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Water Quality Characteristics of Storm Sewer Discharges and Combined Sewer Overflows

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INTRODUCTION

With increasing urban development and more stringent water quality standards for receiving streams, urban storm runoff has become recognized as a significant source of pollution. This circular, which is based upon a review of pertinent case studies, emphasizes the water quality aspects rather than the quantity of storm water and combined sewer overflows.

It summarizes the characteristics of combined and separate storm sewer discharges, the storm water pollution load estimates and models, the impact of storm runoff on receiving waters, and methods and estimated costs for pollution abatement. For those consulting engineers, planners, and state and municipal agencies with responsibilities for minimizing the impact of urban runoff on Illinois streams, this information should provide a better understanding of the complexities involved in developing and financing needed treatment.

Until the past decade or so, only the quantitative aspects of storm water discharges were the primary concern of design engineers, though mention of the quality aspects of storm runoffs appeared sporadically in the technical literature of the 1940s and 1950s. Recognizing urban storm runoff as a significant source of pollution, the U. S. Public Health Service authorized several demonstration projects. Results of studies performed by consulting engineers, municipal agencies, university research teams, and state organizations have been reported as part of the Water Pollution Control Series published by the Water duality Office of the Federal Environmental Protection Agency. These and other sources cited in this review are listed at the end of this publication. Also, a list of additional references has been included to permit examination of related research activities if desired.

This report has been prepared under the guidance of Ralph L. Evans, Head of the Water Quality Section of the Illinois State Water Survey, and under the general supervision of Dr. William C. Ackermann, Survey Chief. Consideration of the quality of storm and combined sewer runoff began as a part of the Survey's effort to compile a data base for use in developing water quality management prediction models for river basins that would encompass the characteristics of urban storm runoff.

QUALITY CHARACTERISTICS

Many studies involving the hydraulic characteristics of urban storm runoff have shown the difficulty of collecting storm water within sewers and have pointed out the necessity of overflows. In the past the principal interest was to develop ways to get the storm water out of the urban area and into a water course. Now, with concern for quality of the water courses, the problem is not only to remove the storm water but also to minimize pollution to the receiving stream.

Palmer[1] found in Detroit, Michigan, that no satisfactory reduction in the number of storm overflow occurrences can be made by any reasonable increase in interceptor capacity. Neither is there any satisfactory reduction in the duration of storm overflows by increasing overflow capacity. McKee[2] found in the Boston, Massachusetts, area that storm water runoff equal to dry weather sanitary sewage flow is produced by a rainfall intensity of approximately 0.01 inch/hour after impervious surfaces were wetted. He estimated that with combined sewer interceptors designed to collect flows as great as 9 times the dry weather flow, 82 percent of the incoming sewage would overflow from storms of 0.5 inch/hour. Camp[3] brought to focus the need for chlorination of storm water for public health reasons. Complete separation of sanitary and storm sewers and treatment are now considered to be the ultimate but unlikely solution for the control of pollution from surface runoff.

The quality and quantity of storm runoff will depend on several factors. Intensity, duration, and areal extent of storms, and the time intervals between successive storms have significant effects both on the quantity and quality of runoff. Land contours, land uses, population densities, incidence and nature of industries, size and layout of sewer systems, and other factors also have their influence.

Studies on storm water qualities differ widely in pattern and background conditions. Therefore observations for combined sewer or separate storm sewer overflow characteristics cannot be consolidated as representative conditions throughout the United States.

Data obtained from the various studies pertaining to the quality characteristics of combined overflows and separate storm sewer overflows are presented in table 1. Brief descriptions, where available, of the drainage areas contributing to these runoff characteristics are given below.

Combined sewer drainage areas are described as follows:

Baltimore, Maryland.[4] The main sewer serving the study area drains 177 acres. Average slope of the drainage basin is 3.0 feet per 100 feet. Thirty percent of the drainage area is impervious. The soil varies from red clay to light gravelly loam. All the area was developed by the construction of private detached dwellings.

Bucyrus, Ohio.[5] The drainage basin represents a typical small midwest community with a combined sewer system serving an area of 90 square miles. The city is located on an end moraine and the topography is generally flat to slightly rolling. The mean annual temperature is 51 F and the mean annual precipitation is 36 inches. The city has a population of 13,000 and is moderately industrialized.

Cincinnati, Ohio.[6] The combined sewer watershed investigated is 2380 acres of rolling terrain within the city of Cincinnati. The area is characterized by two main valleys running approximately east and west. Most of the commercial and industrial sections are located in these valleys; the residential housing is found on the ridges. About 55 percent of the area is residential, 17 percent commercial, 5 percent industrial, and the rest open land and parks. Population of this area according to 1960 census was 26,000 with an average of about 11 persons per acre.

Detroit, Michigan.[1] Metropolitan area. No general description of the area studied is available.

Detroit, Michigan.[1] The Detroit Conners Creek combined sewer system was studied. The topography is flat. The sewer, located in the northeast portion of

Table 1. Summary of Characteristics of Combined and Separate Storm Sewer Discharges

Location	pH	Suspended solids *(mq/l)*	i/olatile suspended solids *(mq/l)*	COD *(mq/l)*	BOD *(mg/l)*	Total nitrogen *(mq/l)*	Total phosphorus *(mq/l)*	Total coliform *(MPN/100ml)*
			Combined Sewer Discharges					
Baltimore, Md.[4]	-	396-2509	26.3-57.9**	-	-	-	-	-
Bucyrus, Ohio	-	306-675	96-390	-	31-177	0.5-l6.9†	2.0-15.1	-
Cincinnati, Ohio[6*]	-	450-1460	30-280	96-2000	130-700	-	-	-
Detroit, Mich.[1]	-	250	50-200	-	50	-	-	i*.3X10^6
Detroit, Mich.[7]	-	260-510	92-310	-	92-410	6.0-9.9	10.1-34.0	-
Philadelphia, Pa.[8]	-	1-15	-	-	36-148	-	-	1X10^7-1X10
Portland, Ore.[9]	4.5-6.0	70-325	57-166	138-324	57-155	3.7-7.0	-	-
Sacramento, Calif.[10]	6.5-7.5	30-500	30-311	59-431	75-328	-	-	1.2X10^5-8.6X10^6
Washington, D. C.	5..6-6..7	135-2000	10-1280	80-1760	10-470	1.0-16.5	0.8-9.4	1*.2X10^5-5.8X10^6
			Separate Storm Sewer Discharges					
Ann Arbor, Mich.'	-	1*70-1*1*00	31-530	-	24-49	-	1.2-9.4	-
Cincinnati, Ohio[12]	5..3-8..7	5-1200	1-290	20-610	1-173	0.3-7.5	0.0-7.3	2.9X10^3-1*.6X10^5
Detroit, Mich.	-	310-9H	136-370	-	96-231*	-	-	25X10^3-9.3X10^5
Sacramento, Calif.	-	19-211	3-211	21-176	2l*-283	-	-	5.5X10^3-1.0X10^6
Washington, D. C.	5..6-6..7	130-11,280	0-880	29-1514	3-90	0.5-6.5	0.2-4.5	1.2X10^3-3.2X10^6

**Data from May 12, 1970 storm*

***Volatile suspended solids in percent*

†Nitrogen as NO_3

the city, serves about 25 percent of the city's population in an area of approximately 22,000 acres. The northern portion of the drainage area is residential and commercial and the southern portion consists primarily of heavy industries.

Philadelphia, Pennsylvania.[8] The drainage basin consists of 5400 acres with a highly developed residential area, predominantly developed with single family row houses. The population density is 32 persons per acre. The average imperviousness is 75 percent.

Portland, Oregon.[9] The sampling area covered 25,000 acres of Portland's metropolitan area. The drainage basin is residential with about 30,000 single family residences. A broad spectrum of services is available with automobile related services heavily represented.

Sacramento, California.[10] The city, lying within the alluvial plain of the Sacramento Valley, has a flat topography with ground elevations ranging from 10 to 40 feet above mean sea level. The average annual rainfall is approximately 17 inches and practically all of this rainfall occurs during the period of November through April.

Washington, D. C.[11] The drainage basin area is 4200 acres. The land use is 69 percent residential, 13 percent industrial, 12 percent parks and open spaces, and 6 percent commercial.

The separate storm sewer areas in table 1 are described as follows:

Ann Arbor, Michigan.[7] This separate storm sewer system serves an area of approximately 3800 acres, most of which is within the city. Some rural drainage also enters the system. The area is largely developed as a residential and commercial community but also has light industries. The topography of Ann Arbor is hilly.

Cincinnati, Ohio.[12] Field studies on storm water runoff from a 27-acre residential and light commercial urban watershed served by separate sewer systems in the Mt. Washington section of Cincinnati are reported. The buildings on the watershed include single family houses, 4-family apartment buildings, stores, restaurants, fire house, church, and other public buildings. There are paved parking lots, asphalt and concrete paved streets, lawns, backyard gardens, and a park. The resident population density is 9 persons per acre. Thirty-seven percent of the area is impermeable. The runoff coefficient and time of concentration were estimated to be about 0.37 and 15 minutes, respectively.

Detroit, Michigan.[1] Results pertain to samples taken at a catch basin in the business district of Detroit during a storm on March 22, 1949.

Sacramento[10] *and Washington, D. C.*[11] The general features previously described for these two locations hold good for the separate storm sewer discharges.

STORM RUNOFF POLLUTION LOAD ESTIMATORS AND MODELS

Hedley and King,[13] on the basis of their observations on storm runoffs from the Haunch Valley drainage area (steep, about 100 acres), estimated pollution loads on an effective impervious area basis. For combined sewer overflows they estimated the BOD load to be 6 lb/acre and the suspended solids load to be about 16 lb/acre during the storm.

Burm, Krawczyk, and Harlow[7] estimated the pollution loads for a Detroit area which is served by a combined sewer system and for Ann Arbor which is served by a separate sewer system. The results are shown in table 2.

Table 2. Pollutional Load Factors

Constituents	Combined sewer, Detroit (lb/acre)	Separate storm sewer, Ann Arbor (lb/acre)
Phenols	0.042	0.002
BOD	90	31
NH3-N	6.2	0.7
Organic N	1.6	0.4
Suspended solids	200	1010
Volatile suspended solids	93	185
Total PO_4	11.0	2.8
NO_3-N	0.15	0.8

Weibel et al.,[12] from their Cincinnati studies, have given a comparison of the strength of separate storm sewer discharges with that of domestic sewage. The results are shown in table 3.

Table 3. Comparison of Urban Storm Water Runoff Loads with Domestic Sewage Loads

	Domestic sewage		Urban runoff loads as percentage of sewage loads	
Constituents	*(lb/day/acre)*	*(lb/year/acre)*	During runoff	Annually
Suspended solids	1.5	540	2400	160
COD	2.6	960	520	33
BOD	1.5	540	110	7
Total PO_4	0.19	68	70	5
Total N	0.23	82	200	14

Bryan,[14] on the basis of his studies on urban drainage in North Carolina, came to the conclusion that the total weight (presumably on an annual basis) contribution of BOD by storm water was about equal to the sanitary waste water effluent from secondary treatment at 85~95 percent efficiency. This compares favorably with the findings of Weibel et al.[12] The contribution of total organic matter as measured by chemical oxygen demand in storm water was greater than that attributable to the discharge of sanitary waste water. The total solids contribution by urban storm water was substantially larger than would be expected from average raw domestic waste water. The contribution of phosphate was nominal for the storm water in comparison with that of domestic waste water.

The American Public Works Association,[15] on the basis of studies in the metropolitan Chicago area, reported that street refuse-litter creates a water pollution potential, when it comes in contact with runoff waters resulting from precipitation or thaws, in direct proportion to the amount and nature of these urban environment wastes. The pollution potential can be reduced and minimized by better municipal sanitation practices, the use of more sophisticated equipment, and improved public cooperation and participation. The significant component of street litter, in terms of producing water pollution potential by runoff, was found to be the dust and dirt fraction. This varied from 0.4 to 5.2 pounds per day per 100 feet of curb. The soluble dust and dirt contained appreciable amounts of water pollution contaminants. The weighted amounts of these constituents were:

BOD, 5 mg/g; COD, 40 mg/g; nitrogen forms, 0.4 mg/g; phosphate, <0.05 mg/g; total bacteria counts, >10 million/g; coliforms, >1 million/g; and fecal enterococci, 5400/g. The BOD of street litter was found to be equivalent to 25 persons per day per mile.

The observations of Burgess and Niple, Ltd.[5] pertaining to BOD, suspended solids, and other parameters on combined sewer overflows for different storm events at Bucyrus, Ohio, are shown in table 4. The values observed suggest the likelihood of more variation being caused by meteorological differences in the overflow event than by differences in the physical features of the sewer districts.

Table 4. Summary of Waste Loads to Sandusky River, Ohio, for Five Overflow Events

Overflow event	Over-flow period (min)	BOD		Suspended solids		Volatile suspended solids (mg/l)	Total phos-phates as PO_4 (mg/l)	Nitrate nitrogen as NO_3 (mg/l)
		Average (mg/l)	(lb/100 acre)	Average (mg/l)	(lb/100 acre)			
February 8, 1969								
Sewer Dist. 8	120	120	55	570	260	-	8.3	3.0
Sewer Dist. 17	105	51	26	615	313	-	6.7	3.1
Sewer Dist. 23	165	86	50	670	390	-	6.5	2.5
March 24, 1969								
8	150	146	112	675	520	390	12.0	2.0
17	135	161	92	670	340	289	11.3	2.7
23	135	104	40	505	192	280	11.8	2.5
May 7, 1969								
8	107	118	28	430	103	200	7.3	1.4
17	60	172	43	454	114	291	12.2	0.8
23	110	116	57	660	325	368	15.1	0.5
June 13, 1969								
8	200	41	185	375	1700	126	2.3	9.1
17	190	31	69	413	900	96	2.0	9.3
23	177	36	111	652	2050	160	9.7	16.9
August 9, 1969								
8	140	177	336	-	-			
17	110	112	230	306	630			
23	170	112	178	-	-			

Roy F. Weston, Inc.[11] used the following values in their assessment of pollutional effects from a separate storm sewer system for a Washington, D. C., area: BOD, 19 mg/l; suspended solids, 1700 mg/l; total phosphate, 1.3 mg/l; and total nitrogen, 2.1 mg/l.

The generalized trend of pollution concentrations with time during a storm, as postulated by Metcalf and Eddy, Inc.[16] is shown in figure 1. This figure confirms the importance of initial flush time from a storm sewer system in considering treatment needs. It is probable that the magnitude for each constituent will differ with the time interval between storm events. However, there would appear to be a predictable flush time for each storm sewer system.

A consortium of research contractors[17] proposed a mathematical model (urban runoff) for pollution concentrations with time and verified the model in actual case studies. The proposed model is:

$$P_o - P = P_o (1 - e^{-kt}) \quad (1)$$

where

P = amount of particular pollutant on the surface initially present

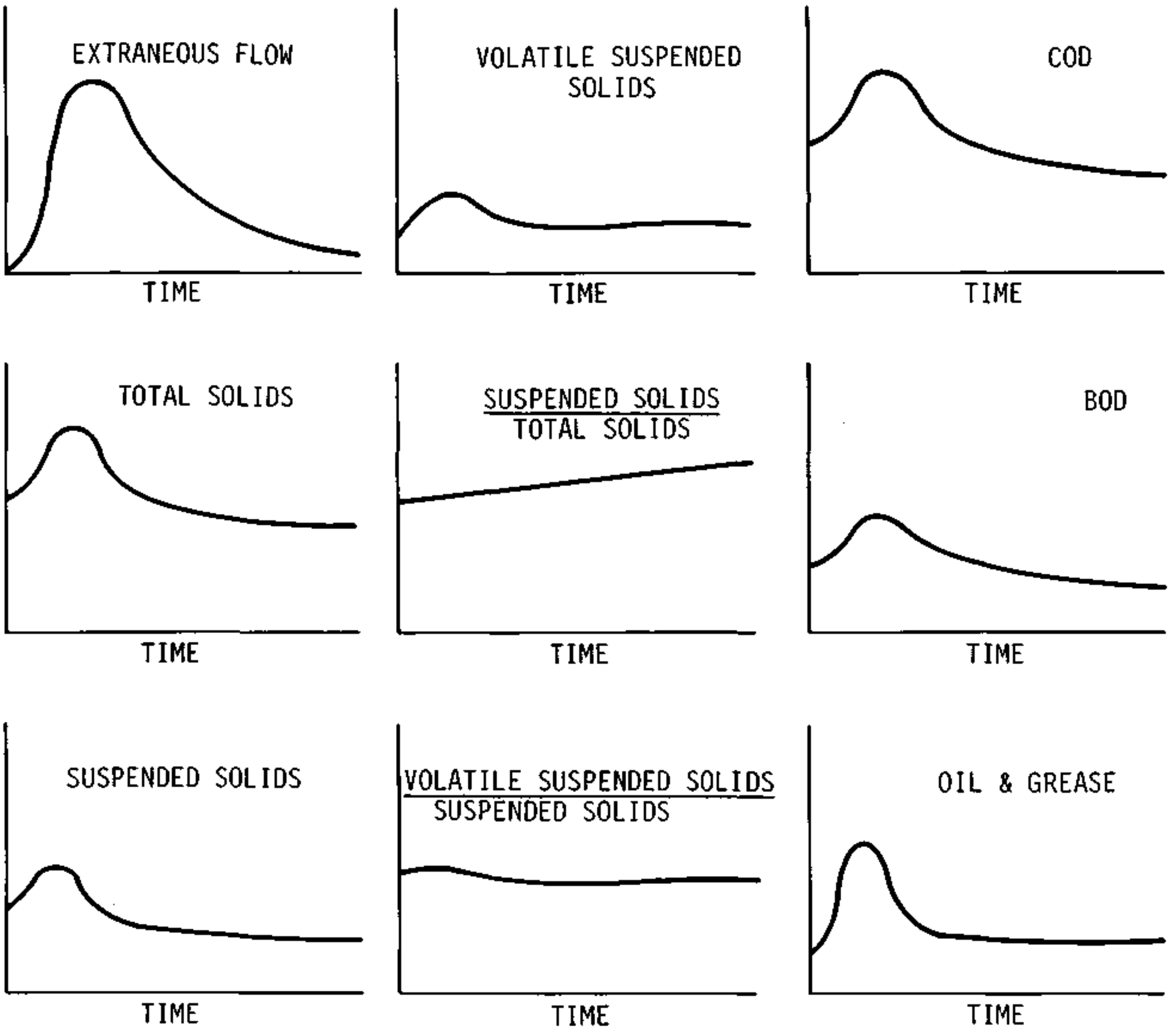
$P - P$ = amount of pollution washed away in time t

k = factor proportional to the rate of runoff r, where $k=br$ and b is a constant

To determine b, it was assumed that a uniform runoff of 0.5 inch/hour would wash away 90 percent of the pollutants in 1 hour. This leads to the equation

$$P_o - P = P_o (1 - e^{-4.6rt}) \quad (2)$$

Certain modifications to the basic model (equation 2) for predicting suspended solids and BOD have been proposed to refine the agreement between the observed and predicted values for these parameters. The University of Cincinnati Department of Civil Engineering[6] developed a mathematical model for urban runoff quality essentially on the same principles and assumptions as in equation 2. The major difference is that an integral solution was developed by this group instead of the stepwise solution suggested by the consortium. The amount of a pollutant remaining on a runoff surface at a particular time, the rate of runoff at that time, and the general characteristics of the watershed were found to be given



(After Metcalf and Eddy, Inc.[16]*)*

Figure 1. Graphs of water quality parameter trends during wet weather

by the following relationship.

$$P = P_0 e^{-kv_t} \tag{3}$$

where

P_0 = amount of pollutant on the surface

P = amount of pollutant remaining on the surface at time t
v_t = accumulated runoff water volume up to time t
$= \int_0^t q \partial t$
q = runoff intensity at time t
k = constant characterizing the drainage area

IMPACT OF STORM WATER RUNOFF ON RECEIVING WATERS

Gannon and Streck[18] reported on the influence of the discharge from separate storm water sewers in Ann Arbor, Michigan, on the Huron River following a storm on the evening of July 20, 1964. They found that the DO level in the river was depressed from about 10 mg/l to 2 mg/l. The effect lasted about 24 hours after the storm ceased, and a river stretch of 2 miles below the outfall was found to be affected.

Burm[19] studied the bacteriological effects of combined sewer overflows from Detroit, Michigan, on the Detroit River and concluded that the duration of adverse effects was proportional to the intensity of rains. Coliform densities exceeded 100,000 per 100 ml in the river after a moderate rain, and the effects of overflow discharges were felt for several days after the actual overflows had ceased.

The results of a detailed water quality survey of the Sandusky River in Ohio before and after rainstorms have been reported by Burgess and Niple, Ltd.[5] They found that the BOD concentration of the Sandusky River, immediately downstream from Bucyrus, varied from an average of 6 mg/1 during dry weather to a high of 51 mg/l during overflow discharges. The total coliforms (by the membrane filter technique) varied from an average of 400,000 per 100 ml during dry weather to a high of 8,800,000 per 100 ml during overflow discharges. The effects of combined sewer overflows on the Sandusky River in and below the city of Bucyrus were visually apparent. The size of the Sandusky River is indicated by the median flows of the river at Bucyrus in June, July, and August of 1969 which were 13, 6.9, and 4.8 cfs, respectively.

In assessing the effects of storm water overflows from the Oakland and Berkeley, California, area on San Francisco Bay, Metcalf and Eddy, Inc.,[16] reported that although dissolved oxygen was depressed by overflows, the average DO levels were well above the minimum objective of 5.0 mg/l during the rainy season. Only localized and short-lived DO levels below the minimum DO objective were noted during the rainy season. Coliform bacteria after an overflow event were found to produce a concentration above the selected objective (total coliform MPN not higher than 1000 per 100 ml more than 20 percent of the time in a 30-day period) for approximately 2.6 days after each overflow event.

METHODS AND COSTS FOR MINIMIZING POLLUTION FROM STORM WATER

In 1964 the U. S. Public Health Service[20] estimated that the cost to provide complete separation of storm and sanitary sewers throughout the country would range from $20 to $30 billion. Since storm sewer discharges constitute a significant pollution load on the receiving waters, all the storm runoffs should be considered for treatment, regardless of whether they are combined with municipal sewage before they reach a natural water course. All of the proposed methods for controlling pollution from storm runoffs dwell on some aspect of storage, after a storm event, and subsequent means of treating the storm water. The methods of storage and subsequent treatment proposed are quite varied, as discussed below.

In Boston, Massachusetts, complete separation of storm and sanitary sewer systems was considered infeasible.[21] Chlorination of combined overflows in contack tanks constructed at selected outlets prior to discharge to nearby water courses was estimated to cost about $533 million. Construction of holding tanks and subsequent disposal with the normal waste water flow in the sewerage system was estimated to cost about $814 million. The least expensive plan was found to be deep tunnel storage and subsequent disposal by an ocean outfall and diffuser system. A 15-year frequency rainstorm of 24-hour duration was considered for design purposes.

For the metropolitan Chicago area, a deep tunnel storage system consisting of conveyance tunnels and mined storage reservoirs, and subsequent treatment of combined sewer overflows at treatment plants was found to be the best solution for abating pollution from storm runoffs.[22] The complete separation and holding tank concepts were found to be much more expensive. The deep tunnel conveyance and storage system was estimated to cost about $1 billion. The deep tunnel system as presently proposed would serve an area of 62 square miles in the Lake Calumet area. The envisioned 10-year program would include the entire 300 square miles and the combined sewer area of the Chicago area. The system in its first stage of development was considered to have a storage capacity that would limit the overflow to the waterway to a maximum of only 25 percent of the total storm runoff in all but one storm of the 96-year precipitation record.

Karl R. Rohrer Associates, Inc.[23] reported on the feasibility of off-shore underwater temporary storage of combined sewer flows in flexible tanks. A pilot demonstration facility was constructed in Sandusky, Ohio, where combined sewer overflows from a 14.86-acre residential drainage area was directed to two 100,000-gallon collapsible tanks anchored underwater in Lake Erie. The stored overflows were pumped back to the sewer system after a storm event for subsequent treatment. During 1 year of operation, a total of 988,000 gallons of storm water overflow was contained and returned for treatment. As constructed, the facility cost was about $1.88 per gallon of storage capacity, but future projections indicate possible costs of less than 40 cents per gallon.

Burgess and Niple, Ltd.,[5] in their study of various aspects of combined sewer overflows in Bucyrus, Ohio, considered six alternatives. These alternatives and their estimated costs are:

1	Complete separation of sanitary waste and storm water	$8,800,000
2	Interceptor sewer and lagoon system	5,220,000
3	Stream flow augmentation	5,000,000
4	Treatment of overflows with a system consisting of gravity interceptor, grit chamber, settling tanks, chlorination facilities, anaerobic digester, and sludge drying beds. (The treatment facility will provide 1.5 hours of detention time for a 2-year, 1-hour design storm)	8,810,000
5	Chlorination of overflows. System consists of interceptor sewers, contact tanks, and chlorination facilities capable of providing a chlorine dosage of 40 mg/l.	3,000,000
6	Off-stream treatment consisting of pump station, low head dam, and lagoon system	1,700,000

The Envirogenics Company,[10] considered three alternate storage systems for Sacramento, California, namely, underground storage, surface storage, and stabilization ponds. Costs for various storage facilities to accommodate rainstorms of three different frequencies are contained in their report. The company considered dissolved air floatation, mechanical screening, and chlorination for treating urban runoff prior to final disposal.

Simpson and Curtis[24] reported on the feasibility of a large stabilization retention basin in the off-shore waters of Lake Erie as a method of treating combined sewer overflows from the Cleveland metropolitan area. The proposed plan included a shoreline collection system to convey flows to the basin and was designed to serve an area of approximately 38,800 acres, The proposed stabilization basin would have a volume of 30,000 acre-feet. The capital cost for the basin and the complete collection system at 1968 cost levels was estimated to be approximately $83,500,000. Total annual cost of operation, maintenance, and amortization was estimated at $4,767,000.

Waller[25] has reported on a retention tank for solving the combined sewage overflow problems facing the city of Halifax, Canada (population 100,000). The total cost for the complete installation is reported to be $400,000. The retention tank which has a capacity of approximately 1 million gallons is intended to provide 15 minutes detention for a peak flow of 150 cfs. Chlorination facilities were designed to provide a dosage of 30 mg/l for flows up to 40 cfs.

The U. S. Public Health Service[20] has reported unit costs for certain pollution abatement programs. These are reproduced in tables 5, 6, and 7.

SUMMARY

The case studies cited and the treatment costs tabulated in this report should provide a reasonable basis for developing a preliminary prediction model encompassing the characteristics of storm water runoff in a river basin. Inputs such as topography, imperviousness, soil type, land use, etc., for each metropolitan area will have to be developed. The basic considerations, however, have been reviewed here. For additional or supporting data 25 additional references not cited in this report are provided.

Table 5. Cost for Holding Tanks for Temporary Impoundment of Combined and/or Storm Water Overflows

Location	Total Project cost	Cost per acre	Cost per capita
Clinton, Iowa	$ 2,655,000	$1400	$ 88
Haverhill, Mass.	25,000,000	8800	545
Lawrence, Mass.	21,000,000	9500	300
Lowell, Mass.	53,000,000	9150	590
Mission Township, Main Sewer District, No. 1, Kansas	4,000,000	1000	67
New York, N. Y.			
Jamica Bay	65,000,000	5150	*
East Chester Bay	35,000,000		*
Upper East River	81,000,000	2130	*
Average		5034	318

**Population served unknown*

Table 6. Costs of Chlorine Contact Tanks for Partial Disinfection of Combined and/or Storm Water Overflows

Location	Total project cost	Cost per acre	Cost per capita	Annual chlorine cost
Haverhill, Mass.	$11,500,000	$4050	$250	$30,000
Lawrence, Mass.	9,800,000	4400	140	24,000
Lowell, Mass.	23,700,000	4060	264	56,000

Table 7. Costs of Lagoons Used for Controlling Storm Water Flow

Location	Total project cost	Cost per acre	Cost per capita
Exter, N. H.	$320,000	$640	$80
Richards Gegaur Air Force Base, Mo.	280,000	700	--
Tacoma, Wash.	115,000	39*	19*

**Estimated from incomplete data*

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