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Stormwater Pollution Abatement Technologies

by

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Foreword

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land air and water systems. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This publication covers the most current technologies and management practices employed in remediating contaminated urban stormwater runoff. As society progresses and expands, stormwater runoff becomes an increasingly more significant source of pollutants entering our Nation's waterways. More impervious surfaces, building in flood plains, and increased industrial/business/human activities all contribute to diffuse source pollution. This significance is evident from the high pollutant loadings from diffuse sources that still enter our waterways even though tight controls have been initiated over previously unchecked point source discharges from industry and wastewater treatment plants. Significant water quality problems still exist and this publication presents the basic ideas, strategies and technologies that can be used to comply with the Clean Water Act mandated urban stormwater permit requirements and to satisfactorily combat the impact of diffuse source pollutants on our waterways.

E. Timothy Oppelt, Director
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Abstract

This publication presents information regarding best management practices (BMP's) and pollution abatement technologies that can provide treatment of urban stormwater runoff. Included in the text are a general approach which considers small storm hydrology, and watershed practices which covers public education, regulations, and source control of pollutants. Also covered are source treatment of pollutants which include vegetative BMP's and infiltration practices. Uses and modifications of installed drainage systems, types of end-of-pipe treatments including biological, chemical and physical treatments and storage and reuse of stormwater are also covered.

Additionally, several tables list recommended publications should the reader wish to explore any subject matter further.

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Section 1

Introduction

This report covers the control and treatment of stormwater in relation to the removal or reduction of the stormwater pollutant loads. The control of stormwater to prevent flooding is not the emphasis of this report. Many of the pollution abatement technologies discussed will help attenuate stormwater flows. However, as they are generally designed for small storm events they will not provide sufficient capacity for the large events. Although prevention of stormwater flooding is not discussed in this report a drainage system design should consider both pollutant and flooding aspects of stormwater.

Strategically, the best way to control and treat urban stormwater runoff is through a combination of regulations, best management practices (BMPs), and treatment processes. The optimal combination will be site specific, depending on site characteristics, specific pollutants involved, and cost considerations.

Regulations and BMPs will be effective tools in controlling urban stormwater runoff because they tend to be preventative in nature. Mandating effluent limits and creating zoning laws are examples of this. BMPs may also include such practices as upgrading current systems (treatment devices, sewer systems, stormwater conveyance systems, etc.) or developing proper management techniques (solid waste management, street sweeping, etc.).

Source treatment and flow attenuation may come into play by designing such devices that will intercept or infiltrate stormwater runoff back into the groundwater system prior to introduction into the stormwater or combined sewer overflow (CSO) conveyance system. This can have a huge savings on design and construction of treatment facilities. Examples of such devices are swales, filter strips, porous pavement, and stormwater wetlands.

BMPs may also include using the existing drainage systems for storage (in-line or in-sewer storage) or creating off-line storage facilities. A low cost example of an off-line storage method is the Flow Balance Method (FBM). This method stores overflow from storm or combined sewer outfalls until such time as the wastewater treatment plant can handle the volume of overflow.

End-of-Pipe treatment may be necessary for controlling stormwater pollution. This can be expensive if not used in conjunction with the other methods mentioned above. There are times when this cannot be avoided and the costs may therefore be high. The problem with End-of-Pipe treatment is that most of these systems are based on continuous flow. Stormwater is intermittent in nature and can pose a problem for traditional treatment methods, e.g., maintaining biomass in a biological treatment system, or proper amount of chemical addition to variable flows. Some methods will function better than others and it is up to the system designer to determine the best treatment system.

The reader may wish to delve into these subjects in greater detail than is presented in this text. There are tables presented that list recommended literature as well as the references listed in the end of the publication.

Section 2

General Approach and Strategy

Small Storm Hydrology

The selection of suitable abatement technologies requires an understanding of the size and distribution of storm events. These contribute to the total volume of storm runoff and with knowledge of the pollutant concentrations provide the total pollutant load. Generally the smaller storm events are the critical storms to consider, because for many parts of the USA, 85% of all the rains are less than 0.6 in. (15 mm) in depth and can generate about 70% of the total annual storm runoff (Pitt 1987). The characteristics of small and large storm events can be very different in terms of the storm runoff generated, pollutant load, and receiving water impacts. However, the frequent small storms will have a more persistent impact, and less frequent large storms will have a larger impact but allow time for recovery between events. For small storm events, any inaccuracy in the estimation of the initial abstractions and the soil infiltration rates can significantly change the calculated storm runoff pollutant load. The initial abstractions include the rainfall depth required to satisfy surface wetting, surface depression storage, interception by hanging vegetation, and evaporation. Together with soil infiltration rates, the initial abstractions need to be accurately estimated to calculate the storm runoff volume. Initial abstractions for relatively impervious urban surfaces have been found to account for the first 0.2 - 0.4 in. (5 - 10 mm) of a storm event (Pitt 1987). Others (Pecher 1969, Viesman *et al.* 1977) have reported initial abstractions of between 0.02 - 0.14 in. (0.5 - 3.5 mm) for pavement areas depending on whether the areas are flat or sloping steeply. Figure 2-1 illustrates the runoff capture volume rates in Cincinnati, Ohio. Note that 95% of the runoff will be captured for the first 0.5 watershed in. (12.7 mm)(as stated above, 85% of all storms are less than 0.6 in. (15 mm)). This indicates that small precipitation events need to be considered when designing stormwater quality treatment facilities. Increases in design detention volume above these values will not significantly affect the percent capture (Urbonas and Stahre 1993).

Traditional stormwater flood control is concerned with the peak storm runoff flow rates from relatively infrequent large storm events and their conveyance to prevent flooding. This is a different set of criteria from that needed for storm runoff pollution control. Therefore the use of data, storm runoff coefficients, models, etc. intended or developed to meet stormwater flood control requirements should be used with

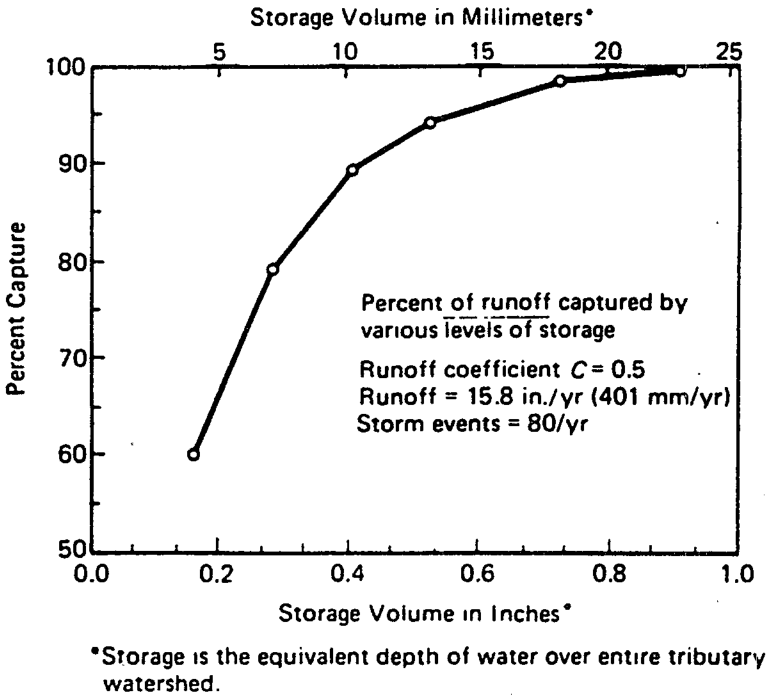

Figure 2-1. Runoff capture volumes in Cincinnati, Ohio (Urbonas and Stahre, 1993).

caution. This is illustrated by initial abstractions which can be a major portion of a small storm but will be a relatively insignificant portion of a large storm. In other words just because a model for an area has been verified as providing accurate information for large storm events does not mean it will predict small events with the same level of confidence.

A model developed and presently being updated for the calculation of urban stormwater runoff pollutant loads from small storms is: *Source Loading And Management Model: An Urban Nonpoint Source Water Quality Model (SLAMM)*, (Pitt 1988). This model concentrates on the parameters discussed above to better estimate the urban storm runoff pollutant loads before and after application of best management practices (BMPs). However this is mainly applicable to small areas and does not give a continuous time analysis. There are, however, a number of other models such as the US EPA's Storm Water Management Model (SWMM) which will allow a continuous time analysis for large drainage areas. Continuous time analysis will provide an optimum design for storage and treatment facilities based on long term historical weather patterns.

It should not be taken from the above that the large infrequent storm events do not cause polluted urban storm runoff or significant impacts on receiving waters but that their infrequency makes them a less significant factor than the smaller frequent storms. Communities must design control systems that meet applicable regulations and these control systems may include large systems.

There are several other factors which will effect the stormwater runoff pollutants and their concentrations, as discussed elsewhere, and these will also need to be taken into consideration when estimates are made of the urban storm runoff pollutant load.

Strategy

The intermittent, widespread, and variable nature of urban stormwater runoff will require a flexible and creative approach to achieve the optimal control and treatment solution. This approach is likely to be responding to regulations and may be include Best Management Practices (BMPs) and treatment processes. Traditional wastewater treatment methods, particularly secondary treatment processes that tend to operate under conditions closer to steady state, will not necessarily be suitable for the fluctuating loads of stormwater runoff. On the other hand, technologies used to control and treat combined sewer overflows (CSOs) are more likely to be applicable for the stormwater runoff and advantage should be taken of any experience or facilities of CSO origin that have application for separate stormwater runoff. Successful stormwater management to control urban storm runoff pollution will require an areawide approach combining prevention, reduction, and treatment practices/technologies. It is highly unlikely that one method will provide the best solution to control the widespread diffuse nature of stormwater runoff and achieve the water quality required.

Establishing an urban storm runoff pollution prevention and control plan requires a structured strategy which will include the following steps:

- Define Existing Conditions
- Set Site-Specific Goals
- Collect and Analyze Data
- Refine Site-Specific Goals
- Assess and Rank Problems
- Screen BMPs and Treatment Technologies
- Select BMPs and Treatment Technologies
- Implement Plan
- Monitor and Re-evaluate

It is very likely that advantage can be taken of previous studies for either stormwater or CSO to get a head start. The above strategy is described in *Handbook: Urban Runoff Pollution Prevention and Control Planning* (U.S. Environmental Protection Agency 1993a). Additional references that describe planning approaches for urban storm runoff pollution prevention and control are contained in Table 2-1.

Table 2-1. Planning Approaches

Literature Reference	Urban Surface Water Management (Walesh 1989)	Developing the Watershed Plan (US EPA 1991a)	Developing Goals for Nonpoint Source Water Quality Projects (US EPA 1991b)	Santa Clara Valley Nonpoint Source Study- Volume II: NPS Control Program (SCVWD 1990)	State of California Storm Water Best Management Practice Handbooks (Camp Dresser & McKee 1993)	Urban Storm Water Management and Technology: Update and User's Guide (US EPA 1977a)
Determining existing conditions	Establish objectives and standards Conduct inventory	Identify problems and opportunities and determine objectives Develop resource data	Inventory resources and forecast conditions	Initiate public participation Define existing conditions Review regulatory problems Define goals and objectives	Define goals Assess existing conditions	Assess existing data Compare conditions vs. objectives Determine extent of runoff problem
Quantifying pollution sources and effects	Analyze data and prepare forecasts	Interpret, analyze, and evaluate data and forecasts	Identify problems Develop goals or objectives	Define and describe problems	Set priorities	Conduct selective field monitoring Refine problem estimates
Assessing alternatives	Formulate alternatives Compare alternatives and select recommended plan	Formulate and evaluate alternatives Evaluate and compare alternatives	Formulate alternatives Evaluate alternatives	Identify NPS control measures Evaluate control measures Develop evaluation criteria Examine and screen measures Select measures Reassessment	Select near-term BMPs	Assess alternatives
Developing and implementing the recommended plan	Prepare plan implementation program Implement plan	Select alternative and record decision	Select best alternatives and record decision	Recommend control measures and implementation program	Implement near-term program Assess program effectiveness	Determine attainable improvements

The above strategy will provide the control goal to be achieved which is then used as the basis for selection of suitable technologies or approaches. The goal(s) should initially be broad and not specific because the process of reviewing the technologies or approaches available will in itself generate information to focus and refine the goal(s) to meet cost, level of control, public opinion, feasibility, and other restraints. A flexible approach, which, through an iterative process of review and adjustment is focused to a specific action plan, is the only real method by which the complexity of urban stormwater can be managed. The specific action plan will also need to be subject to reassessment once feedback on its implementation is available.

The above is only a very brief indication of the extensive work which will be required before the actual abatement technologies are implemented and more detail is given in the above reference (U.S. Environmental Protection Agency 1993a). The remainder of this report is concerned with an overview of the abatement technologies available. The report reviews the technologies by separating the drainage system into three physical areas of:

- watershed area (i.e., storm runoff generation/collection area)
- installed and/or modified/natural drainage system (i.e., conveyance pipes, channels, storage, etc.)
- end-of-pipe (i.e., point source)

Technologies applicable to each of these areas are discussed and can be divided into structural and non-structural. The non-structural will cover approaches such as public education, regulations, and local ordinances which will have their main application to the upstream collection area. The structural approaches will be the main options for the drainage system and end-of-pipe areas and tend to be the more expensive items.

The technologies and approaches for stormwater management referred to as BMPs generally cover the non-structural or low-structural stormwater runoff controls. The point at which a stormwater management technology changes from a BMP to a unit treatment process (i.e.,"high-structural" control) is often unclear, therefore in this report BMPs refer to the upstream watershed area prevention and/or control measures only.

As stated previously the optimal solution is likely to be an integrated approach using several practices and technologies. The management of the watershed using BMPs to prevent or control pollution at the source is likely to offer the most cost effective solution and tend to be the basis of many stormwater management plans. However, although BMPs will be the preferred option they will not always be feasible or by themselves sufficient to achieve the control objectives. For older and more heavily urbanized areas BMPs are likely to have a limited application and some form of treatment prior to discharge may be required. There are a number of publications cited in Table 2-2 which cover the present state-of-the-art on stormwater management using BMPs but do not generally review the end-of-pipe treatments that could be applied to stormwater as a final line of control. This report will therefore include the treatment options available for stormwater pollution control and which appear to be ignored in many stormwater management manuals.

It should however be emphasized that it will be more cost effective to prevent potential urban storm runoff pollution problems and protect existing resources than to construct pollution controls once a problem exists. Unfortunately for many areas the problems exist and retrospective prevention is not a feasible solution.

The implementation of any stormwater management program will need to meet financial and probably schedule restraints, therefore an early review and improved utilization of existing facilities can offer several advantages. These options are likely to be the quickest and least costly to be implemented but it is also important that they should meet the objectives developed from the earlier stormwater management planning process. Examples might include the enforcement of existing regulations to control soil erosion during construction activities and adaption of existing stormwater storage intended for flood control to also provide quality control for small storm events. New installations should consider design for both flood control and pollutant removals.

The public does not generally perceive stormwater to be an environmental pollution problem. Furthermore they do not appreciate the direct connection between some of their actions and the pollution consequences (e.g.,disposal of engine oil and household toxic liquids down a storm drain or throwing litter on the street which is transported by the storm runoff into the receiving water). Gaining public support to cooperate in the implementation and to pay for a stormwater management plan will be a major challenge. A strategy of concentrating efforts and resources on high priority areas where results are likely to be achieved, and seen to be achieved, will help generate public support.

Table 2-2. Urban Runoff and CSO BMP References

Document Title	Author or Editor	BMPs Included	Information Available
Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs, 1987	Schueler	Detention Infiltration Vegetative Filtration Quality Inlets	General Description Effectiveness Design Use Limitations Maintenance Cost Examples

Table 2-2 (continued). Urban Runoff and CSO BMP References

Document Title	Author or Editor	BMPs Included	Information Available
Protecting Water Quality in Urban Areas, 1989	MPCA	Housekeeping Detention Infiltration Vegetative Quality Inlets	General Description Effectiveness Use Limitations Maintenance Cost Examples
Guide to NPS Control, 1987	US EPA	Housekeeping Detention Infiltration	General Description Effectiveness Cost
Water Resource Protection Technology: A Handbook of Measures to Protect Water Resources in Land Development, 1981	Urban Land Institute	Housekeeping Detention Infiltration Vegetative Quality Inlets	General Description Effectiveness Design Use Limitations Maintenance Costs
Urban Targeting and Urban BMP Selection, 1990	Woodward-Clyde	Housekeeping Detention Infiltration Vegetative	General Description Effectiveness Design Use Limitations
Combined Sewer Overflow Pollution Abatement, 1989	WPCF	Housekeeping Collection System Storage Treatment	General Description Design Effectiveness Maintenance Cost
Urban Stormwater Management and Technology: An Assessment, 1974	US EPA	Housekeeping Collection System Storage Treatment	General Description Design Maintenance Use Limitations
Decision Maker's Storm Water Handbook: A Primer, 1992	Philips-US EPA Region V	Housekeeping Detention Infiltration Vegetative Filtration Quality Inlets	General Description Effectiveness Design Use Limitations Maintenance Examples
Urban Storm Water Management and Technology: Update and User Guide, 1977	US EPA	Source Control Collection System Storage Treatment	General Description Design Maintenance Use Limitations

Table 2-2 (continued). Urban Runoff and CSO BMP References

Document Title	Author or Editor	BMPs Included	Information Available
Control and Treatment of Combined Sewer Overflows, 1990	Moffa	Source Control Collection System Storage Treatment	General Description Design Maintenance Use Limitations
Coastal Nonpoint Source Control Program: Management Measures Guidance, 1993	US EPA	Housekeeping Infiltration Vegetative Filtration Quality Inlets	General Description Effectiveness Design Use Limitations Maintenance Cost Examples
The Florida Development Manual: A Guide to Sound Land and Water Management, 1992	Livingston, et al.	Housekeeping Infiltration Vegetative Quality Inlets	General Description Effectiveness Design Use Limitations Maintenance Cost Examples
Storm Water Management Manual for the Puget Sound Basin, 1991	WA DOE	Housekeeping Infiltration Vegetative Quality Inlets	General Description Effectiveness Design Use Limitations Maintenance Cost Examples
Stormwater Management, 1992	Wanielista and Yousef	Water Quality Infiltration Detention	General Description Effectiveness Examples Cost
Stormwater: Best Management Practices and Detention for Water Quality, Drainage, and CSO Management, 1993	Urbonas and Stahre	Storage Source Control Detention Treatment Water Quality	General Description Effectiveness Design Use Limitations
Integrated Stormwater Management, 1993	Field, O'Shea and Chin	Detention Management Vegetative Infiltration Flood Control Reclamation Collection Systems	General Description Effectiveness Design Use Limitations

Section 3

Watershed Area Technologies and Practices

There are many BMPs, but all BMPs are not suitable in every situation. It is important to understand which BMPs are suitable for the site conditions and can also achieve the required goals. This will assist in the realistic evaluation for each practice of: the technical feasibility, implementation costs, and long-term maintenance requirements and costs. It is also important to appreciate that the reliability and performance of many BMPs has not been well established, with most BMPs still in the development stage. This is not to say that BMPs cannot be effective, but that they do not have a large bank of historical data on which to base design to be confident that the performance criteria will be met under the local conditions. The most promising and best understood BMPs are detention and extended detention basins and ponds. Less reliable in terms of predicting performance, but showing promise, are sand filter beds, wetlands, and infiltration basins (Roesner *et al.* 1989).

A study of 11 types of water quality and quantity BMPs in use in Prince George's County, Maryland (Metropolitan Washington Council of Governments 1992a) was conducted to examine their performance and longevity. The report concluded that several of the BMPs had either failed or were not satisfying the designed performance. Generally wet ponds, artificial marshes, sand filters, and infiltration trenches achieved moderate to high levels of removal for both particulate and soluble pollutants. Only wet ponds and artificial marshes demonstrated an ability to function for a relatively long time without routine maintenance. BMPs which were found to perform poorly were infiltration basins, porous pavement, grass filters, swales, smaller "pocket" wetlands, extended detention dry ponds, and oil/grit separators. Infiltration BMPs had high failure rates which could often be attributed to poor initial site selection and/or lack of proper maintenance.

The above report contains many more details and recommendations on the use of BMPs. It is important to note that the reported poor performance of some of the BMPs is likely to be a function of one or more of: the design, installation, maintenance, or suitability of the area. Greater attention to these details is likely to significantly reduce the failure rate of BMPs. Other important design considerations include: safety for maintenance access and operations, hazards to the general public through safety (e.g., drowning) or nuisance (e.g., mosquito breeding area), acceptance by the public (e.g., enhance area aesthetics), and to assume conservative performances in the design until the historical data can justify a higher reliable performance.

For any BMP involving soil infiltration of the storm runoff it is important to consider the possible effects this could have on the groundwater. These could range from a relatively minor local raising of the water table resulting in reduced infiltration rates to more serious pollution of the groundwater, particularly if this is also used as a water source. Stormwater runoff is likely to have very low levels of pollution when compared to chemical and gasoline leaks/discharges and the soil will have some natural capacity to hold pollutants. However the long-term build up of pollutants in the soil and/or groundwater from storm runoff infiltration is not well known. Therefore infiltration of urban storm runoff, especially from industrial and commercial areas which are likely to have higher levels of pollution should be treated with caution.

Infiltration of storm runoff can offer significant advantages of controlling storm runoff at the source, reduced risk of down stream flooding, recharge of groundwater, and groundwater supply to streams (i.e., low-flow augmentation or maintaining stream flow during dry-weather periods). All of these and probably other advantages can be offered at a relatively low cost by infiltration and therefore the advantages will need to be judged against any pollution risks from urban runoff.

The majority of treatment processes which can be readily applied to urban storm runoff are only effective for removal of the settleable solids. Removal of dissolved or colloidal pollutants will be minimal and therefore pollution prevention or control at the source offers an effective way to control the dissolved pollutants. Fortunately though, many pollutants in the form of heavy metals and organic chemicals show significant association with the suspended solids (SS) (Pitt and Field 1990, Pitt *et. al.* 1991, 1993, 1994). Therefore removal of the solids will also remove the associated pollutants.

The previously mentioned goals for a stormwater management plan can be achieved in the watershed area via three basic avenues:

> *Regulations, Local Ordinances, and Public Education*. This should be the primary objective because it is likely to be the most cost effective. Mainly non-structural practices will be involved and application to new developments should be particularly effective.
>
> *Source Control of Pollutants*. This will be closely related to the above. Both non-structural and structural practices can be used to prevent pollutants coming into contact with the stormwater and hence storm runoff. Management and structural practices will include: flow diversion practices which keep uncontaminated stormwater from contacting contaminated surfaces or keep contaminated stormwater from contacting uncontaminated stormwater by a variety of structural means; exposure minimization practices which minimize the possibility of

stormwater contacting pollutants by structural (diking, curbs, etc.) and management (coverings, loading and unloading practices) practices; mitigative practices which include plans to recover released or spilled pollutants in the advent of a release; preventative practices which include a variety of monitoring techniques intended to prevent releases; controlling sediment and erosion by vegetative and structural means; and infiltration practices which provide for infiltration of stormwater into the groundwater (structural and vegetative means) thereby reducing the total runoff.

Source Treatment, Flow Attenuation, and Storm Runoff Infiltration. These are mainly structural practices to provide upstream pollutant removal at the source, controlled stormwater release to the downstream conveyance system, and ground infiltration or reuse of the stormwater. Upstream pollutant removal provides treatment of stormwater runoff at the specific highly polluting locations where it enters the stormwater conveyance system. Areas of this type include but are not limited to vehicular parking areas, vehicular service stations, bus depots, industrial loading areas, etc.

The following provides brief details of BMPs, but a reader should appreciate many of these BMPs can be combined and/or modified to best suit the conditions of the watershed under consideration. More information on BMPs can be found in the references listed in Table 2-2.

Regulations, Local Ordinances, and Public Education

The regulatory approach can address a wide variety of stormwater management aspects, some of which are listed below. For any regulations to work there will need to be an existing framework within which to place the regulations (e.g., local ordinances, zoning, planning regulations, etc.) together with dedicated resources to enforce them. Without the institutional systems to set them up and enforce them, they will not be effective.

Regulations can be an important pollution prevention BMP with particular application to new developments to ensure that the pollution is prevented or controlled at the source and any implementation and maintenance costs are included in the development costs. New York State has compiled a manual on BMPs for new developments (New York State 1992).

Some typical regulations include:

- Land use regulations
    - zoning ordinances
    - subdivision regulations
    - site plan review procedures
    - natural resource protection
- Comprehensive storm runoff control regulations
- Land acquisition

Further details on a regulatory approach are contained in *Handbook: Urban Runoff Pollution Prevention and Control Planning* (U.S. Environmental Protection Agency 1993a) and *Urban Stormwater Management and Technology: Update and Users' Guide* (U.S. Environmental Protection Agency 1977).

Public education can have a significant role to play because an aroused and concerned public has the power to alter behavior at all levels. However if the stormwater management plans are not adequately communicated and public opinion responded to, this power of the public can work against the implementation of a stormwater plan if viewed as an unnecessary extra cost and restriction on freedom.

Gaining the public support as with all education does not stop but is a continuous process and applies to all sectors of the public. These sectors are listed below and discussed in the following paragraphs:

- residential
- commercial
- industrial
- governmental

The residential sector is made up of everyone living in a drainage area and therefore education should focus on large groups. Long range education goals can be tackled through school programs and shorter range goals may be achieved through community groups. Advantage should be taken of working with groups looking for community improvement projects and opportunities arising from news media coverage and the associated publicity.

The commercial sector is a fairly large and often diffuse group to communicate with. Both the owners/managers and their staff will need to be included in any communication together with new businesses opening; existing businesses moving, expanding, and closing; and employee turnover. Methods of communication may include news announcements in the local press, mailed news items, individual contact by a public official and follow up repeated contacts to answer questions and cope with employee turnover. Public education can benefit from failures, such as violations of regulations which result in a citation or fine, and reported in the local press. This not only informs the public about regulations but also provides an incentive for the regulations to be followed because they are seen to be enforced.

The industrial sector is a smaller group and can be educated by direct contact with public officials, education of the consultants from whom industry seeks advice, and by education of trade associations. Indirect education opportunities are provided by speaking to meetings of professional organizations and by writing in professional newsletters and journals. Industrial decision makers are a relatively small group, which when informed or made aware of their obligations are likely to respond.

Public officials should also communicate with other public officials and governmental institutions to ensure that they are aware of a stormwater management program and its implications. Examples include: road, sanitation, and parks departments; and workers at public institutions such as hospitals and prisons.

A multi-level, multi-target public education program can help to avoid problems in implementing a stormwater management program. Further information on communicating a stormwater management program to the public can be found in *Designing an Effective Communication Program: A Blueprint for Success* (U.S. Environmental Protection Agency 1992a), and *Urban Runoff Management Information/Education Products* (U.S. Environmental Protection Agency 1993b). The latter reference is a catalog of material and publications which are available.

Source Control of Pollutants

Source controls are generally non-structural practices many of which can be termed as "good housekeeping" practices. They can be very effective in that they are pollution prevention options some of which are listed below:

- Cross-connection identification and removal
- Controlled construction activities
- Street sweeping
- Solid waste management
- Animal waste removal
- Toxic and hazardous waste management
- Reduced use of fertilizer, pesticide, and herbicide
- Reduced roadway sanding and salting
- Material and chemical substitution

Research of illicit or inappropriate cross-connections into separate stormwater drainage systems has shown that these can add a significant pollutant loading

(Montoya 1987, Pitt and McLean 1986, Schmidt *et al.* 1986, and Washtenaw Co. 1988). This is also recognized in the National Pollution Discharge Elimination System (NPDES) permits for stormwater discharges which require investigation of dry-weather flows (DWF) at stormwater outfalls. This will involve inspecting outfalls for DWFs, identification of illicit discharges from analysis of DWF samples, tracing the discharge source, and corrective action. DWF can originate from many sources. The most important sources may include sanitary wastewater (from sewerlines or septic tank systems), industrial and commercial pollutant entries, and vehicle maintenance activities. It should be recognized that not all DWF will be a pollutant source and they may be caused by infiltrating potable water supplies and clean groundwater. A full illicit connections investigation is likely to be time consuming and costly. A methodology for identifying illicit discharges in the DWF and tracing the source using distinct characteristics of potential sources is described in *Investigation of Inappropriate Pollutant Entries into Storm Drainage Systems: A User's Guide* (U.S. Environmental Protection Agency 1993c) and *Investigation of Dry-Weather Pollutant Entries into Storm Drainage Systems* (Field *et al.* 1994). The *User's Guide* concentrates on procedures which are relatively simple and which do not require sophisticated equipment or training. At a minimum the procedures should identify the most severely contaminated outfalls to assist in prioritizing areas to be investigated first and at best will identify the pollutant source. A stormwater management plan that ignores investigation of DWF is very likely to find that goals set to improve receiving water quality will not be achieved due to pollutants discharged in DWF.

Soil erosion from construction sites together with wash off from stock piled material and ready mix concrete trucks can be a major source of pollutants (suspended solids) for the relatively short construction duration. Requirements for phased removal of vegetative cover and early re-establishment of ground cover combined with detention of stormwater for sedimentation and filtering will help reduce the pollution from construction site stormwater runoff. It is important to also consider the period following construction when vegetative ground cover has still to be fully established and occupants of new buildings may undertake landscaping. Further information can be found in *Reducing the Impacts of Stormwater Runoff from New Development* (New York State 1992) and *Storm Water Pollution Prevention for Construction Activities* (U.S. Environmental Protection Agency 1992b).

Street sweeping studies (U.S. Environmental Protection Agency 1979d, 1985) concluded: that typical reduction in storm runoff pollutant loadings can be between 5 and 10 percent for street sweeping carried out every two days (beyond two days a week does not significantly reduce the solids loading any further, as illustrated in Figure 3-1); street cleaners did not significantly remove the smallest particulates ($<100\ \mu m$) that the rain washes off; street cleaners were able to remove large fractions of large particulates ($>200\ \mu m$); the reduction in storm runoff pollutant load is much less than the pollutant load removed by sweeping (since street surfaces only

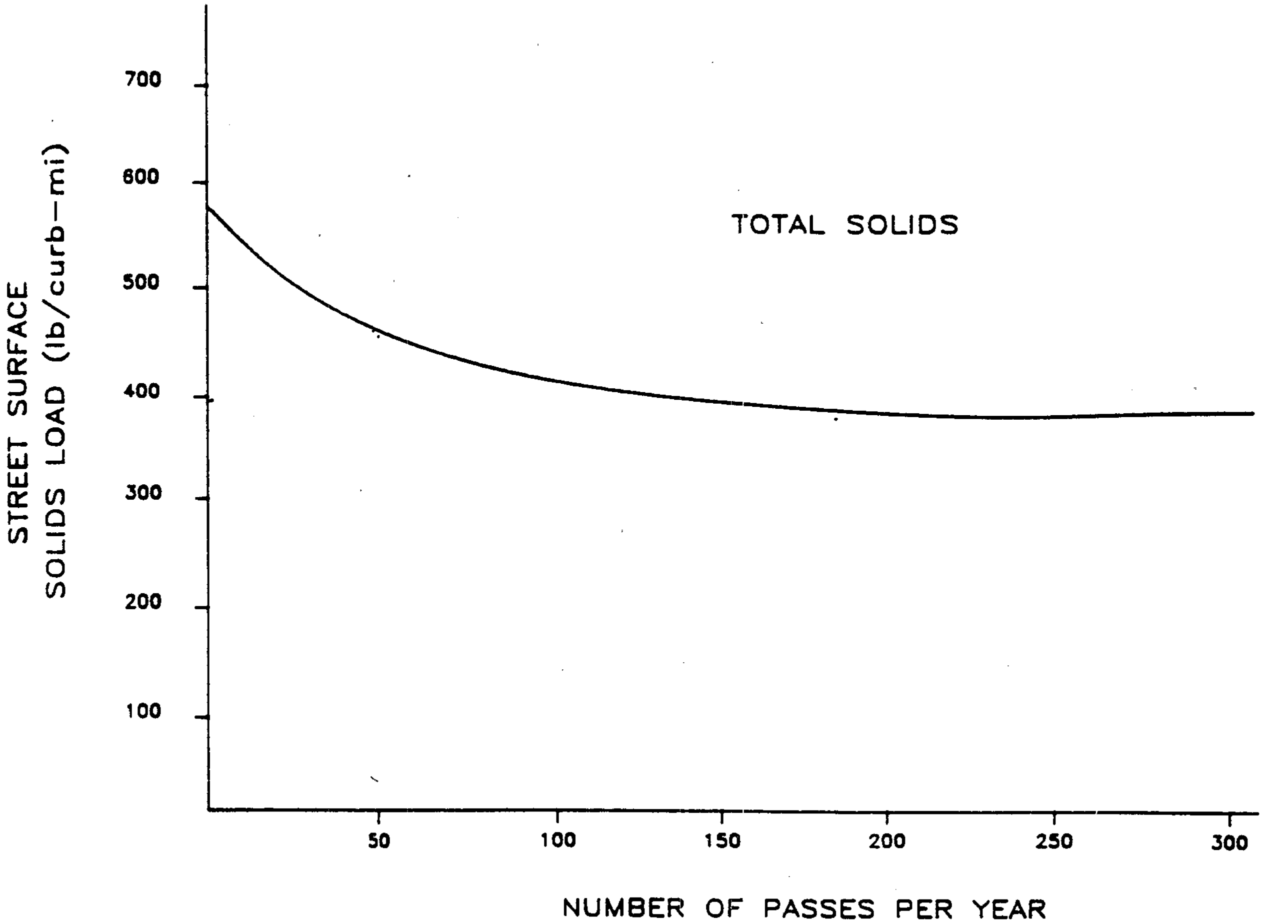

Figure 3-1. Street cleaner productivity Bellevue, Washington (Data from U.S. EPA 1985).

contribute ≤ 0.5 the total pollutant load) which can lead to a false sense of effectiveness; pavement type and condition have a pronounced affect on performance (as illustrated in Figure 3-2); and street sweeping results are highly variable and the results from one city cannot be applied to another city. The above comments together with the fact that street storm runoff is only a part of the outfall discharge would imply that street cleaning is not particularly effective on its own but should be part of an overall program. Street cleaning is likely to be more effective for removal of heavy metals from vehicle emissions which tend to associate with the particulates.

Sweeping of parking areas, storage, and loading/transfer areas should be included in a cleaning program. Concentrated cleaning during certain seasons is likely to be effective, e.g., during early spring in the snowbelt, when leaves accumulate in the fall,

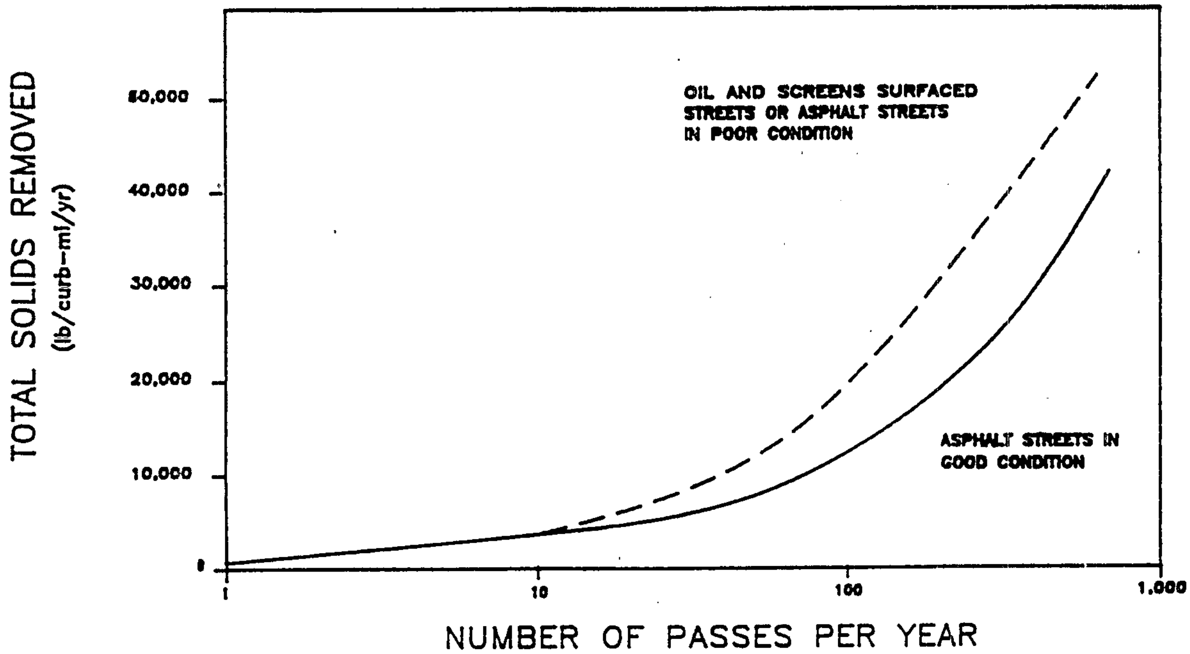

Figure 3-2. Street Sweeping: Annual amount removed as a function of the number of passes per year at San Jose, California test site. (U.S. EPA 1979d).

and prior to rainy seasons. Although the effectiveness of the above is not generally proven, street cleaning does offer aesthetic improvements in the removal of large items from the streets and receiving water. Fugitive emissions from street sweeping will lead to increased air pollution and may need to be considered if an intensive street sweeping program is part of a stormwater management plan.

Solid Waste Management involves the collection and proper disposal of solid waste to maintain clean streets, residences and businesses. It can also be extended for collection of items such as leaves during the fall. A study of stormwater runoff into Minneapolis lakes found that phosphorus levels were reduced by 30 - 40% when street gutters were kept free of leaves and lawn clippings (Minnesota Pollution Control Agency 1989).

Domesticated and wild animal wastes represent a source of bacteria and other pollutants such as nitrogen that can be washed into the receiving waters. A study in San Francisco, California (Colt 1977) estimated that the dogs, cats, and pigeons produced 54,500, 9,000, and 2,200 lb (247, 4, and 1 metric tonnes), respectively of nitrogen a year for an area of 30,480 acres (12,343 ha). On an annual basis, bulk precipitation, dog wastes, and fertilizer respectively, accounted for 49, 23, and 22% of the total nitrogen runoff. Controls through regulation and public education, if successful, could therefore have a major impact based on these figures.

Toxic and hazardous waste management should review methods to prevent the dumping of household and automotive toxic and hazardous wastes into municipal stormwater inlets, catchbasins, and other storm drainage system entry points. Public education, special collection days for toxic materials, and posting of labels on stormwater inlets to warn of the pollution problems of dumping wastes are possible management options.

Fertilizers, pesticides, and herbicides washed off the ground during storms can contribute to water pollution. Agriculture, recreation parks, and gardens can be sources of these pollutants. Controlling the use of these chemicals on municipal lands and educating gardeners and farmers to use the minimum amounts required and appropriate application methods can help reduce nutrient and toxic pollutants washed off by storm runoff.

Sand and salt are applied as deicing agents to roads in many areas of the United States that experience freezing conditions and are then washed off by the melt water and stormwater runoff. Effects of highway deicing appear most significant in causing contamination and damage of groundwater, public water supplies, roadside wells, farm supply ponds, and roadside soils, vegetation, and trees (U.S. Environmental Protection Agency 1971). Deicers also contribute to deterioration of highway structures and pavements, and to accelerated corrosion of vehicles. Studies (U.S. Environmental Protection Agency 1971) indicated that major problems in the control of deicing chemicals were the excessive application, misdirected spreading, poor storage practices, inaccurate weather forecasting and the logistics of setting up the deicing operation. To address these problems two manuals of practice on the application and storage of deicing chemicals (U.S. Environmental Protection Agency 1974a, 1974c) were produced to give recommendations and improvements. They provide comprehensive details on storage management, layout, handling, application for various storm and temperature conditions, and use and calibration of equipment to minimize the amount of chemicals used. Studies were conducted on alternative deicing methods (U.S. Environmental Protection Agency 1972a, 1976a, 1978) but these were more costly than the use of rock salt and therefore would be unlikely to have general economic application.

Section 4

Source Treatment, Flow Attenuation, and Storm Runoff Infiltration

Vegetative BMPs

These developing practices have been the subject of many publications in the last 20 years, a few of which are listed in Table 2-2. Readers are directed to these or similar publications for more detailed information.

Knowledge of the performance of these systems is limited but the above publications do contain lessons learned from their implementation and in some cases failure. Existing urbanized areas are unlikely to have the land space available for installation of many of these practices and in these situations their application will be restricted.

Swales

These are generally grassed stormwater conveyance channels which remove pollutants by filtration through the grass and infiltration through the soil. A slow velocity of flow, <1.5 ft/s (<46 cm/s), nearly flat longitudinal slope, $<5\%$, ft/s and vertical stand of dense vegetation higher than the water surface, ≥ 6 in. (15 cm) total height, are important for effective operation (Metropolitan Washington Council of Governments 1992b). Swales can be enhanced by the addition of check dams and wide depressions to increase storm runoff storage and promote greater settling of pollutants. A further enhancement would be in the development of a wetland channel (Urbonas and Stahre 1993), but good design would be necessary to minimize the disadvantages of difficult maintenance access, mosquito breeding and aesthetics to maximize the benefits of greater treatment potential.

Filter Strips

These are vegetated strips of land which act as "buffers" by accepting storm runoff as overland sheet flow from upstream developments and providing similar treatment potential mechanisms to that of swales, prior to discharge of the storm runoff to the storm drainage system. Low velocity flows, installation of a level spreader and/or land grading to ensure sheet flow over the filter strip, and dense vegetative cover will enhance the filter strip performance (Metropolitan Washington Council of Governments 1992b, Yu *et al.* 1993).

Stormwater Wetlands

These can be natural, modified natural, or constructed wetlands and remove pollutants through sedimentation, plant uptake, microbial decomposition, sorption, filtration, and exchange capacity. It is important to note that natural wetlands will be covered by regulations that will limit what can be discharged to the wetland and any modifications to enhance the wetland performance. Constructed stormwater wetlands can be designed for more effective pollutant removal with elements such as: a forebay for solids capture; meandering flow for extended detention of low flows; benching of bottom for different water depths and associated plants; and pondscaping with multiple species of wetland trees, shrubs and plants (Metropolitan Washington Council of Governments 1992b).

Constructed wetland systems are increasingly being used and developed for wastewater treatment and this area could be a source of information (e.g., Water Environment Federation 1990, U.S. Environmental Protection Agency 1988) in addition to information in stormwater BMP publications.

Detention Facilities

One of the most common structural controls for urban storm runoff and pollution loading is the construction of local ponds (including wetlands) to collect storm runoff, hold it long enough to improve its quality, and release it to receiving waters in a controlled manner. The basic removal mechanism for detention ponds is through settling of the solids with any associated pollutants, but controlled release will also attenuate the stormwater flows which can be a benefit to receiving water streams that suffer from erosion and disturbance of aquatic habitat during peak flow conditions.

It should be realized that a detention facility designed to provide pollution control for a particular size of storm is not likely to provide the same level of treatment for smaller or larger storms. Therefore as an example a detention facility designed to capture and release over a certain period a 10 year storm event may need to have the discharge control orifice designed for a 2 year storm in addition to the 10 year storm to provide discharge control and hence treatment over a spread of storm events (Urbonas and Stahre 1993). Detention ponds are in effect small dams and the safety aspects associated with failure and overtopping should also be considered in the design.

In a heavily urbanized landscape there is likely to be limited opportunities to use the types of detention facilities mentioned below, but use can be made of flat roof storage, temporary flooding of recreational areas such as parks and paved precinct areas, and automobile parking areas. Use of these facilities will obviously cause user inconvenience and possible hazard which will need to be assessed along with the frequency and duration of flooding. Also the users and people responsible for maintenance should be aware of the designed function of these detention facilities so that they do not take measures to prevent their flooding.

Extended Detention Dry Ponds

These temporarily detain a portion of stormwater runoff for up to 48 h (a 24 h limit is more common) using an outlet control. They provide: moderate but variable removal of particulate pollutants; negligible soluble pollutant removal; and quick accumulation of debris and sediment (Metropolitan Washington Council of Governments 1992b). The performance can be enhanced by use of a forebay to allow sedimentation and easier removal from one area. Many dry ponds which were originally intended for flood control can be modified or retrofitted to serve as wet ponds thereby providing the additional benefit of removing pollutants as well.

Wet Ponds

These have a permanent pool of water for treating incoming stormwater runoff. Wet ponds have capacity greater than the permanent pond volume which permits storage of the influence stormwater runoff and controlled release of the mixed influent and permanent pond water. They can provide moderate to high removal of particulate pollutants and reliable removal rates with pool sizes ranging form 0.5 - 1.0 in. (12.7 - 25.4 mm) of storm runoff per impervious acre (Metropolitan Washington Council of Governments 1992b). Wet ponds offer better removals and less maintenance than dry ponds but need to be well designed to ensure they are a benefit to an area and do not cause aesthetic, safety, or mosquito breeding problems. The performance and maintenance requirements can be helped by installing a forebay to trap sediments and allow easier removal, and through use of a fringe wetland on a shallow water bench around the pond perimeter.

There are several variations and combinations that can be used for the above detention systems to enhance the stormwater treatment and/or better suit local conditions. Further details on the design, performance, maintenance and any special requirements/problems, are available (Metropolitan Washington Council of Governments 1992b, 1987, Wanielista and Yousef 1992, and Urbonas and Stahre 1993).

Infiltration Practices

Infiltration practices have a high potential of controlling stormwater runoff by disposal at a local site level. However, the soil and water table conditions have to be suitable, a sufficiently conservative design has to be used, and adequate maintenance has to be undertaken to minimize the possibility of system failure. The importance of using only suitable sites together with adequate design and maintenance cannot be over stressed for this BMP. Another important aspect is the potential for groundwater pollution. Dissolved pollutants which show little association with solids would be the immediate concern but other pollutants could be more of a problem in the long term. Sandy soils generally have high infiltration rates and a potential to filter the stormwater well. However they are unlikely to provide good removals through sorption or ion exchange. Soil with a high organic content is likely to offer better capacity to absorb pollutants but at a slower infiltration rate.

Infiltration in its simplest form involves maximizing the pervious area of ground available to allow infiltration of stormwater and minimize the storm runoff. This can be enhanced by directing storm runoff from impervious paved and roof areas to pervious areas, assuming sufficient infiltration capacity exists. Regulations which encourage the incorporation of a high proportion of pervious areas, particularly for new developments, can be effective.

Infiltration Trenches

These are shallow, excavated trenches that have been backfilled with stone to create an underground reservoir. Stormwater runoff which is diverted into the trench gradually exfiltrates from the trench into the surrounding soil and in many cases eventually to the water table. There is no real performance data on infiltration trench removals but they are believed to have a good capacity to remove particulate pollutants and a moderate capability to remove soluble pollutants. Variations on this system include the use of perforated pipes to allow exfiltration and conveyance or storage of stormwater in excess of the filtration rate. Clogging of infiltration trenches is the most common cause of their failure. It is important to protect them from sediment loads during and after construction until the surrounding runoff area has eveloped ground cover to minimize erosion and sediment transport. The system can be enhanced and clogging reduced by providing pretreatment in the form of grass filter strips to filter particulates out of the storm runoff before reaching the infiltration trench (Metropolitan Washington Council of Governments 1992b).

Infiltration Basins

These are similar to dry ponds (unlined), except that infiltration basins have an emergency spillway only and no standard outlet structure. The incoming stormwater runoff is stored until it gradually exfiltrates through the soil of the basin floor. The comments made about infiltration trenches will also apply to infiltration basins. Additionally, unlined detention ponds will allow some degree of infiltration.

Porous Pavement

This is a permeable, specially designed, concrete or asphalt mix which provides an alternative to conventional pavement, allowing stormwater to percolate through the porous pavement into a deep gravel storage base area that also acts as a subsurface foundation (Figure 4-1). The stored storm runoff then gradually exfiltrates into the surrounding soil. In areas where soil has a slow infiltration rate sub-surface piping may be installed to direct the stormwater away. Field studies have shown that porous pavement systems can remove significant levels of both soluble and particulate pollutants (Metropolitan Washington Council of Governments 1992b, U.S. Environmental Protection Agency 1981b, 1980). The previous caution about infiltration BMPs affecting the groundwater also applies here. This system tends to be used in areas such as parking areas with gentle slopes and relatively light traffic. Sites which lack areas to form detention ponds or provide sufficient pervious areas can find this an attractive alternative. Sediment loads will clog the surface and should be avoided, this will be particularly important during construction. Also regular maintenance of cleaning the surface should be done. On some installations the gravel bed/storage layer has been extended beyond the plan limits of the pavement and returned up at the edge of the pavement. This can enable, with suitable design, any excess storm runoff to be collected by the perimeter gravel. Construction costs of a porous pavement parking lot will be approximately equal to that of a conventional pavement parking lot requiring stormwater inlets and subsurface piping (Field *et. al.* 1993).

Another type of porous pavement is constructed using modular interlocking blocks with open cells which are placed over a deep stone storage base similar to the above porous pavements. This is illustrated in Figure 4-1.

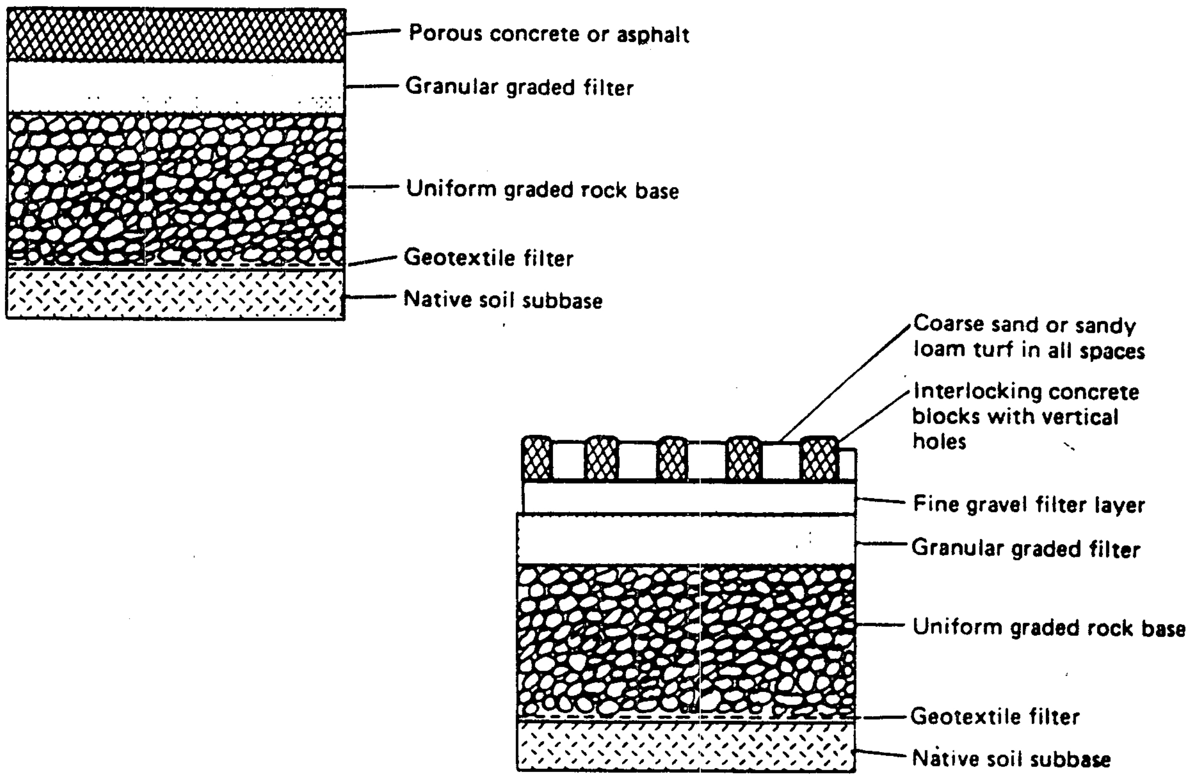

Figure 4-1. Cross-section porous pavement and cellular porous pavement (Urbonas and Stahre 1993).

Section 5

Installed Drainage System

The goal of upstream BMPs will be to provide sufficient stormwater control to ensure that further downstream treatment is not needed. However, particularly for urban areas it is highly unlikely that this goal will be totally achieved and further drainage system and end-of-pipe controls will need to be considered.

Control practices which can be applied to the drainage system are relatively limited, especially for existing systems, and involve the items listed below:

- Removal of illicit or inappropriate cross-connections
- Catchbasin cleaning
- Critical source area treatment devices
- Infiltration
- In-line storage
- Off-line storage

Many of the control options are similar to those used for CSO control and in the case of new developments there is the option to install either separate or combined sewer systems. A combined sewer system with treatment is likely to provide the most effective solution in an urban/commercial environment where BMPs are unlikely to provide sufficient reduction of urban storm runoff pollution. Whether a combined sewer would be the most effective choice would depend on many factors including the required degree treatment of separate stormwater discharges. In less urbanized areas with strongly enforced BMPs and public support there is a much greater possibility of the downstream stormwater in a separate system needing no further treatment.

For new combined or separate systems, advantage can be taken of increasing the pipe size and gradient to provide in-line storage and self cleaning, respectively. This will incur an additional cost which should be relatively small, but the feasibility will be subject to site conditions and available hydraulic head. Existing separate (and combined) drainage systems can be modified for in-line storage by the addition of flow control devices (weirs, flow regulators, etc.).

Established urban areas with separate stormwater drainage systems are most likely to have an existing stormwater pollution problem which needs to be rectified. The following covers some of the options available.

Illicit or Inappropriate Cross-Connections

This control was discussed in Section 3 under source control but also appears here because of its close relation to the drainage system. Identification and removal of illicit or inappropriate connections may provide a partial or complete solution but will be time consuming and costly with no guarantee of success. Depending on the likely magnitude of the cross-connection problem it is worth considering the alternative of accepting the pollution problem and providing treatment. If this decision is made early in the investigation there is the potential to maximize the use of resources on the treatment option.

Catchbasin Cleaning

A catchbasin has a sump below the outlet invert to capture settled solids, usually has a baffle or inserted pipe to capture floatables, and is distinct from an inlet which has no sump. Pollution control performance is variable with the trapped liquid generally having a high dissolved pollutant content, which is purged from catchbasins during a storm event contributing to intensification of the stormwater runoff pollutant loading. Countering this negative impact is the removal of pollutants associated with the settled solids and floatables (e.g., heavy metals and organics) retained in, and subsequently cleaned from the basin (U.S. Environmental Protection Agency 1977b). A regular cleaning schedule is important to maintain the catchbasin performance with a frequency such that sediment build up is limited to 40 - 50% of the sump capacity (U.S. Environmental Protection Agency 1977b) or at least twice a year depending upon conditions.

A study (U.S. Environmental Protection Agency 1983a) conducted in West Roxbury, Boston, Massachusetts took three catchbasins, cleaned them and monitored four runoff events at each catchbasin. The average pollutant removals per storm are shown in Table 5-1. The same study also looked at the effectiveness of screening the stormwater runoff through U.S. standard no. 8 brass mesh installed in the three catchbasins. The results indicated screens offered a slight gain in overall pollutant removal efficiency for catchbasins. The screens were effective for the removal of coarse material that could cause aesthetic problems in the receiving water but the potential for clogging and decomposition of trapped material reduced their value unless weekly cleaning was carried out. The present increased emphasis on stormwater management has resulted in a review of the role that screening at inlets and catchbasins can play. The City of Austin, Texas has developed its own form of inlet filter (Captur™) which is a relatively coarse screen for removal of larger stormwater debris, and others (Emcon North West) have developed screens utilizing filter material (5 - 100 μm) for removal of SS. The Storm and Combined Sewer Pollution Control Research Program of the U.S. EPA through the University of

Alabama at Birmingham is presently evaluating a number of inlet or catchbasin screening/filtering devices (U.S. Environmental Protection Agency 1992c).

Table 5-1. Pollutants Retained in Catchbasin

Constituent	% Retained
SS[a]	60-97
Volatile SS	48-97
COD[b]	10-56
BOD[c]	54-88

[a]Suspended solids
[b]Chemical oxygen demand
[c]5-day biochemical oxygen demand

(EPA-600/2-83/043)

Critical Source Area Treatment Devices

Research into the source of stormwater pollutants has shown that certain critical source areas can contribute a significant portion of the total urban storm runoff pollutant load (Pitt *et. al.* 1991, 1993, 1994). Treatment of the critical source areas can therefore offer the potential for a greater benefit to reduce downstream pollutant loads. Potential critical source areas include: vehicle service, garage, or parking areas; storage and transfer yards; and industrial materials handling areas exposed to precipitation.

Sand Filters

These use a bed of sand through which the storm runoff is filtered prior to discharge to the drainage system or ground infiltration. Sand filters can offer high removal rates for sediment and trace metals, and moderate removals for nutrients, BOD, and fecal coliform (Metropolitan Washington Council of Governments 1992a). The arrangement of the sand filter bed can vary from an open pit with perforated pipes under the sand bed as shown in Figure 5-1, to a more sophisticated trench stormwater inlet as shown in Figure 5-2 which includes a sediment chamber, weir and sand filter chamber. Washington DC has installed a few sand filters in chambers in the line of the drainage pipes for treatment of urban storm runoff. The storm runoff passes along the drainage pipe, enters the chamber, passes through the sand filter bed, and returns to the drainage pipe. An overflow bypass is incorporated in the chamber to handle flows in excess of the filter bed capacity.

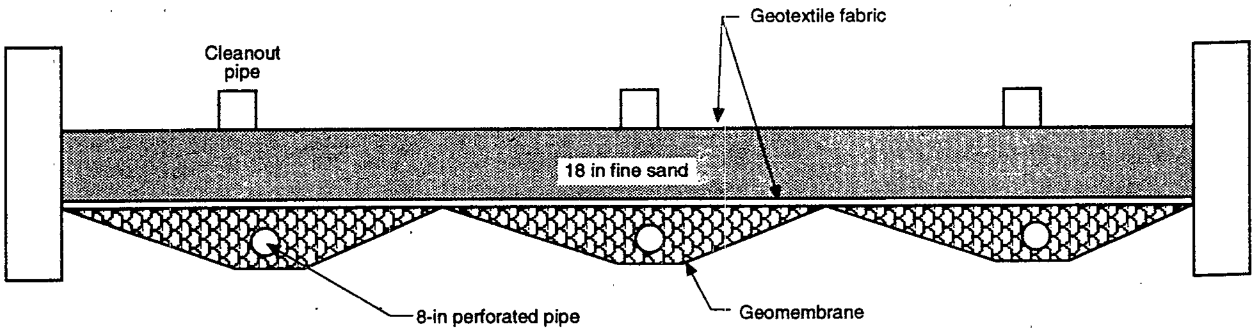

Figure 5-1. Conceptual design of a sand filter system MWCG 1992a.

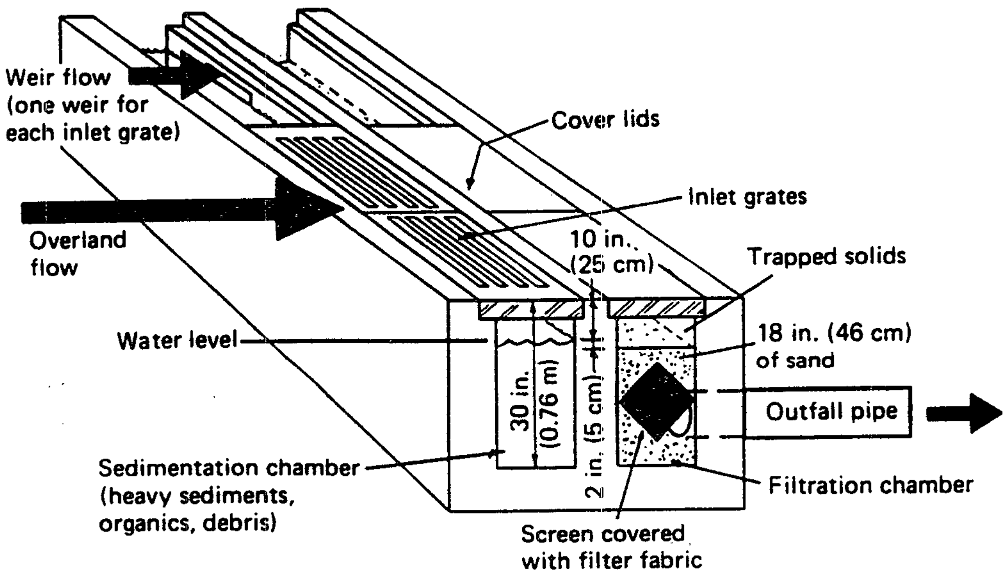

Figure 5-2. Sand filter stormwater inlet (Urbonas and Stahre 1993).

Maintenance of sand filter beds involves removal of debris from the surface, replacement of the top layer of sand, and raking of the surface. The frequency of this maintenance will be controlled by the rate of accumulation of filtered material.

Oil-Grit Separators

These are usually three stage underground chambers designed to retain storm runoff, remove heavy particulate by settling, and remove hydrocarbons by trapping floating material or adsorption onto settled solids. They have limited pollutant removal capability and only appear to trap coarse-grained solids and some hydrocarbons. Removal of silt and clay, nutrients, trace metals, and organic matter is expected to be slight. Without regular clean out maintenance (e.g., every 3 months), resuspension is likely to limit any long term removal.

Enhanced Treatment Device

Research is presently being conducted to develop a treatment device for runoff generated by small but critical toxicant source areas. This will consist of first, a relatively small chamber filled with plastic, hollow slotted media to promote cascading and aeration of the inflow and volatilization of volatile compounds, together with a sump to collect any heavier solids that settle out. The first chamber will then feed the runoff into a second, sedimentation chamber incorporating tube or plate settling for enhancing sedimentation with floating sorption pillows to remove floating oil and grease. This chamber may also be fitted with aeration facilities depending on the results of the demonstration. The final chamber will contain a sand filter bed which will may also be enhanced with either a homogeneously mixed layer of sand and peat, or a granular activated carbon layer to improve removals (U.S. Environmental Protection Agency 1992c). This treatment device is shown in Figure 5-3.

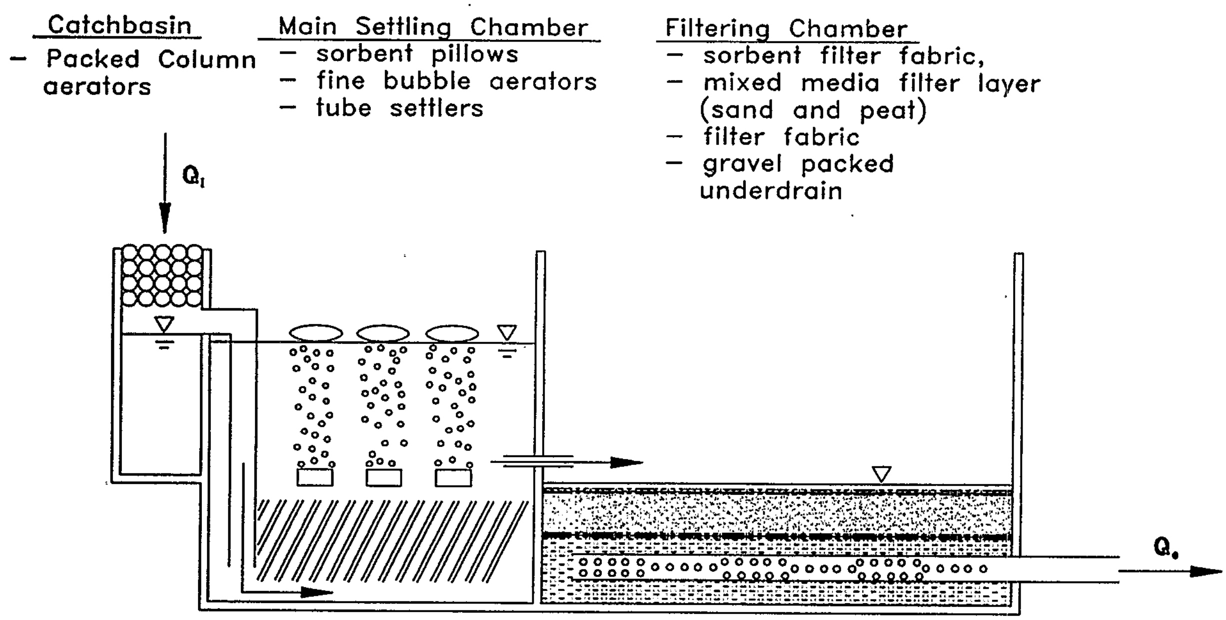

Figure 5-3. Multi-chambered enhanced treatment device.

The above research study will also install and monitor a filtering and pre-infiltration device (SAGES), shown in Figure 5-4. The intention of this device is to provide a high level of filtration treatment to the storm runoff prior to local infiltration into the ground.

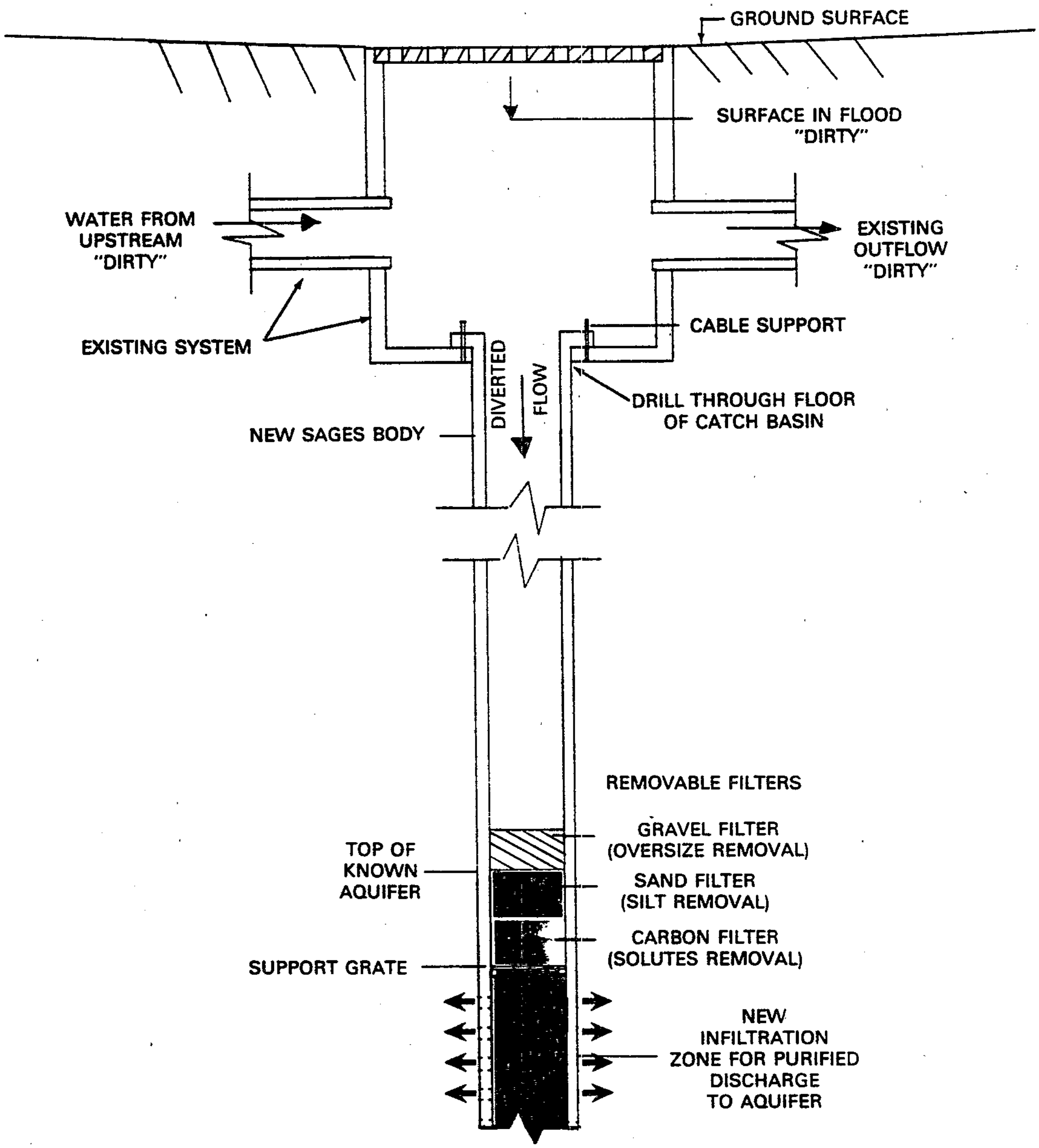

Figure 5-4. SAGES Unit (931026 Ontario Limited, J. Van Egmond).

Infiltration

New installations offer the possibility of using porous conveyance pipes to promote infiltration, but this can only be recommended where the soil and water table conditions are suitable and stormwater pollutants will not cause a problem.

In-line Storage

This is the use of the unused volume in the drainage system network of pipes and channels to store storm runoff. In-line storage capacity can also be provided by storage tanks, basins, tunnels, or surface ponds which are connected in-line to the conveyance network. To gain maximum benefit from in-line storage it should be combined with some form of treatment, otherwise only flow attenuation will be achieved. The in-line storage is unlikely to offer any treatment in itself through settling as the intent will be to make the system self cleaning to reduce maintenance requirements. However, if the storage is combined with an end of pipe treatment the flow attenuation will help equalize the load to the treatment process, hence optimizing the size of the treatment plant and costs.

The concept of combining storage and treatment to minimize the storage and treatment capacity required and hence optimize the cost to control polluted stormwater is an important relationship. Further cost effective solutions might be found if existing treatment facilities can be used, such as connection to an existing wastewater system. This is discussed in more detail later in the report as the storage does not necessarily need to be provided by in-line storage.

Even without treatment, flow attenuation will help equalize the pollutant loading to be assimilated by the receiving water and reduce the peak flows and consequent erosion in the receiving stream. This can have a major benefit to reduced disturbance of the aquatic ecosystem.

The degree to which the existing conveyance system can be used for storage will be a function of: the pipe or channel sizes which will provide the storage volume; the pipe or channel gradient (relatively flat lines are likely to provide the most storage capacity without susceptibility to flooding of low areas); suitable locations for installation of control devices such as weirs; and the reliability of the installed control. It will be essential that accurate details of the existing system be collected from field surveys and as-built drawings. This will allow the storage capacity, numbers and locations of controls, and risk of upstream flooding to be assessed. This will also be invaluable in new drainage system design where conveyance pipes and channels can be up-sized and hydraulic controls can be designed into the system for added system storage and routing.

Controls used to restrict flow causing a back up and storage in the system fall into two categories, either fixed or adjustable. Fixed systems are likely to be cheaper and require less maintenance but do not offer the flexibility and potential to maximize the storage potential. Adjustable systems can offer the advantage of being connected to a real-time control (RTC) system which, via a system of rainfall measurements and forecasts, monitoring of stormwater levels in critical sections of the drainage system, and input of this data into a computer system, can be adjusted to hold back or release stormwater to maximize storage capacity of the whole drainage system. RTC systems have been installed and are being further developed to control complex sewerage systems in the CSO field. The sophistication offered by an RTC system is unlikely to offer a cost effective solution for a separate storm drainage system unless there is a large in-line storage capacity and the stored runoff is to be treated.

Typical examples of fixed and adjustable flow regulators are:

Fixed Regulators	Adjustable Regulators
Orifices	Inflatable dams
Weirs (lateral and longitudinal)	Tilting plate regulators
Steinscrew	Reverse-tainter gates
Hydrobrake	Float-controlled gates
Wirbeldrossel	Motor-operated
Swirl	or Hydraulic gates
Stilling-pond weir	

Some of the above are relatively inexpensive, quick to install, and an effective means of increasing storage. Several publications (Urbonas and Stahre 1993, U.S. Environmental Protection Agency 1977a, 1970a, 1970b) on CSO control can provide more information on the above regulators. However, as stated earlier, without treatment the advantage of storage is only in flow attenuation. It should also be noted that some of the above regulators will concentrate the heavier solids in the stored storm runoff for a more concentrated later release.

Off-line Storage

This refers to storage that is not in-line to the drainage conveyance system. Storage is achieved by diverting flow from the drainage system when a certain flowrate is exceeded. The diverted water is stored until sufficient capacity is available downstream. The off-line storage can be provided by any arrangement of basins, tanks, tunnels, etc. and, if gravity filling and emptying is not possible, it will involve pumping the water into or out of storage.

Off-line storage as with in-line storage can be designed to be relatively self cleaning or have facilities to re-suspend the settleable solids. Examples can be found in books on stormwater (Metcalf & Eddy 1981, Field 1990, Urbonas and Stahre 1993). Off-line storage can also be used to provide treatment by sedimentation with the sludge either collected or diverted to a wastewater treatment plant.

Many of the regulators listed under in-line storage can be used to divert the flow once the predetermined flowrate has been exceeded. In addition to the above listed regulators, vortex and helical bend regulators/concentrators can be used. As their name suggests they will concentrate the heavier solids into the underflow which will continue to be conveyed along the drainage pipes. Therefore end-of-pipe treatment is required if this concentrated pollutant load is to be prevented from reaching the receiving water. The regulator/concentrator can offer advantages for end-of-pipe treatment when the flow needs to be regulated to prevent the treatment capacity being exceeded. End-of-pipe treatment can be satellite or central treatment. This is discussed further in the end-of-pipe treatment section.

Flow Balance Method (FBM)

The system provides a means of storing discharged urban storm runoff in the receiving water. This allows either pump back for treatment, when capacity is available, or treatment of the runoff by sedimentation until the next storm runoff event displaces the stored volume. The method was first developed in Sweden (Soderlund 1988) as a means of protecting lakes against pollution from stormwater runoff and has since been demonstrated for control of CSO in a marine receiving water in Jamaica Bay, New York City, NY (Field *et al.* 1990, Forndran *et al.* 1991).

Storage in the receiving water is achieved by forming a tank using flexible plastic curtains suspended from pontoons. The curtains are anchored to the receiving water bottom by concrete weights and the base of the tank is formed by the receiving water bed. The relatively low cost of the materials and construction gives this system cost advantages over conventional concrete and steel tank systems (estimated to be one-fifth to one-tenth the cost), requires only a minimal amount of land space for controls and access, and has flexibility to expand the volume if required at a later date.

The Swedish freshwater lake installations use a connected system of bays with openings between adjacent/sequential tanks to facilitate movement of the stormwater and lake water between tanks. Lake water can enter and leave these FBMs via the last tank in the series which has an opening to the lake. Plug flow set up by the discharging stormwater displaces the lake water from the first to the second bay and on down the line until the discharge finishes or each bay is filled with stormwater (i.e., stormwater has to pass through all of the bays to gain access to the lake). A reverse flow sequence occurs during pumpback of the stormwater to the wastewater treatment plant (WWTP). Figure 5-5a shows the FBM freshwater system.

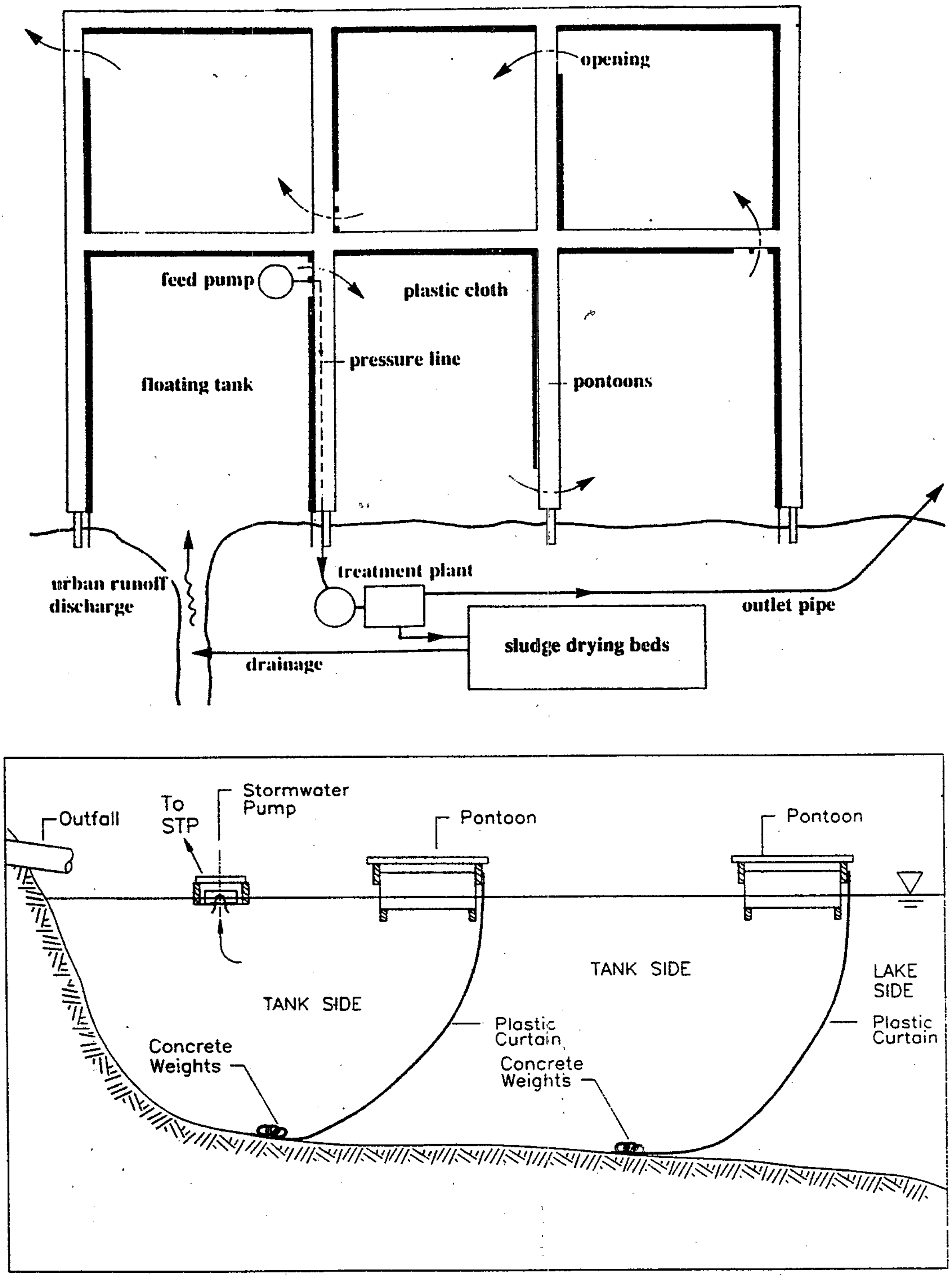

Figure 5-5a. Flow Balance Method (FBM) - freshwater configuration.

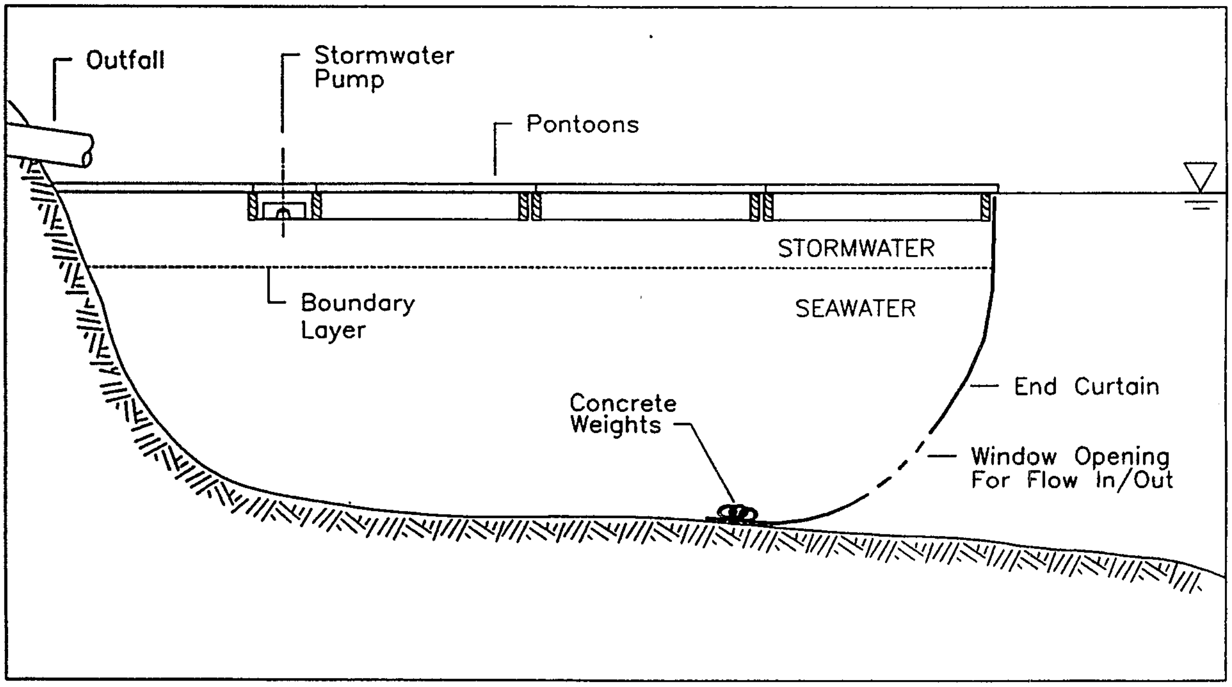

Figure 5-5b. Flow Balance Method (FBM) - seawater configuration.

Sweden has invested in three of these installations which have all been in operation for a number of years. The systems have withstood wave action up to 3 ft (0.9 m) as well as severe icing conditions. If a wall is punctured, patching is easily accomplished and general maintenance has been found to be inexpensive. The FBM has been successfully demonstrated in these lakes resulting in improved water quality in the lakes (Soderlund 1988, Pitt and Dunkers 1993). The marine FBM demonstration (see Figure 5-5b) utilizes a different operating principle of density difference for displacement instead of plug flow. One tank is used and the seawater is displaced vertically by the lower density CSO influent floating on the higher density seawater, and hence forming a stratified layer of CSO above the lower seawater layer. The demonstration project is in two phases. The first phase concentrated on proving the feasibility of the system concept to: displace seawater; form a stable CSO layer; pump the CSO back to the WWTP; and for the system structure to withstand a marine environment including tidal exchange, freezing, and coastal storms. The second phase (presently in progress) expands the system capacity from 0.41 Mgal (1550 m^3) to 2 Mgal (7570 m^3), and concentrates on monitoring the system performance (U.S. Environmental Protection Agency 1990).

During the two year demonstration project the system withstood the marine environment (the FBM was located in a relatively sheltered seawater creek) with no structural damage or material degradation observed. The system was exposed to tidal ranges up to 7 ft (2 m), winds gusting to 40 mph (64 km/h), and icing conditions. The system was shown to retain CSO in a stratified layer which remained relatively stable and could be pumped back to the WWTP. The FBM proved effective in trapping floatable material and a means of floatable material removal is part of the next phase. Pumpback of the settled solids from the FBM bed has been incorporated into both phases.

It is important to note that, although an FBM can offer a cost effective and quick to construct storage facility, it requires a suitable location and does have limits on its performance. There will be a certain amount of mixing with the receiving water. Not all of the stored volume will be pumped back, and any settleable solids will settle out of the stored storm runoff (regular pumpback of the accumulated sediment would help over come this problem). The low cost and quick construction potential of the FBM could favor the use of this system as a temporary measure in cases of a severe problem which needs attention. The FBM does use the existing natural receiving water and therefore will require all the necessary permits involved in these situations.

Maintenance

In order for the drainage system and the controls to work efficiently they should all be regularly maintained. This will generally consist of removing sediments from control devices, flushing drainage lines, and general inspections to identify any problems. Regular maintenance will also minimize any build up of material which could be flushed out by a surge from a large storm event, and thereby minimize the shock loading caused by intermittent storm events.

Section 6

End-of-Pipe Treatment

Biological Treatment

Biological treatment provides a means of removing organic pollutants from the storm runoff either aerobically or anaerobically. For this treatment to be effective the systems must be operated continuously to maintain an active biomass or be able to borrow the biomass from a system which does operate continuously. Biological processes are relatively sensitive and can be affected by the variable flow conditions and the relatively high concentration of nonbiodegradable solids in storm runoff. These factors tend to make high-rate physical treatment processes more suitable for stormwater applications with their ability to handle high and variable flow rates and solids concentrations.

Partial exceptions to the above are biological systems which include attached growth, e.g. the trickling filter (with honeycomb plastic medium) and the rotating biological contactor (RBC) which are less susceptible to overloading shock loads compared to other biological systems, e.g. activated sludge processes. RBCs have achieved high removals at flows 8 - 10 times their base flow for CSO treatment (U.S. Environmental Protection Agency 1974d). RBCs though like all biological processes need a food source to keep the microbes alive during extended dry periods and therefore have their limitations. The remainder of this section will therefore concentrate on the physical/chemical treatment processes which tend to be more suitable for treatment of stormwater.

Use of Existing Treatment Facilities

As stated earlier any use of existing facilities is likely to provide cost effective treatment, providing an economic means of connecting the stormwater drainage system to the facility is possible.

Use of spare capacity at wastewater treatment plants is one option, particularly if storage can be provided to equalize the storm runoff load. Even if the biological system has very little capacity the primary treatment systems can often function well at somewhat higher overflow rates which if combined with disinfection of the discharged storm runoff will offer significant treatment. Stormwater also tends to have a higher percentage of heavier solids than sanitary sewage which will benefit removals at higher overflow rates.

An alternative could be to construct additional primary treatment at a wastewater treatment plant (WWTP) to run in series with existing facilities during dry-weather flow (DWF) for improved treatment of DWF and run in parallel during wet-weather flow for some control over the total flow.

Use of any storage facilities, either at an end-of-pipe or an upstream location, could provide treatment by sedimentation or storage to be released when treatment capacity is available.

Physical/Chemical Treatment

These processes generally offer: good resistance to shock loads, ability to consistently produce a low suspended solids (SS) effluent, and adaptability to automatic operation. Those described below are, with the exception of high gradient magnetic separation and powdered activated carbon, only suitable for removal of SS and associated pollutants. The extent of removals will depend on the SS characteristics and the level of treatment applied. The physical/chemical systems to be discussed are:

- Screening
- Filtration
- Dissolved air flotation
- High gradient magnetic separation
- Powdered activated carbon-alum coagulation
- Disinfection
- Swirl concentrators/regulators

Screening

Screens can be divided into four categories with the size of the SS removed directly related to the screen aperture size:

Screen Type	Opening Size
Bar screen	>1 in. (>25.4 mm)
Coarse screen	3/16-1 in. (4.8-25.4 mm)
Fine screen	1/250-3/16 in. (0.1-4.8 mm)
Microscreen	<1/250 in. (<0.1 mm)

Bar and coarse screens have been used extensively in WWTP at the headworks to remove large objects. Depending on the level of treatment required for the storm runoff the smaller aperture sized coarse screens may be sufficient, however a higher level of treatment can be achieved using the bar and coarse screens in conjunction with the fine or microscreens. Design of screens can be similar to that for WWTP and CSO, but with consideration for stormwater characteristics of intermittent operation and possible very high initial loads which may not reflect WWTP operation characteristics. A self-cleaning system should be included for static screens to save manual cleaning during storm events together with automatic start up and shut down. Catenary screens fall into the coarse screen category. They are rugged and reliable and commonly used for CSO facilities. Therefore they are likely to be a good screen for use with storm runoff.

Table 6-1 lists screening devices that fall into the fine screen and microscreen category, and were developed and used for SS removal from CSO. With no information on screening of separate stormwater, the information on screening CSO is a good starting point and the information given below is from CSO studies. Design parameters for static screens, microstrainers, drum screens, disc screens, and rotary screens are presented in Tables 6-2, 6-3, and 6-4. The removal efficiency of screening devices is adjustable by changing the aperture (size of opening) of the screen placed on the unit, making these devices very versatile. In other words the efficiencies of a screen treating a waste with a typical distribution of particle sizes will increase as the screen aperture decreases.

Solids removal efficiencies are affected by two mechanisms; straining by the screen, and filtering of smaller particles by the mat deposited by the initial straining. Suspended matter removal will increase with increasing thickness of filter mat because of the filtering action of the mat itself, which is especially true for microstrainers. This will also increase the headloss across the screen. A study in Philadelphia (Field 1972) showed (on a 23 μm aperture microscreen (Microstrainer)) that with a large variation in the influent SS, the effluent SS stayed relatively constant (e.g., if a 1000 mg/L influent SS gave a 10 mg/L effluent SS, then a 20 mg/L influent SS would still give a 10 mg/L effluent SS). Accordingly, treatment efficiencies vary with influent concentration.

Microscreens and fine screens remove 25 - 90% of the SS, and 10 - 70% of the BOD_5, depending on the screen aperture used and the wastewater being treated. The above Philadelphia study showed that improved removals and increased flux densities (hydraulic loadings) are possible using polyelectrolyte addition. This is also likely to be the case with storm runoff but laboratory coagulation studies would be needed to find the best polyelectrolyte and dosage for the particular storm runoff characteristics. The optimum dosage will change with changes in the storm runoff characteristics requiring some form of automated monitoring (e.g., SS monitoring) for adjustment of dosage or setting of an average effective dosage.

More detailed descriptions of the various screening devices are available in the literature (U.S. Environmental Protection Agency 1977a, Metcalf & Eddy 1981, Field 1990, Water Environment Federation 1992).

Table 6-1. Description of Screening Devices Used in CSO Treatment

Type of Screen	General Description	Process Application	Comments
Drum Screen	Horizontally mounted cylinder with screen fabric aperture in the range of 100-843 μm. Operates at 2-7 r/min.	Pretreatment	Solids are trapped on inside of drum and are backwashed to a collection trough.
Microstrainers*	Horizontally mounted cylinder with screen fabric aperture 23-100 μm. Operates at 2-7 r/min.	Main Treatment	Solids are trapped on inside of drum and are backwashed to a collection trough.
Rotostrainer	Horizontally mounted cylinder made of parallel bars perpendicular to axis of drum. Slot spacing in the range of 250-2500 μm. Operates at 1-10 r/min.	Pretreatment	Solids are retained on surface of drum and are removed by a scraper blade.
Disc Strainer	Series of horizontally mounted woven wire discs mounted on a center shaft. Screen aperture in the range of 45-500 μm. Operates at 5-15 r/min.	Pretreatment, main treatment, or posttreatment of concentrated effluents.	Unit achieves a 12-15% solids cake.
Rotary Screen	Vertically aligned drum with screen fabric aperture in the range of 74-167 μm. Operates at 30-65 r/min.	Main treatment	Splits flow into two distinct streams: unit effluent and concentrate flow, in the proportion of approximately 85:15.
Static Screen	Stationary inclined screening surface with slot spacing in the range of 250-1600 μm.	Pretreatment	No moving parts. Used for removal of large suspended and settleable solids.

*A vertically mounted microstrainer is available, which operates totally submerged at approximately 65 r/min. Aperture range is 10-70 μm (microns). Solids are removed from the screen by a sonic cleaning device.

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Table 6-2. Design Parameters for Static Screens

Hydraulic loading, gal/min/ft of width	100-180
Incline of screens, degrees from vertical	35*
Slot space, μm	250-1600
Automatic controls	None

*Bauer Hydrasieves™ have 3-stage slopes on each screen: 25°, 35°, 45°.
gal/min/ft X 0.207 = l/m/s

(EPA-600/8-77/014)

Table 6-3. Design Parameters for Microstrainers, Drum Screens, and Disc Screens

Parameter	Microstrainers	Drum Screen	Disc Screen
Screen aperture, μm	23-100	100-420	45-500
Screen material	stainless steel or plastic	stainless steel or plastic	wire cloth
Drum speed, r/min			
Speed range	2-7	2-7	5-15
Recommended speed	5	5	-
Submergence of drum, %	60-80	60-70	50
Flux density, gal/ft^2/min of submergence screen	10-45	20-50	20-25
Headloss, in.	10-24	6-24	18-24
Backwash			
Volume, % of inflow	0.5-3	0.5-3	-*
Pressure, lb/in.^{2}	30-50	30-50	-

*Unit's waste product is a solids cake of 12-15% solids content

gal/min/ft^2 X 2.445 = m^3/h/m^2
in. X 2.54 = cm
ft X 0.305 = cm
lb/in.^{2} X 0.0703 = kg/cm^2

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Table 6-4. Design Parameters for Rotary Screens

Screen aperture, μm	
Range	74-167
Recommended aperture	105
Screen material	stainless steel or plastic
Peripheral speed of screen, ft/s	14-16
Drum speed, r/min	
Range	30-65
Recommended speed	55
Flux density, gal/ft²/min	70-150
Hydraulic efficiency, % of inflow	75-90
Backwash	
Volume, % of inflow	0.02-2.5
Pressure, lb/in.²	50

ft/s X 0.305 = m/s
gal/ft²/min X 2.445 = m³/m²/h
lb/in² X 0.0703 = kg/cm²

(EPA-600/8-77/014)

Filtration

Dual-Media High-Rate Filtration (DMHRF) (>8 gal/ft²/min (20 m³/m²/h)) removes small particulates that remain after screening and floc remaining after polyelectrolyte and/or coagulant addition. As implied this provides a high level of treatment that can be applied after screening together with automated operation and limited space requirements. To be most effective, filtration through media that are graded from coarse to fine in the direction of flow is desirable. A single filter material with constant specific gravity cannot conform to this principle since backwashing of the bed automatically grades the bed from coarse to fine in the direction of washing; however, the concept can be approached by using a two layer bed. A typical case is the use of coarse anthracite particles on top of less coarse sand. Since anthracite is less dense than sand, it can be coarse and still remain on top of the bed after the backwash operation. Typically a unit is comprised of 5 ft of No. 3 anthracite (effective size 0.16 in. (4.0 mm)) placed over 3 ft of No. 612 sand (effective size 0.08 in. (2.0 mm)). This arrangement was shown superior to both coarser and finer media tested separately (U.S.

Environmental Protection Agency 1972b). Another alternative would be an upflow filter, but these units have limitations in that they cannot accept high hydraulic loadings (filtration rates).

The principal parameters to be evaluated in selecting a DMHRF system are the media size, media depth, and filtration rate. Since much of the removal of solids from the water takes place within the filter media, their structure and composition is of major importance. Too fine a medium may produce a high-quality effluent, but also may cause excessive headlosses and extremely short filter runs. On the other hand, media that are too coarse may fail to produce the desired clarity of the effluent. Therefore, the selection of media for DMHRF should be made by pilot testing using various materials in different proportions and at different flow rates. Depth of media is limited by headloss and backwash considerations. The deeper the bed, the greater the headloss and the harder to clean. However, there should be sufficient bed depth to retain the removed solids without break-through during the filter run period at the design hydraulic loading.

Information is available on the use and design of DMHRF for treatment of drinking water, but a number of pilot studies have also been done using CSO which should provide more relevant information. The studies (U.S. Environmental Protection Agency 1972b, 1979a, 1979b) used 6, 12, and 30 in. (15, 30, and 76 cm) diameter filter columns, with anthracite and sand media with and without various dosages of coagulants and/or polyelectrolytes. A preliminary (420 μm) screening process was used upstream of the DMHRF to extend the treatment run time before backwashing. It was found that SS removal increased as influent SS concentration increased, and decreased as hydraulic loading increased.

Removal efficiency for the filter unit was about 65% for SS, 40% for BOD_5 and 60% for chemical oxygen demand (COD). The addition of polyelectrolyte increased the SS removal to 94%, the BOD_5 removal to 65%, and the COD removal to 65%. The length of filtration run averaged 6 h at a hydraulic loading of 24 gal/ft^2/min (59 m^3/m^2/h).

Tables 6-5, 6-6, and 6-7 show removals of SS, BOD_5, and heavy metals for a study in New York, New York (U.S. Environmental Protection Agency 1979a). Design parameters for DMHRF are presented in Table 6-8 (U.S. Environmental Protection Agency 1977a).

Table 6-5. CSO-DMHRF Average SS Removals (New York, NY)

	Plant Influent (mg/l)	Filter Influent (mg/l)	Filter Effluent (mg/l)	Filter Removals (%)	System Removals (%)
No Chemicals	175	150	67	55	62
Poly Only	209	183	68	63	67
Poly & Alum	152	142	47	67	69

(EPA-600/2-79/015)

Table 6-6. CSO-DMHRF Average BOD_6 Removals (New York, NY)

	Plant Influent (mg/l)	Filter Influent (mg/l)	Filter Effluent (mg/l)	Filter Removals (%)	System Removals (%)
No Chemicals	164	131	96	27	41
Poly Only	143	129	84	35	41
Poly & Alum	92	85	53	38	43

(EPA-600/2-79/015)

Dissolved Air Flotation (DAF)

This is a unit operation used to separate solid particles or liquid droplets from a liquid phase. Separation is brought about by introducing fine air bubbles into the liquid phase. As the bubbles attach to the solid particles, the buoyant force of the combined particle and air bubbles is great enough to cause the particle to rise. Once the particles have floated to the surface, they are removed by skimming. The most common process for forming the air bubbles is to dissolve air into the waste stream under pressure and then release the pressure to allow the air to come out of solution. The pressurized flow carrying the dissolved air to the flotation tank is either (1) the entire stormwater flow, (2) a portion of the stormwater flow (split flow pressur-ization), or (3) recycled DAF effluent.

Higher overflow rates (1.3 - 10.0 gal/ft^2/min (3.2 - 25 m^3/m^2/h)) and shorter detention times (0.2 -1.0 h) can be used for DAF when compared to conventional settling (0.2 -0.7 gal/ft^2/min (0.5 - 1.7 m^3/m^2/h); 1.0 - 3.0 h). Studies for CSO have shown that a treatment system consisting of screening (using a 297μm

Table 6-7. Removal of Heavy Metals by DMHRF (New York, NY)

	Cadmium	Chromium	Copper	Mercury	Nickel	Lead	Zinc
Average removal, %*	56	50	39	0	13	65	48

*concentration basis

(EPA-600/2-79/015)

Table 6-8. Design Parameters for DMHRF

Filter Media Depth (ft)		Headloss (ft)	5-30
No. 3 anthracite	4-5		
No. 612 sand	2-3	Backwash	
		Volume (% of flow)	4-10
Effective Size (mm)		Air	
Anthracite	4	Rate (standard ($ft^3/min/ft^2$)	10
Sand	2	Time (min)	10
		Water	
		Rate $gal/ft^2/min$)	60
		Time (min)	15-20
Flux density ($gal/ft^2/min$)			
Range	8-40		
Design	24		

ft X 0.305 = m
$gal/ft^2/min$ X 2.445 = $m^3/m^2/h$
standard $ft^3/min/ft^2$ X 0.305 = $m^3/m^2/min$

(EPA-600/8-77/014)

aperture with a hydraulic loading rate of 50 $gal/ft^2/min$ (122.3 $m^3/m^2/h$)) followed by DAF can offer an effective level of treatment (U.S. Environmental Protection Agency 1977c, 1979c).

The basis of the system being that the screening removes the particles that are too heavy for the air bubbles to carry, and the DAF system removes the floating, neutral buoyancy and remaining negative buoyancy particles. The addition of chemical flocculent in the form of ferric chloride and cationic polyelectrolyte was shown in the above two references to improve the removals. Table 6-9 shows the screening-DAF system design parameters (U.S. Environmental Protection Agency 1977a).

Table 6-9. Screening and DAF Design Parameters

Overflow Rate (gal/ft²/min)	
Low rate	1.3-4.0
High rate	4.0-10.0
Horizontal Velocity (ft/min)	1.3-3.8
Detention Time (min)	
Flotation cell range	10-60
Floatation cell average	25
Saturation tank	1-3
Mixing chamber	1
Pressurized Flow (% of total flow)	
Split-flow pressurization	20-30
Effluent recycle pressurization	25-45
Air to Pressurized Flow Ratio (standard ft³/min/100 gal)	1.0
Air to Solids Ratio	0.05-0.35
Pressure in Saturation Tank (lb/in.²)	40-70
Float	
Volume (% of total volume)	0.75-1.4
Solids concentration (% dry weight basis)	1-2

$gal/ft^2/min \times 2.445 = m^3/m^2/h$
$ft/min \times 0.00508 = m/s$
$standard\ ft^3/min/100\ gal \times 0.00747 = m^3/min/100\ l$
$lb/in.^2 \times 0.0703 = kg/m^2$

(EPA-600/8-77/014)

As with the other treatment processes discussed there is not any data available for treatment of separate storm runoff, however from the CSO data it would appear that except for sedimentation, screening-DAF is likely to be the most expensive treatment system.

High-Gradient Magnetic Separation (HGMS)

This is a relatively new treatment technology for treatment of storm runoff or CSO but has been used successfully for a number of years in the treatment of water for or from industrial processes. A high degree of treatment is possible with this process, which will probably be greater than required to meet permitting requirements alone.

In its simplest form, the high gradient magnetic separator consists of a canister packed with a fibrous ferromagnetic material that is magnetized by a strong external magnetic field (coils surround the canister). The water to be treated is passed through the canister and the fibrous ferromagnetic matrix causes only a small hydraulic resistance because it occupies less than 5% of the canister volume.

Upstream of the canister the water is prepared by binding finely divided magnetic seed particles, such as magnetic iron oxide (magnetite), to the nonmagnetic contaminants. Binding the magnetic seed is accomplished in two general ways: adsorption of the contaminant to the magnetic seed; and chemical coagulation (alum).

The magnetic particles are trapped on the edges of the magnetized fibers in the canister as the water passes through. When the matrix has become loaded with magnetic particles, they are easily washed off by turning off the magnetic field and backflushing. Particles ranging in size from soluble through settleable ($>0.001\mu m$) may be removed with this process and design parameters for HGMS are presented in Table 6-10.

Table 6-10. Preliminary Design Parameters for High Gradient Magnetic Separators

Magnetic Field Strength, kG*	0.5-1.5
Maximum Flux Density, gal/ft^2/min	100
Maximum Detention Time, min	3
Matrix Loading, g solids/g of matrix fiber	0.1-0.5
Magnetite Addition, mg/l	100-500
Magnetite to SS Ratio	0.4-3.0
Alum Addition, mg/l	
Range	90-120
Average	100
Polyelectrolyte Addition, mg/l	0.5-1.0

*Kilogauss.
gal/ft^2/min X 2.445 = m^3/m^2/h

(EPA-600/8-77/014)

HGMS can offer rapid filtration for many pollutants with greater efficiency than for sedimentation because the magnetic forces on the fine particles may be many times greater than gravitational forces. *Urban Stormwater Management and Technology: Update and User's Guide* (U.S. Environmental Protection Agency 1977a) provides details of bench and pilot scale studies which have been conducted using HGMS to treat CSO (U.S. Environmental Protection Agency 1977a).

For HGMS and all other treatments that involve an additive to enhance the solids removal, there is a need to accommodate the variation in storm runoff SS concentrations. This will require automatic monitoring and adjustment of the additive dosage for efficient operation.

Powdered Activated Carbon-Alum Coagulation

A treatment option which has the potential to remove dissolved organics is the use of powdered activated carbon with alum added to aid in subsequent clarification. This was demonstrated at a 100,000 gal/d (379 m^3/d) pilot unit in Albany, New York (Field 1990, U.S. Environmental Protection Agency 1973c) using municipal sewage and CSO. A short flocculation period followed the addition of alum with settling of solids by gravity and disinfection of the effluent or filtering (tri-media) and disinfection prior to discharge.

Carbon regeneration in a fluidized bed furnace and alum recovery from the calcined sludge were also demonstrated, as was reuse of the reclaimed chemicals. Average carbon losses per regeneration cycle were 9.7%. Average removals were in excess of 94% for COD, 94% for BOD_5, and 99% for SS with no filtration.

Disinfection

Disinfection is generally practiced at WWTPs to control pathogenic microorganisms. The development of disinfection techniques and measurement of their effectiveness to kill pathogens has been mainly derived from the sanitary wastewater field, where the concern has been to measure the presence of fecal contamination and ability to kill any pathogens and viruses of human origin. Because it is both difficult and expensive to isolate and measure specific pathogens in water, methods were developed to monitor certain indicator organisms, i.e., microorganisms indicative of the presence of fecal contamination. Bacteria of the total coliform (TC) group became the generally accepted indicator for fecal pollution, but includes different genera which do not all originate from fecal wastes (e.g., *Citrobacter, Klebsiella,* and *Enterobacter).*

An improvement over the TC test is the more selective fecal coliform (FC) test, which selects primarily for *Klebsiella* and *Escherichia coli (E. coli)* bacteria. *E. coli* is the bacteria of interest because it is a consistent inhabitant of the intestinal tract of humans and other warm-blooded animals. The FC test though, is still not specific to enteric bacteria, and human-enteric bacteria in particular. In 1986 a US EPA publication (U.S. Environmental Protection Agency 1986) recommended that states "begin the transition process to the new (*E. coli* and enterococci) indicators." However, many states still retain the TC and FC criteria and the most widely used bacteriological criterion in the United States is the maximum of 200 FC/100 Ml.

For discharges of separate storm runoff the above criterion is unlikely to give a true indication of the potential risk of infection, as many of these indicator bacteria also originate from soils, vegetation, and animal feces. Stormwater runoff can contain high densities of the nonhuman indicator bacteria and epidemiological studies of recreational waters receiving stormwater runoff have found little correlation between indicator densities and swimming related illnesses (U.S. Environmental Protection Agency 1983b, 1984a, Calderon *et al.* 1991). In addition a number of non-enteric pathogens found in stormwater runoff have been linked to respiratory illnesses and skin infections, a risk which is not assessed by the present fecal indicators.

Although the present standards and indicators are unlikely to reflect the actual human disease contraction potential, i.e., pathogenicity of a storm flow and its receiving water, they are the only practical standards available. Also urban storm runoff has a high potential to be contaminated by sanitary cross connections which would make the standards more relevant. Therefore, until other more relevant indicators are developed and proven the present standards should be used but with the caution that they may over or under estimate the true risk. The paper entitled *The Detection and Disinfection of Pathogens in Storm-Generated Flows* (O'Shea and Field 1992) covers this subject in more detail.

Conventional municipal sewage disinfection generally involves the use of chlorine gas or sodium hypochlorite as the disinfectant. To be effective for disinfection purposes, a contact time of not less than 15 min at peak flowrate and a chlorine residual of 0.2 -2.0 mg/L are commonly recommended. However, a different approach is required for storm runoff, because the flows have characteristics of intermittency, high flowrate, high SS content, wide temperature variation, and variable bacterial quality. Further aspects of disinfection practices which require consideration for storm runoff are:

1- A residual disinfecting capability may not be permitted, because chlorine residuals and compounds discharged to natural waters may be harmful to human and aquatic life (i.e., formation of carcinogens, e.g., tri-halomethanes).

2- The coliform count is increased by surface runoff in quantities unrelated to pathogenic organism concentration. Total coliform or fecal coliform levels may not be the most useful indication of disinfection requirements and efficiencies.

3- Discharge points requiring disinfection are often at outlying points on the drainage system and require unmanned, automated installations.

The disinfectant used to treat storm runoff should be adaptable to intermittent use, be effective, and be safe and easy to dose the effluent with. Table 6-11 shows disinfectants that might be used for storm flow disinfection. Chlorine and hypochlorite will react with ammonia to form chloramines and with phenols to form chorophenols. These are toxic to aquatic life and the latter also produce taste and odor in the water. Chlorine dioxide (ClO_2) does not react with ammonia and completely oxidizes phenols. Ozone has a more rapid disinfecting rate than chlorine, is effective in oxidizing phenols, and has the further advantage of supplying additional oxygen to the effluent. The increased disinfecting rate of ozone requires shorter contact times and results in a lower capital cost for a contactor, as compared to that for a chlorine contact tank. Ozone does not produce chlorinated hydrocarbons or a long lasting residual as chlorine does, but it is unstable and must be generated on-site just prior to application. Therefore, capital investment in a generating plant is required along with the operation and maintenance.

Another disinfection technique that promises short detention times and the absence of toxic reaction products is the use of ultraviolet (UV) light irradiation. The effectiveness of the early systems was limited for water with high concentrations of solids which tended to attenuate the UV energy. Later systems emit higher intensity radiation for more effective treatment. More recently modulated UV light has been reported to reduce viable bacteria by approximately 100 fold compared to populations observed after similar exposure to UV light that lacked modulation (Bank *et al.* 1990).

The characteristics of storm runoff (i.e., intermittent and often high flows) together with the need to minimize capital costs for a treatment operation, lend themselves favorably to use of high rate disinfection. This refers to achieving either a given percent or a given bacterial count reduction through the use of: decreased disinfectant contact time; increased mixing intensity; increased disinfectant concentration; chemicals having higher oxidizing rates; or various combinations of these. Where contact times are less than 10 min, (usually in the range 1 - 5 min), adequate mixing is a critical parameter, providing complete dispersion of the disinfectant and forcing disinfectant contact with the maximum number of microorganisms. The more physical collisions high-intensity mixing causes, the lower the contact time requirements. Mixing can be accomplished by mechanical flash mixers at the point of disinfectant addition and at intermittent points, or by specially designed plug flow contact chambers containing closely spaced, corrugated parallel baffles that create a meandering path for the wastewater (U.S. Environmental Protection Agency 1973b).

Table 6-11. Characteristics of Principal Storm Flow Disinfection Agents

Characteristics	Chlorine	Hypochlorite	Chlorine Dioxide	Ozone
Stability	Stable	6-month half-life	Unstable	Unstable
Reacts with ammonia to form chloramines	Yes	Yes	No	No
Destroys phenols	At high concentrations	At high concentrations	Yes	Yes
Produces a residual	Yes	Yes	Short-lived*	No
Affected by pH	More effective at pH < 7.5	More effective at pH < 7.5	Slightly	No
Hazards	Toxic	Slight	Toxic; Explosive	Toxic

*Chlorine dioxide dissociates rapidly.

(EPA-600/8-77/014)

High-rate disinfection was shown (for CSO) to be enhanced beyond the expected additive effect by sequential addition of Cl_2 followed by ClO_2 at intervals of 15 - 30 s (U.S. Environmental Protection Agency 1975a, 1976b). A minimum effective combination of 8 mg/L of Cl_2 followed by 2 mg/L of ClO_2 was effective in reducing TC, FC, fecal streptococci, and viruses to acceptable target levels and compared to 25 mg/L Cl_2 or 12 mg/L ClO_2. It was surmised that the presence of free Cl_2 in solution with chlorite ions (ClO^-_2, (the reduced state of ClO_2)) may cause the oxidation of ClO^-_2 back to its original state. This process would prolong the existence of ClO_2, the more potent disinfectant.

An equation and concept to enable the effect of high rate mixing to be taken into account in the disinfection process is provided (U.S. Environmental Protection Agency 1973b). A velocity gradient (G), as defined in the equation below is used as a measure of the mixing intensity, but is also a measure of the opportunities for microorganism and disinfectant matter collisions per unit time per unit volume.

$$G=(1730/\sqrt{viscosity(centipoise)})\ (\sqrt{(velocity[ft/s])([channel\ slope[ft/ft])})$$

The product of velocity gradient and contact time (GT) is the number of opportunities for collisions per unit volume during the contact time.

It is important to note that if high-rate mixing is to be relied upon to provide effective disinfection the velocity gradient should not reduce if the flowrate reduces i.e., if the mixing intensity depends on the velocity of flow and not mechanical mixing then the level of disinfection will be reduced at low flowrates. There will be some offset of this due to longer detention times at lower flowrates but the intensity of mixing will be the more significant parameter. Use of a Sutro weir for the influent and effluent will help maintain the peak rate velocity at all flowrates.

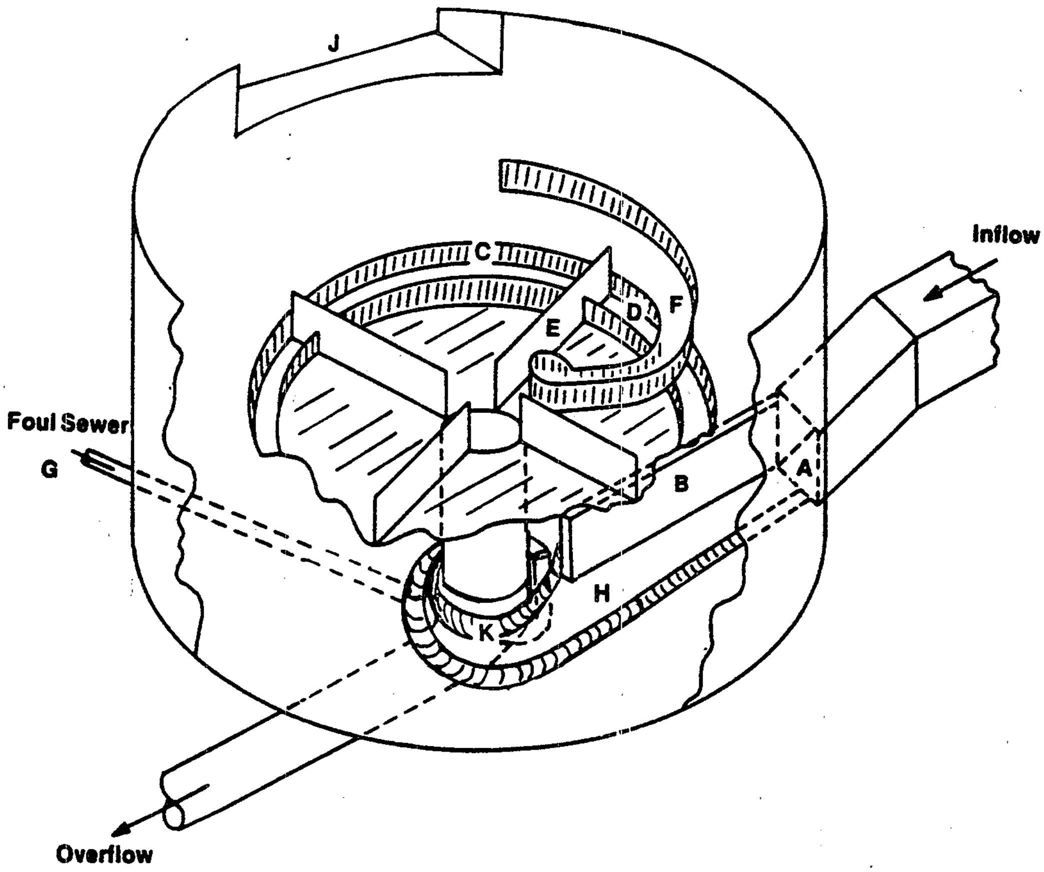
Swirl Regulators/Concentrators

These are compact flow throttling, and solids separation devices which also collect floatable material. The performance of the swirl device is very dependant on the settling characteristics of the solids in the stormwater. The EPA swirl is most effective at removing solids with characteristics similar to grit ($\geq$0.008 in. (0.2 mm) effective diameter, 2.65 specific gravity). It is important to appreciate this aspect of swirl devices and not expect significant removals of fine and low specific gravity solids.

The three most common configurations are the EPA swirl concentrator, the Fluidsep™ vortex separator, and the Storm King™ hydrodynamic separator. Although each of the separators is configured differently, the operation of each unit and the mechanism for solids separation are similar. The flow enters the unit tangentially and follows the perimeter wall of the cylindrical shell, creating a swirling, quiescent vortex flow pattern. The swirling action throttles the influent flow, and causes solids to be concentrated at the bottom of the unit. The throttled underflow containing the concentrated solids passes out through an outlet in the bottom of the unit, while the clarified supernatant passes out through the top of the unit. Various baffle arrangements are provided to capture floatables in the supernatant which are then usually carried out in the underflow as the storm subsides and the water level in the swirl unit falls. During low flow conditions all of the flow passes out via the bottom outlet and only when the flow increases does the throttling effect and build up of water in the swirl occur.

The solids separation is helped by the flow patterns, with the influent being deflected into a slower moving inner swirl pattern after one revolution around the perimeter of the swirl unit. Gravity separation occurs as particles follow a "long path" through the outer and inner swirl. Solids separation is also assisted by the shear forces set up between the inner and outer swirls, along the perimeter walls, and bottom. An EPA swirl regulator/concentrator is shown in Figure 6-1.

The swirl device can offer a compact unit which functions as both a regulator for flow control and a solids concentrator, and when combined with treatment of the relatively heavy settleable solids can provide an effective treatment system. There are a number of references (U.S. Environmental Protection Agency 1973a, 1974b, 1977d, 1982, 1984b) which provide performance and design information for the EPA swirl regulator/concentrator. A degritter version of the EPA swirl has also been developed (U.S. Environmental Protection Agency 1977d, 1981a) which has no underflow and only removes the grit (detritus) portion.



A Inlet ramp
B Flow deflector
C Scum ring
D Overflow weir and weir plate
E Spoilers
F Floatables trap
G Foul sewer outlet
H Floor gutters
I Downshaft
J Secondary overflow weir
K Secondary gutter

Figure 6-1. Isometric view of a swirl combined sewer overflow regulator/separator (U.S. EPA 1982).

Section 7

Storage and Treatment Optimization

As stated previously, storage alone will only offer flow attenuation, and treatment alone will only treat a fraction of the stormwater flow, or have such a large capacity to handle peak flows that the costs will be prohibitive. Therefore combining the storage/treatment, finding the best balance, and if possible using existing facilities is likely to provide the most cost effective solution for treatment of urban storm runoff.

No two situations are likely to be the same but a cost analysis to produce curves of storage alone, treatment alone, and the combined cost will produce an optimized cost curve as shown in Figure 7-1. Factors such as the number of storms which are likely to exceed the capacity of the combined system need to be taken into account, but this approach will provide useful information on which to base a decision (Field *et al.* 1994, U.S. Environmental Protection Agency 1972b).

Due to the variable nature of storm events there will always be some storm events which generate runoff in excess of the storage/treatment capacity. The excess runoff will be treated by gravity settling in the storage basin prior to being discharged to the receiving water. Use of the swirl regulator/concentrator or degritter described above can provide some treatment to the runoff which is either diverted to storage (alleviating bottom solids accumulation problems) or the receiving water.

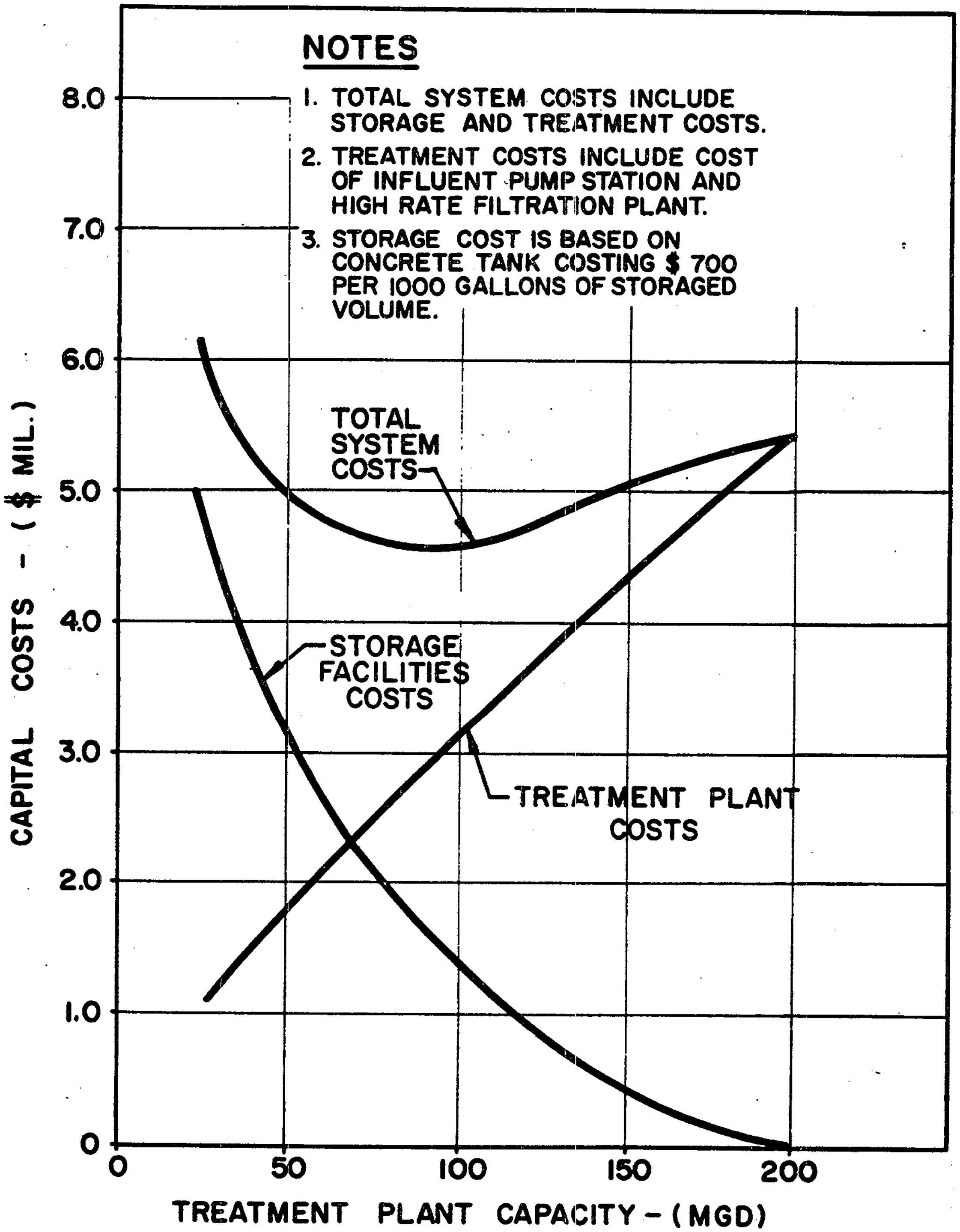


Figure 7-1. Estimated capital costs of storage and treatment for 200 MGD overflow (U.S. EPA 1972b).

Section 8

Beneficial Reuse of Stormwater

The reuse of municipal wastewater for industry, non-potable domestic usages, and groundwater recharge has been practiced for many years. In 1971 an EPA nationwide survey estimated that current reuse of treated municipal wastewater for industrial water supply, irrigation, and groundwater recharge was 53.5 billion gal/yr, 77 billion gal/yr, and 12 billion gal/yr (200 million m^3/yr, 290 million m^3/yr, and 45 million m^3/yr), respectively (Environmental Protection Agency 1975b). It is reasonable to expect that reuse of treated wastewater and/or stormwater for industrial cooling, non-potable domestic water supply, and park and golf course irrigation will increase in the future.

Many of the treatments discussed above are likely to produce an effluent quality which is of a higher standard than that required to meet a stormwater permit. Where there are suitable circumstances, an opportunity exists to take advantage of this higher effluent quality for reuse of the storm runoff. The intended reuse will govern the level of treatment required but careful selection, design, and use of pilot studies should result in the required combination of the above technologies to achieved required effluent quality.

The additional cost to provide treatment above that required to satisfy a discharge permit will need to be less than the cost of water from other sources for economic viability. With increasing demands on potable water supplies the concept of reuse, in particular where a non-potable water quality standard is required, will make this an increasingly more viable option. The report "Reclamation of Urban Stormwater" from *Integrated Stormwater Management* provides details and a hypothetical case study (Field *et al.* 1993).

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