Water quality effects of potential urban best management practices: a literature review. No. 97 1977

Oberts, Gary L.

Madison, Wisconsin: Wisconsin Department of Natural Resources, 1977

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A Literature Review

Technical Bulletin No. 97
DEPARTMENT OF NATURAL RESOURCES
Madison, Wisconsin
1977

ACKNOWLEDGMENTS

This paper was prepared at the request of the Dane County Regional Planning Commission, Madison, Wisconsin, who recognized the need for such a literature review in preparing their Federal Water Pollution Control Act Ammendments of 1972, Section 208, Water Quality Management Planning Program. This paper was critically reviewed by J. G. Konrad and R. T. Bannerman.

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Production Credits

Editor: Ruth L. Hine
Copy Editors: Susan Nehls and Leslie Dock
Graphic Artist: Richard Burton

ABSTRACT

This paper presents a review of the literature regarding the water quality effects of all the readily available urban management practices commonly used to alleviate or control pollution from such sources as construction, street runoff, litter, combined sewer overflows, and all predominantly urban activities that potentially add pollutants to streams.

Three alternative management approaches for dealing with pollution from urban runoff are discussed: source control, collection system control, and discharge treatment.

WATER QUALITY EFFECTS OF POTENTIAL URBAN BEST MANAGEMENT PRACTICES: A LITERATURE REVIEW

By
Gary L. Oberts

Technical Bulletin No. 97
DEPARTMENT OF NATURAL RESOURCES
Madison, Wisconsin
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INTRODUCTION

One of the most critical aspects of developing a water quality management program is determining which of the available alternatives or set of alternatives appears most suitable for inclusion in a recommended implementation program. This paper discusses the water quality effects of all the readily available urban management practices commonly used to alleviate or control pollution from such sources as construction, street runoff, litter, combined sewer overflows, and all predominantly urban activities that potentially add pollutants to our streams.

There are essentially three alternative management approaches to select from in dealing with pollution from urban runoff: first is source control where pollutant migration is limited on site; next is a collection system wherein runoff and its associated pollutants are gathered at a point different from the area where it originates; and finally the treatment system which accumulates urban wastewater and treats it by physical, chemical, biological or mixed methods prior to discharge to a water body. The methods available within each of these management approaches will be individually reviewed with respect to operation, water quality effectiveness, and relative costs, if available.

Caution must be exercised in evaluating the costs of many of the techniques. In most instances, the literature available does not adequately describe conditions surrounding the installation or use of the particular technique. Also, any reported costs have generally risen tremendously and have become very difficult to evaluate; therefore, costs are given with the year of the quote after the figure and should be used only to gauge relative prices. Appendix A lists sediment and erosion costs for a study done in California and Virginia, and Appendix B lists collection and treatment costs for 19 studies from within the United States.

There will not be a table listing of literature values for the various parameters monitored in referenced studies. Anyone desiring such information will find it readily available through searching the articles contained in the Literature Cited section at the end of this paper.

A final note should be added that many of the pieces of literature conclude with recommendations for implementation, but no subsequent information is available as to whether or not the practice was indeed implemented. In situations where the disposition of the project is not known, all available information will be included and the lack of the follow-up information noted.

NATURE OF THE PROBLEM

The first difficulty that must be faced in attempting to minimize pollution from urban runoff is that the rainfall occurs in a predominantly impervious cover area, followed by a significant amount of stormwater runoff. The runoff picks up accumulated sediments, nutrients, metals, and other toxicants and transports them into the stormwater receiving system, most often with the largest degree of concentration occurring on the rising side of the runoff hydrograph. This phenomenon has generally been termed the "first flush" and has been witnessed in many studies, including the City of Milwaukee, Wisconsin Dept. of Public Works (1975), Colston (1974), Shaheen (1975), Weibel et al. (1964), and Wilber and Hunter (1975b). Vitale and Sprey's (1974) report for the U.S. Council on Environmental Quality stated that 0.3 to 1.0 inches of runoff generally contains over 85 percent of the BOD for an event. It should be noted, however, that a first flush does not always occur, its absence affected by such variables as the nature of the storm, antecedent conditions, and the transport system for the runoff (Dunbar and Henry 1966; Poertner 1976a; Wilber and Hunter 1975a).

The major identified sources of urban stormwater pollution include: (1) vehicular and industrial emissions and leakages, (2) combined sewer overflows, (3) skid control salts and grit, (4) street and construction litter, (5) nutrients from fertilizers and animals, (6) pesticides, (7) atmospheric fallout, and (8) deciduous leaves. The addition of these highly concentrated materials to a receiving stream in relatively short duration often creates a shock load and results in such deterimental effects as oxygen depletion and toxicity from metals (APWA 1969; Colston 1974; McGriff 1972; Vitale and Sprey 1974), permanent changes in downstream biota (Shaheen 1975), and increased eutrophication of downstream quiescent water bodies (McGriff 1972).

Shaheen (1975) reported that "...urban stormwater is frequently a significant portion of the total pollution entering receiving waters on a yearly basis, and is always significant on a shock-load basis as is encountered during periods of runoff." Significant contributions relative to treatment plant discharges come in the form of suspended solids, nutrients, BOD and COD, heavy metals, and related urban pollutants such as oil and grease, asbestos, pesticides, and bacteria. This tremendous load of pollutants comes from a combination of highly concentrated runoff and storm-related flows in the range of 3 to 200 times dry weather flow (Dunbar and Henry 1966; Lager 1974; Nebolsine and Vercelli 1974; Weibel 1969). Amy et al. (1974) in reviewing the mechanisms required for pollutant migration, reported that rainfall intensities of 0.5, 0.27, 0.15, 0.08 and 0.02 inches will remove respectively 90, 70, 50, 30, and 10 percent of road surface particles from the road to the runoff collection system.

The primary stream pollutant by weight and volume is sediment, which merits further attention because of the tendency of some metals, pesticides, and nutrients to adsorb onto the soil particles. Urban stormwater quality may be characterized as having suspended sediment concentrations greater than or equal to those of raw sewage (Colston 1974; Poertner 1976b; Weibel 1969), with the predominant sources of sediment being erosion, fallout, and vehicle deposition. The largest single contributing factor to sediment generation is construction. Yorke and Herb (1976) found in prior studies that sediment yields in the 25,000-120,000 tons/mile^2 range were common for urban construction in the Montgomery Co., Maryland area, and, in their study of eight small drainage basins, found annual sediment yields from 7.2 to 101 tons/acre with an average of 32.7 tons/acre. Highway construction in the Scott Run Basin of the Potomac Basin was generally responsible for sediment yields averaging 151 tons/acre/year and residential construction in Kensington, Maryland yielded sediment at the annual rate of 189 tons/acre during 2½ years of monitoring (Guy and Ferguson 1970). In a literature survey of urbanizing areas, Chen (1974) found that soil erosion rates for construction areas ranged from 50 to 200 tons/acre/year. Piest (1965), in a study of 72 watersheds with drainage areas from 100 to 100,000 acres, reported that for most of these watersheds more than 50 percent of soil losses were attributable to storms with a frequency of occurrence less than one year and, therefore, recommended that small-scale, inexpensive remedial conservation measures be implemented in potential erosion areas.

Nutrient input as a result of urban runoff is critical since it becomes a contributing factor to eutrophication of downstream quiescent waters. Data on a study of Mirror Lake in Wisconsin (Knauer 1975) showed that the lake received approximately 50 percent of the total annual phosphorus loading from urban runoff. Shapiro and Pfannkuch (1973) stated that "the chief cause of the increased productivity and subsequent aesthetic deterioration of the Minneapolis Chain of Lakes is the channeling of storm drainage with its high concentrations of algal nutrients to the lakes beginning in the late 1920's." Storm runoff containing phosphorus levels 3-17 times those loadings suggested by Vollenweider (1968) as resulting in eutrophic lakes, flows into the Minneapolis lakes; runoff from a residential commercial area of Cincinnati (Weibel 1969) suggests similar surpassing of thresholds for both inorganic N and total P. Kluesener and Lee (1974) concluded that 85 percent of the total P and 35-40 percent of the total N influent to Lake Wingra (Madison, Wisconsin) were attributable to urban storm runoff and that most of the nutrients were derived from precipitation, dust fall, leaching from vegetation, street litter, fertilizer, and petrochemical combustion. Konrad et al. (1976) reported that event data on the Menomonee River in the Milwaukee metropolitan area indicate: that the concentration of total P and total Kjeldahl N ususally increase during a runoff event; that they generally coincide with changes in the hydrograph; and that the loading during an event may account for a significant fraction of the total baseline loading for the entire month in which the event occurs.

Oxygen-demanding substances which are introduced to streams through urban runoff present another serious problem to stream health, that being oxygen depletion. Oxygen demand from urban areas is best represented through chemical oxygen demand (COD), but this information is often not available as a monitored parameter because biological oxygen demand (BOD) has historically been utilized as the most convenient means of reporting demand. Forty to 80 percent of the total annual COD and BOD entering the receiving waters of a city provided with secondary treatment can be caused by sources other than treatment plants, with 94-99 percent of the total COD and BOD load during a storm event contributed from such sources as sewer overflows, storm sewers, direct runoff, and treatment plant bypasses (Vitale and Sprey 1974). These inflows may exert an oxygen demand 40-200 times greater than normal dry weather flow. Pitt and Amy (1973) reported that the immediate toxic effects of road surface runoff are most likely due to extreme oxygen demand rather than effects of heavy metals and, in a simulation, showed that approximately two-thirds of the BOD_5 was exerted during the first day after runoff. Colston (1974) concluded in his Durham, N.C. study that 40-50 percent of the COD material in urban runoff was susceptible to biodegradation in 20 days. A further appreciation for the magnitude of the oxygen demand problem can be attained when one notes that in Durham during wet periods in 1972, organic yield measured as COD in urban runoff was 4.5 times that of raw sewage, while several other studies (APWA 1969; Lager and Smith 1974; Poertner 1976a; Weibel 1969) reported BOD loading from urban runoff equal to or stronger than secondary effluent.

Toxic heavy metal loading from urban storm runoff merits attention as a potential nondegradable aid to stream deterioration capable of reaching critical levels in quiescent areas where it is able to accumulate in bottom sediments. Heavy metals usually concentrate themselves by precipitating out of the water at neutral or alkaline pH, by adsorbing on clay, or by binding to hydrous oxides of Fe or Mn (Wilber and Hunter 1975b). The general solubilities of heavy metals are in the range of less than 10 percent but Pb, Cu, Cd, and Zn were found sufficiently soluble to cause toxic effects to certain aquatic organisms under select conditions, such as soft water (Pitt and Amy 1973). Vitale and Sprey (1974), for a typical moderate-sized city, arrived at annual loading rates of 100,000-200,000 lb of Pb and 6,000-30,000 lb of Hg. In their study of Lodi, N. J., Wilber and Hunter (1975a, b) reported that Pb, Zn, and Cu account for 90-98 percent of the total metals observed, with Pb and Zn equal to 80 percent, and Cr and Ni occurring in small quantities. Pitt and Amy (1973) found that industrial areas have the greatest load and concentration of heavy metals, with commercial areas being the least. As with several other urban-associated parameters, loading of heavy metals during an urban storm event has been found to be a significant portion of the entire load to the stream, including treatment plant effluent (Colston 1974; Nebolsine and Vercelli 1974; Pitt and Amy 1973; Shaheen 1975; Wilber and Hunter 1975a, b).

Several other contaminants find their way into surface water as a result of urban runoff. Weibel (1969) found that 90 percent of his Cincinnati runoff samples from a separate sewer area contained more than 2,900 total coliforms per 100 ml., and therefore exceeded the limit for full body recreational contact. Lager (1976) and Poertner (1976a) also reported significant quantities of bacteria in runoff. Grease and oil were found to be major organic constituents of street surface contaminants (Pitt and Amy 1974). Asbestos from brakes, clutches, and tires also constitutes a major road surface pollutant in urban areas (Shaheen 1975).

It becomes increasingly obvious in reviewing the available literature that urban runoff makes an extremely large contribution to stream pollution and that a far greater amount of attention should be placed on alleviating this problem before additional money is spent on urban area treatment plant upgrading beyond the secondary level. Colston (1974) concluded in his study that "if Durham provided 100 percent removal of organics and suspended solids from the raw municipal wastewater on an annual basis, the total reduction of pollutants discharged to Third Fork Creek would only be 52 percent for COD; 59 percent for ultimate BOD; 5 percent for suspended solids; and 6, 11, 21, 12, and 43 percent for Cr, Cu, Pb, Ni, and Zn, respectively." Additionally, Colston stated that approximately 20 percent of the downstream water quality was not controlled by municipal wastes, but instead by urban runoff. Conclusions similar to Colston's have also been drawn by AVCO (1970), Colston and Tafuri (1975), and Vitale and Sprey (1974). Also, similar discussions were used to point out the waste of time and money for sewer separation in areas with combined systems (Burgess and Niple, 1969; Field and Tafuri 1973; Nebolsine and Vercelli 1974).

MANAGEMENT PRACTICES

SOURCE CONTROL

The first method for management of urban runoff pollution is control of potential pollutants on-site or within a small sphere of influence. The various management methods discussed in this section include increased infiltration, retention of runoff/reduction of erosion, reduction in contaminant deposition, and removal of contaminants. These methods are generally very effective for small, upstream basins and will be relatively inexpensive compared to larger structural solutions. Many of the costs associated with the practices discussed in this section can be found in Appendix A.

Increased Infiltration

Perhaps the simplest of all runoff control techniques involves providing a runoff surface porous enough to allow the water to infiltrate into the subsurface layers or into a collection system. McGriff (1972) discussed the water quality effects of urbanization on the hydrology and groundwater regimes of localized areas where on-site infiltration is not allowed to occur.

Porous pavement utilization on parking lots and roadways presents one of the more attractive small-scale alternatives of immediate runoff control. The Franklin Institute conducted an investigation (Thelen et al. 1972) for the U.S. EPA on porous pavement and concluded that among its benefits were: relief from combined sewer overflows, possible augmentation of municipal water supplies, improvement of traffic safety, preservation of vegetation, relief from flash flooding, and aesthetics. The water quality benefits of porous pavements included: dissipation of runoff energy and associated suspended sediments, infiltration of soluble pollutants and some fine material, recharge of groundwater, and elimination of most hydraulic conduits and collection systems where water tends to gather and become stagnant. Recent applications of porous pavements have proven effective in Stuttgart, Germany; the University of Delaware at Newark; and Woodlands, Texas (Engineering-News Record 1973; Landscape Architecture 1974a). Jackson and Ragan (1974) used numerical solutions of the Boussinesq equation to examine the hydrological behavior of a porous system with subdrains to slowly release infiltrated runoff, and determined that substantial control of a runoff hydrograph can be obtained, but without proper maintenance, clogging will become a "significant" problem. Costs for porous paved areas have been found to be equal to or less expensive than conventional paving because generally a minimum of hydraulic conveyance systems are required (Engineering-News Record 1973; Landscape Architecture 1974b; Thelen et al. 1972).

Caution must be exercised in utilizing porous pavement in colder climates. Although freeze-thaw cycle tests have been conducted and found successful (Thelen et al. 1972), the pavement will freeze and buckle if adequate subsurface drainage is not provided or if severe weather is common. Design information on porous pavement structures is available in all of the appropriate literature cited in this section and will not be reviewed here.

A second very effective method of inducing on-site infiltration of urban runoff water is to design pervious collection basins or ditches in conjunction with a drainage system located in a small drainage area. This method has been successfully utilized in Bellvue, Washington (Haro 1973) on a municipal parking lot and has effectively delayed runoff, induced infiltration to groundwater, and filtered sediment and oil out of the runoff water at very little initial or subsequent cost. Parkhurst et al. (1968) discussed the benefits to be derived from reuse of wastewater after percolation, which adequately filters small quantities of residual solids, organics, and bacteria in the first few feet of soil. More large-scale efforts will be discussed in a later section on increased infiltration collection systems.

An additional method for cutting down on urban runoff after a storm event is disconnecting roof drains from hydraulic conduit systems and allowing them to drain over a pervious surface. The AWPA (1969) found in their Chicago study that approximately 40 percent of the combined sewer overflows studied might be eliminated if all of the roof leaders were disconnected from the sewer system and directed elsewhere. Also, utilization of small check structures which slow runoff and allow increased infiltration to occur through the natural stream bed can be effective. These two methods are very inexpensive and can show tremendous small-scale local reductions in peak discharge and associated pollutants.

Retention of Runoff / Reduction of Erosion

This section addresses those practices which are by far the most commonly utilized pollutant reduction systems. Included in this discussion are all structures or practices designed to dissipate rainfall/runoff energy, trap sediment, protect exposed ground, and reestablish vegetative cover. In general, these practices are extremely effective and inexpensive (relative costs can be found in Appendix A). Practices similar to those discussed here have been responsible for decreasing sediment yield by 60-80 percent on construction projects in Montgomery Co., Maryland since the establishment of a sediment control program (Yorke and Herb 1976). Using an equation based on the Universal Soil Loss Equation, the U.S. EPA (1973) pre-

TABLE 1. *Reduction of erosion losses through the utilization of grass and grass-soil filters*

Parameter	Percent Reduction	
	Grass	Grass-soil
COD	19	88
SS (suspended solids)	34	99.6
VSS (volatile suspended solids)	26	97
Turbidity	97	98
Total coliforms	84	98
Fecal coliforms	50	98

*After Popkin (1973)

dicted erosion control effectiveness of from 90 to 96 percent for methods and combinations of methods discussed in this section.

The most elemental practice in retarding runoff and reducing erosion is the establishment of a good vegetative cover to dissipate rainfall energy, slow runoff velocities, retain moisture and trap sediments. Soil detachment is principally caused by raindrop impact, with drops hitting at a velocity of up to 9 m/sec (30 ft/sec), and by shearing from flowing water (Meyer et al. 1976). Major erosion does not begin until runoff reaches a critical condition, so immediate reestablishment of vegetative cover is essential. Johnson (1961) outlines various highway-related erosion control methods, most of which are discussed in subsequent parts of this section.

Revegetation, either by sodding, hydroseeding, manual seeding, or planting of shrubbery, should begin as soon after disturbance as possible, keeping in mind that such climatic variables as rain (or lack of it), wind, and temperature may inhibit germination or may totally remove the desired vegetation from the site. A fescue-bluegrass mixture for rapid germination and fast growth has been shown to be very effective on properly prepared and fertilized, shallow to moderate slopes (Meyer et al. 1971) and reed canarygrass has proved effective in stabilizing seepage areas (Augustine 1966; Bondurant et al. 1975). Vegetation is most efficient when it is young, sturdy, and resilient, and therefore, is of least benefit in winter and early spring (Parsons 1965).

The water quality effects of revegetation are quite noticeable and fairly rapid. The Fairfax Co., Virginia *Erosion and Siltation Control Handbook* (1972) (U.S. EPA 1973) indicated that grasses and sods are 90-99 percent effective in controlling erosion losses from construction sites. Popkin (1973) reported considerable reductions resulting from the utilization of grass and grass-soil filters (Table 1).

Vegetation strips also serve to improve the runoff water with which they come in contact. Tollner et al. (1975) feel that sediment-laden water spread over a vegetated strip can be greatly improved in quality. Kao et al. (1975) concluded that grass filter strips provide excellent trapping efficiency especially for construction areas. Their research shows that a minimum of 85-percent sediment removal will result with an 8-ft grass strip used with shallow flow, and this efficiency can be increased when alternating grassed and bare areas are used. The State of Maryland et al. (1972) found that the best performance in vegetative stripping can be achieved by using tall, dense stands of turf-forming grasses.

Covering an exposed area with any type of a number of available mulches will generally prove very effective in controlling erosion until vegetation becomes established by maintaining greater infiltration rates, increasing the hydraulic roughness, and absorbing the shear stress of the runoff (Meyer et al. 1976), as well as dissipating rainfall energy and maintaining soil moisture. Annual sediment yields from land under active development ranging from several hundred to 100,000 tons/square mile (Meyer et al. 1971) can be significantly reduced through minimizing the duration of bare soil exposure. Straw mulch (small-grain) has proven effective on a less-than-12-percent slope at an application rate of 2 tons/acre and on a 15-percent slope at a rate of 4 tons/acre (Augustine 1966; Chen 1974; Meyer et al. 1971; Meyer and Romkens 1976; U.S. EPA 1973). Lattonzi et al. (1974) reported reductions in interrill erosion on a 20-percent silt loam slope of 40 percent at an application rate of ¼ ton/acre, 80 percent at a rate of 1 ton/acre, and negligible at a rate of 4 tons/acre. The erosion rates for this 20-percent slope were found by Lattonzi et al. to be about one-half those of a similar soil with a 2-percent slope, and concluded that for all slopes (averaged), a straw mulch application rate of ½ ton/acre will reduce erosion by 35-40 percent and an application rate of 2 tons/acre will reduce erosion by 75-80 percent. Best results for mulching are obtained when the mulch is tacked with an emulsified asphalt, fertilized, watered, and applied during dry periods when wash-out potential is minimized (Parsons 1965; U.S. EPA 1973). A Meyer et al. (1972) study on a silt-loam area with a 12-percent slope showed that in cases where a topsoil was applied over a disturbed area, reworked with fertilizer, seeded with a fescue-bluegrass mixture, and mulched, the plots averaged 77-percent vegetation establishment in seven weeks and up to 86 percent in eight months. A similar area, without mulching, yielded revegetation of only 36 percent in seven weeks and 48 percent in eight months.

The most economical, effective, and practical method for achieving fast revegetation is hydromulching, a process which applies a slurry mixture of seed, mulch, fertilizer, and lime at a cost of less than one-half the price of a comparable, hand-applied mixture (U.S. EPA 1973). The U.S. EPA reported that 1973 costs were variable, from $25 to $900/acre, with the unit cost decreasing as the acreage increased, and that optional fumigation with methyl bromide to kill noxious weeds may increase the price six-fold.

Straw mulching, however, loses its effectiveness on steep slopes because of underrilling and its tendency to be washed away, so alternate materials must be considered as the mulching medium. Woodchips have been found to be 94-98 percent effective at a recommended application rate of 60-100 yards^3/acre (U.S. EPA 1973). Meyer et al. (1972) showed that woodchip application at a rate of 15-25 tons/acre can adequately control erosion on a 20-percent slope, 150 ft long, during a 2.5-inch rainfall, but long-term protection was not available because the chips eventually washed away and rilling was allowed to begin. The cost of woodchip mulch, however, will most likely exceed straw or hay mulch by a factor of from two to seven (Ateshian 1976), dependent upon thickness.

Crushed stone mulch (0.5-1.5 inches) is also a viable alternative to straw and hay. Meyer et al. (1972), in the same study area discussed above, found that stone mulch application at a rate of 100-200 tons/acre was excellent in reducing erosion. Application rates of 135 tons/acre proved effective for all tests at a 1972 cost of $0.01/ft^2$ (sodding cost — $0.05-$0.20/ft^2$). Also, at adequate rates, rilling did not occur and flow was confined within the mulch layer. Gravel proved similarly effective at 70 tons/acre. Similar results for mulches are reported by Meyer and Romkens (1976).

Wood fiber mulch applied at a rate of 1,000-1,500 lb/acre in a slurry can be as effective as woodchips (U.S. EPA 1973). Portland cement was reported ineffective for erosion control on a 20-percent slope (Meyer et al. 1972).

Chemical mulches of various types and trade names are available as soil stabilizers during periods of revegetation. Most chemical mulches penetrate the soil and serve several functions, such as soil stabilizer and binder, moisture holder, and mulch tack. Several brand name mulches are reviewed in the report by the State of Maryland et al. (1972), including Aerospray 52 Binder, Aquatain, Curasol AE, Curasol AH, DCA-70, Petroset SB, and Terra Tack, in addition to liquid asphalt. Reference to this publication will yield information on each particular brand and method of application. Costs for all of the chemical mulches were not available, but Ateshian (1976) reported that the 1973 cost of Petroset SB was about three times that of hydroseeding for ten acres and about equal to the cost of straw or hay mulch. Soil stabilizers can be used effectively and economically for such projects as highway construction and application to high value crop cover (Moldenhauer and Gabriels 1972).

In areas where erosion potential is greatest, more expensive but durable substitutes for mulching must be utilized to prevent sheet and rill erosion. Excelsior blankets are machine-produced mats of curled wood excelsior with long (8-inch) fiber length (U.S. EPA 1973). These stapled-in-place mats dissipate rainfall energy and runoff velocities, insulate the soil, and retain soil moisture. The 1973 cost of excelsior matting was about $11,000/acre (Ateshian 1976).

Jute netting consists of heavy woven mesh of undyed and unbleached twisted jute fibers of rugged construction and is used in the establishment of vegetation (U.S. EPA 1973). These nets are stapled in place and cost approximately 40 percent as much as excelsior mats. Seeding can be done either before or after the jute netting is applied.

Other types of blankets or mats include fiberglass mats, Glassroot fiberglass mats, mulch blankets, plastic filter sheets, and Fabriform erosion control mats. A discussion of these alternative methods can be found in the State of Maryland et al. (1972) report. Parsons (1965) recommends mats for stabilizing seeded areas and suggests using a rapidly germinating and growing grass mixture even if it is not the best grass at maturity because, for critical areas, a rapid revegetation is essential to control erosion.

In addition to revegetation and cover protection, on-site sediment protection can be obtained by small-scale structural solutions to slow runoff and dissipate energy. The objective of this type of structure is to reduce forward velocity of the sediment particles so that they will be allowed to fall out in a settling area (Bondurant et al. 1975), designed with a decreasing flow depth near the outlet and increasing flow width through the structure. Bondurant et al. (1975) reported sediment removal efficiencies of from 56 to 96 percent for two sediment ponds in southern Idaho, and based on these findings, recommended triangular-shaped ponds with a deep inlet wedging up to the outlet and a grass filter strip on the embankment for intermittent flow. Tryon et al. (1976) claimed excavated sediment traps were "incomparably superior" to small detention dams in terms of cost, acceptance by industry, lack of failure, and sediment trapping efficiency for Missouri Ozark earth-moving operations; such excavated pits cost between $50 and $150 each in 1976 and average 75- to 99-percent sediment removal efficiencies compared to detention dam efficiencies of 30-50 percent for similar operations.

Efficiencies noted above are not at all uncommon for sediment trapping structures. Oscanyan (1975) found that three sediment basins associated with construction activities on 65-acre Olnay Manor Special Park in Montgomery Co., Maryland got 99 percent or better sediment removal efficiencies. Lumb et al. (1974) projected a 20-percent decrease in peak runoff with its associated sediments could be achieved through detention storage on a 10.8-acre residential site in DeKalb Co., Georgia. Shapiro and Pfannkuch (1973) conducted settling experiments which showed that as much as 68 percent of the total P entering the Minneapolis Chain of Lakes could be removed by settling storm drainage for two hours, but generally less than 50-percent removal can be expected. Colston (1974) postulated that a sediment basin in his Durham, N.C. study area could decrease the COD load by 60 percent. U.S. EPA (1973) estimated the effectiveness of small-scale sediment basins at 70-percent trap efficiency.

Multiple-use structures can be utilized in areas where land is in short supply or costs are prohibitive. The Melvina Detention Reservoir in Chicago (Poertner 1974) was built for $892,000 to hold the pumping station overflow for a 4-mile^2 area and can also be used for tobogganning and skiing in the winter and volleyball and basketball in the summer. Rooftop ponding can provide convenient temporary storage with controlled release in small urban drainage areas (Stem 1975) provided that the available roofing areas are nearly flat, well supported, and impervious. The best example of a rooftop detention project is the downtown Denver Skyline Urban Renewal Project (Amy et al. 1974; Poertner 1974; Rice 1971) which required the developers to detain on-site the rainfall occurring on their building. The recommended design criterion was for detention of a 1-inch/hour storm with a return frequency of ten years (Poertner 1974). Verification of the effectiveness of this system was not available in the literature reviewed. Similar systems can be easily established for parking lots where minimum use areas can be utilized for stormwater storage and sediment settling (Poertner 1974 and 1976b; Rice 1971; Stem 1975). Design criteria for rooftop systems and parking lot storage are given in Hittman Associates (1973). Discussion of additional small-scale ponding and other related sediment trapping structures is given in Hittman Associates (1973), State of Maryland et al. (1972), and Stem (1975). In general, most literature recommends designing these structures for 2- to 10-year frequency storms and shows effectiveness in reducing erosion in the 50- to 60-percent range.

The final alternative available in reducing runoff and erosion for small areas involves land-altering activities where recontouring on-site can provide desired results. Structures and methods utilized here include: diversion dikes to divert runoff from unstable areas; filter berms to remove sediments in a graded right-of-way; filter inlets of gravel or crushed rock at storm sewer inlets; interceptor dikes to divert runoff to temporary outlets; level spreaders to spread concentrated runoff at nonerosive velocities; and construction coordination and phasing to expose a minimum amount of bare soil (State of Maryland et al. 1972). Grades in disturbed areas should be less than 33 percent (preferably flat) with the above structures placed to cut both the effective length of the slope and the velocity of the runoff down the slope and should be followed by sediment compaction and rapid revegetation (Chen 1974; State of Maryland et al. 1972). Caution should be utilized when soil-disturbing methods such as soil ripping and scarification are chosen to improve infiltration. Such variable successes as surface runoff reduction of 85 percent (Aldon 1976) and failures with average losses of 54 tons/acre (Meyer et al. 1971) have been reported for such methods.

Reduction of Contaminant Deposition

One obvious method of minimizing the amount of pollutant runoff from an urban site is through minimizing the input of that pollutant into the system. For urban areas, this particularly applies to unnaturally occurring substances such as street litter, pesticides, and road deicing and anti-skid agents. The water quality effects of an anti-litter program are not documented and most likely are not able to be documented because of quantification difficulties and pollutant potential of the large numbers and variable nature of litter. The best program to fight litter pollution would include an education effort for the citizenry, as well as numerous and well-maintained litter collection areas.

Pesticide toxicities have been very well documented in past literature and will not be discussed here. The simple rule for pesticide usage in urban areas should be moderation in the amount utilized because overusage could potentially make available large quantities of toxic material mobilized by runoff.

Road salt and anti-skid agents, however, are items whose application can be controlled and whose water quality implications can be evaluated. One of the foremost problems mentioned in relation to use of road salts is excessive use through anticipation of snowfalls or through negligence of the proper application techniques. Typical single salt application rates may range from 200-4,000 lb/mile of highway and consist of NaCl, CaCl, and an abrasive which will usually remain after the soluble salts have washed away (APWA 1969; Sartor and Boyd 1972). Actual road-related water quality samples have yielded Cl concentrations commonly ranging from 1,500 to 25,000 mg/l (APWA 1969; Field 1973), a level which can disturb shrubs, trees, and vegetation and can percolate into groundwater systems, where it can contaminate such water supplies for an extended duration. An anticorrosive agent which utilizes the hexavalent form of Cr may be toxic and a cyanide additive to prevent caking may be severely toxic, but little is known of the environmental effect of these potential contaminants (APWA 1969; Field 1973; Sartor and Boyd 1972). Field (1973) felt that the rust-inhibiting additives (chromate complex) do not produce results significant enough to justify continued use. Sartor and Boyd (1972) stressed the necessity of covering a salt storage area by pointing out that in an area receiving 40 inches of precipitation yearly, a salt pile left exposed for six months would lose 5 percent of its volume, not including wind loss. This lost volume, with its associated salts and toxic additives, then makes its way into local surfacewater and groundwater systems as a pollutant.

Removal of Contaminants

Perhaps the most readily available and economic management practice for the control of urban nonpoint source pollution in a high density, developed area is removal of contaminants from roads before they are allowed to become part of the runoff regime. Foremost on the list of removal methods is street sweeping. Field and Tafuri (1973) reported that it may be cheaper to remove solids by sweeping than collecting them in a sewer system, with 1973 costs for street sweeping at \$24-\$30/ton of solids versus sewer system costs of \$60-\$70/ton of solids, but cautioned municipalities to be aware of the limitations in the effectiveness of sweeping with respect to particle size pick-up.

Sartor and Boyd (1972) found that the quantity and nature of material existing on street surfaces was extremely variable and obviously is dependent upon the length of time since the last sweeping, rainfall, or road flushing. The implications of keeping streets free of debris are extremely far-reaching because of the pollutants associated with street litter, principally being oxygen-demanding substances, heavy metals, nutrients, and pesticides. The APWA (1969) found that the most significant component of street litter was the dust and dirt fraction, which is the most critical fraction with respect to water quality because most pollutants associate with particles in the dust and dirt size range or smaller. The APWA goes on to report that broom-style street sweeping is ineffective for particles smaller than dirt and that vacuum sweepers are about 95-percent effective, but not for fine or clay-sized particles. Sartor and Boyd (1972), in their extensive study of street surface contaminants, found that 50 percent of all particles found in streets range in size from 104-840 microns and that particles less than 43 microns may contain: 25 percent of the total oxygen demand, up to 50 percent of the total heavy metals, 33-50 percent of the algal nutrients, and up to 75 percent of the total pesticides while comprising only 5.9 percent by weight of the total solids. The figures by Sartor and Boyd gained increased significance when they reported that street sweepers leave behind 85 percent of the material finer than 43 microns and 52 percent of the material finer than 246 microns, essentially concluding that street sweeping is ineffective in reducing pollutant inputs to runoff collection systems and serves only to improve aesthetic qualities. Optimum sweeper efficiencies shown in Table 2 indicate the relative ineffectiveness of sweeping found by these authors.

Nutrients, heavy metals, and pesticides all generally appear to associate with particle sizes less than those for which pick-up efficiencies are acceptable. The pick-up efficiencies in Table 2 yield average removal efficiencies as shown in Table 3. These findings led Sartor and Boyd to conclude that "even under well-operated and highly efficient street-sweeping programs, the broad spectrum of pollutants accumulated under urban and suburban streets represent a nonpoint pollution potential well in excess of the presently allowable discharge from municipal treatment plants." Also, "removal effectiveness is actually greater than 70 percent for the larger fractions (more than 246 microns), dropping somewhat for the middle-sized fraction, and decreasing to an insignificant amount for the smallest fraction" where most of the pollutants are associated.

Similar conclusions to those of Sartor and Boyd are contained in the work of the APWA (1969) in Chicago with urban runoff. They found that 72 percent of the material in street sweepers they studied was of the dust and dirt fraction, and concluded that sweepers were about 95-percent effective for coarse material but generally left fine material behind. Additionally, they found that dustfall particles in the size range, 20-40 microns, result from air pollution generated by such activities as manufacturing, incineration, mining, refining, construction, and combustion of fossil fuels and may annually total 500-900 tons/mile^2 in urban areas. APWA also reported that industrial areas tended to provide maximum street litter and commercial areas a somewhat lesser amount, but both were higher in litter generation than residential areas.

Further substantiation of the failure of street sweepers in picking up the potential toxic material pollution from urban runoff comes from Pitt and Amy (1973) who reported that more than 50 percent of all metals in street surface material are found in size ranges less than 495 microns. Their study further reported that normal street-sweeping operations show removal efficiencies ranging from 38 percent for Cd to 56 percent for Cr, with an overall average of 49 percent for all metals. Pitt and Amy further noted that particles in the smaller size ranges appear to contain a higher percentage of grease and oil than larger sizes, probably due to a greater surface area-to-unit weight ratio.

TABLE 2. *Efficiency of street sweeping related to particle size**

Size of Street Litter	Pick-up Efficiency (%)
Small particles**	
2,000	79
840-2,000	66
246-800	60
104-246	48
43-104	20
<43	15
Avg.	50
Large pieces (litter and debris)	95-100

*After Sartor and Boyd (1972)
**Particle size is in microns.

A final piece of information on street sweeping was presented by Shaheen (1975) who studied urban roadways in Washington, D.C. and reported that advanced mechanical or vacuum street sweepers can possibly pick up 90 percent of the street particles, but only about 65 percent of the BOD will be removed from a 1- to 3-day accumulation and the fraction not picked up (10 percent) is the fine particles with which most pollutants are associated. He additionally stated that less than 5 percent by weight of traffic-related deposits originate directly from motor vehicles, but these 5 percent are most important by virtue of their toxicity. Shaheen, as well as Sartor and Boyd (1972), Amy et al. (1974), and Pitt and Amy (1973), believed that carefully planned, frequent sweeps with better equipment — specifically, brooms that do not redistribute the material — can improve the amount of pollutants moving toward urban receiving systems, but they can not reduce these pollutants to an entirely acceptable level.

A significant problem which generally inputs a large amount of P to our streams is leaf deposition on street surfaces (Cowen and Lee 1973; Kluesener and Lee 1974; Sartor and Boyd 1972; Shapiro and Pfannkuch 1973). The research of Cowen and Lee (1973) further indicated that cut-up or disturbed leaves yield about three times the soluble P of intact leaves and, therefore, should not be burned in gutters where runoff will carry away the P-rich ashes. A rigorous program of leaf removal in the autumn should markedly decrease P loading due to leaf decomposition.

COLLECTION SYSTEM CONTROL

The second major category of urban management practices to control nonpoint pollutants involves methods or structures which deal with the pollutants after they have reached a hydraulic collection system. These methods are generally located downstream from the pollutant donor area and tend to be larger scale than those practices addressed in the last section on source control. There are four approaches to this type of management practice, including: reduction of in-channel erosion, increase of runoff water infiltration, storage of runoff, and removal of contaminants from the system. These methods are generally more expensive than source controls because of their size and requirement for predevelopment engineering design.

Reduction of In-Channel Erosion

There are two different approaches to reducing erosion within a drainage channel — grade control and bank protection. Grade control structures are designed emplacements, such as check dams, that stabilize the hydraulic grade and/or control headward cutting (State of Maryland et al. 1972). The effectiveness of grade control comes from the reduction it provides in reducing stormflow velocities and in removing stream sediment load as the stream reaches the quiescent areas behind the structures. Water quality effects of these structures were not available from actual study areas, but it can be logically implied that in most cases, sediment load is decreased and, concurrently, pollutants associated with sediment also settle out.

Streambank protection, by natural or structural methods, can effectively be applied to decrease a type of erosion which commonly results in a 100-percent sediment delivery ratio to a stream. Streambank erosion is a natural geologic process which cannot be stopped, but which can be retarded. The simplest form of channel protection is the utilization of vegetation. The degree of vegetation will of course be a function of the amount of the channel cross-section carrying water year-round. Grassed waterways have been used as an agricultural conservation practice by SCS for many years and logically can be applied with equal success to urban construction and disturbed areas. The discussion in the previous section (Source Control) on the effects of vegetation addressed the benefits derived from covering bare soil with vegetation. The critical thing to look for in channel vegetation is fast germination and growth and year-round stability; for example, bermudagrass and low-growing wood materials such as small willows have good qualities, whereas legumes are generally too weak and should be used only to promote growth of other species or where other species will not grow (Parsons 1965). Seeding should be used only if the design flow velocity is less than or equal to 4 ft/sec; sod from 4-7 ft/sec; and structural solutions for velocities

TABLE 3. *Average removal efficiencies for critical parameters by street sweeping**

Parameter	Total Removal Efficiency (%)
Total solids	55.2
BOD_5, COD	42.9, 31.1
Kjeldahl N	43.9
Phosphates	22.1
Total heavy metals	50.3
Pesticides	44.7

*After Sartor and Boyd (1972)

greater than 7 ft/sec or for highly erodible soils (State of Maryland et al. 1972).

The State of Maryland et al. (1972) discussed other streambank control methods which are utilized less frequently than vegetation. Gabions are large, multi-celled rectangular wire mesh boxes which are filled with rocks and which line the banks to dissipate streamflow energy and cover exposed soil. Flexible downdrains and chutes are channels constructed of flexible material designed to conduct erosive water from one elevation to another. Erosion checks are porous, mat-like material installed in a slit trench perpendicular to flow to allow for greater infiltration. Fabriform erosion control mats consist of fluid mortar which has been injected under pressure into flexible fabric forms above and below the waterline to stabilize the banks. As with the vegetation discussed in the previous paragraph, water quality effects are not documented, but must be implied.

Increase of Runoff Water Infiltration

Urban stormwater runoff is often referred to as a resource out of place. Inducing this water to infiltrate into the groundwater system is one very beneficial way to put runoff to work.

The most popular way to increase infiltration is through trenches or ponds. These structures are usually shallow excavations with a very permeable material such as gravel or sand as bottom material, located over a permeable substrate thus allowing runoff water to freely percolate through to the groundwater regime (Stem 1975). These systems probably will require a fair amount of expensive maintenance due to the tendency of the coarse bottom material to clog with fines, a problem that can be partially solved by routing the water over vegetation prior to allowing its entrance to the pond. Long Island, New York realized the potential of runoff water in 1935 and established approximately 2,100 recharge basins by 1971. These basins drain residential and commercial areas principally in central Long Island so the water will be naturally filtered prior to reaching the groundwater table (Aronson and Seaburn 1974). The Long Island pits are generally excavated in the surficial glacial deposits and range in size from 0.1 to 30 acres, averaging one acre. Infiltration is enhanced and clogging minimized in four ways (Aronson and Seaburn 1974): (1) the basin floor is at two levels allowing presettling of fines in the deeper part; (2) retention basins are maintained with the overflow discharging to the recharge area; (3) diffusion wells are "punched" through the basin bottoms to provide for additional recharge area; and (4) the bottom is scarified or broken up, or a thin layer can be removed.

Fresno, California has made optimum use of its stormwater runoff. The Fresno Metropolitan Flood Control District has established recharge basins to collect stormwater and induce infiltration for subsequent use as a groundwater-derived freshwater supply (Nightingale 1975). The basins are excavated up to eight meters deep and are planted with bermudagrass so that they can also serve as recreation areas. Nightingale used several of the recharge basins to determine selected heavy metal mobility and to document toxicity potentials relative to the groundwater drinking supply. The results of this study showed that Pb, Zn, and Cu have migrated to some degree up to 60 cm into the soil, but that they are effectively filtered out in the upper 5 cm, reaching background levels at 15-30 cm. The recharge method, therefore, seems to be a very effective management method to concentrate metals in one area rather than allowing migration downstream in surface waters, but recharge conditions are such that this method is not applicable to all situations. Fresno also has the Leaky Acres Project which utilizes agricultural surface runoff to artifically recharge the groundwater supply through ten recharge basins totaling 117 acres (Nightingale and Bianchi 1973). Water quality has increased under the Leaky Acres Project area probably due to filtration of pollutants in the bottom material of the recharge ponds. Berend et al. (1975) discussed a recharge project in Israel and the problems resulting from introducing recharge water which is too high in suspended sediments.

Other methods utilized for inducing infiltration include dry wells, wet and dry ponds, and special fill impoundments. Stem (1975) discussed the design and functionality of these structures.

Storage of Runoff

Storing runoff water for subsequent slow release to a stream or a treatment process is probably the most cost-effective method available for reducing pollution downstream from an urban area (Lager and Smith 1974; Landscape Architecture 1974a; Mallory 1973; Rice 1971). Several storage methods are available including: ponds or basins, tunnels, utilization of existing conduit systems, and tanks.

Perhaps the most economically attractive off-line storage method is creating some type of basin, if land is available for a structure to be developed. Ponding can help the economics of a drainage system by temporary retention, as well as aiding in the improvement of water quality (Rice 1971) and providing other potential beneficial uses such as drinking, industrial, or recreation water (Mallory 1973). The water quality effects of storage through ponding are discussed in greater detail in a following section on physical treatment of collected water, but generally it can be expected that suspended solids and associated pollutants will be reduced roughly in proportion to the duration of the detention. Vitale and Sprey (1974) recommended storage and subsequent release for treatment with proper maintenance of the sewerage system as the best way to deal with urban water pollution. They reported that an 85-percent decrease in BOD can be realized by capturing the first ⅓ to 1 inch of runoff. A very successful program has been conducted at Chippewa Falls, Wisconsin where, in 1969-70, 93.7 percent of the total combined sewer overflow discharge volume was withheld from the receiving stream, stored, and subsequently pumped to a treatment plant (U.S. EPA 1972). The detention basin is made of paved asphalt and has a storage volume of 8.66 acre-ft. The U.S. EPA (1972) reported that this structure in 1969-70 was responsible for stopping 98.2 percent of the total BOD_5 and 95.8 percent of the total SS which normally would have overflowed via the combined sewage. The 1969 total capital cost for the system was $610,067 with an operation and maintenance cost of $7,300/year. Boston's Cottage Farm Stormwater Treatment Station consists of six parallel storage basins designed to provide primary treatment plus chlorination (Lager and Smith 1974). Milwaukee and New York City also have some type of storage system with chlorination (Field and Tafuri 1973). Woodlands, Texas, a new town being built on 18,000 acres near Houston, utilizes retention ponds on major stream channels to provide for water quality improvement and sediment control, as well as flood control. Cost of development of this "natural" drainage system was about one-fourth the cost of a conventional system (Landscape Architecture 1974a). Dunbar and Henry (1966) reported that ponds can improve water quality by reducing BOD 30 percent with a detention period of one hour for a one-year storm, with a reduction of up to 60 percent suspended material. For lesser rains, reductions of 45 percent in BOD and 65 percent in suspended material can be expected.

Storage of stormwater can also be accomplished by using underground geologic formations or man-made tunnels. The Cook Co. Flood Control Coordinating Committee (1972) originally recommended the temporary underground storage of waters from severe storms. The system that has been developed consists of 120 miles of conveyance tunnels intercepting 640 overflow points in a 375-mile² area and storing it at depths of 150-290 feet in Silurian dolomite for subsequent treatment. The 1972 price of this project was $1.22 billion. Akron, Ohio has developed underground void space (effectively 33 percent) storage in a void filled with washed gravel and enclosed in a watertight plastic liner (Lager and Smith 1974). The system collects combined sewage overflow and holds it for dewatering to a treatment plant. A study by the City of St. Paul, Minnesota (1973) proved the potential benefits of underground storage in geologic formations, but a system has not yet been developed.

Utilization of existing storage capacity within a drainage conduit system has been effectively used by Seattle, Washington in their Computer Augmented Treatment and Disposal (CATAD) system (Leiser 1974). The system is computer-directed to maximize the storage volume available in trunk and interceptor sewers. Up to 80-90 percent of peak loading has been reduced. This totals an average decrease of 68 percent for the eight parameters shown in Table 4. Leiser (1974) analyzed the overall system performance by stating "as storm intensities increase, the relative performance improvement diminishes with the more improved control systems because the maximum amount of additional storage is limited by the volume within the collection system." The total system during the test period reduced overflow volumes by 73.6 percent in supervisory control, 97.2 percent in automatic control, and 85.8 percent under combined advanced control modes. During the course of the study, the Duwamish River (receiving stream) increased in dissolved oxygen by 1-2 mg/l, and decreased in coliform counts by 50 percent.

Detroit, Michigan has developed a computerized system through which an operator can anticipate runoff and increase the treatment plant pumping rate to allow for greater interceptor storage (Lager and Smith 1974). Minneapolis-St. Paul utilizes inflatable Fabridams which deflate when storm flows threaten to surcharge the sewer line. A total overflow volume reduction of 35-70 percent has been achieved, dependent upon the storm (Lager and Smith 1974); and the number of overflows has been decreased by 58 percent, with total overflow duration down 88 percent including almost total capture of spring thaw runoff. Anderson (1970) described the Minneapolis-St. Paul system and discussed the objectives of establishing such a system with its associated water quality monitoring network. A similar system was proposed in Cleveland, Ohio (Pew et al. 1973), but subsequent information is not available. One further method of in-system utilization of storage is discussed by Stem (1975) and involves storage in over-sized pipes, enlarged storm drains, and/or inlet structures with controlled release. These methods are seldom used because of high cost and their tendency to clog, but present an easily maintained alternative for areas under development where installation does not present a problem.

Storage tanks, whether located above ground or below, provide an attractive alternative to methods requiring an unavailable amount of land. Tanks will normalize flow and provide sediment storage volume, but tend to be expensive to design and construct and are often logistically impossible to locate (Dunbar and Henry 1966). A U.S. EPA demonstration project utilizing a 3.9-million gallon tank to intercept combined sewer overflow from 570 acres in a residential and commercial area of north Milwaukee, Wisconsin proved successful (City of Milwaukee 1975), with five years of data showing that tanks should be an effective means of decreasing combined sewer discharges. From November 1971 to October 1972 the tank prevented 67 percent of the possible combined sewage and 70 percent of the associated suspended solids from being discharged to the Milwaukee River, with other parameters showing similar removal percentages. Studies done by the City of Milwaukee on BOD and SS removal indicate that removals could range from 30 to 80 percent for tanks sized at 1-6 million gal/mile² drainage area, and further indicate that removal due to volumetric retention is much more significant than removal due to sedimentation. Continued use could provide removal efficiencies of 79 percent BOD and 80 percent SS at an approximate annual maintenance cost (in 1975) of $30,000.

Columbus, Ohio has had storm standby tanks at a Whittier Street site since 1932 to provide partial treatment of combined sewer overflows (Dodson et al. 1971). These tanks were modified in 1967-68 to remove settled sludge to the treatment plant. In 24 events from May 1968 to June 1969, the tanks were re-

TABLE 4. *Effect of in-system storage on pollutants discharged to receiving waters**

Parameter	Decrease in Loading (%)
NH_3-N	58
NO_3-N	80
PO_4	68
Settleable solids	66
SS	65
VSS	68
BOD	64
COD	76
Average for eight parameters	68

*After Leiser (1974)

sponsible for reductions of total suspended solids by 15-45 percent, settleable solids by 20-80 percent and BOD by 15-35 percent, and for an increase in DO by 8-200 percent, all with detention times of 20-180 minutes. Dodson et al. (1971) conclude that "substantial reductions in concentrations of solids and BOD can be expected by operation of the modified standby tanks," principally through reductions at times of increased discharge.

An underwater storage tank was developed for use in Cambridge, Maryland for temporary storage of combined sewage overflow before treatment (Melpar 1970). The 200,000-gallon flexible underwater tank was located 1,300 ft offshore in the Chaptank River. The system was capable of collecting 96 percent of the average annual overflow at a 1970 cost of less than $1.85/1,000 gal, preventing a discharge of 7,136 lb of BOD annually. Unfortunately, public reaction was against the facility and finally caused the $159,033 system to be dismantled before thorough evaluation could be completed.

A system similar to the above was successfully demonstrated in Sandusky, Ohio (Rohrer Associates 1971). The system consisted of two 100,000-gal collapsible tanks anchored in Lake Erie to collect combined sewage overflows from a 14.86-acre residential area. The one-year evaluation of the project showed that 988,000 gallons of sewage were contained for subsequent treatment at a cost of $1.88/gal of storage, a relatively high cost. Future projections included decreasing this cost to $0.40/gal, if possible.

Other tank systems have been installed and successfully operated at West Berlin, Germany (Weibel 1969); Lancaster, Pennsylvania, a silo structure with other physical measures (Huber et al. 1973); and Jamaica Bay in New York City, Humboldt Avenue in Milwaukee, and Washington, D. C. (Lager and Smith 1974). A system of underground storage tanks has also been proposed for San Francisco at shallow depths near the shoreline (Poertner 1976b).

Removal of Contaminants from the System

Once contaminants reach a hydraulic conduit for removal elsewhere, they may in fact settle out, become entangled in waste material, or move very slowly toward the discharge point. Several practices are available to clean collection points and encourage movement through the system.

Sartor and Boyd (1972), as a result of specially conducted field studies, concluded that "catch basins (as they are normally employed) are reasonably effective in removing coarse inorganic solids from storm runoff but are ineffective in removing fine solids and most organic matter," the primary polluting agents. These materials gather in catch basins and remain during interim periods, often turning septic, and can have a substantial impact when a storm event washes this material into a drainage system (AWPA 1969). Sartor and Boyd reported that "effluents from dirty catch basins exert a significant pollutional load on receiving waters and/or waste treatment plants." The APWA (1969) sampled catch basins after several days without rain and found BOD_5 values ranging from 35 to 225 ppm. This result led to their conclusion that "catch basins may be one of the most important single sources of pollution from stormwater flows". Solutions to the problem of "septic" catch basin pollutant introduction into stormwater include frequent and thorough cleaning, elimination of use, and better design (Adgate 1976).

Many pollutants and sediments settle out prior to arriving at a treatment or discharge point. Flushing of streets and sewers presents a management practice capable of partially normalizing pollutant flow to a treatment plant. The object of a flushing exercise is to minimize the quantity of solids deposition during dry weather periods so that a "first flush" of pollutants will not occur with a stormflow (Adgate 1976), but instead the pollutants will be hydraulically conveyed to a treatment facility. A study on sewer flushing done by the FMC Corp. (1972) showed that cleansing efficiency is dependent upon flush volumes, flush discharge rate, sewer slope, sewer length and diameter, and sewage flow rate. They found that flush waves generated using flush volumes ranging from 300-900 gal at average release rates from 200-3,000 gal/min were found to remove 20-90 percent of the solids deposited in the 800-ft long test sewers (12-18 inches in diameter). A study of the Dorchester Bay area of Boston, Massachusetts (Pisano 1976) showed that daily flushing of 100 critical segments of sewer reduced total daily predicted solids deposition in 3,000 segments by 50 percent. A Sartor and Boyd (1972) flushing test showed that 80-99 percent of the flushed street solids larger than 243 microns were removed by a catch basin, but after five minutes of flushing, none of the material less than 43 microns was left in the basin. In general, flushing, if properly done, can be effective in removing material from a street, out of a catch basin, or through a sewer to a treatment plant.

Once sediments and pollutants reach a sewer, there is often a tendency for them to settle and become part of a "first flush" problem when the next storm arrives. In response to this phenomenon, polymers have been developed for injection into sewage flow to reduce pipe friction and thereby increase flow rates by reducing viscous friction (Kirkpatrick 1970). In tests, flow increases of 140 percent were attained with polymer concentrations of 150-200 mg/l. A prototype polymer injection test was conducted by the Dallas Water Utilities District on a 24-inch sewer line and was found effective in reducing sewer head if injected when the sewer was surcharged. Additionally, the polymer was found nontoxic, but it did tend to increase sedimentation, exert a BOD_5 of 1.56 mg/l, and reduce water retention capacity of sewage sludge.

TREATMENT OF DISCHARGE

In areas that are highly developed and have existing combined or separate sewer systems, a large-scale structural treatment method may be the only feasible way to eliminate pollutants prior to stormwater-related discharges. These practices are generally very expensive and require a specific engineering design to make it compatible with the system within which it is placed. There are three types of treatment — physical, chemical, and biological — but most systems will use a combination of treatments to acquire the best overall water quality prior to discharge. As with the costs discussed in the previous sections, prices of treatment practices are difficult to evaluate because they refer to only one specific set of circumstances, but relative price ranges can be implied from reported figures. Representative costs are summarized for twenty projects in Appendix B.

Physical Treatment

Physical methods of treatment are generally very effective for sediment removal and are easily adapted to automatic operation for rapid storage and shutdown, but they are generally less effective in the removal of organics and nutrients than biological or physical-chemical methods (Amy et al. 1974). There are five methods of physical treatment generally in use today. These are settling, filtration, screening, dissolved air flotation, and swirl regulators/separators, in addition to various combinations of these used in sequence.

Primary clarification settling can usually be about 30 percent effective for removal of BOD and about 60 percent for suspended solids (Lager and Smith 1974). The detention basin system installed at Chippewa Falls, Wisconsin (discussed in a previous section) has shown a removal efficiency of 18-70 percent SS and 22-74 percent BOD_5 (Lager and Smith 1974). The Boston Cottage Farm Stormwater Detention Facility began operation in May of 1971 at a total cost of $6.3 million. The facility consists of six parallel settling basins with a maximum capacity of 1.3 million gal. Treatment costs are $4.81/gal, including all phases of the operation and chlorination prior to discharge, and annual operation and maintenance costs of $65,000 (Lager 1974). Removal efficiencies for this system have been reported by Lager (1974) to be: 100 percent for coliform, 85 percent for settleable solids, 40 percent for SS, and erratic for BOD_5. Colston (1974) recommended settling of Durham, N.C. urban runoff because it is relatively inexpensive and can produce removal efficiencies of 61 percent for COD, 77 percent for SS, and 53 percent for turbidity. Shapiro and Pfannkuch (1973) conducted settling experiments on runoff water from the Minneapolis Chain of Lakes and concluded that a decrease in total phosphorus by settling alone would range from 13-68 percent. The principal disadvantage of settling systems is that they require a large area in which to be installed and for this reason are often not feasible for urban areas.

Most available literature on physical filtration discusses the Cleveland, Ohio dual-media, ultra high rate (UHR) filter system (Amy et al. 1974, Lager and Smith 1974; Nebolsine and Vercelli 1974; Nevolsine et al. 1972). The Cleveland pilot program was at the Southerly Wastewater Treatment Plant and was designed to evaluate the system's effectiveness on combined sewer overflows. The basic Cleveland system consists of prescreening followed by filtration through five ft of number 3 anthracite coal, over three ft of number 612 sand, and yields removal efficiencies of 93 percent SS and 65 percent BOD (Nebolsine et al. 1972) with the addition of a polyelectrolyte. The 1972 capital cost of this project was $23,000/mgd with total annual operation and maintenance costs of $3,880/mgd. Lager and Smith (1974) summarized data from seven projects involving filtration of some type and found removal efficiencies as high as 100 percent (Table 5). These figures show the high treatment efficiencies that can be derived from filtration. Other advantages include lowland area requirements, and simplified automatic operation (Nebolsine and Vercelli 1974).

Screening of urban wastewater through screens of various sizes provides an effective practice generally for coarse and medium grain particles. The efficiency of screens treating normal waste with a normal distribution of sizes will increase as the size of the screen openings decreases and as the thickness of the screen mat increases (Lager and Smith 1974). Several studies utilizing some type of screen were reviewed by Lager and Smith (1974) to determine removal efficiencies. It should be noted that the studies involved did not necessarily address runoff from storm-related events, but generally involved combined sewer overflow and treatment process effluent. The demonstration projects evaluated by Lager and Smith were at Philadelphia, Pennsylvania (Cochrane Division 1970 and 1972); Milwaukee, Wisconsin (Rex Chainbelt, Inc. 1972); Cleveland, Ohio (Nebolsine et al. 1972); Lebanon, Ohio (Bodien and Stenberg 1969); Chicago, Illinois (Hulme 1970); Letchworth, England (Water Pollution Research 1966); and East Providence, R.I. (Fram Corp. 1969). Results from these tests show that microstrainers average removal efficiencies of 70 percent SS and 60 percent BOD_5, while fine screens have efficiencies of 38 percent SS and 16 percent BOD_5. Rotary fine screen efficiencies ranged from 60-90 percent settleable solids, 30-32 percent SS and 16-25 percent COD. Additionally, Lager and Smith report that 25-micron screens average 75-percent SS removal and 400-micron screens average only 25-percent SS removal.

The City of Portland, Oregon (1971) utilized rotary screening on combined sewage overflows as part of a U.S. EPA demonstration project. The 105-micron screening had an effective open area of 47.1 percent. Removal efficiencies for storm-related overflows were 54.8 percent settleable solids, 26.6 percent SS, and 15.5 percent COD, with the effectiveness decreasing in the presence of oil and grease or paint. Additional studies by Amy et al. (1974), Nebolsine and Vercelli (1974), Nebolsine et al. (1972), and Vitale and Sprey (1974) yielded removal efficiencies of various screening devices shown in Table 6. The advantages, therefore, of screening as a physical treatment method are: effective solids removal, small land requirements, and the ability to be placed in remote areas. However, the major disadvantage is that it is not effective in reducing organic or oxygen-demanding material.

Dissolved air flotation (DAF) is a physical process whereby injected air bubbles attach to particulate matter in water and raise it to the surface of the retention area where skimming occurs (Bursztynsky et al. 1975; Lager and Smith 1974; White and Cole 1973). A demonstration DAF facility was funded by U.S. EPA for the Baker Street treatment plant, San Francisco, California. The DAF process here involves trash racks, short-term sedimentation, DAF, and chlorination in a 24-mgd facility draining 167 acres (White and Cole 1973). The problem in this area is that any rainfall over a 0.02-inch/hour intensity resulted in combined sewer overflows into San Francisco Bay. The inital evaluation of the facility during dry weather flow (2.5 mgd) was reported by White and Cole (1973). They found that alum doses to aid flocculation could increase system effectiveness and that removal efficiencies decreased with

TABLE 5. *Removal efficiencies of seven projects involving some type of filtration**

Parameter	Removal Efficiency (%)
BOD	44-93
COD	35 (one study)
Total P	90-95
Turbidity	79-96
SS	70-100

*From Lager and Smith (1974)

TABLE 6. *Removal efficiencies for selected parameters by screening devices*

Parameter	Removal Efficiency (%)
BOD; COD	4-50; 4.5-41
Organic material	10-70
Settleable solids	50-74
SS	15-90

increased liquid load because of the increased turbulence. The efficiencies shown in Table 7 reflect the function of liquid load on effectiveness. Engineering Sciences, Inc. (1971) studied the performance of the Baker Street facility with raw sewage; ranges and averages for removal efficiences are presented in Table 8. A subsequent wet weather evaluation of the facility was done by Bursztynsky et al. (1975) at a wet weather loading rate of 145 m^3/m^2 (day) and an alum dosage of 75 mg/l. This evaluation yielded the removal rates shown in Table 9. Bursztynsky et al. predicted that the Baker Street structure should intercept about 113 overflows annually. The total 1970 cost of the facility was $2,093,655 (White and Cole 1973).

Dissolved air flotation facilities have also been installed in: Milwaukee, Wisconsin; Racine, Wisconsin; and Fort Smith, Arkansas (Lager and Smith 1974). Results from these and from studies by Amy et al. (1974) and the Rhodes Technology Corp. (1970) are summarized in Table 10. The advantages of a DAF system are its: effectiveness in removal of solids, phosphorus, and oxygen-demanding substances; short detention time of about 10-30 minutes versus four hours for a clarifier; enhancement of the sedimentation process; increased performance through alum addition; and easy automatic operation. The major disadvantages of the DAF system are that it is not effective at removing nitrogen or oil and grease and it requires a relatively large area for installation.

The final single feasible physical treatment system is swirl regulators/separators. The swirl unit has no moving parts but instead regulates flow by a central circular weir-spillway while simultaneously treating combined wastewater by swirl action and liquid-solid separation (Field 1976). During high flow, the skimmed flotables from the top of the unit and the heavy solids from the bottom are diverted to an interceptor sewer for subsequent treatment while the high volume supernatant is discharged, the whole process lasting only seconds to minutes. A prototype swirl device was installed in Syracuse, N.Y. to control overflows from a 54-acre residential area (Field 1976). The 3.6-m diameter unit could handle a maximum capacity of 8.9 mgd with a flow through time of only 23 seconds. The results of tests reported by Field showed a total mass loading decrease in suspended solids of 44-65 percent and in BOD of 50-82 percent. The 1976 cost of the Syracuse unit was $55,000 and $2,500/hour plus $2,000 annual operation and maintenance.

A swirl concentration was installed as part of a combination treatment system in Lancaster, Pennsylvania in 1972 to remove solids prior to settling, aeration, and screening (Huber et al. 1973). The cost for the 36-ft diameter chamber was $100,000 (Sullivan 1973). Water quality effects of this swirl unit are not available.

The advantages of using a swirl regulator/separator are its: low relative cost, absence of primary mechanical parts, effectiveness in removal of flotable

TABLE 7. *Effect of liquid load on removal efficiency for selected parameters*

	Removal Efficiency (%)	
Parameter	@1,000 gpd/ft^2	@5,000 gpd/ft^2
Total SS	90	15
Flotables	80	95
BOD; COD	80; 80	30; 35
Ortho PO_4	100	80
Total N	30	20

TABLE 8. *Removal efficiencies associated with the Baker Street Plant, San Francisco, California**

	Removal Efficiency (%)		
Parameter	Maximum	Minimum	Average
Flotables	100.0	60.0	95.2
Settleable solids	93.5	0.0	47.7
BOD	70.5	13.5	46.1
COD	77.0	10.8	44.4
Ortho PO_4	99.0	43.4	80.9
Total N	53.0	0.0	18.4
Oil and grease	63.2	0.0	29.1
Fecal coliform	near 100	99.4	99.9

*From Engineering Sciences, Inc. 1971

TABLE 9. *Removal efficiencies associated with the Baker Street Plant, San Francisco, California as affected by wet weather flow**

Parameter	Removal Efficiency (%)
Total SS	51
Flotable solids	68
Settleable solids	94
Turbidity	66
BOD; COD	82; 40
Oil and grease	0
Kjeldahl N	47
Fecal coliform	near 100

*From Bursztynsky et. al. (1975)

TABLE 10. *Removal efficiencies for dissolved air flotation facilities*

Parameter	Removal Efficiencies (%) With Chemicals	Without Chemicals
Total SS	56-69	70-90
BOD	26-40	42-57
COD	41	45
Total N	14	17
Total P	0-16	69-70

TABLE 11. *Removal efficiencies for the screening/DAF system at Milwaukee, Wisconsin **

Parameter	Removal Efficiencies (%) "First Flush"	Without Chemicals	With Chemicals
SS	72	43	71
VSS	75	48	71
COD	64	41	57
BOD	55	35	60
Total Kjeldahl N	46	29	24

*From Mason (1972)

and settleable solids, and automatically induced operation. The major disadvantages are the amount of space required and the difficulty in removing organic material and nutrients.

Many of the systems utilizing physical methods of treatment combine some of the practices and produce a more effective operation. Racine, Wisconsin has a screening/DAF system developed in 1973 to treat combined sewer overflows at a cost of $1,730,000 ($30,000/mgd) with annual operation and maintenance costing $10,000 (Gupta and Agnew 1973; Lager 1974). The system consists of two modular screening/DAF tanks, with mechanical and drum screens. Removal efficiencies for this system ranged from 60-70 percent BOD and 70-80 percent SS.

A similar 5 mgd screening/DAF system was developed in Milwaukee, Wisconsin to treat combined sewer overflows from a 495-acre residential area (Mason 1972). The wastewater enters the system and is screened through 297-micron screens before the effluent continues to the air flotation chamber. Air bubbles (50 microns in diameter) are injected into the effluent and the liquid-solid separation occurs, sometimes aided by chemical flocs. Mason points out that this system does not remove significant amounts of dissolved pollutants, but will achieve the overall removal efficiencies reported in Table 11. The chemicals used were 20 mg/l $FeCl_3$ and 4 mg/l cationic polyelectrolyte. The total 1972 price for the facility was $90,000 or $18,000/ mgd with a total operating cost of $0.0309 per gallon.

The Lancaster, Pennsylvania study noted previously utilizes several physical processes. The wastewater first goes through full-scale swirl concentration for solids removal, then into a 160,000-ft^3 "silo" tank for settling and aeration, and finally through a microstrainer and chlorination prior to discharge (Huber et al. 1973).

In summary, physical treatment processes for urban stormwater runoff are very effective for particulate removal of flotable and settleable solids, and are generally effective for BOD and COD removal. The units are inexpensive relative to total sewage treatment facilities, but will tend to require large land areas for installation. The units are easily adapted for automatic operation and can be developed to conduct removed contaminants to a treatment plant.

Chemical Treatment

Chemical forms of wastewater treatment usually consist of flocculation assistance and chlorination, generally occurring in combination with some method of physical or biological treatment. Since chemical treatment is usually not a single treatment method, this section will address the mechanics of the process with detailed applications discussed in the previous and subsequent sections.

The process of chemical clarification through flocculation and settling can provide a major portion of pollutant removal from urban stormwater runoff. Through the use of lime, Fe or Al salts, polyelectrolytes, or combinations thereof, flocs or coagulated particles form and settle due to their increased weight relative to the liquid medium within which they are suspended (Lager and Smith 1974). Chemical clarification of raw sewage (for comparison) consistently has been shown to provide 65- to 75-percent removal of organics, with 90- to 98-percent removal of BOD and 80- to 98-percent removal of phosphorus (Lager and Smith 1974). Vitale and Sprey (1974) report that chemical flocs can be effective in heavy metal removal prior to treatment of wastewater. Chemical flocculent effectiveness can be further evaluated in the other sections of the treatment category.

Disinfection through the utilization of some form of chlorine is very effective

(98-99 percent) in destroying pathogenic organisms with only a contact time of 2-4 min at 5 mg/l for combined sewage (Lager and Smith 1974). Dunbar and Henry (1966) suggest that stormwater may need a dose of 20-30 mg/l with 15-min contact time to make it safe for full-body recreation uses and that perhaps 50 mg/l is required to remove viruses. During a storm-related event, Dunbar and Henry (1966) reported that a treatment system will probably need a chlorine amount sufficient to treat 200 times the dry weather flow.

Pontius et al. (1973) conducted a study at New Orleans, Louisiana to determine the disinfection effectiveness of adding sodium hypochlorite (NaOCL) to drainage pumping station discharge prior to release to Lake Pontchortrain. Sixteen high volume and twenty low volume events were treated during the study. The results showed that total and fecal coliforms were "significantly" reduced, up to 99.99 percent, but rapid recovery of the coliform levels occurred within 24 hours to full pretreatment levels for total coliform and to one order of magnitude less for fecal coliform. The amortized cost of this effort was $53,600/year or $.000051/gal for the chemicals.

To summarize, chemical treatment is seldom used alone, but is generally used as an effective flocculent and disinfectant in combination process treatment. Chemical treatment is a very inexpensive and necessary addition to any treatment process where a desire is shown to eliminate pathogenic organisms.

Biological Treatment

The objective of a biological treatment system is to remove the nonsettleable colloidal solids and to stabilize the dissolved organic matter occurring in urban stormwater runoff, normally accomplished by biologically converting a portion of the organic matter present in the wastewater into cell tissue, which subsequently can be removed by gravity settling (Lager and Smith 1974). Biological systems have not been extensively used for urban runoff treatment because the biomass upon which the treatment process depends must be kept alive between events or allowed to grow again with each new event, a routine which is upset by erratic loading (Lager and Smith 1974; Nebolsine and Vercelli 1974). The most common biological systems are: contact stabilization, high-rate trickling filtration, rotating biological contactors, and treatment lagoons.

The control stabilization method utilizing activated sludge is described by Lager and Smith (1974). Basically, the overflow is mixed with the activated sludge and aerated prior to settling in a clarifier. The concentrated sludge is then again aerated, during which time the organics become stabilized in sludge which is recycled to the contact basin to be mixed with new incoming flow. The whole process takes several hours. A U.S. EPA demonstration project was developed at Kenosha, Wisconsin to demonstrate the effects of a contact stabilization rocess on combined sewer overflows. This project additionally demonstrates the effectiveness of using a dry weather treatment facility as a biomass supply for an adjacent wet weather system. Table 12 lists the removal efficiencies of this system (Rex Chainbelt, Inc. 1973). This system is very effective in SS and BOD_5 removal, but was expensive to develop and is dependent upon a dry weather facility and the sewer system associated with it.

Trickling filters utilize large circular tanks filled with a filter medium such as crushed stone or plastic upon which biological slimes grow. Organic removal occurs as a result of an adsorption process at the surface of the medium (Lager and Smith 1974). The hydraulic loading to the system can be low, high or ultra-high, depending upon the treatment requirements. A U.S. EPA demonstration project was funded at New Providence, N. J. to treat both dry weather flow and combined sewer overflows from heavily infiltrated sanitary sewers. This system is capable of treating extremely variable flows by keeping the biomass continually alive on both the plastic media wet weather filter and the rock media dry weather filters (Lager and Smith 1974). Table 13 lists removal efficiencies for the New Providence Facility and results from a personal communication between Lager and Smith (1974) and Elson T. Killam Associates, Inc. This system appears very effective for SS and BOD (85-95 percent), but tests show no significant removal of total N or P; also, the plastic media proves to be more effective and less expensive than rock (Lager and Smith 1974). The initial 1974 cost of the New Providence System was $1,410,000 (Lager 1974). Further substantiation for the effectiveness of trickling filters is presented by Amy et al. (1974), who reported high rate systems with removal efficiencies of approximately 65 percent for organics and SS.

Rotating biological contactors are basically a cross between a trickling filter system and an activated sludge system wherein biomass is grown on large rotating disks and exposed to combined sewage which it removes by adsorption (Lager and Smith 1974). A literature survey by Lager and Smith yielded removal efficiencies of 60-95 percent BOD and SS, 80-90 percent settleable solids, 40 percent N, and 50 percent P. COD removals of 70 percent or better can be

TABLE 12. *Removal efficiencies for contact stabilization demonstration project at Kenosha, Wisconsin*

Parameter	Removal Efficiency (%)
Total solids	35
Total volatile solids	48
SS	92
VSS	87
Total BOD_5	83
Dissolved BOD_5	68
Total organic C	80
Dissolved organic C	30
Total Kjeldahl N	50
Total PO_4-P	50
Total coliform	91
Fecal coliform	83

TABLE 13. *Removal efficiencies for the New Providence, New Jersey filter medium facility*

Operating Conditions	Removal Efficiency (%) BOD	SS
Dry Weather		
1st year	86	87
part of 2nd year	94	93
Wet Weather		
1st year	64	67
part of 2nd year	87	86

TABLE 14. *Removal efficiencies for bio-disc demonstration project at Milwaukee, Wisconsin*

Parameter	Removal Efficiency (%) Dry Weather	Wet Weather
BOD_5	77	54
COD	70	33
Settleable solids	90	82
SS	77	70
N	38	no data
P	53	no data

maintained for systems treating 8-10 times its dry weather flow. Generally, they found that removal efficiencies are a function of contact time, with efficiencies of 60-70 percent for contact times of less than 15 to 30 min. Detention times of greater than 30 min will yield removal efficiencies up to 60 percent for large increases in loading to the system. A U.S. EPA demonstration project was developed at Milwaukee, Wisconsin to study the application of this system to combined sewer overflows. The results of monitoring this project are listed in Table 14.

This method of treatment proves fairly effective but should have clarification after treatment to remove the sloughed biomass which tends to increase the BOD and COD of the effluent. The advantages of rotating biological contactors are: the ability to handle large rapid flow fluctuations if the biomass is maintained, low power requirements, and cleanliness. The disadvantages are: the requirement for base flow to keep the biomass alive, little biological process control, and need for enclosure in colder climates, as well as additional evaluation to further determine system effectiveness (Lager and Smith 1974).

There are four types of treatment lagoons which utilize biological processes. These are oxidation ponds, aerated lagoons, facultative lagoons, and anaerobic lagoons. The latter will not be discussed because the anaerobic process is not compatible with nonuniform, urban loading (Lager and Smith 1974). In oxidation ponds, a symbiotic relationship exists between algae and bacteria in an aerobic environment generated primarily by oxygen from the algae. Detention time in such a system for combined sewage should be about twenty days. Removal efficiencies vary tremendously, with rates from −50 to 60 percent SS and −10 to 70 percent BOD (Lager and Smith 1974) dependent upon such factors as loading, detention time, oxygen supply, and mixing. In aerated lagoons, the biological process is similar to that in the oxidation ponds but oxygen is supplied mechanically to the treatment process, which usually covers several lagoons in sequence. Lager and Smith reported removal efficiences of 75-95 percent for both BOD and SS, dropping off as detention times drop below five days. Facultative lagoons contain three layers of biological activity: the upper aerobic zone, the middle facultative zone, and the lower anaerobic zone (Lager and Smith 1974). Basically, settled material is stabilized in the anaerobic bottom while dissolved and suspended matter is oxidized in the upper layer, with the middle facultative zone acting as a transition area. This system is usually aided through artificial aeration. Facultative lagoons generally have removal efficiencies of 50-90 percent BOD and 50 percent SS for combined sewage. As might be expected, more attention must be devoted to the facultative system than the other two lagoon types to assure proper operation. Several U.S. EPA demonstration projects have been developed utilizing some form of lagoon treatment. The removal efficiencies of these projects are summarized in Table 15. The major advantage of lagooning for biological treatment is effective removal of BOD, SS and coliforms at a relatively reasonable price. The major disadvantages are the land required for the lagoon and the alteration that must be rendered the biological system.

TABLE 15. *Removal efficiencies of treatment lagoons for various cities**

	Removal Efficiency (%)				
	Springfield, IL	**Shelbyville, IL**		**Mount Clemens, MI**	**E. Chicago, IN**
Parameter	Oxidation Pond	Oxidation Pond	Facultative Pond	Aerated Lagoon - Oxidation Pond	Aerated - Facultative Lagoon
BOD_5	27	47	91	91	50
SS	20	57	-4	92	50
VSS	increased	30	28	–	–
DO	increased	–	–	–	–
P	22	40	69	–	–
N	–	56	62	–	–
Coliforms	72	86	96	–	–

*From Lager and Smith (1974)

In summary, biological systems are very effective at waste removal, but very sensitive to urban runoff. High volume urban storm-related runoff can wash away biomass and/or destroy it because of the toxicity of some of its inherent contaminants, such as heavy metals and road salts. Capital costs for the various biological systems range from $6,445 per mgd for the Springfield, Illinois oxidation ponds to $79,150/mgd for the New Providence, N. J. trickling filter, with operation and maintenance costs of from $0.01/1,000 gal to $0.06/1,000 gal (Lager and Smith 1974). Biological systems, therefore, are not recommended for most urban runoff uses because of sensitivity and high prices relative to physical and chemical treatment processes.

Combination of Treatment Systems

By far the most commonly used combination of treatment processes is the physical-chemical system. This combination usually involves some type of liquid-solid separation with the aid of chemical flocculents and disinfection with chlorine, resulting in a very high quality effluent. Lager and Smith list the unit processes involved in a typical physical-chemical treatment as: chemical clarification, capable of removing 50-70 percent BOD, 90-98 percent SS, and 80-98 percent P; recovery of flocculent aid if lime is used; filtration to remove the flocculated particles and remnant sediment; and carbon adsorption to remove soluble organics, also including regeneration of activated carbon. Systems utilizing this sequence are briefly discussed in Lager and Smith (1974) and the removal efficiencies are reported in Table 16. Albany, N. Y. is the only plant included in the above figures that treats combined sewer overflows. The system operates as follows: raw wastewater contacts powdered activated carbon for organics removal, then is coagulated with alum; the flocculated material is then settled out with the help of a polyelectrolyte and sometimes passed through a tri-media filter (Shuckrow et al. 1973). A total contact time of less than 15 min is required for equilibrium removal of sorbable organics, but a residual nonadsorbable fraction of 10-20 mg/l BOD and 20-50 mg/l COD existed at times in the sewage and could not be removed. Total treatment of raw plus combined sewage can be accomplished in less than 50 min with average removal efficiencies of 94 percent COD, 94 percent BOD and 99 percent SS, resulting in average effluents of 36 mg/l COD, 17 mg/l BOD, and 5 mg/l SS, but P removals of only 31 percent (Shuckrow et al. 1973). Tertiary treatment could be rendered with carbon doses of 500 mg/l, alum at 200 mg/l, and a polyelectrolyte at 2.0 mg/l. The 1973 capital costs for the Albany system were $1,791,300 for 10 mgd and $10,670,100 for 100 mgd with an operation and maintenance cost of $0.19/1,000 gal and $0.12/1,000 gal, respectively (Shuckrow et al. 1973).

Other systems utilizing physical-chemical treatment exist in: Milwaukee, Wisconsin (involving a screening/DAF/chemical coagulant system discussed previously) and Cleveland, Ohio (involving a high rate filtration and alum system discussed previously, capable of removing total P up to 66 percent). Additionally, a microstraining and disinfection system in a Philadelphia, Pennsylvania residential area of 11.2 acres resulted in removal efficiencies of 20-98 percent SS and 25-40 percent COD and TOC at a 1973 cost of $6,750/cfs or $13,100/acre (Glover and Herbert 1973; Kelbaugh et al. 1970). Colston (1974) predicted that alum in addition to quiescent settling could yield removal efficiencies of 84 percent COD, 97 percent SS, and 94 percent turbidity for an urban area of Durham, N. C. Shapiro and Pfannkuch (1973) felt that alum added to a one-hour settling program could remove up to 86 percent total P, increasing to 95-percent removal with two hours of settling. Evans et al. (1968) conducted lab-scale tests on urban runoff from Cincinnati, Ohio and concluded that nonchemical settling and chlorination were not effective in lowering COD, BOD, N, and P, but could reduce coliform bacteria by 99.99 percent. Most literature reviewed suggested alum doses of 10-60 mg/l and chlorine doses of 2-5 mg/l. The advantages of a physical-chemical system are: effective removal of solids, organics, and P; easy adaptation to automatic operation; good resistance to shock loading and urban runoff; rapid startup and shutdown; and little land use requirements. The disadvantages of such a system are: high relative capital costs and operation and maintenance costs, additional chemical costs, and complex operation.

Combination treatment systems using physicalbiological-chemical processes are not common for urban runoff because of the sensitivity of the biological system. Such a physical-biological-chemical system is in use in Mount Clemens, Michigan. The system consists of three multiple-use lagoons in sequence, with the first an aerated storage lagoon; the second an oxidation pond; and the third another aerated lagoon (Lager 1974). Additionally, there is a microstrainer between the first and the second ponds, and high rate pressure filtration and chlorination prior to release from the third pond. Removal efficiencies for BOD and SS are greater than 90 percent. Capital costs for the system in 1974 were $1,080,000 or $5,100/acre of drainage area. The major advantage of this system is high quality treatment, but the disadvantage of biological sensitivity seems to be a major obstacle in its wide acceptance.

In summary, physical-chemical combination systems appear much more attractive from an operational standpoint than a system with physical-biological-chemical processes. A physical-chemical sequence involving liquid-solid separation aided by chemicals, carbon adsorption, and chlorination appears to be an extremely effective alternative for treatment of urban stormwater runoff.

TABLE 16. *Removal efficiencies for physical-chemical systems**

Parameter	Removal Efficiency (%)
BOD_5	90-97
COD	75-96
TOC	74-94
SS	85-100
P	90-99
N	45-98
Coliforms	99+
Turbidity	85-99+

*After Lager and Smith (1974)

CONCLUSIONS

1. Stormwater runoff for urban systems is most efficiently handled in lower density, urbanizing areas by systems incorporated into the development stage before structures prevent their inclusion. In high density, developed areas, runoff is best handled by good "housekeeping" and through one of a series of treatment methods subsequent to collection.

2. Nonpoint sources of pollution present a very strong contribution to total annual pollutant loading to streams and should be addressed before secondary treatment plants are upgraded any further.

3. Discharge of urban stormwater runoff into quiescent waters should be minimized so toxic levels will not be allowed to accumulate.

4. Source control of urban runoff-related pollution is an inexpensive and effective means of reducing on-site pollutant generation or stopping pollutants from leaving the small-scale drainage area in which a disturbance occurs. The cost of controlling pollutants on-site is, in most cases, less expensive than remedial control measures once the pollutants leave the site and move downstream.

5. Collection system control of urban runoff-related pollution generally costs more than source control, but presents alternative management systems in the situation where small-scale, on-site control is not feasible or possible.

6. Treatment of urban runoff is the most expensive method of dealing with the storm-related pollutant problem, but often presents the only alternative for highly developed urban areas where sources and collection control is not possible.

7. The most cost-effective means of urban runoff control for areas not extremely built-up is rapid stabilization of disturbed areas or critical runoff areas combined with detention facilities to hold the associated runoff water for a period of time to allow pollutants to settle out of suspension.

8. The most cost-effective means of urban runoff control for urban areas which are extremely built-up is treatment of the runoff water by physical-chemical processes, generally consisting of settling with added chemical flocculent aids, carbon adsorption, and chlorination.

9. Several popular methods of urban runoff management, including street sweeping, catch basin installation, and biological treatment, have not proven effective as a sole means of treatment, but may prove effective when combined with some other management alternatives.

10. It becomes obvious in reviewing the literature that the setting of water quality standards for nonpoint source pollution will not involve the same philosophical approach as point sources. Nonpoint standards must address periods of high flow when a "design waste load" becomes difficult to evaluate. As a result, an analysis must be done to find which pollutants or associated pollutants are creating the greatest water quality problems on specific reaches of receiving streams, and a load/event limit must be established as a form of nonpoint standard.

11. Public participation in reducing urban runoff-related pollution can involve such activities as reducing litter, detaching roof leaders, keeping vehicles adequately maintained, educating fellow citizens, reducing amounts of fertilizer used, etc.

12. In general, most pollutants, other than sediment alone, are associated with fine-sized particles, less than 246 microns, and most nonsediment loading associated with urban runoff comes from these fine particles.

APPENDIX A

Sediment and Erosion Control Costs, California and Virginia.
After Ateshian (1976) and Holtes et al. (1973)

Category and Procedure/Method	Size	Unit	Total Cost: California	Total Cost: Virginia
Structural Measures				
1. Gravel & Earth Check Dam	1 x 5	ft^3	$ 1.84	–
	2 x 10	ft^3	1.72	–
	2 x 15	ft^3	0.83	–

Category and Procedure/Method	Size	Unit	Total Cost California	Virginia
2. Rock Riprap Check Dam	2 x 5	ft^3	7.00	$ 5.99
	3 x 10	ft^3	6.71	5.74
	4 x 15	ft^3	6.80	5.87
	5 x 20	ft^3	8.17	6.96
3. Concrete Check Dam	2 x 5 x 4	yd^3	598.00	541.00
	6 x 10 x 8	yd^3	288.00	259.00
	5 x 18 x 14	yd^3	261.00	233.00
	7 x 20 x 20	yd^3	217.00	195.00
4. Concrete Chute	6 x 40	ft^2	5.40	4.72
5. Diversion Dike	15	yd^3	12.93	10.65
6. Erosion Check-Jute	4 x 152	ft	3.43	2.65
7. Filter Berm	30	ft^3	10.63	9.87
8. Flexible Down Drain	24" Ø x 300'	ft	7.34	7.03
9. Flexible Erosion Control Mats	4" x 25' x 1,320'	ft^2	1.18	1.11
10. Gabions	10	yd^2	30.10	24.82
	100	yd^2	15.50	13.85
	1,000	yd^2	12.67	11.35
11. Level Spreader	15	ft	3.80	3.16
	44	ft	1.90	1.57
	78	ft	1.63	1.36
12. Sandbag Barrier	180	sacks	3.10	2.44
13. Sectional Down Drain	24" Ø x 40'	ft	14.55	11.85
	24" Ø x 234'	ft	10.91	9.13
14. Sediment Retention Basin	6 x 30	ft^3	13.78	11.40
	7 x 30	ft^3	12.88	10.90
	8 x 40	ft^3	10.51	8.99
15. Storm Sewer Inlet Protection	straw	bale	7.86	6.62
16. Gravel Weir	8" x 4' x 6'	weir	10.44	8.99
Vegetative Measures				
17. Chemical Soil Stabilizer	10	acre	1,300.00	1,250.00
18. Excelsior Mat	1	acre	12,200.00	10,200.00
19. Hydroseeding	1	acre	858.00	–
	10	acre	427.00	–
	30	acre	344.00	–
20. Fumigation (Methyl Bromide)	10	acre	2,344.00	–
21. Jute Mesh (Ludlow)	1	acre	7,700.00	6,700.00
22. Sodding	1	acre	14,800.00	14,300.00
23. Sod Plugs – 4 sq. in.	1	acre	11,300.00	10,300.00
24. Straw or Hay	10	acre	1,200.00	1,100.00
25. Wood Chips				
a. 3 inch	1	acre	8,000.00	7,200.00
b. ¾ inch	1	acre	3,100.00	2,800.00

Appendix A continued.

Category and Procedure/Method	Size	Unit	Total Cost	
			California	Virginia
Removal of Sediments				
26. Excavation/Removal				
a. Sediments from Streets		yd^3	$ 8.00	–
b. Sediments from Basement		yd^3	77.00	–
c. W/bucketline from Sewers		yd^3	144.00	–
d. W/vactor from Sewers		yd^3	68.00	–
e. Sediments from:				
(1) Reservoir (capacity in millions)	0-.5	yd^3	1.40	–
	.5-1	yd^3	1.15	–
	1-2	yd^3	2.40	–
	2-3	yd^3	2.00	–
	3-4	yd^3	1.75	–
	4-6	yd^3	1.55	–
	6-10	yd^3	1.30	–
	10+	yd^3	1.20	–
(2) Debris Basin	0-.02	yd^3	2.55	–
	.02-.04	yd^3	2.00	–
	.04-.06	yd^3	1.60	–
	.06-.08	yd^3	1.40	–
	.08-.10	yd^3	1.25	–
27. Dredging	200 yd^3/hr.	yd^3	0.40	–
	400 yd^3/hr.	yd^3	0.33	–
	1,500 yd^3/hr.	yd^3	0.17	–
28. Water Treatment				
a. Filtration	1	10^6 gal	87.00	–
	5	10^6 gal	50.00	–
	10	10^6 gal	38.00	–
	50	10^6 gal	23.00	–
b. Coagulation & Filter	1	10^6 gal	295.00	–
	5	10^6 gal	180.00	–
	10	10^6 gal	145.00	–
	50	10^6 gal	87.00	–

APPENDIX B

Collection and Treatment System Costs

Project	Method/Source	Cost: Capital: Total	Cost: Capital: Per Unit	Cost: O & M (Per Unit)
Chippewa Falls, WI	Detention Basin, U.S.-EPA (1972)	$610,067	$ 6,779/acre	$ 7,300/year
Chicago, IL	Tunnel Storage, Cook Co. Flood Control Coord. Comm. (1972)	$1.22 billion	$ 5,083/acre	–
Cambridge, Maryland	Underwater Tank, Melpar (1970)	$159,033	$ 7,850/acre	$ 1.85/1,000 gal.
Sandusky, Ohio	Underwater Tank, Rohrer Assoc. (1971)	–	–	$ 1.88/gal
Boston, Cottage Farm	Detention, Lager (1974)	$6.3 million	$ 404/acre	$65,000/year
Cleveland, Ohio	Ultra-high Filtration, Nebolsine et al. (1972)	–	$23,000/mgd	$ 3,880/mgd
San Francisco, Baker St.	Dissolved Air Flotation, White and Cole (1973)	$2.094 million	$12,539/acre	–
Syracuse, NY	Swirl Regulator/Separator, Field (1976)	$109,000	$ 2,018/acre	$ 2,000/year
Racine, WI	Screening/DAF, Lager (1974)	$1.73 million	$30,000/mgd	$10,000/year
Milwaukee, WI	Screening/DAF, Mason (1972)	$ 90,000	$18,000/mgd ($181/acre)	$ 0.0309/gal
New Orleans, LA	Sodium Hypochlorite, Pontius et al. (1973)	–	–	$53,600/year or $ .000051/gal
New Providence, NJ	Trickling Filter, Lager and Smith (1974)	$1.41 million	–	$.061/1,000 gal
Kenosha, WI	Contact Stabilization, Rex Chainbelt (1973)	$1.566 million	$ 1,710/acre	$.048/1,000 gal
Milwaukee, WI	Rotating Contractor, Lager and Smith (1974)	$312,000	$ 8,940/acre	$.044/1,000 gal
Shelbyville, IL	Oxidation Pond, Lager and Smith (1974)	$2.6 million	$ 5,100/acre	–
Springfield, IL	Oxidation Pond, Lager and Smith (1974)	$432,000	$ 250/acre	$.01/1,000 gal
Mt. Clemens, MI	Aerated Lagoon, Lager and Smith (1976)	$1.08 million	$ 5,100/acre	–
Albany, NY	Physical-chemical Shuckrow et al. (1973)	$1.79 million for 10 mgd $10.67 million for 100 mgd		$.19/1,000 gal $.12/1,000 gal
Philadelphia, PA	Microstrain/disinfectant, Glover and Herbert (1973)	$146,000	$13,000/acre	–

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ADDITIONAL REFERENCES (ANNOTATED)

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1975. Practical alternatives in storm runoff control. *in* Proceedings: National Symposium on Urban Hydrology and Sediment Control; University of Kentucky, July 28-31, 1975. Univ. Ky. Rep. UKY BU 109.

Alternatives to conventional hydraulic conduit removal of stormwater off-site are discussed. Practices discussed include ponding, roof storage, parking lot retention, infiltration, and porous pavements.

BURGESS AND NIPLE CONSULTING ENGINEERS
1969. Stream pollution and abatement for combined sewer overflows — Bucyrus, Ohio. Fed. Water Qual. Adm. Rep. 11024 FKN 11/69.

Various alternative measures for control of combined sewer overflows for Bucyrus are examined. Information is presented on the nature of the overflow problem and solution proposals are made with cost estimates included. The study recommends a system utilizing interceptor sewers and biological treatment lagoons for an approximate cost of $5.2 million.

DAVIS, W. J. AND A. T. BAIN
1975. Watershed management in Montgomery Co., Maryland: A Case Report. *in* Proceedings: National Symposium on Urban Hydrology and Sediment Control; University of Kentucky, July 28-31, 1975. Univ. Ky. Rep. UKY BU 109.

The Montgomery Co. watershed management program is described and aspects of the program are discussed. Examples are given of projects within the county which were implemented under this program, and associated problems are discussed. The main purpose of the Montgomery Co. effort is to structurally control runoff from the 10- to 50-year return interval storms, in addition to nonstructurally controlling activities in the floodplain.

FIELD, R. AND E. J. STRUZESKI
1972. Management and control of combined sewer overflows. J. Water Pollut. Control Fed. 44(7):1,345-1,393.

This report presents an overview of the Storm and Combined Sewer Pollution Control Research, Development, and Demonstration Program under the U. S. Public Health Service. Basically, a state-of-the-art summary is given of both source and treatment systems for control of storm-related pollution. Some advantages and disadvantages of the systems are discussed.

GESSLER, J.
1976. The dilemmas of setting sediment standards. *in* Proceedings of the Third Federal Interagency Sedimentation Conference; Denver, March 22-26, 1976. Sediment. Comm. Water Resour. Counc.

The author discusses the "biotic and geomorphic" aspects of setting sediment standards. Caution must be exercised in not setting the standards at a nonenforceable level. Standards should consider grain size distribution, inorganic sediments, and organic sediments, and should be within the range of natural fluctuations.

HOLT, C. L. R., JR.
1973. The sediment problem in Wisconsin's streams. *in* The Governor's Conference on Erosion and Sediment Control: Proceedings; Madison, April 26-27, 1973. Univ. Wis.-Extension and State Board of Soil and Water Conserv. Dist.

Sediment is considered a pollutant in Wisconsin statutes. Soil loss in Wisconsin varies from 3-3,500 tons/mile^2 with an average of 100 tons/mile^2. Also about 80-90 tons/mile^2 of material is carried in solution in the state's groundwater.

JENS, S. W. AND H. M. REITZ
1975. Some notes on changing approaches to urban stormwater management. *in* Proceedings: National Symposium on Urban Hydrology and Sediment Control; University of Kentucky, July 28-31, 1975. Univ. Ky. Rep. UKY BU 109.

Various aspects of urban, highly developed stormwater systems are discussed, including the phases involving interception, collection, storage, treatment, and disposal. Details are discussed and examples cited for some of the above aspects.

ROFFMAN, H. K., A. ROFFMAN, B. D. MCFEATERS, AND J. R. NORRIS
1975. The effect of large shopping complexes on quality of storm water runoff. *In* Proceedings: National Symposium on Urban Hydrology and Sediment Control; University of Kentucky, July 28-31, 1975. Univ. Ky. Rep. UKY BU 109.

A literature survey was conducted to determine the nature of the water quality problem of concentrated commercial establishments and vehicle-related pollutants. Analyses were also evaluated for rainfall, snowfall, and sediments. The authors concluded that properly designed and located shopping complexes should not adversely affect water quality.

VAN WEELE, B.
1974. Management of flood control and drainage in the urbanizing zone. *in* Proceedings: National Symposium on Urban Rainfall and Runoff and Sediment Control; University of Kentucky, July 29-31, 1974. Univ. Ky. Rep. UKY BU 106.

A master plan is being developed for flood control and drainage in the 400-mile^2 Fairfax Co. area west of Washington, D. C. The plan is discussed and future work on the project is outlined.

WALLER, D. H. AND W. A. COULTER
1976. Winter runoff from an urban catchment. Research Ont. Minist. Environ. Res. Rep. No. 41.

Information about winter runoff and snowmelt was obtained for a 163-acre combined sewer area in Halifax, Nova Scotia. Natural and cultural data were collected and evaluated.

WANIELISTA, M. P., Y. A. YOUSEF, AND W. M. MCLELLON
1975. Transient water quality responses from nonpoint sources of pollution. Fla. Tech. Univ., Orlando, Fla. Paper presented at the 48th Annual Conf. of the WPCF, Miami Beach, Fla. October 7, 1975.

Some literature reviewed shows that often water downstream from urban areas is controlled by nonpoint source inputs. The authors cite two studies in Florida on mass loadings and lakes, and suggest that loading standards should be developed in addition to concentration standards.

TECHNICAL BULLETINS (1974-76) *

No. 75 Surveys of lake rehabilitation techniques and experiences. (1974) Russell Dunst, Stephen M. Born, Paul D. Uttormark, Stephen A. Smith, Stanley A. Nichols, James O. Peterson, Douglas R. Knauer, Stevens L. Serns, Donald R. Winter and Thomas L. Wirth

No. 76 Seasonal movement, winter habitat use, and population distribution of an east central Wisconsin pheasant population. (1974) John M. Gates and James B. Hale

No. 78 Hydrogeologic evaluation of solid waste disposal in south central Wisconsin. (1974) Alexander Zaporozec

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