of vacuum street cleaners (Pitt 1979) and regenerative-air street cleaners (Pitt and Shawley 1982) showed very few differences in performance when compared to more standard mechanical street cleaners. These earlier tests were conducted in areas having much higher street loadings, especially for the larger particle sizes, than in Bellevue. It is expected that the high loadings of the large particles armored the small particles, so they could not be removed. For high loadings, it may be best to use a tandem operation, where the streets are first cleaned with a mechanical street cleaner to remove the large particles, followed by a regenerative-air street cleaner to remove the finer particles.

Ellis (1986) concluded that street cleaning is most efficient if conventional street sweeping (using broom operated equipment) is conducted in a tandem operation with vacuuming, and if it is done three times per week. He did find that conventional tandem sweeping-vacuum machines are very sensitive to the clogging of their filters and to street moisture levels which causes particles to adhere to the street surface, preventing their efficient removal. General street cleaning efficiency depends on the speed of the machines, the number of passes, the street loading and street texture, and interference from parked vehicles (Pitt 1979).

Much information concerning street cleaning productivity has been collected in many areas. The early tests (Clark and Cobbin 1963; and Sartor and Boyd 1972) were conducted in controlled strips using heavy loadings of simulates instead of natural street dirt at typical loadings. Later tests, from the mid 1970s to mid 1980s, were conducted in large study areas (20 to 200 ha) by measuring actual street dirt loadings on many street segments immediately before and after typical street cleaning. These large-scale tests are of most interest, as they monitored both street surface phenomena and runoff characteristics. The following list briefly describes these large-scale street cleaning performance tests that have been conducted in the U.S.:

- San Jose, California, tests during 1976 and 1977 (Pitt 1979) considered different street textures and conditions; multiple passes, vacuum-assisted, and two types of mechanical street cleaners; a wide range of cleaning frequencies; and effects of parking densities and parking controls.
- Castro Valley, California, tests during 1979 and 1980 (Pitt and Shawley 1982) considered street slopes, mechanical and regenerative-air street cleaners, and several cleaning frequencies. This was an early Nationwide Urban Runoff Program (NURP) project of the U.S. EPA (EPA 1983).
- Reno/Sparks, Nevada, tests during 1981 (Pitt and Sutherland 1982) considered different land-uses, street textures, equipment speeds, multiple passes, full-width cleaning, and vacuum and mechanical street cleaners in an arid and dusty area.
- Bellevue, Washington, tests from 1980 through 1982 (Pitt 1985) considered mechanical, regenerative-air, and modified regenerative-air street cleaners, different land-uses, different cleaning frequencies, and different street textures in a humid and clean area. This was also a NURP project (EPA 1983).
- Champaign-Urbana, Illinois, tests from 1980 and 1981 (Terstriep, *et al*. 1982) examined spring clean-up, different cleaning frequencies and land-uses, and used a three-wheel mechanical street cleaner. This was also a NURP project (EPA 1983).
- Milwaukee, Wisconsin, tests from 1979 to 1983 (Bannerman, *et al*. 1983) examined various street cleaning frequencies at five study sites, including residential and commercial land-uses and large parking lots. This was also a NURP project (EPA 1983).
- Winston-Salem, North Carolina, tests during their NURP (EPA 1983) project examined different land-uses and cleaning frequencies.

Sutherland (1996, and with Jelen 1996) conducted tests using a new style street cleaner that shows promise in removing large fractions of most of the street dirt particulates, even the small particles that are most heavily contaminated. The Enviro Whirl I, from Enviro Whirl Technologies, Inc. is capable of much improved removal of fine particles from the streets compared to any other street cleaner ever tested. This machine was also able to remove large fractions of the fine particles even in the presence of heavy loadings of large particles. This is a built-in tandem machine, incorporating rotating sweeper brooms within a powerful vacuum head. Model analyses for Portland, OR, indicate that monthly cleaning in a residential area may reduce the suspended solids discharges by about 50%, compared to only about 15% when using the older mechanical street cleaners that were tested during the early 1980s. This equipment is currently being evaluated in large-scale tests by the Wisconsin Department of Natural Resources and WI Dept. of Transportation (Bannerman, personal communication).

The pollutant removal benefits of street cleaning is directly dependent on the contributions of pollutants from the streets. In the Pacific Northwest region of the U.S., the large number of mild rains results in much of the runoff pollutants originating from the streets. In the Southeast, in contrast, where the rains are much larger, with greater rain intensities, the streets contribute a much smaller fraction of the annual pollutant loads for the same residential land uses. However, in heavily paved areas, such as on freeways, large parking lots or paved storage areas, street cleaning of these surfaces, especially with an effective machine like the Enviro Whirl, should result in significant runoff improvements.

These many tests have examined a comprehensive selection of alternative street cleaning programs. Not all alternatives have been examined under all conditions, but sufficient information has been collectively obtained to examine many alternative street cleaning control options. Few instances of significant and important reductions in runoff pollutant discharges have been reported during these large-scale tests.

The primary and historical role of street cleaning is for litter control. Litter is also an important water pollutant in receiving waters. Litter affects the aesthetic attributes and recreation uses of waters, plus it may have direct negative biological and water quality effects. Litter has not received much attention as a water pollutant, possibly because it is not routinely monitored during stormwater research efforts. The City of New York conducted a special study to investigate the role of enhanced street cleaning (using intensive manual street sweeping) to reduce floatable litter entering the City's waterways (Newman, *et al*. 1996). During the summer of 1993, the City hired temporary workers to manually sweep near-curb street areas and sidewalks in a pilot watershed area having 240 km of curb face. Two levels of manual sweeping supplemented the twice per week mechanical street cleaning the area normally receives. Continuous litter monitoring was also conducted to quantify the differences in floatable litter loadings found on the streets and sidewalks. An additional four manual sweepings each week to the two mechanical cleanings reduced the litter loadings by about 64% (on a weight basis) and by about 51% (on a surface area basis). Litter loading analyses were also conducted in areas where almost continuous manual sweeping (8 to 12 daily sweeps, 7 days per week) was conducted by special business organizations. In these special areas, the litter loadings were between 73 and 82% cleaner than comparable areas only receiving the twice weekly mechanical cleaning. They concluded that manual sweeping could be an important tool in reducing floatable pollution, especially in heavily congested areas such as Manhattan. New York City is also investigating catch basin modifications and outfall netting for the control of floatable litter.

Normal street cleaning operations for aesthetics and traffic safety purposes are not very satisfactory from a stormwater quality perspective. These objectives are different and the removal efficiency for fine and highly polluted particles is very low. Unless the street cleaning operations can remove the fine particles, they will always be limited in their pollutant removal effectiveness. Some efficient machines are now available to clean porous pavements and infiltration structures, and new tandem machines that incorporate both brooms and vacuums have recently been shown to be very efficient, even for the smaller particles. Conventional street cleaning operations preferentially remove the largest particles, while rain preferentially remove the smallest particles. In addition, street cleaners are very inefficient when the street dirt loadings are low, when the street texture is course, and when parked cars interfere. However, it should also be noted that streets are not the major source of stormwater pollutants for all rains in all areas. Pavement is the major source of pollutants for the smallest rains, but other areas contribute significant pollutants for moderate and large rains. Therefore, the ability of street cleaning to improve runoff quality is dependent on many issues, including the local rain patterns and other sources of runoff pollutants. More research is needed to investigate newer pavement cleaning technologies in areas such as industrial storage areas and commercial parking areas which are critical pollutant sources.

Prevention of Dry-Weather Pollutant Entries into Sewerage Systems

Inappropriate discharges to separate storm drainage systems can be a significant source of the pollutants being discharged to an urban receiving water. It is important that these sources be identified and corrected. Interest in these sources is an outgrowth of investigations into the larger problem of determining the role urban stormwater runoff plays as a contributor to receiving water quality problems. The U.S.EPA's Storm & Combined Sewer Overflow Pollution Control Research and Nationwide Urban Runoff Programs, helped highlight the problem with data confirming pollution found in urban storm drainage systems. Regulations, such as the National Pollution Discharge Elimination System (NPDES), require that certain industries and municipalities conduct investigations to determine the locations of inappropriate dry-weather entries into storm drainage systems.

One example of the magnitude of the problem associated with inappropriate discharges follows. A study in Sacramento, CA. (Montoya 1987) found that slightly less than half the volume of water discharged from a stormwater drainage system was not directly attributable to rainfall induced runoff. Illicit and/or inappropriate entries to the storm drainage system are likely sources of the additional discharges and can account for a significant amount of the pollutants discharged from storm drainage systems.

The methods described in the following discussion were developed through EPA funding and can be applied to detection of inappropriate discharges associated with dry-weather flows (Pitt, *et al*. 1993).

Common non-stormwater entries include: sanitary wastewater; automobile maintenance and operation waste products; laundry wastewater; household toxic substances and pollutants; accident and spill waste streams; runoff from excessive irrigation; and industrial cooling water, rinse water, and other process wastewater. Although these sources can enter the storm drainage system a variety of ways, they generally result from: (1) direct connections, such as wastewater piping either mistakenly or deliberately connected to the storm drains; or (2) indirect connections, which include infiltration into the storm drainage system and spills received by drain inlets. Sources of contamination can be divided into those discharging continuously and those discharging intermittently.

Investigative Procedures

The procedures described here provide an investigative procedure that will allow a user to first determine whether significant non-stormwater entries are present in a storm drain, and then identify the potential source responsible (e.g., industrial, residential, or commercial) as an aid to ultimately locating the source.

Drainage Area Mapping

The mapping exercise is carried out as a desktop operation using existing data/information and field visits to collect additional data/information and/or confirm existing information. It must contain complete descriptions of the drainage areas, including: outfall locations, drainage system layout, subcatchment boundaries for each outfall, critical land-use areas, permitted discharges to the storm drainage system, city limits, major streets, streams, etc.

Tracer Selection

To detect and identify non-stormwater entries, the dry-weather outfall discharge is analyzed for selected tracers. The selected tracers are relatively unique components of the potential contaminating sources and hence provide a means to identify them. An ideal tracer should exhibit the following properties:

- Significant difference in concentrations between polluting and non-polluting sources;
- Small variations in concentrations within each likely pollutant source category;
- A conservative behavior (i.e., no significant concentration change due to physical, chemical, and/or biological processes); and
- Ease of measurement with adequate detection limits, good sensitivity and repeatability.

A review of case studies and literature characterizing potential inappropriate entries led to the recommended tracers (listed below) to identify common pollutant sources (e.g., sanitary wastewater, septic tank effluent, laundry wastewater, vehicle wash wastewater, potable water, and natural waters):

- **Specific Conductivity-** Specific conductivity can be used as an indicator of dissolved solids. The variation between water and wastewater sources can be substantial enough to indicate the source of a dry-weather flow, and because the measurement is easy, quick, and inexpensive, it is a suggested tracer.

- **Fluoride-** Fluoride concentration were shown to be a reliable indicator of potable water where fluoride levels in the raw water supply are adjusted to consistent levels and where groundwater has low to non-measurable natural fluoride levels. Fluoride can often be used to separate treated potable water from untreated water sources. Untreated water sources can include local springs, groundwater, regional surface flows or non-potable industrial waters. If the treated potable water has no fluoride added, or if the natural water has fluoride concentrations close to potable water fluoride concentrations, then fluoride may not be an appropriate indicator. Some industrial and commercial wastewaters may contain large concentrations of fluorides, making quantitative analyses difficult, however.

- Hardness- Hardness is useful in distinguishing between natural and treated waters (like fluoride), as well as between clean treated waters and waters that have been subjected to domestic use. It should be noted that hardness of waters varies considerably from place to place, with groundwaters generally being harder than surface waters.

- Ammonia/Ammonium- The presence or absence of ammonia (NH_3), or ammonium ion (NH_4^+), has been commonly used as a chemical indicator for prioritizing sanitary wastewater cross-connection drainage problems. Ammonia should be useful in identifying sanitary wastes and distinguishing them from commercial water usage.

- Potassium- Greater potassium concentrations have been noted for sanitary wastewater compared to potable water. These potassium increases following domestic water usage reveal its potential as a tracer parameter.

- Surfactants - Surfactants from detergents used in household and industrial laundering and other cleaning operations results in its high concentrations in wastewater. Anionic surfactants account for approximately two thirds of the total surfactants used in detergents, and are commonly measured as Methylene Blue Active Substances (MBAS). Some researchers (Alhajjar, *et al*. 1989) have not found surfactants in septic tank effluent suggesting that surfactants can be totally degraded in the septic tanks. Surfactants can be used to identify sanitary or laundry wastewater sources and distinguish between infiltrating septic tank effluent and other washwaters. Surfactants was the most useful tracer to identify problematic waters.

- pH- The pH of most dry-weather flow sources is close to neutral (pH = 7). However, pH values may be extreme (below 6 and above 9) in certain inappropriate commercial and industrial flows or where groundwaters contain dissolved minerals. If unusual pH values are observed, then the drainage system needs to be carefully evaluated. Note that pH values are log-transformed values and therefore flow contributions cannot be proportioned using pH directly in the same way "linear" concentration values can.

- Temperature - An elevated temperature of a receiving water can indicate contamination, particularly in cold weather. Sanitary wastewater and cooling water are examples of causes to temperature elevation and a rough heat balance may be conducted to identify a grossly contaminated outfall.

It is essential that the investigation have adequate local tracer data for all the potential sources in a study area. Local tracer data is obtained by sampling discharges for specific desired tracers at potential pollution sources that produce specific process wastewaters, regardless of whether or not an illicit entry to the storm drainage system is present. This becomes your data base of "local" characteristics of those tracers of that local area for comparison to background flows and storm drainage characteristics of that local area. For each tracer, the concentration means and standard deviations for all the potential source flows, including the natural waters or background waters (e.g., groundwaters). The data is necessary to confirm the source and the proportion of the outfall dry-weather flow contributed by the source (example given later). Without this information the likelihood of identifying the pollutant sources is greatly reduced. It is important to note that the tracer data should not be built up from data obtained for other area investigations.

A number of exotic tracers have also been proposed (cholesterol compounds, caffeine, pharmaceuticals, DNA characteristics of *E. coli* bacteria, stable ion ratios, etc.), but the analytical methods are usually very expensive and the detection sensitivities are inadequate for many of these potential tracers. However, it is likely that some of these, or others, may become very useful through further research and method development.

Field Surveys

Field investigations are used to locate and record all outfalls, and involve physically wadding, boating, etc. the receiving waters in search of all known and unknown outfalls. At each outfall the inspection and sampling should at least include:

- Accurate location of outfall and assignment of ID number;
- Photographs of outfall;
- Outfall discharge flow rate estimate (and note whether continuous or intermittent discharge);
- Physical inspection and record of outfall characteristics including odor, color, turbidity, floatable matter (fecal matter, sanitary discards, solids, oil sheen, etc.), deposits, stains, vegetation effected by pollutants, damage to outfall structure, and discharge water temperature; and

- Collection of dry-weather discharge samples for tracer analyses in the laboratory (specific conductivity and temperature can be field measured).

Intermittent flows will be more difficult to confirm and sample. Additional field visits, use of automatic samplers, and/or flow damming or screening techniques must be utilized for indicating and obtaining samples of intermittent flows.

Analyses of Data/Samples

The recommended analytical procedures and associated equipment in Pitt, *et al*. (1993) have been selected based on laboratory and field testing of analytical methods using the following criteria:

- Appropriate detection limits;
- Freedom from interferences;
- Good analytical precision (repeatability);
- Low cost and good durability; and
- Minimal operator training.

For consistent results the analyses should be carried out in the laboratory and not in the field, except for temperature and specific conductivity. Field analyses may be conducted for pH by using portable pH meters or litmus paper depending upon the degree of accuracy required and time constraints. Note that pH is a support tracer and not a primary parameter. The analysis method must provide adequate detection limits (i.e., measurement of the lowest required concentration) and precision (i.e., consistent results). In order to estimate the required detection limit it is necessary to know or estimate the tracer mean concentration and standard deviation.

Investigation and Remediation

The investigation of pollutant sources are divided into two major areas:

1. Analysis of outfall dry-weather data/observations to correlate with potential sources.
   - Observable parameters;
   - Simple check list for major flow component identification;
   - Flow chart for most significant flow component identification;
   - Matrix algebra solution of simultaneous equations; and
   - Matrix algebra considering probability distributions of library data using Monte Carlo statistical modeling

2. Upstream surveys to progressively narrow down the drainage area(s) of concern and locate the pollutant source(s).

Observable parameters are items covered by physical inspection, consisting of odor, color, turbidity, floatables, stains, vegetation, etc. These parameters will be clearly visible and indicate gross contamination at outfalls and may be indicators of intermittent flows. Observable parameters cannot be relied upon as a sole method for the evaluation of outfalls. A contaminated discharge may not be visible and can only be determined by other methods (Lalor 1993, Pitt, *et al*. 1993).

Emerging Critical Source Area Controls

The following discussion presents a few specialized options that can be used at small critical source areas, or at existing stormwater controls where enhanced control is needed. These options cause minimal interference with the site use. Some of these devices have been in use for some time, but have not been widely implemented, while others are relatively new control devices with limited, but promising, performance information. There are obviously additional controls that may be suitable for this use, but the following controls (filtration, combination practices, and chemical assisted settling) have substantial available performance data and have been shown to be broadly applicable. These controls are used when significant stormwater quality improvement is needed, beyond the litter and grit capture capabilities of the above described public works practices.

Filtration of Stormwater

Small source area stormwater runoff treatment devices using various forms of filtration have been developed and used at many locations, especially in areas having poor soils where infiltration (too clayey) or wet detention ponds (too sandy) cannot be used. The following paragraphs describe the different filtering media that have been evaluated for stormwater control, summarized from Clark and Pitt (1999).

Sand

The use of sand filtration is common throughout the U.S. Water supply treatment plants have successfully used sand filtration for many years and wastewater treatment plants often use sand filtration to polish their effluent before release. Sand filtration of stormwater began in earnest in Austin, Texas, as a replacement to wet detention ponds in arid areas having sandy soils where it would be difficult to maintain a suitable wet pond. The Austin sand filters are used both for single sites and for drainage areas less than 20 ha. The filters are designed to hold and treat the first 13 mm of runoff and the pollutant removal ability of the sand filters has been found to be very good.

According to the City of Austin design guidelines, the minimum depth of sand should be 0.5 m. If the City's design guidelines are followed, the expected pollutant removal efficiencies, which are based upon the results of the City of Austin's stormwater monitoring program, are as follows:

Pollutant	Removal Efficiency (%)
Fecal Coliform Bacteria	76
Total Suspended Solids (TSS)	70
Total Nitrogen	21
Total Kjeldahl Nitrogen	46
Nitrate - Nitrogen	0
Total Phosphorus	33
BOD	70
Total Organic Carbon	48
Iron	45
Lead	45
Zinc	45

Ref: City of Austin 1988.

In Washington, D.C., sand filters are used both to improve water quality and to delay the entrance of large slug inputs of runoff into the combined sewer system. Water quality filters are designed to retain and treat 8 to 13 mm of runoff with the final design based upon the amount of imperviousness in the watershed.

The State of Delaware considers the sand filter to be an acceptable method for achieving the eighty percent reduction requirement of suspended solids. Sand filters in Delaware are intended for sites which have impervious areas that will drain directly to the filter. The purpose of the sand filter is to help prevent or postpone clogging of an infiltration device. According to the State of Delaware guidelines, sand filtration is "intended for use on small sites where overall site imperviousness is maximized. Examples of these sites would be fast food restaurants, gas stations or industrial sites where space for retrofitting with other infiltration devices, such as detention ponds, is not available" (Shaver undated).

According to Delaware's recommendations, the sand filter will adequately remove particulates (TSS removal efficiency 75 - 85 %) but will not remove soluble compounds. Studies of a sand filter in Maryland show that it is now just becoming clogged after six years of use in a heavily used parking lot. Inspection of the sand below the surface of the filter has shown that oil, grease and finer sediments have migrated into the filter, but only to a depth of approximately 50 to 75 mm (Shaver undated).

It has been generally expected that sand would retain any particles that it trapped. However, during controlled tests Clark and Pitt (1999) found that fresh sand (without aging and associated biological growths) by itself did not retain stormwater toxicants (which are mostly associated with very fine particles). This lack of ability to retain stormwater toxicants prompted the investigation of other filtration media during their research. Combinations of filtration media, especially those using organic materials (activated carbon, peat moss, composted leaves and ion exchange resins) along with sand, are currently being investigated for their ability to more permanently retain stormwater pollutants.

Composted Leaves

Composts made from yard waste, primarily leaves, have been found to have a very high capacity for adsorbing heavy metals, oils, greases, nutrients and organic toxins due to the humic content of the compost. These humic compounds are stable, insoluble and have a high molecular weight. The humics act like polyelectrolytes and adsorb the toxicants.

The composted leaf filter was developed by W&H Pacific (now Stormwater Management, Inc.) for Washington County (Washington), the Unified Sewer Agency and the Metropolitan Service District of Washington County (W&H Pacific 1992). The initial filter design consists of a bottom impermeable membrane with a drainage layer above. Above the drainage layer is a geotextile fabric above which is the compost material. A new design, the CSF II includes a concrete vault, having a flow spreader and a main tank area. The tank includes modular units containing the compost, and the stormwater flows horizontally through the compost. These modular units can be easily removed for maintenance and be used for a variety or mixture of media. The actual pollutant removal occurs in the compost material. The removal processes that occur in the compost are filtration, adsorption, ion exchange and biodegradation of organics. Testing of a prototype of the initial design has shown the following pollutant removal rates:

Pollutant	Removal Rate (%)
Turbidity	84
Suspended Solids	95
Total Volatile Suspended Solids	89
COD	67
Settleable Solids	96
Total Phosphorus	40
Total Kjeldahl Nitrogen	56
Cooper	67
Zinc	88
Aluminum	87
Iron	89
Petroleum Hydrocarbons	87

Ref: W&H Pacific 1992.

Peat Moss

Peat is partially decomposed organic material, excluding coal, that is formed from dead plant remains in water in the absence of air. The physical structure and chemical composition of peat is determined by the types of plants (mosses, sedges and other wetland plants) from which it is formed. Peat is physically and chemically complex and is highly organic. Peat's main components are humic and fulvic acids and cellulose.

Peat's permeability varies greatly and is determined by its degree of decomposition and the plants from which it came. Generally, the more decomposed the peat is, the lower its hydraulic conductivity. Peats are generally light-weight when dry and are highly adsorptive of water. Because of the lignins, cellulosic compounds and humic and fulvic acids in peat, peat is highly colloidal and has a high cation-exchange capacity. Peat also is polar and has a high specific adsorption for dissolved solids such as transition metals and polar organic compounds. Peat has an excellent natural capacity for ion exchange with copper, zinc, lead and mercury, especially at pH levels between 3.0

and 8.5. This adsorption, complexing and exchange of various metal cations occur principally through the carboxyl, phenolic and hydroxyl groups in the humic and fulvic acids. This capacity to bind and retain cations, though, is finite and reversible and is determined mostly by the pH of the solution.

Peat is an excellent substrate for microbial growth and assimilation of nutrients and organic waste materials because of its high C:N:P ratio, which often approaches 100:10:1. Nitrifying and denitrifying bacteria are typically present in large numbers in natural peat. Peat's ability to retain phosphorus in the long-term is related to its calcium, aluminum, iron and ash content with the higher the content of each of the above constituents, the higher the retention capability.

Peat moss (sphagnum moss) is a fibric peat. It has easily identifiable undecomposed fibrous organic materials and its bulk density is generally less than 0.1 g/cc. Because of its highly porous structure, peat moss can have a high hydraulic conductivity, up to 140 cm/hr. It is typically brown and/or yellow in color and has a high water holding capacity.

For filtration devices, peat generally has been combined with sand to create a peat-sand filter (PSF). The PSF is a "man-made" filtration system, unlike the sand or peat filtration systems that were first used as wastewater treatment systems in areas where these soils naturally occur. The PSF removes most of the phosphorus, BOD and pathogens and with a good grass cover, additional nutrient removal occurs.

The Peat-Sand Filter System developed by the Metropolitan Washington Council of Governments (Washington, D.C.) has a good grass cover on top underlain by 300 to 500 mm of peat. The peat layer is supported by a 100 mm mixture of sand and peat which is supported by a 500 to 600 mm layer of fine to medium grain sand. Under the sand is gravel and the drainage pipe. The mixture layer is required because it provides the necessary continuous contact between the peat and the sand layers, ensuring a uniform water flow. Because this is a biological filtration system, it works best during the growing season when the grass cover can provide the additional nutrient removal that will not occur in the peat-sand regimes of the system (Galli 1990).

The PSF is usually an aerobic system. However, modifications to the original design by the Metropolitan Washington Council have been made to account for atypical site conditions or removal requirements. The estimated pollutant removal efficiency for the PSF system for stormwater runoff is given below:

Pollutant	Removal Efficiency (%)
Suspended Solids	90
Total Phosphorus	70
Total Nitrogen	50
BOD	90
Trace Metals	80
Bacteria	90

Ref. Galli 1990.

Design of Stormwater Filters

The information obtained by Clark and Pitt (1999) can be used to develop design guidelines for stormwater filtration, especially in conjunction with additional reported information in the literature. The design of a stormwater filter needs to be divided into two phases. The first phase is the selection of the media to achieve the desired pollutant removal goals. The second phase is the sizing of the filter to achieve the desired run time before replacement of the media. The main objective of this research was to monitor a variety of filtration media to determine their pollutant removal capabilities, as noted previously. However, it soon became apparent that the filters were more limited by clogging caused by suspended solids in the stormwater, long before reductions in their pollutant removal capabilities could be identified. Pretreatment of the stormwater so the suspended solids content is about 10 mg/L, or less, is probably necessary in order to take greater advantage of the pollutant retention capabilities of most media. This level of pretreatment, however, may make further stormwater control unnecessary, except for unusual conditions. Of course, it may be more cost-effective to consider shortened filter run times, without pretreatment, and not utilize all of the pollutant retention capabilities of the media. Urbonas (1999) monitored the performance of full-scale stormwater filters in Denver and reported serious problems with untreated stormwater bypassing the filters due to clogging. Therefore, much care needs to be taken when designing stormwater filtration to ensure acceptable performance over relatively long periods.

Selection of Filtration Media for Pollutant Removal Capabilities

The selection of the filter media needs to be based on the desired pollutant removal performance and the associated site conditions. If based on suspended solids alone for untreated stormwater (a likely common and useful criteria, but resulting in shortened service life), then the filtration media would be ranked according to the following:

1) >90% control of suspended solids: compost/sand, activated carbon/sand, Zeolite/sand, Enretech/sand
2) 80 - 90% control of suspended solids: sand, peat/sand
3) very little control of suspended solids: filter fabrics

If based on a wider range of pollutants for untreated stormwater, then the ranking would be as follows:

1) sand, activated carbon/sand, Enretech/sand (no pollutant degradation, but sand by itself may not offer "permanent" pollutant retention until aged and has biological growths and/or deposition of silts and oils
2) Zeolite/sand (no degradation)
3) compost/sand (color degradation)
4) peat moss/sand (turbidity and pH degradation)
5) filter fabrics alone (very little pollutant removal benefit)

Pre-settling of the stormwater was conducted to reduce the solids loadings on the filters to increase the run times before clogging in order to take better advantage of the pollutant retention capabilities of the filters. Settling reduced the stormwater suspended solids to about 10 mg/L, with about 90% of the particles (by volume) less than 10 µm in size. The untreated stormwater had a suspended solids concentration of about 30 to 50 mg/L, but many of the particles were larger, with about 90% of the particles being less than 50 µm. The pre-settling also reduced the other stormwater pollutants (color and turbidity by about 50%, and COD by about 90%, for example). This pre-settling was similar to what would occur with a well designed and operated wet detention pond. This pre-settling had a significant effect on the filter performance, as noted, and the rankings would be as follows, considering a wide range of stormwater pollutants (suspended solids removal by itself would not be a suitable criteria, as it is not likely to be reduced any further by the filters after the pre-settling):

1) peat moss/sand (with degradation in color, turbidity, and pH)
2) activated carbon/sand (no degradation, but fewer benefits)
3) Enretech/sand, forest/sand, sand (few changes, either good or bad)
4) compost/sand (many negative changes)

Obviously, knowing the stormwater control objectives and options will significantly affect the selection of the treatment media. This is most evident with the compost material. If suspended solids removal is the sole criterion, with minimal stormwater pre-treatment, then it is the recommended choice (if one can live with a slight color increase in the stormwater, which is probably not too serious). However, if a filter is to be used after significant pre-treatment in order to have a longer filter life, a compost filter would be the last choice (not considering economics).

Design of Filters for Specified Filtration Durations

The filtration durations measured during these tests can be used to develop filter designs. It is recommended that allowable suspended solids loadings be used as the primary controlling factor in filtration design. Clogging is assumed to occur when the filtration rate becomes less than about 1 m/day. Obviously, the filter would still function at smaller filtration flow rates, especially for the smallest rains in arid areas, but an excessive amount of filter by-passing would likely occur for moderate rains in humid areas. The wide ranges in filter run times as a function of water are mostly dependent on the suspended solids content of the water, especially when the water is pre-treated.

Therefore, the suspended solids loading capacities are recommended for design purposes. The filter capacity ranges may be grouped into the following approximate categories, as shown on Table 1.

Table 1. Expected Full-Scale Media Flow Capacities

Capacity to <1 m/day	Capacity to 10 m/day	Filtration Media Category
5,000 gSS/m^2	1,250 gSS/m^2	Enretech/sand; Forest/sand
5,000	2,500	Compost/sand; Peat/sand
10,000	5,000	Zeolite/sand; Act. Carbon/sand
15,000	7,500	Sand

Filter designs can be made based on the predicted annual discharge of suspended solids to the filtration device and the desired filter replacement interval. As an example, Table 2 shows the volumetric runoff coefficients (Rv) that can be used to approximate the fraction of the annual rainfall that would occur as runoff for various land uses and surface conditions, based on small-storm hydrology concepts (Pitt 1987). In addition, Table 3 summarizes likely suspended solids concentrations associated with different urban areas and waters.

Table 2. Volumetric Runoff Coefficients (Rv) for Different Urban Areas

Area	Volumetric Runoff Coefficient (Rv)
Low density residential land use	0.15
Medium density residential land use	0.3
High density residential land use	0.5
Commercial land use	0.8
Industrial land use	0.6
Paved areas	0.85
Sandy soils	0.1
Clayey soils	0.3

Table 3. Typical Suspended Solids Concentrations in Runoff from Various Urban Surfaces

Source Area	Suspended Solids Concentration (mg/L)
Roof runoff	10
Paved parking, storage, driveway, streets, and walk areas	50
Unpaved parking and storage areas	250
Landscaped areas	500
Construction site runoff	10,000
Combined sewer overflows	100
Detention pond water	20
Mixed stormwater	150
Effluent after high level of pre-treatment of stormwater	5

Using the information in the above two tables and the local annual rain depth, it is possible to estimate the annual suspended solids loading from an area. The following three examples illustrate these simple calculations.

1) A 1.0 ha paved parking area, in an area receiving 1.0 m of rain per year:

(50 mg SS/L) (0.85) (1 m/yr) (1 ha) (10,000 m^2/ha) (1,000 L/m^3) (g/1,000 mg) = 425,000 g SS/yr

Therefore, if a peat/sand filter is to be used having an expected suspended solids capacity of 5,000 g/m^2 before clogging, then 85 m^2 of this filter will be needed for each year of desired operation for this 1.0 ha site. This is about 0.9% of the paved area per year of operation. If this water is pre-treated so the effluent has about 5 mg/L suspended solids, then only about 0.2% of the contributing paved area would be needed for the filter. A sand filter would only be about 1/3 of this size.

2) A 100 ha medium density residential area having 1.0 m of rain per year:

(150 mg SS/L) (0.3) (1 m/yr) (100ha) (10,000 m^2/ha) (1,000 L/m^3) (g/1,000 mg) = 45,000,000 g SS/yr

The unit area loading of suspended solids for this residential area (450 kg SS/ha-yr) is about the same as in the previous example (425 kg SS/ha-yr), requiring about the same area dedicated for the filter. The reduced amount of runoff is balanced by the increased suspended solids concentration.

3) A 1.0 ha rooftop in an area having 1.0 m of rain per year:

(10 mg SS/L) (0.85) (1 m/yr) (1 ha) (10,000 m^2/ha) (1,000 L/m^3) (g/1,000 mg) = 85,000 g SS/yr

The unit area loading of suspended solids from this area (85 kg SS/ha-yr) is much less than for the other areas and would only require a filter about 0.2% of the roofed drainage area per year of operation.

It is recommended that the filter media be about 50 cm in depth and that a surface grass cover be used, with roots not extending beyond half of the filter depth. This should enable a filtration life of about five times the basic life observed during these tests. In addition, it is highly recommended that significant pre-treatment of the water be used to reduce the suspended solids concentrations to about 10 mg/L before filtration for pollutant removal. This pre-treatment can be accomplished using grass filters, wet detention ponds, or other specialized treatment (such as the sedimentation chamber in the multi-chambered treatment train, MCTT). The selection of the specific filtration media should be based on the desired pollutant reductions, but should in all cases include amendments to plain sand if immediate and permanent pollutant reductions are desired.

Chemical Assisted Sedimentation

Chemical addition has been used for many years in water treatment, and in lake management. More recently, full-scale implementations of chemical assisted settling has been used for the treatment of stormwater in wet detention ponds or at outfalls into small urban lakes. The chemicals tested and used include alum (generally a complex of aluminum and sulfate), ferric chloride, and aluminum chloride compounds, plus various coagulant aids.

Gietz (1981), in a series of laboratory tests in Ontario, found that an alum dosage of 4 to 6 mg/L was the most effective for highly polluted stormwater runoff. Over-dosages of alum and ferric chloride generally gave poor results. He found that it was difficult to add the correct dosage of coagulant because of the changing pollutant concentrations in the runoff. Low flow velocities also reduced mixing effectiveness and may require mechanical assistance. The flocs that were formed with the coagulants were easily disturbed by runoff turbulence.

Kronis (1982), in a series of Ontario bench- and pilot-scale tests, found that disinfection of stormwater with NaOCl at 5 mg/L available chlorine reduced fecal coliform populations to less than 10 organisms per 100 ml. He identified alum dosages of 30 mg/L as a preferred coagulant, with 10 to 30 percent increases in removals of particulate residue, BOD_5, COD, and total phosphorus as compared to plain sedimentation. However, chemical assisted settling generally produced moderate and erratic reductions in bacteria populations. Disinfection in wet detention ponds may be expensive, but it may be the only feasible method of significantly reducing bacteria populations in areas with serious bacteria problems.

Heinzmann (1993) described the development of a coagulation and flocculation treatment procedure for stormwater in Berlin, Germany. He found that because the stormwater was weakly buffered and was very soft, a polyaluminum chloride, with a cationic coagulant aid (polyacrylamid), was most suitable. A constant dosage of 0.06 mmol/L (as Al) was used, resulting in pH levels always greater than 6. The constant dosage was possible because the pH and buffering capacity of the stormwater was relatively constant during storms. He found that the best enhanced stormwater treatment process used coagulation and flocculation in a pipe designed for both microfloc and macrofloc formation, and final separation by filtration. The filtration was much better than the one hour sedimentation typically used in Berlin sedimentation tanks. He did find that a six minute flocculation time was sufficient before filtration. He found significant removals of phosphorus (to <0.2 mg/L), organic compounds (including PCB and PAHs), solids (to <5 mg/L), lead and copper. However, very poor removal of zinc was noted, and pollution prevention (decreased use of galvanized metals) was recommended. In the one-hour sedimentation tanks, without any chemical addition, the phosphorus (about 0.5 mg/L) and solids (about 50 mg/L) effluent concentrations were not nearly as low. The costs for this enhanced treatment (7 to 10 DM/m^3 in 1990) was about 10 to 40% higher than with the ordinary one-hour sedimentation tanks alone.

Pitt and Dunkers (1994) described a full-scale stormwater treatment plant, using the Karl Dunkers' system for treatment of separate stormwater and lake water. This system has been operating since 1981 in Lake Rönningesjön, near Stockholm, Sweden. The treatment facility uses ferric chloride and polymer precipitation and crossflow lamella clarifiers for the removal of phosphorus. The overall phosphorus removal rate for the 11 years from 1981 through 1991 was about 17 kg/year. About 40% of the phosphorus removal occurred from sedimentation processes, while the remaining removal occurred in the chemical treatment facility. This phosphorus removal would theoretically cause a reduction in phosphorus concentrations of about 10 μg/L per year in the lake, or a total phosphorus reduction of about 100 μg/L during the data period since the treatment system began operation. About 70% of this phosphorus removal was associated with the treatment of stormwater, while about 30% was associated with the treatment of lake water. The lake phosphorus concentration improvements averaged about 50 μg/L, only about one-half of the theoretical improvement, probably because of sediment-water interchange of phosphorus, or other unmeasured phosphorus sources.

The 1996 NALMS (North American Lakes Management Society) conference included several presentations describing the use of alum for stormwater treatment. Harper and Herr (1996) described the historical use of alum to treat stormwater entering Lake Ella in Tallahassee, FL, which began in 1986. A liquid slurry of alum is injected into the major storm drainage entering the lake, on a flow-weighted basis during rains. The alum forms precipitates with phosphorus, suspended solids, and heavy metals, which then settle in the lake. This treatment system resulted in immediate and substantial improvements to Lake Ella water quality. There are currently 23 alum stormwater treatment systems in Florida. Harper and Herr (1996) report that alum treatment of stormwater has consistently achieved 90% reductions in total phosphors, 50 to 70% reductions in total nitrogen, 50 to 90% reductions in heavy metals, and >99% reductions in fecal coliform bacteria. The precipitates of the phosphorus and heavy metals have been shown to be extremely stable over a wide range of dissolved oxygen and pH conditions.

Harper and Herr (1996) also reported on a very large alum project at Lake Maggiore in St. Petersburg. This 156 ha lake receives stormwater from a 927 ha watershed. Water quality problems were noted as early as the 1950s that included fish kills, algal blooms, nuisance macrophyte algal growths, and high bacteria levels. An environmental assessment determined that an 80% reduction in the annual phosphorus discharges from the stormwater and baseflow would result in an acceptable trophic status for the lake. Five alum treatment plants were then designed and were put in operation in August 1997, comprising the largest alum stormwater treatment system ever built.

An alum pilot-scale treatment system for stormwater, located in Minnesota, was described by Kloiber and Brezonik (1996). This system injected 1 mg/L (as Al) alum into a storm sewer at a pumping station just upstream of a 1.2 acre wet detention pond. The few minutes travel time between injection and the pond allowed 75 to 80% reductions in soluble reactive phosphorus. However, the pond retained only 40% of the added aluminum, increasing to 70% when a coagulant aid was used. The lowest total aluminum concentration in the pond effluent was 0.26 mg/L, still exceeding the water quality standard. They concluded that closer evaluations of the toxicity and bioavailability of the aluminum associated with alum stormwater treatment is needed. During treatability tests of stormwater from critical source areas, Pitt, *et al*. (1995) found that alum addition significantly increased the toxicity of the water (as indicated using the Microtox screening procedure).

Pitt (preliminary findings) recently conducted a series of chemical addition treatability tests for stormwater. He examined alum, ferric chloride, and ferric sulfate (all with and without organic polymers), and organic polymers alone. He also tested the benefits of adding a microsand (75 to 150 μm) as a coagulant aid. Preliminary findings indicate that ferric chloride with the microsand is the most effective chemical for treating stormwater. The concentrations of the ferric chloride are in the range of 30 to 80 mg/L, and the microsand is added to produce a turbidity of about 200 NTU. Heavy metals (copper, lead, and zinc, in both particulate and filterable forms) and toxicants (as indicated by the Microtox™ screening test) removals have been greater than 80%, with many tests greater than 95%. Phosphates are also significantly reduced (by about 50%). Alum actually added toxicity (possibly through zinc contamination in the alum, or by the dissolved aluminum) and many of the polymers also added COD and toxicity. It was not clear how sensitive dosage control would have to be in order to provide acceptable levels of heavy metal control by chemical treatment in stormwater.

Combination Practices

Example of Combination Practices using Filtration: The Multi-Chambered Treatment Train (MCTT)

The multi-chambered treatment train is an example of a stormwater device that utilizes a combination of processes, especially pretreatment of stormwater using sedimentation, followed by media filtration. It was developed based on early EPA sponsored research on treatability of stormwater at critical source areas (Pitt, *et al*. 1995). The MCTT contains aeration, sedimentation, sorption, and sand/peat filtration and was developed by Pitt, *et al*. (1999). The MCTT is most suitable for use at relatively small and isolated paved critical source areas, from about 0.1 to 1 ha (0.25 to 2.5 acre) in area, where surface land is not available for stormwater controls. Typical locations include gas stations, junk yards, bus barns, public works yards, car washes, fast food restaurants, convenience stores, etc., and other areas where the stormwater has a high probability of containing high concentrations of oils and filterable toxic pollutants that are difficult to treat by other means. A typical MCTT requires between 0.5 and 1.5 percent of the paved drainage area, which is about 1/3 of the area required for a well-designed wet detention pond, and is generally installed below ground. A pilot-scale MCTT was constructed in Birmingham, AL, at a large parking area at the University of Alabama at Birmingham campus, and tested over a six month monitoring period. Two additional full-scale MCTT units have also been constructed and were monitored as part of Wisconsin's 319 grant from the U.S. EPA. Complete organic and metallic toxicant analyses, in addition to conventional pollutants, are included in the evaluation of these units.

Figure 3 shows a general cross-sectional view of the MCTT. It includes a special catchbasin followed by a two chambered tank that is intended to reduce a broad range of toxicants (volatile, particulate, and dissolved). The MCTT includes a special catchbasin (based on Lager, *et al*.'s 1977 design) followed by two tank chambers that is intended to reduce a broad range of suspended solids and stormwater toxicants (volatile, particulate, and dissolved). The runoff enters the catchbasin chamber by passing over a flash aerator (small column packing balls with counter-current air flow) to remove any highly volatile components present in the runoff (unlikely). This catchbasin also serves as a grit chamber to remove the largest (fastest settling) particles. The second chamber serves as an enhanced settling chamber to remove smaller particles and has inclined tube settlers to enhance sedimentation. The settling time in this main settling chamber usually ranges from 20 to 70 hours. This chamber also contains fine bubble diffusers and sorbent pads to further enhance the removal of floatable hydrocarbons and additional volatile compounds. The water is then pumped to the final chamber at a slow rate to maximize pollutant reductions. The final chamber contains a mixed media (sand and peat) slow filter, with a filter fabric layer. The MCTT is typically sized to totally contain all of the runoff from a 6 to 20 mm (0.25 to 0.8 in) rain, depending on treatment objectives, inter-event time, typical rain size, and rain intensity for an area.

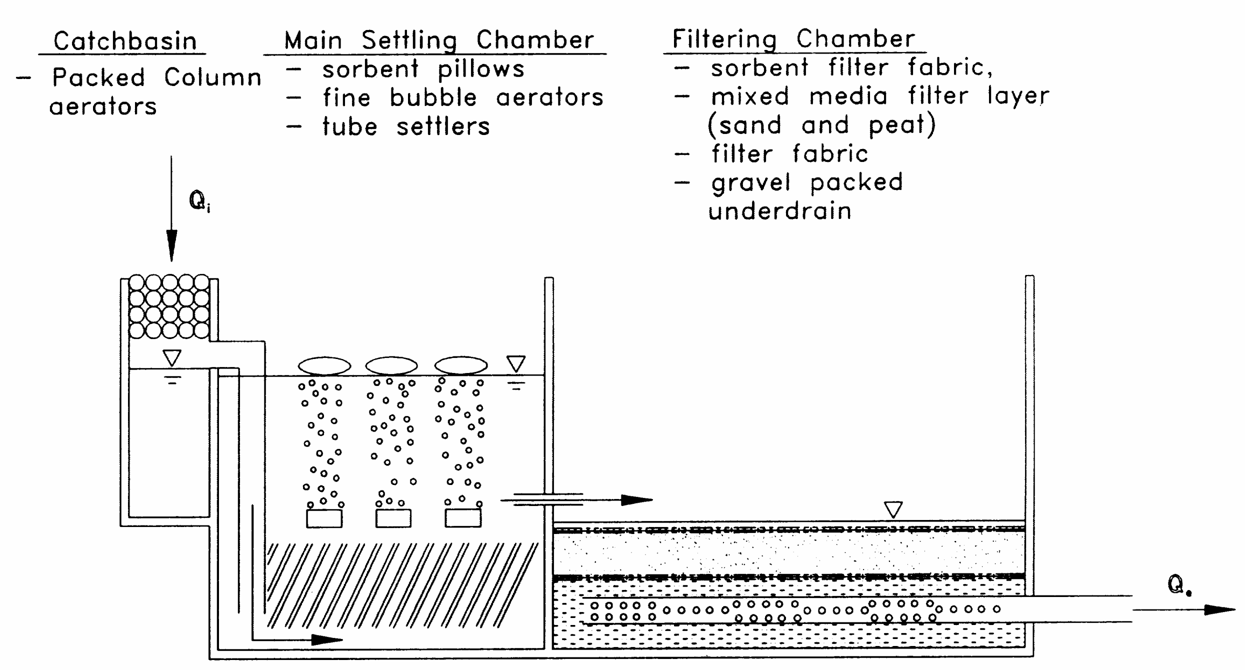

Figure 3. General schematic of MCTT (Pitt, *et al.* 1999).

Table 4 shows the median toxicity reductions for various holding times for a 2.1m deep main settling chamber, based on laboratory bench-scale treatability tests. Table 5 shows how this device would operate for Birmingham, Alabama, rains. Short holding times result in much of the annual rainfall being treated (the unit is empty before most of the rains begin, because it rains about every 3 to 5 days), but each rain is not treated very well, because of the short settling periods. Therefore, the annual treatment level approaches a constant level with long holding periods. In this example, a relatively large main settling chamber is needed in order to contain large fractions of most of the rains. Long-term continuous analyses have been conducted to identify the most cost-effective MCTT sizes (and holding times) for different treatment objectives for many U.S. locations (Pitt 1996).

Table 4. Median Toxicity Reductions for Different Treatment Holding Times

Holding Period for 2.1 m depth (h)	Median Toxicity Reduction (%) per Individual Rain
6	46
12	60
24	75
36	84
48	92
72	100

Table 5. Effects of Storage Volume and Holding Periods on Annual Runoff Treated and on Total Annual Toxicity Reduction (Birmingham, AL rains)

	Storage volume corresponding to: 12.7 mm rain with 10.2 mm runoff (0.50 in. rain with 0.40 in. runoff)		Storage volume corresponding to: 38.1 mm rain with 33.5 mm runoff (1.50 in. rain with 1.32 in. runoff)	
Holding Period (h)	**% Annual Runoff Treated**	**% Annual Toxicity Reduction**	**% Annual Runoff Treated**	**% Annual Toxicity Reduction**

6	84	36	100	46
12	62	37	100	60
24	52	39	98	73
36	48	41	91	77
48	46	42	88	81
72	44	44	84	84

During monitoring of 13 storms at the Birmingham pilot-scale MCTT facility (designed for 90% toxicity reductions), the following overall median removal rates were observed: 96% for total toxicity (as measured using the Microtox™ screening test), 98% for filtered toxicity, 83% for suspended solids, 60% for COD, 40% for turbidity, 100% for lead, 91% for zinc, 100% for n-Nitro-di-n-proplamine, 100% for pyrene, and 99% for bis (2-ethyl hexyl) phthalate. The color was increased by about 50% due to staining from the peat and the pH decreased by about one-half pH unit, also from the peat media. Ammonia nitrogen was increased by several times, and nitrate nitrogen had low removals (about 14%). The MCTT performed better than intended because of the additional treatment provided by the final ion exchange/filtration chamber. It had very effective removal rates for both filtered and particulate stormwater toxicants and suspended solids. Increased filterable toxicant removals were obtained in the peat/sand mixed media filter/ion exchange chamber, at the expense of increased color, lowered pH, and depressed COD and nitrate removal rates.

Increases in color and a slight decrease in pH occurred during the filtration step at the pilot-scale unit. The main settling chamber resulted in substantial reductions in total and dissolved toxicity, lead, zinc, certain organic toxicants, suspended solids, COD, turbidity, and color. The filter/ion exchange unit is also responsible for additional filterable toxicant reductions. However, the catchbasin/grit chamber did not indicate any significant improvements in water quality, although it is an important element in reducing maintenance problems by trapping bulk material.

Results from the full-scale tests of the MCTT in Wisconsin (Corsi, *et al*. 1999) are encouraging and collaborate the high levels of treatment observed during the Birmingham pilot-scale tests. Table 6 shows the treatment levels that have been observed during seven tests in Minocqua (during one year of operation) and 15 tests in Milwaukee (also during one year of operation), compared to the pilot-scale Birmingham test results (13 events). These data indicate high reductions for SS (83 to 98%), COD (60 to 86%), turbidity (40 to 94%), phosphorus (80 to 88%), lead (93 to 96%), zinc (90 to 91%), and for many organic toxicants (generally 65 to 100%). The reductions of dissolved heavy metals (filtered through 0.45 µm filters) were also all greater than 65% during the full-scale tests. None of the organic toxicants were ever observed in effluent water from either full-scale MCTT, even considering the excellent detection limits available at the Wisconsin State Dept. of Hygiene Laboratories that conducted the analyses. The influent organic toxicant concentrations were all less than 5 µg/L and were only found in the unfiltered sample fractions. The Wisconsin MCTT effluent concentrations were also very low for all of the other constituents monitored: <10 mg/L for SS, <0.1 mg/L for phosphorus, <5 µg/L for cadmium and lead, and <20 µg/L for copper and zinc. The pH changes in the Milwaukee MCTT were much less than observed during the Birmingham pilot-scale tests, possibly because of the added activated carbon in the final chamber in Milwaukee. Color was also much better controlled in the full-scale Milwaukee MCTT.

The Milwaukee installation is at a public works garage and serves about 0.1 ha (0.25 acre) of pavement. This MCTT was designed to withstand very heavy vehicles driving over the unit. The estimated cost was $54,000 (including a $16,000 engineering cost), but the actual total capital cost was $72,000. The high cost was likely due to uncertainties associated with construction of an unknown device by the contractors and because it was a retro-fit installation. As an example, installation problems occurred due to sanitary sewerage not being accurately located as mapped.

The Minocqua site is at a 1 ha (2.5 acre) newly paved parking area serving a state park and commercial area. It was located in a grassed area and was also a retro-fit installation, designed to fit within an existing storm drainage system. The installed capital cost of this MCTT was about $95,000 and included the installation of the 3.0 X 4.6 m (10ft X 15ft) box culverts used for the main settling chamber (13 m, or 42 ft long) and the filtering chamber (7.3 m, or 24 ft long). In perspective, these costs are about equal to the costs of installation of porous pavement (about $40,000 per acre of pavement).

Summary

There are numerous stormwater treatment options available. General approaches for stormwater control can be described based on site specific rainfall and runoff distributions and a knowledge of local receiving water problems and use goals. The following general strategy could be reasonably followed, with numerous exceptions and substitutions available. On-site infiltration can be utilized to completely control (and eliminate) runoff from the smallest, and most common storms. This would significantly reduce the number of events occurring (and decrease the violations of bacteria and some heavy metals), while helping to match the pre-development hydrology of the area (protecting in-stream habitat). Moderate to large events are most effectively controlled through wet detention ponds where the water is treated before discharge. The large events are the basis for storm drainage design to prevent flooding damage. The largest events that may occur in an area will exceed the capacity of the storm drainage system. Therefore, site development must provide for these failures by directing excess water through safe secondary drainage systems and away from homes and primary transportation corridors. This general approach is most suitable in developing areas. Retro-fitting stormwater controls is much more challenging, less effective, and more costly.

Table 6. Performance Data for Full-Scale MCTT Tests, Compared to Birmingham Pilot-Scale MCTT Results (median reductions and median effluent quality)

	Milwaukee MCTT (15 events)	Minocqua MCTT (7 events)	Birmingham MCTT (13 events)
suspended solids	98 (<5 mg/L)	85 (10 mg/L)	83 (5.5 mg/L)
volatile suspended solids	94 (<5 mg/L)	na[a]	66 (6 mg/L)
COD	86 (13 mg/L)	na	60 (17 mg/L)
turbidity	94 (3 NTU)	na	40 (4.4 NTU)
pH	-7 (7.9 pH)	na	8 (6.4 pH)
ammonia	47 (0.06 mg/L)	na	-210 (0.31 mg/L)
nitrates	33 (0.3 mg/L)	na	24 (1.5 mg/L)
Phosphorus (total)	88 (0.02 mg/L)	80 (<0.1 mg/L)	nd[b]
Phosphorus (filtered)	78 (0.002 mg/L)	na	nd
Microtox® toxicity (total)	na	na	100 (0%)
Microtox® toxicity (filtered)	na	na	87 (3%)
Cadmium (total)	91 (0.1 µg/L)	na	18 (0.6 µg/L)
Cadmium (filtered)	66 (0.05 µg/L)	na	16 (0.5 µg/L)
Copper (total)	90 (3 µg/L)	65 (15 µg/L)	15 (15 µg/L)
Copper (filtered)	73 (1.4 µg/L)	na	17 (21 µg/L)
Lead (total)	96 (1.8 µg/L)	nd (<3 µg/L)	93 (<2 µg/L)
Lead (filtered)	78 (<0.4 µg/L)	na	42 (<2 µg/L)
Zinc (total)	91 (<20 µg/L)	90 (15 µg/L)	91 (18 µg/L)
Zinc (filtered)	68 (<8 µg/L)	na	54 (6 µg/L)
benzo(a)anthracene	>45 (<0.05 µg/L)	>65 (<0.2 µg/L)	nd
benzo(b)fluoranthene	>95 (<0.1 µg/L)	>75 (<0.1 µg/L)	nd
dibenzo(a,h)anthracene	89 (<0.02 µg/L)	>90 (<0.1 µg/L)	nd
fluoranthene	98 (<0.1 µg/L)	>90 (<0.1 µg/L)	100 (<0.6 µg/L)
indeno(1,2,3-cd)pyrene	>90 (<0.1 µg/L)	>95 (<0.1 µg/L)	nd
phenanthrene	99 (<0.05 µg/L)	>65 (<0.2 µg/L)	nd
pentachlorophenol	na	na	100 (<1 µg/L)
phenol	na	na	99 (<0.4 µg/L)
pyrene	98 (<0.05 µg/L)	>75 (<0.2 µg/L)	100 (<0.5 µg/L)

na[a] : not analyzed
nd[b]: not detected in most of the samples

In addition to the general approach outlined above, special consideration needs to be applied to critical source areas. These areas have higher than normal unit area pollutant loadings, especially for toxicants. Typical critical source areas include areas have some of the following characteristics: large amounts of pavement, storage of equipment or materials, scrap yards, frequent automobile starts, vehicle maintenance areas, etc. Public works practices (catchbasin inlets, oil/water separators, and street cleaning) have been used in these areas to control stormwater. However, these practices are mostly limited to litter and gross pollution control (obvious needed objectives), but have limited pollutant control for most pollutants of interest (such as nutrients, bacteria, solids, and toxicants). Emerging critical source area controls have been developed to provide a much greater level of treatment for stormwater from these areas. These controls must be applicable to small isolated areas and have minimal disturbance to site activities. Some of the most commonly used controls suitable for this use are stormwater filters. Newly developed information for different types of stormwater filters (and combination practices) indicate that moderate to high levels of treatment is possible for runoff from these critical areas.

Therefore, a successful stormwater management program for an area must be driven on site knowledge and objectives and may include numerous and different stormwater control practices.

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