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A MODEL FOR EVALUATING RUNOFF-QUALITY IN METROPOLITAN MASTER PL--ETC(U)
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TECHNICAL PAPER NO. 58

A MODEL FOR EVALUATING RUNOFF-QUALITY IN METROPOLITAN MASTER PLANNING

Jess
L. A. Roesner
H. M.
R. P. Shubinski

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General description of the computation of the quantity and quality of uban storm water runoff by the computer program STORM. Storm runoff is simulated on an hourly time interval for the period of record of rainfall gages. Methodolgy for studying tradeoffs between storage volumes and treatment rates for sewage treatment plants are discussed.

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A MODEL FOR EVALUATING RUNOFF-QUALITY IN METROPOLITAN MASTER PLANNING

by

L. A. Roesner, H. M. Nichandros and R. P. Shubinski,
Water Resources Engineers
710 South Broadway
Walnut Creek, California 94596

A. D. Feldman and J. W. Abbott
The Hydrologic Engineering Center
Sacramento District, Corps of Engineers
Department of the Army
609 Second Street
Davis, California 95616

and

A. O. Friedland
Department of Public Works
City and County of San Francisco
770 Golden Gate Avenue
San Francisco, California 94102

April 1974

TABLE OF CONTENTS

PREFACE

by M. B. McPherson

ABOUT THE MODEL

Without doubt, the following report comprises one of the most significant technical memoranda of the ASCE Program. Documented is a computer model that should see extensive use in total-jurisdiction preliminary sewerage planning, if for no reason other than the simple fact that it is presently the outstanding tool available for that purpose. Combined with the public availability of the user's manual (1) and the computer program, little excuse remains for any local government agency not to investigate the potential applicability of the model for its master planning.

In the Preface of an earlier technical memorandum (2) we noted that mathematical models used for the simulation of urban rainfall-runoff or rainfall-runoff-quality can be divided into three distinct categories: planning models, design models and operations models. We noted that planning models are used in massive applications, such as for metropolitan or city-wide master plans. As an example of the scale encountered the City of Milwaukee has 1,370-miles of separate storm drains and combined sewers within the 97-sq. mi. of the City (3), and these conduits are distributed over 465 drainage catchments having a maximum size of 1,820-acres and a median size of 25-acres (4). When dealing with so many components the model used must be as simple and as flexible as possible.

(1) Hydrologic Engineering Center, Corps of Engineers, "Urban Storm Water Runoff: "STORM'," Generalized Computer Program 723-S8-L2520, Davis, California, May 1974.

(2) Lanyon, Richard F., and James P. Jackson, The Metropolitan Sanitary District of Greater Chicago, "A Streamflow Model for Metropolitan Planning and Design," ASCE Urban Water Resources Research Program, Technical Memorandum No. 20, ASCE, New York, N.Y., January 1974.

(3) Prawdzik, Ted B., Milwaukee Department of Public Works, "Environmental and Technical Factors for Open Drainage Channels in Milwaukee," ASCE Urban Water Resources Research Program, Technical Memorandum No. 12, ASCE, New York, N.Y., February 1970.

(4) Tucker, L.S., "Sewered Drainage Catchments in Major Cities," ASCE Urban Water Resources Research Program, Technical Memorandum No. 10, ASCE, New York, N.Y., March 31, 1969.

That is, data processing for planning applications becomes a much more important practical consideration than the level of sophistication of hydrological process modeling, whereas just the opposite emphasis is required for design applications.

Design models can be very elegant and detailed tools because they are used for analyzing individual catchments and subcatchments in "one-shot" applications where the simulation of detailed performance of discrete elements within a subcatchment must be achieved. Whereas hourly rainfall data is an appropriate input for planning models and for simulating flows in larger streams, 5-minute interval rainfall data (the shortest duration reported by the U.S. Weather Service) is the appropriate input for simulating flows in sewers and small urban streams for design applications. Design models are used as tactical tools and planning models are used as tools of strategy; and operations models necessarily embody both of these capabilities.

HISTORY AND ACKNOWLEDGMENT

The initial version of the model was employed in part of the development of the Department of Public Works, City and County of San Francisco, Master Plan for combined sewer overflow abatement (5), by Water Resources Engineers (WRE). In February, 1973, as part of a training course on "Management of Urban Storm Water, Quantity and Quality" sponsored by The Hydrologic Engineering Center (HEC) of the Corps of Engineers, an advanced version of the model was presented and about one-third of the total course time was devoted to hands-on use of the model by participants. WRE developed this newer version and conducted the course for the HEC. Since then, the HEC developed a user's manual, in September of 1973, which was revised in May of 1974 (1). Added to the model by HEC, and included in the explanations of the newer manual, are capabilities for computing quantity and quality of runoff from nonurban areas, snowfall and snowmelt, and land surface erosion for urban and nonurban watersheds. Because explanations of these features are sufficiently detailed in the newer manual (1) they are not repeated in the following report. Dr. Roesner of WRE assembled the following report with help from the coauthors, using in part the texts of three HEC course lectures on the model. (Eight other lectures from the course comprise a companion technical memorandum (6). An outline

(5) Department of Public Works, "San Francisco Master Plan for Waste Water Management," City and County of San Francisco, September 15, 1971. (In four parts).

(6) Water Resources Engineers and the Hydrologic Engineering Center - Corps of Engineers, "Management of Urban Storm Runoff," ASCE Urban Water Resources Research Program, Technical Memorandum No. 24, ASCE, New York, N.Y., May 1974.

description of the features of the San Francisco Master Plan is included in a previous technical memorandum (7).)

We are greatly indebted to the authors and their organizations for the privilege of presenting this unique, break-through, important report. In due course, copies will be available from the National Technical Information Service. ASCE Program issuance is necessarily restricted to active Program cooperators, numbering over two hundred persons. However, not only are Program products not copyrighted, but anyone who wishes is welcomed, indeed urged, to make as many copies as they can use to enhance dissemination. All we request is that the total contents be reproduced to insure contextual integrity.

In closing, we are impelled to note that the following report epitomizes a central Program objective: advancing the state of the art.

(7) McPherson, M. B., "Innovation: A Case Study," ASCE Urban Water Resources Research Program, Technical Memorandum No. 21, ASCE, New York, N.Y., February 1974.

SECTION 1
INTRODUCTION

BACKGROUND

It has only been within the last decade that the real pollution potential of urban runoff has come to be recognized. In a report published in 1964 by the U.S. Public Health Service [1],* the nationwide significance of pollution from urban runoff was first identified. Since that time, large amounts of effort and money have been devoted to the characterization of the quality of urban runoff and to the development of methodologies and processes to control this source of pollution. Funding for these studies has come from a number of municipalities, some states, and from federal agencies, notably the Environmental Protection Agency (EPA) and recently the U.S. Army Corps of Engineers.

A review of these studies (see References 10 and 11) shows that much work has been done in the following areas:

1. Development of stormwater treatment processes;

2. Sewer system control to maximize pipeline storage, thereby reducing the amount and frequency of overflows; and

3. Characterization of the quality of stormwater and combined sewer discharges.

In addition, several sophisticated mathematical models have been developed (some with funds from the private sector) that describe the time-varying hydraulic response of an urban drainage system to rainfall. A few of these models include descriptions of the quality of urban runoff. The EPA Stormwater Management Model [2] is a typical example of the detail and scope contained within these models.

The information and technological tools that are presently available are deficient, however, in that they do not adequately address some of the initial questions that must be answered in the preliminary planning stage. One of the questions that must be answered prior to developing a pollution control plan is: what is the present and expected future magnitude of pollution loads carried by urban runoff from a given watershed? Extensions of this question include such things as 1) what is the pollution load for an average event, 2) what is it for an extreme event, and 3) how often does a given extreme event occur?

*Numbers in brackets refer to references contained in Section 9.

Given that we can answer these questions, it is then possible to identify some constraints for the stormwater system that is ultimately designed so that the receiving waters will be adequately protected (which is the whole idea of "stormwater management" in the first place). Therefore, it is necessary to identify those systems (i.e., combinations of treatment rate and storage volume) that can meet the constraints. The extremes of these combinations are obvious: All the runoff could be treated as it arrives at the treatment plant, or all the runoff could be stored for later treatment at a conventional treatment plant during off-peak hours. Either of these two alternatives, however, will normally prove to be highly uneconomical. In between these two extremes lie an extremely large number of treatment rates and storage capacities that will satisfy the environmental constraints placed on the system. The problem is to identify the feasible combinations.

REPORT PURPOSE

The purpose of this document is to present an analytical method that can be used in the preliminary planning stage to help answer the types of questions posed above. The method has been coded into a computer program called STORM (Storage, Treatment, Overflow, and Runoff Model). This program represents a method of analysis to estimate the quantity and quality of runoff from small, primarily urban, watersheds. Nonurban areas may also be considered. Land surface erosion for urban and nonurban areas is computed in addition to the basic water quality parameters of suspended and settleable solids, biochemical oxygen demand (BOD), total nitrogen (N), and orthophosphate (PO4). The purpose of the analysis is to aid in the selection of storage and treatment facilities to control the quantity and quality of urban stormwater runoff and land surface erosion. The model considers the interaction of eight variables:

1. precipitation,
2. air temperature for snowpack accumulation and snowmelt,
3. runoff, ... }
4. pollutant accumulation on the land surface, ... } related to land use
5. land surface erosion, ... }
6. treatment rates,
7. storage, and
8. overflows from the storage/treatment system.

Land uses accounted for in the model include: single family residential, multiple family residential, commercial, industrial, parks, and nonurban or undeveloped areas. The program is designed for use with many years of continuous hourly precipitation records. It is a continuous simulation model but may be used for selected single events.

The City of San Francisco used this program in the preliminary planning phase of their Master Plan for Stormwater Management [3]. The Corps of Engineers is currently applying STORM in several of their Urban

Studies, and East Bay Municipal Sewerage District No. 1 (which serves seven cities on the east side of San Francisco Bay) has recently used the model in an inflow/infiltration study of their sanitary sewer system.

The program has been documented by the Hydrologic Engineering Center, Army Corps of Engineers in Davis, California, and is available to the public [4].

HARDWARE AND SOFTWARE REQUIREMENTS

This program is available for the IBM 360/50, UNIVAC 1108, and CDC 6600 or 7600 computer systems. It requires about 35,000 words of core storage and a FORTRAN IV compiler that accepts multiple ENTRY statements. Input is on the card reader and possibly a tape/disk. Output is on a 132 position line printer. One to five additional tape/disk units are required for temporary storage during the processing. The only program differences among the three computer systems are due to ENCODE/DECODE type statements and the way in which multiple output files are handled. Up to three output files are generated on tape/disk for printing at the end of the job.

REPORT FORMAT

The concept of STORM and the method of computing runoff is described in the following section. In Section 3 background information on the quality of urban runoff is presented and the method of computing the quality of urban runoff is developed. Section 4 discusses computations of treatment, storage and overflow. Section 5 describes input data requirements for STORM and the output information it produces. Two actual planning applications of STORM are briefly discussed in Section 6. Examples of other possible applications of STORM are contained in Section 7. Means for transferring water quality data for one location to another are discussed in Section 8. References are listed in Section 9.

SECTION 2
COMPUTATION OF RUNOFF QUANTITY

CONCEPT OF "STORM"

The quantity of urban runoff has traditionally been estimated by using a design storm through frequency-duration-intensity curves or some other statistical means based on rainfall records. Such approaches normally neglect the spacing between storms and the capacity of the urban system to deal with some types of storms better than others.

Often, through natural and artificial storage mechanisms, intense short-duration storms maybe completely contained within storage so that no untreated stormwater overflows to receiving waters. Alternately, a series of closely spaced, moderately sized storms may tax the system to the point that excess water must be released untreated. Consider, for example, Figure 1 which shows the response of two different systems to the same ra :fall trace. System A, which has a relatively high treatment rate and a small storage capacity, will overflow during the high intensity, short duration storm. However, it will completely contain the second storm of moderate intensity and longer duration. System B, on the other hand, which has a low treatment rate and a large storage capacity, completely contains the first storm. Notice that it would also contain the second storm if the system were analyzed independently of the antecedent storm. However, in this case the spacing of the storms is such that the system analysis must include both rainstorms as a single event to accurately describe the system's response to the rainfall trace illustrated in the figure.

A storm cannot be defined by itself, but must be defined taking into account the response characteristics of the urban stormwater system. It is for this reason that an approach was developed that would not only recognize the properties of rainfall duration and intensity, but would also consider storm spacing and the capacity of the urban stormwater system.

Figure 2 shows, pictorially, the interrelationship of the eight stormwater elements considered in this approach for estimating stormwater runoff quality and quantity. In this approach, rainfall washes dust and dirt and the associated pollutants off the watershed to the storage-treatment facilities so that as much stormwater runoff as possible can be treated prior to its release. Runoff exceeding the capacity of the treatment plant is stored for treatment later. When the storage facilities become inadequate to contain the runoff the untreated excess is wasted through overflow directly into the receiving waters.

For a given precipitation record, the quantity, quality, and number of overflows will vary as the treatment rate, storage capacity,

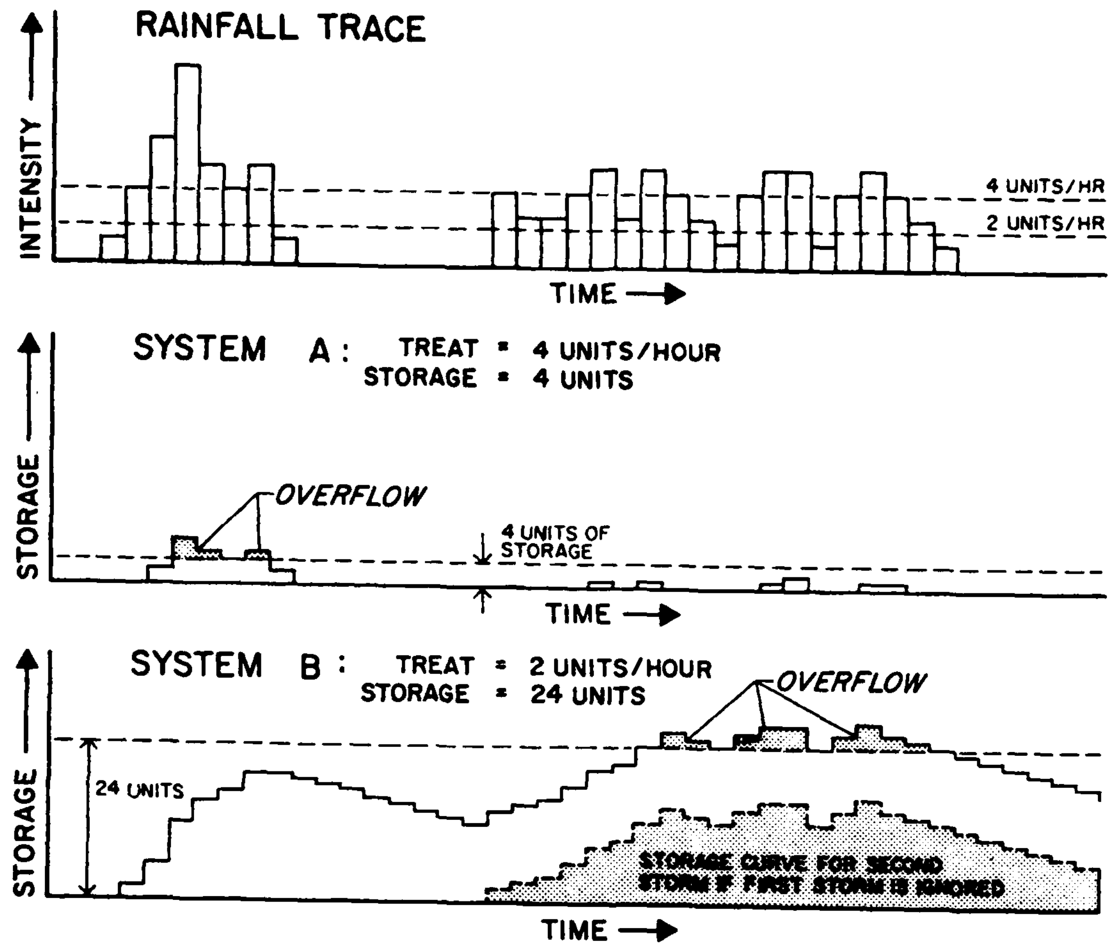

FIGURE 1
System Response Examples

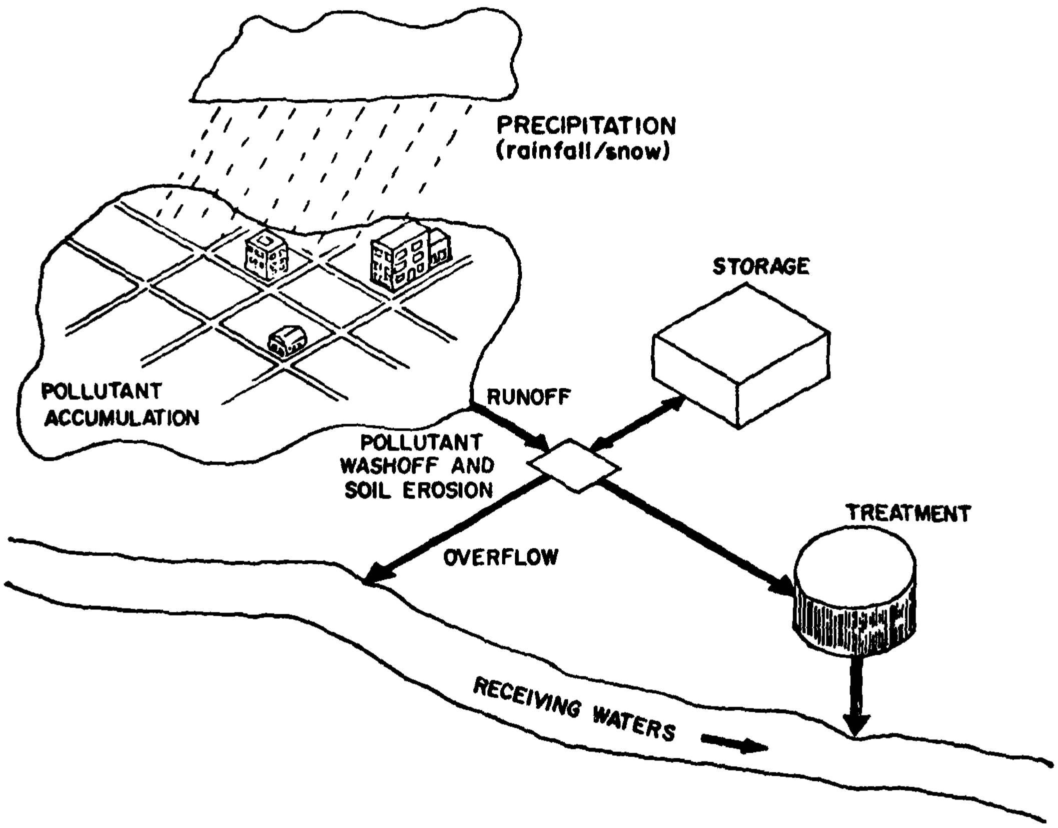

FIGURE 2
Conceptualized View of Urban System Used in "STORM"

and land use is changed. Land surface erosion is a function of land use, soil types, ground slope, rainfall/snowmelt energy and erosion control practices. A typical method of investigation is to alter the treatment, storage, and land use and note the resulting response of the system. A group of alternatives can then be selected from among those meeting the overflow quantity and quality objectives.

COMPUTATION OF THE QUANTITY OF RUNOFF

Runoff is calculated on an hourly basis as a function of rainfall plus snowmelt using the following expression:

$$R = C(P - f) \tag{1}$$

where

- R = urban area runoff in inches per hour;
- C = composite runoff coefficient dependent on urban land use;
- P = rainfall plus snowmelt in inches per hour over the urban area; and
- f = available urban depression storage in inches per hour.

For simplicity we will omit the snowmelt computation in our discussion here. The interested reader is referred to the User's Manual [4] for details of that computation.

The runoff coefficient represents losses due to infiltration. It is computed from land use data as follows:

$$C = C_p + (C_I - C_p) \sum_{L=1}^{m} X_L F_L \tag{2}$$

where

- C_p = runoff coefficient for pervious surfaces;
- C_I = runoff coefficient for impervious surfaces;
- X_L = area in land use L as a fraction of total watershed area;
- F_L = fraction of land use L that is impervious; and
- m = total number of urban land uses.

Before the runoff coefficient is applied, depression storage losses must be satisfied. Depression storage represents the capacity of the watershed to retain water in ditches, depressions and on foliage. The amount of depression storage at any particular time is a function of past rainfall plus snowmelt and evapotranspiration rates. The function is computed continuously using the following expression, where f is in inches:

$$f = f_o + N_D k , \qquad \text{for} \qquad f \leq D \tag{3}$$

where

f_o = available depression storage, in inches, after previous rainfall;

N_D = number of dry days since previous rainfall;

k = recession factor, in inches/day, representing the recovery (evapotranspiration) of depression storage in inches; and

D = maximum available depression storage in inches.

Figures 3a and 3b show graphically the hourly precipitation (P), depression storage (f), precipitation excess (P-f) and the resulting runoff (R). Figures 3b and 3c show how the runoff is distributed between treatment storage and overflow for a system with a treatment rate of 0.02 inches/hour and a storage capacity of 0.16 inches.

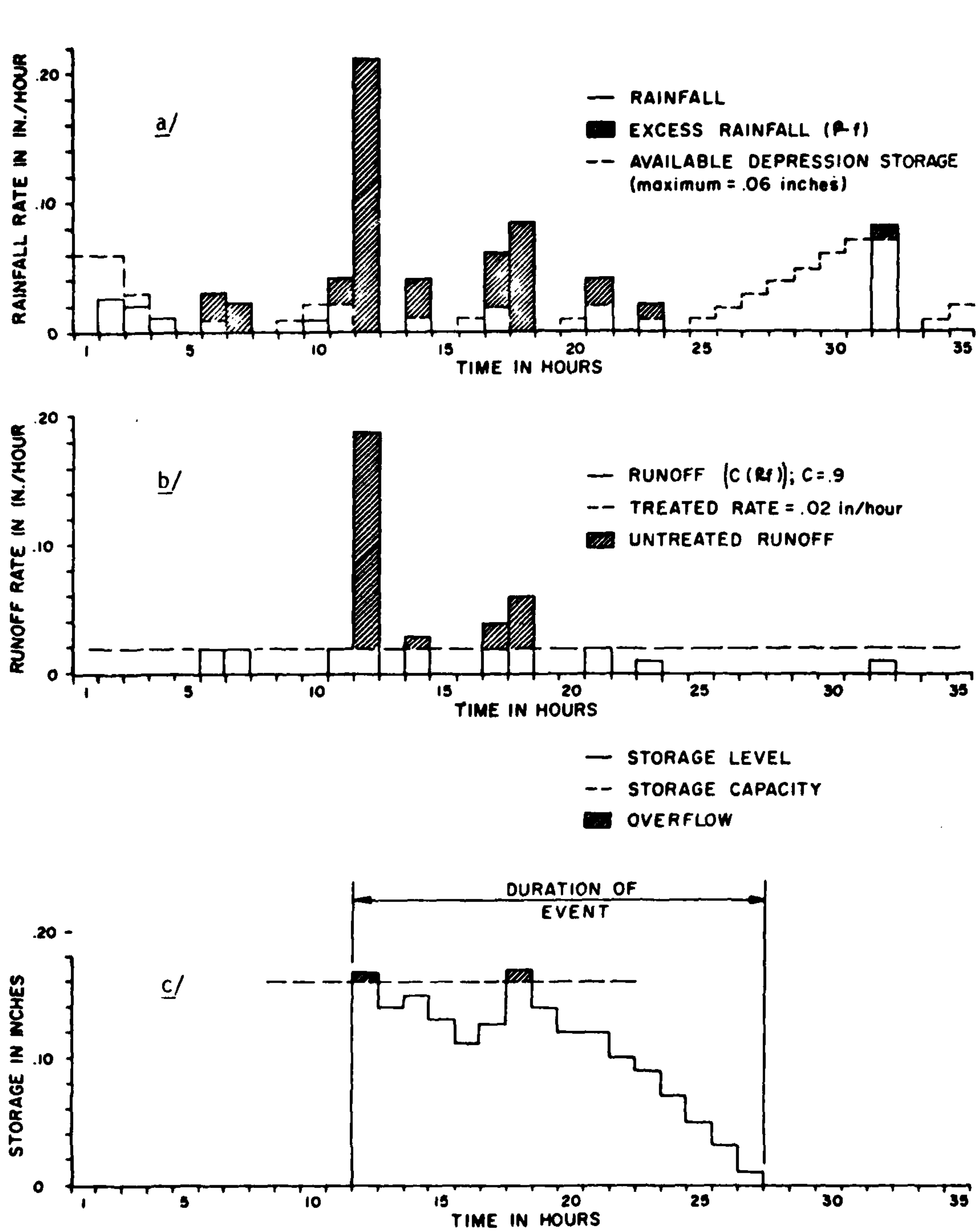

FIGURE 3
Time Histories of Rainfall, Runoff, and Storage

SECTION 3
COMPUTATION OF RUNOFF QUALITY

SOURCES OF POLLUTANTS

Basically, pollutant loads are introduced into urban runoff from three sources:

1. The land surface itself, primarily impervious surfaces;
2. Catch basins; and
3. The sewers in combined systems.

Of these three sources, the land is the most important. Catch basins can be a source of first-flush or shock pollution. An American Public Works Association (APWA) study [5] in Chicago found that:

> ". . . the liquid remaining in a basin between runoff events tends to become septic and that the solids trapped in the basin take on the general characteristics of septic or anaerobic sludge. The liquid in catch basins is displaced by fresh runoff water in the ratio of one-half the volume for every equal volume of added liquid. During even minor rainfall or thaw this displacement factor can release the major amount of the retained liquid and some solids. The catch basin liquid was found to have a BOD content of 60 ppm in a residential area. For even minor storms, the BOD of the catch basin liquid would be seven-and-one-half (7-1/2) times that of the runoff which had been in contact with street litter. Improved design of catch basins, and better operational and maintenance practices, could reduce this first-flush pollutional effect."

In combined sewer systems, wastewater is incorporated into the storm runoff. In addition, the storm runoff, as it passes through large sewers, scours sediment deposited by wastewater flows during preceding dry-weather periods. Figures 4 and 5 illustrate the effects of wastewater sewage and of catch basins and storm sewer scour on the quality of stormwater overflows [6].

As stated above, the most important contributor of pollutants to urban runoff is the land surface itself, primarily the streets and gutters and other impervious areas directly connected to streets or storm sewers. Pollutants accumulate on these surfaces in a variety of ways. There is, for example: debris dropped or scattered by individuals; sidewalk sweepings; debris and pollutants deposited on or washed into streets from yards and other indigenous open areas; wastes and dirt from building and demolition; fecal droppings from dogs, birds and other animals; remnants

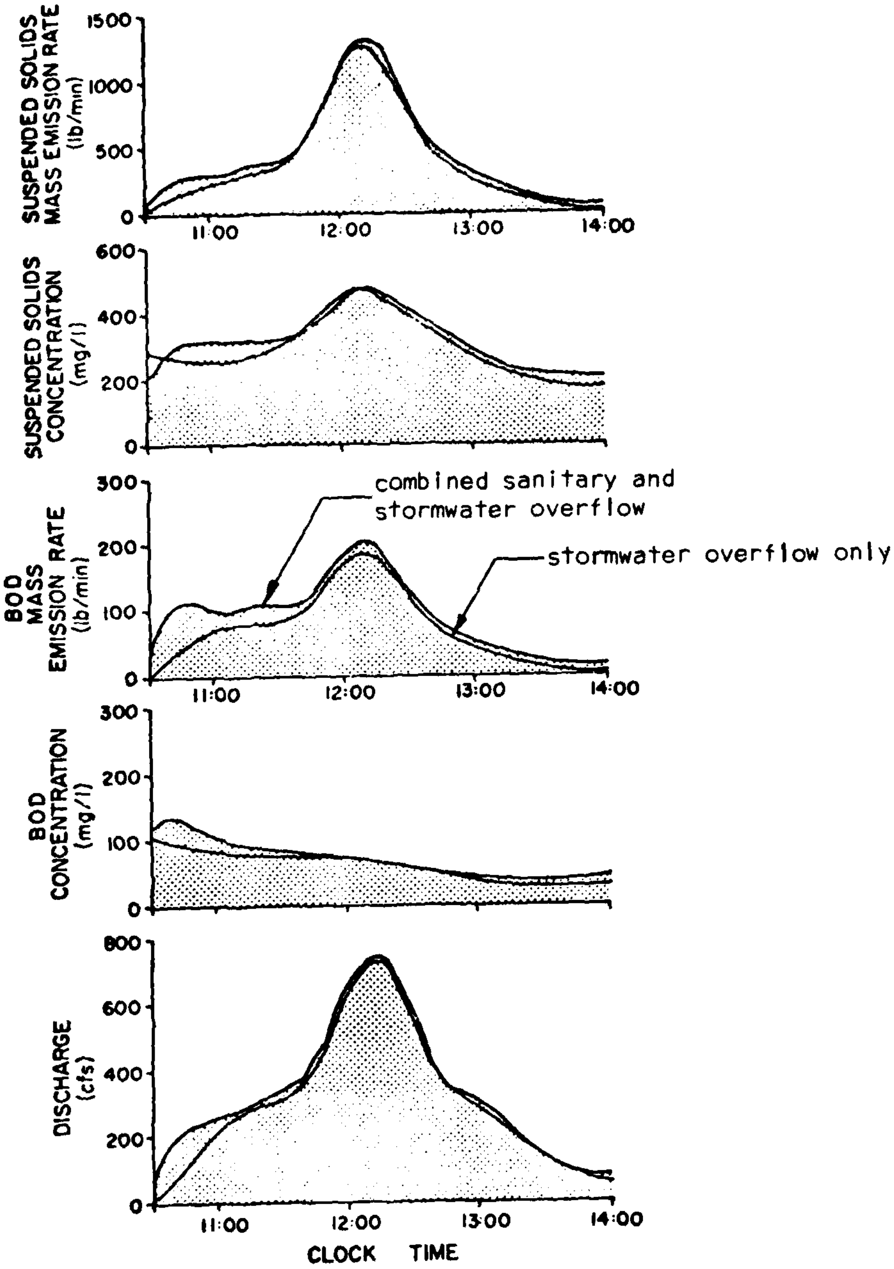

FIGURE 4
Comparison of Stormwater and Combined Overflows
(Selby Street, San Francisco)

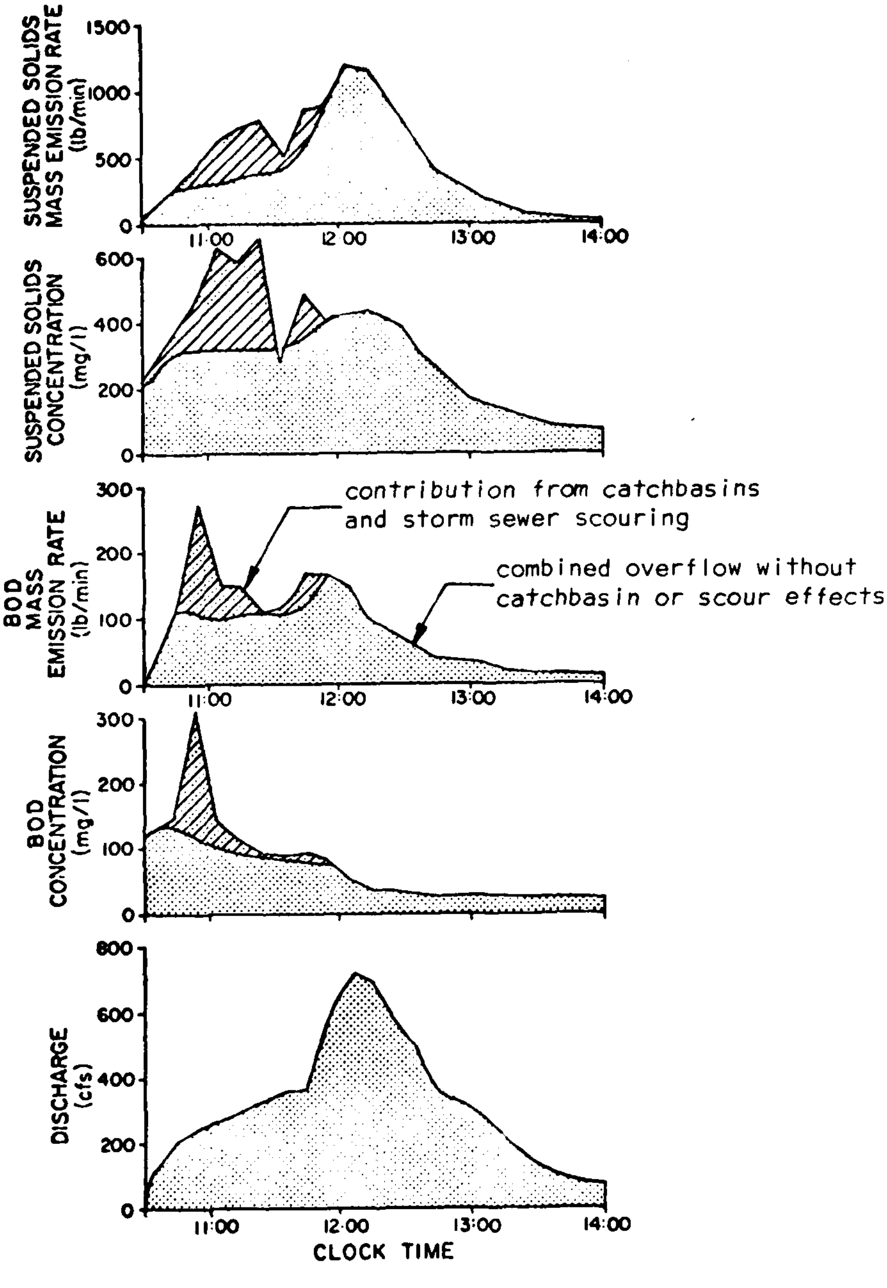

FIGURE 5
First-Flush Pollutional Effects of Catch Basins
And Sewer Scour on Combined Sewer Overflow
(Selby Street, San Francisco)

of household refuse dropped during collection or scattered by animals or wind; dirt, oil, tire and exhaust residue contributed by automobiles; and fallout of air pollution particles. The list could go on and on. Irrespective of the way in which pollutants accumulate on the urban watershed, they are generally associated with one of the following forms of street litter:

1. Rags,
2. Paper,
3. Dust and dirt,
4. Vegetation, or
5. Inorganics.

Table 1, which gives estimated street litter components for a residential area in Chicago, provides a rough measure of the relative importance of these components.

TABLE 1
Monthly Summary of Estimated Street Litter Components, From a 10-acre (4 ha) Residential Area, Chicago**

Month	Street Refuse Components (Tons/Month)					
	Rags	Paper	Dust & Dirt	Vegetation	Inorganic	Total*
Jan.	.0015	.036	.55	.00	.09	.68
Feb.	.0015	.036	.55	.00	.09	.68
March	.0015	.036	.55	.08	.09	.76
April	.0015	.036	.55	.08	.09	.76
May	.0015	.036	.55	.08	.09	.76
June	.0015	.036	.55	.08	.09	.76
July	.0015	.036	.55	.08	.09	.76
Aug.	.0015	.036	.55	.08	.09	.76
Sept.	.0015	.036	.55	.08	.09	.76
Oct.	.0015	.036	.55	.83	.09	1.56
Nov.	.0015	.036	.55	.83	.09	1.56
Dec.	.0015	.036	.55	.00	.09	.68
TOTAL*	.0180	.432	6.60	2.22	1.08	10.48

*Some totals have been rounded off.

It is readily apparent that the most significant component is dust and dirt except during the fall of the year when vegetation (primarily leaves) becomes the dominant component.

**This table is a reproduction of Table 4 in Reference 5.

TYPES OF POLLUTANTS AND LOADING RATES

Nearly all of the pollutants found in urban runoff are associated with the dust and dirt component of street litter. By type, COD, BOD, and solids (suspended and settleables) are found in the greatest quantity. Nitrogen and phosphorus are also found in significant quantities. In areas where street deicing by salting is practiced, winter runoff contains very high chloride concentrations. Other pollutants found in urban runoff include pesticides, herbicides, fertilizers and other chemical additives, heavy metals, and many other known and unknown pollutants.

Data on the rate at which pollutants accumulate on an urban watershed is very scanty. In fact, it is almost non-existent. A lot of data has been collected on the quality of combined sewer overflows and stormwater discharges for various cities in the United States (Tulsa, Oklahoma; Washington, D.C.; Atlanta, Georgia; San Francisco, California; Sacramento, California; and Roanoke, Virginia) as a result of the U.S. Environmental Protection Agency's demonstration grants program for abatement of stormwater pollution. The studies are reported in EPA's Water Pollution Research Series; however, the dissimilar forms in which the data is reported makes it difficult and in some cases impossible to generalize. The problem is that data is often presented as average concentrations or as pounds of pollutant runoff per inch of rain, and the reported values may be for combined wastewater and storm runoff rather than for storm runoff alone.

Even for a given watershed, there is no apt description of "typical" stormwater runoff characteristics because of the variablility of rainfall-runoff patterns. Thus, reports of "mean concentration" or pounds per inch of rainfall are meaningless as generalized variables and they show poor correlation with runoff parameters.

Results from a demonstration project conducted in Tulsa, Oklahoma [7], were summarized in terms of pounds of loading per day per mile of street for each of 15 areas sampled in the study. These results, presented in Table 2, give an indication of the magnitude of pollutant buildup for different land uses. These findings must be viewed with caution, however, because they were computed by taking the "average" concentration of the pollutant for all events monitored, which when multiplied by the total storm runoff gave "total annual mass emissions" converted into a rate per day per mile. A much more useful way to have developed this data would have been to sum the products of discharge and concentrations over each of the observed events and then to sum all such total storm emissions over a year.

One of the best existing sources of information on the rate of accumulation of pollutants on urban watersheds is that data collected in a field study in Chicago by APWA [5]. This study determined the rate of buildup of dust and dirt in the streets on a number of different test areas and then related the concentrations of various pollutants to the dust and dirt. A summary of their findings is contained in Table 3.

TABLE 2
Average Daily Loads Per Mile of Street*
(Tulsa, Oklahoma)

Test Area	Total Street Miles	Average Load: lbs/day/mile of street BOD	COD	Total Solids	Organic Kjeldahl Nitrogen	Soluble Orthophosphate
Residential						
3	14.87	1.41	11.46	120	0.26	0.34
5	16.32	2.80	21.43	43	0.11	0.13
7	6.84	1.20	7.20	63	0.12	0.10
8	6.97	2.72	20.89	69	0.12	0.21
9	3.11	1.12	13.09	47	0.07	0.11
11	49.05	1.60	13.29	66	0.08	0.15
13	5.58	2.58	15.16	81	0.25	0.20
15	2.06	2.47	8.67	56	0.07	0.17
Commerical						
2	7.41	2.54	15.12	92	0.32	0.29
10	12.99	2.10	20.44	82	0.16	0.13
12	3.39	4.53	25.47	113	0.22	0.30
Industrial						
1	11.46	4.85	41.10	838	0.41	1.30
4	28.40	3.98	29.29	175	0.28	0.30
6	12.24	1.70	12.73	49	0.09	0.13
Average Values						
Residential		1.98	13.9	63.1	0.14	0.18
Commercial		3.06	20.3	95.7	0.23	0.24
Industrial		3.51	27.7	354.	0.26	0.57

*Reproduced from Reference 7.

TABLE 3
APWA Findings on Rate of Pollutant Buildup
On Urban Watersheds*

Amount of Dust and Dirt and Strength of BOD by Land Use		
Land Use	Amt. of D/D by land use lb/day/100 ft of curb	BOD of D/D mg/g
Commercial	3.3	7.7
Industrial	4.6	3
Multiple family	2.3	3.6
Single family residence	0.7	5
Assumed weighted average	1.5	5

Amount of Pollutant by Type of Land Use			
Item	Single Family	Multiple Family	Commercial
Water soluble (mg/g)	6.0	5.6	12.4
Volatile water soluble (mg/g)	3.8	3.4	6.9
BOD (mg/g)	5.0	3.6	7.7
COD (mg/g)	40	40	39
PO_4 [illegible]	.05	.05	.07
N [illegible]	.48	.61	.41
Total plate counts [illegible] x 1000	10,900	18,000	11,700
Coliform [illegible] g x 1000	1,300	2,700	1,700
[illegible]	64[illegible]	518	329

To convert the data contained in Table 3 into a form comparable with that of Table 2, the Dust and Dirt is multiplied by 2 (gutters per street) x 52.8 (100's of feet of gutter per mile) x (constituent concentration/1000). E.g., the rate of BOD accumulation on an urban area that is single family residential is: $0.7 \times (2 \times 52.8) \times 5.0/1000 = 0.36$ lbs/day/mile. Rates of pollutant buildup in pounds per day per mile are given in Table 4.

TABLE 4
Average Daily Loads Per Mile of Street
(Chicago, Illinois)

Land Use	Average Load: lbs/day/mile of street			
	BOD	COD	N	PO4
Single Family Residential	0.36	2.95	0.03	0.004
Multiple Family Residential	0.87	9.70	0.15	0.012
Commercial	2.70	13.6	0.14	0.024
Industrial	1.45			

*See Reference 5.

Comparison of the values in Tables 2 and 4 indicates that while the Chicago data is consistently lower than the Tulsa data, the rates of buildup are similar in commercial areas except for PO4. Multiple family residential values for the Chicago area also compare well with the Tulsa data except for PO4. The principal reason for the lower values in the Chicago data is that the reported values are for the soluble portion of the constituents and do not include that portion found in suspended and settleable material. Also, the Tulsa data are approximations based on over-simplified computations. Thus, of the two sets of reported data the Chicago data is probably better, given that the amount of constituents contained in the solids can be determined.

One fact that is quite evident from both the Chicago and Tulsa data is that the rate of buildup of pollutants on an urban watershed varies significantly with land use. Intuition would tell us this is true. Both sets of data indicate that industrial and commercial areas are much dirtier than residential areas. This would be expected since there is higher pedestrian and vehicular traffic densities in these areas. The data shows that pollutant accumulation rates are approximately one and one-half to five times as great in commercial and industrial areas as they are in residential areas.

ENTRY OF POLLUTANTS INTO URBAN RUNOFF

The first raindrops that fall on an urban watershed simply wet the land surface. As additional rain falls the impervious surface will become wet enough that some of the water begins to form puddles, filling the depression storage. This initial rain begins to dissolve the pollutants in the gutters, streets, and on other impervious surfaces and eventually, as this water actually begins to flow off the watershed it carries the dissolved material in it.

As rainfall intensity increases, overland flow velocities become sufficient to pick up solids. Suspended solids are, of course, picked up at smaller velocities than settleable solids. The settleable solids are carried off the watershed in two ways. If the velocity is sufficiently high, the settleable solids may be suspended in the overland flow. At lower velocities, particles may simply be rolled along the bottom surface toward the stormwater inlet.

The rain that initially falls on pervious surfaces infiltrates into the ground. If the rainfall is sufficiently intense, the infiltration capacity may be exceeded and the excess rainfall begins to fill the depression storage on the pervious surfaces. Finally, if the rainfall is of sufficient intensity and duration, runoff will begin to flow off the pervious areas, onto the impervious areas and thence into the stormwater inlets. Present experience, however, indicates that the amount of runoff, and hence the pollution loads, contributed from pervious surfaces in urban areas are small compared to those coming from the impervious areas and can be neglected in determining the quality of surface runoff. This is especially true of surfaces covered with vegetation such as lawns and gardens. Figure 6 illustrates the differences in runoff and pollution load from a watershed that would occur if it was converted from a park (90% pervious) into a multiple residential area (20% pervious).

ESTIMATION OF THE RATE OF POLLUTANT BUILDUP ON URBAN WATERSHEDS

Since dirt is the major component of street litter and is the primary source of pollutants in urban runoff, the most basic approach for estimating pollutant buildup rates would be to relate them to the dust and dirt accumulation rates.

Using APWA units (Table 3) for the rate of dust and dirt accumulation, the rate of buildup DD_L for a given land use L can be expressed as:

$$DD_L = dd_L \times (G_L/100) \times A_L \tag{4}$$

where

DD_L = rate of dust and dirt accumulation on subareas of land use L in lbs/day;

dd_L = rate of dust and dirt accumulation for land use L in lbs/day/100 feet of gutter;

G_L = feet of gutter per acre for land use L; and

A_L = area in land use L in acres.

The rate factor dd_L should be supplied by the user for his area. Default values, which are those shown in Table 3 are incorporated into STORM and can be used if no better data are available.

The initial quantity of a pollutant p on subareas of land use L at the beginning of a storm can then be computed as:

$$P_p = (F_p \times DD_L \times N_D) + P_{po} \tag{5}$$

where

P_p = total pounds of pollutant p on land use L at the beginning of the storm;

F_p = pounds of pollutant p per pound of dust and dirt;

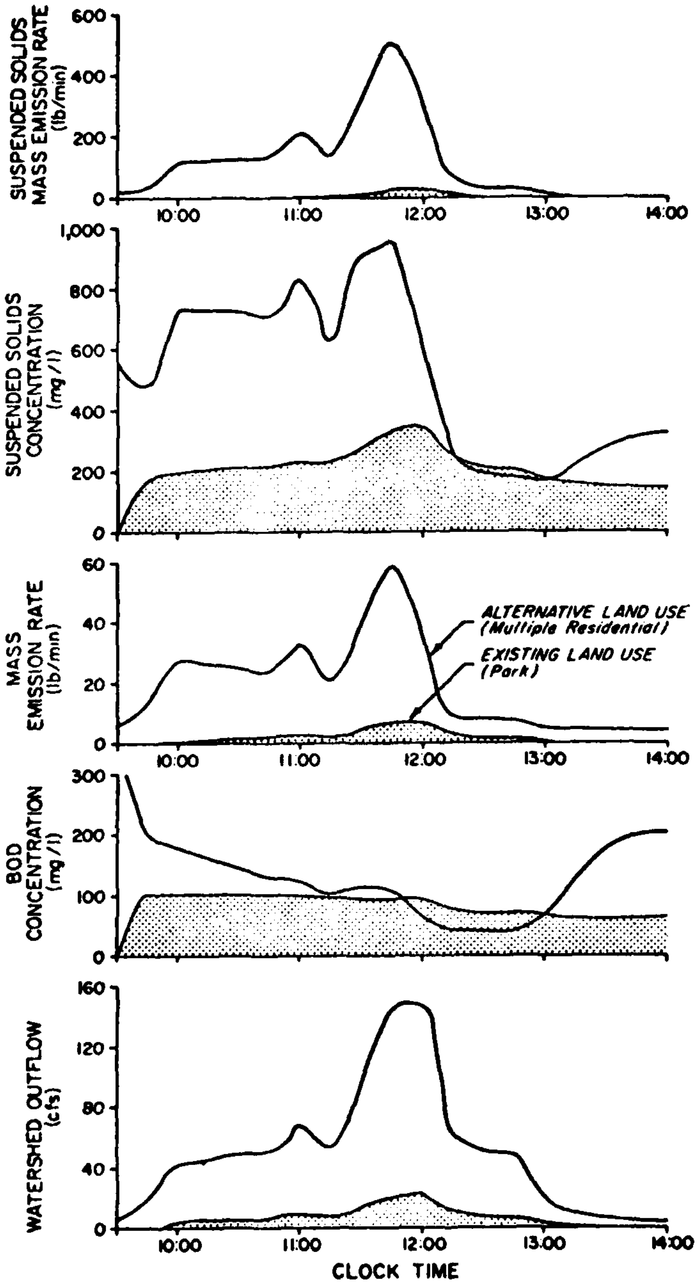

FIGURE 6
Effect of Changed Land Use on Characteristics
Of Subcatchment Runoff, Selby Street

N_D = number of dry days since the last storm; and

P_{po} = total pounds of pollutant remaining on land use L and the end of the last storm.

In practice, P_p is usually limited to the amount that would be accumulated in a 90-day dry period. The reason for this is that the efficacy of extrapolating daily buildup rates beyond this point (which was arbitrarily selected) is uncertain. Moreover, if equation (5) is used repetitively over long periods of time, positive errors could tend to accumulate in P_{po} resulting in overly large values of P_p.

If street sweeping is practiced on the watershed, the correct expression to use for P_p is:

$$P_p = P_{po}(1-E)^n + N_S \times DD_L \times F_p \left[(1-E) + \ldots (1-E)^n\right] + DD_L \times F_p (N_p - n N_S) \qquad (6)$$

where

N_S = number of days between street sweepings;

n = number of times the street was swept since the last storm; and

E = efficiency of street sweeping (0.6 to 0.95).

DETERMINATION OF URBAN RUNOFF POLLUTION LOADS

To compute the amount of pollutant washed off the watershed during a storm, it is assumed that the amount of pollutant removed at any time t is proportional to the amount remaining:

$$\frac{dP_p}{dt} = -KP_p \qquad (7)$$

We stated earlier that the runoff rate Q also affects rate of pollutant removal, therefore K must be functionally dependent upon Q. However, given two identical watersheds except for their area size, for the same rainfall rate r on both watersheds a higher runoff rate would occur from the larger watershed. This area effect can be eliminated by dividing the runoff Q by the impervious area of the watershed. The impervious area is used because only a negligible amount of the runoff comes from the pervious area. Since cfs per acre are equivalent to inches per hour, we can say that K is functionally dependent on the runoff rate R from the impervious area, where R is in inches per hour. Finally, assuming that K is directly proportional to R and that a uniform rainfall of 1/2 inch per hour would wash away 90 percent of the pollutant in one hour (a somewhat arbitrary assumption), we can say that K = 4.6R. Making this substitution into equation (7) and integrating over a time interval Δt (during which R is held constant) gives:

$$P_p(t + \Delta t) = P_p(t)e^{-4.6R\Delta t} \tag{8}$$

Equation (8) is the basic form of the overland flow quality model developed by Metcalf & Eddy, Inc., as part of the EPA Stormwater Management Model [2]. Although it is simplistic and contains many assumptions, it is the best overland flow water quality predictor or simulation model that presently exists. Moreover, experience with that model (See Reference 6 and Volume II of Reference 2) has shown it to give fairly good results.

Some idea of how equation (8) behaves can be gained by examination of Figures 7 and 8. Figure 7 shows that for a constant runoff rate R, the amount of pollutant remaining on the watershed decays exponentially. Under a time varying R the picture is quite different, as illustrated by the upper graph Figure 8. From the curve of P vs. t it can be seen that the amount of pollutant removed during an interval Δt is $P(t)-P(t+\Delta t)$. The rate of removal of mass from the watershed M_p is simply $[P(t)-P(t+\Delta t)]/\Delta t$, which can be expressed as:

$$M_p = P(t) \times (1-e^{-4.6R\Delta t})/\Delta t \tag{9}$$

The variation of M_p with time for the associated hydrograph is plotted in the lower graph of Figure 8. A plot of M_p versus t is termed a pollutograph, one of the most informative methods for expressing the pollutant load carried by urban runoff. To determine the concentration of a pollutant in the runoff as a function of time, one simply divides the pollutograph value M_p by Q (with appropriate conversion factors).

Equation (9) must be modified, however, because not all of the dust and dirt on the watershed is available for inclusion in the runoff at a given time t. Thus pollutants which are tied to the dust and dirt are not all available either. The Storm Water Management Model study [2] found that for suspended solids the available fraction at any time was:

$$A_{sus} \quad 0.057 + 1.4R^{1.1} \tag{10}$$

For settleable solids it has been assumed that the availability factor is

$$A_{set} = 0.028 + 1.0R^{1.8} \tag{11}$$

With regard to BOD, nitrogen and phosphate, recall that the APWA data [5] described the dissolved fraction, which is independent of the amount of

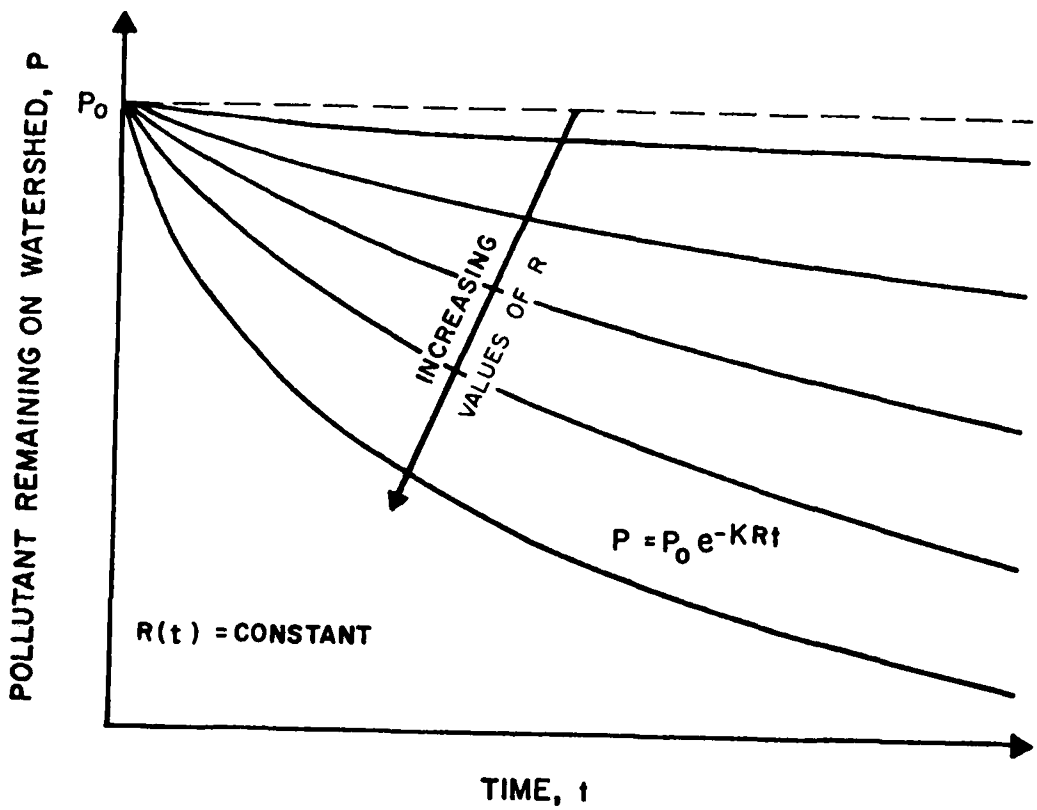

FIGURE 7
Basic Form of the Overland Flow Quality Model

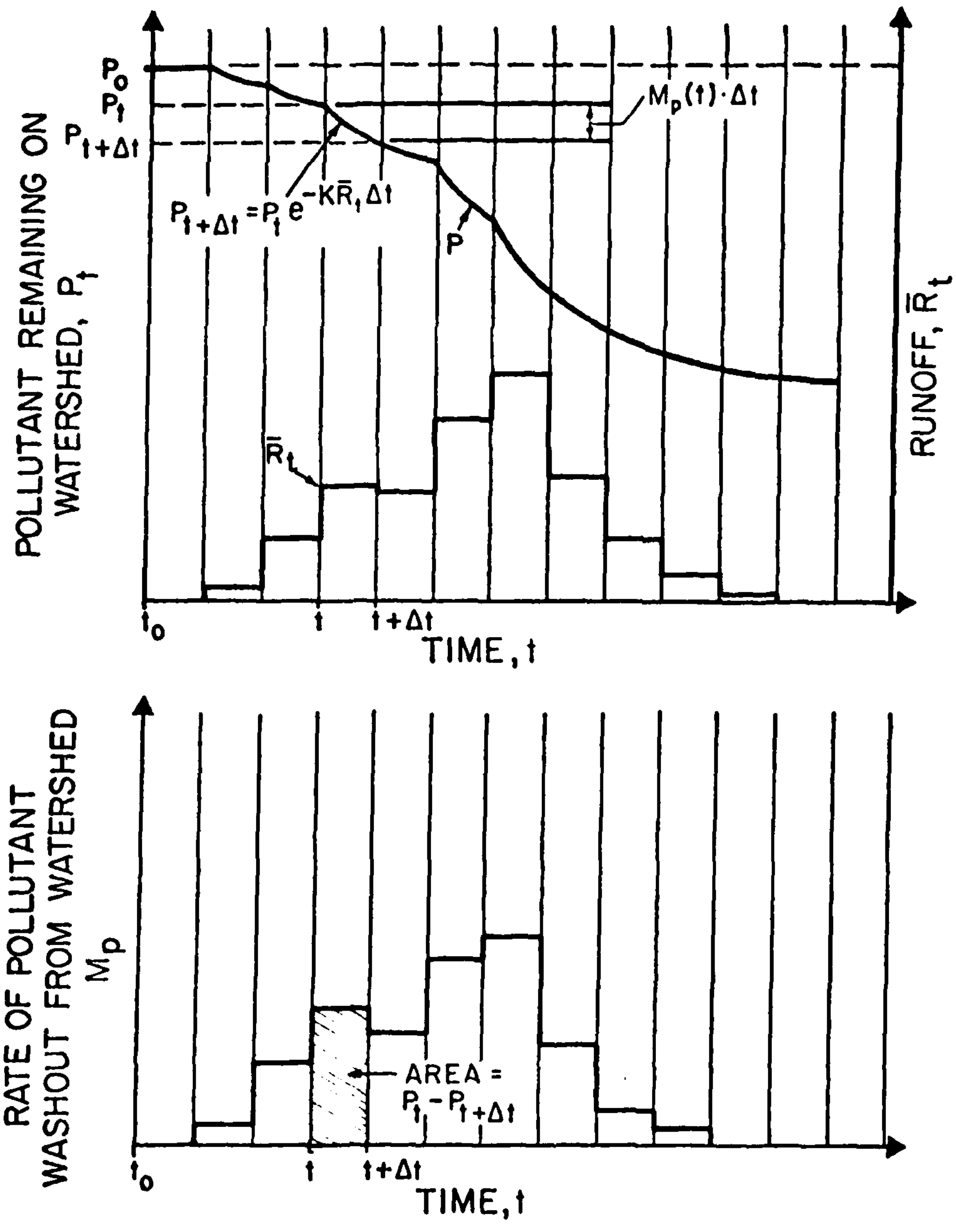

FIGURE 8
Development of Pollutograph (M_p vs. t)
From Time History of P_t

solids available for runoff. In the Storm Water Management Model study it was found that the BOD associated with the suspended solids was about 10 percent of the suspended solids load. We have further assumed that the BOD tied to the settleable solids is 2 percent of the settleable solids. For nitrogen and phosphate, we have assumed that BOD, N, and PO4 are associated with suspended and settleable solids in the same proportion as they are in the dissolved state.

Thus, correcting equation (9) for available suspended and settleable solids and adding the BOD, N and PO4 found in the solids, we get the following set of equations which are used in STORM:

Suspended Solids

$$M_{sus}(t) = A_{sus} P_{sus}(t) \times EXPT \tag{12}$$

where

$$A_{sus} = 0.057 + 1.4R^{1.1}$$

$$EXPT = (1-e^{-4.6R\Delta t})/\Delta t, \text{ with } \Delta t = 1 \text{ hour}$$

Settleable Solids

$$M_{set}(t) = A_{set} P_{set}(t) \times EXPT \tag{13}$$

where

$$A_{set} = 0.028 + R^{1.8}$$

BOD

$$M_{bod}(t) = P_{bod}(t) \times EXPT + 0.10\, M_{sus} + 0.02\, M_{set} \tag{14}$$

Nitrogen

$$M_{nit}(t) = P_{nit}(t) \times EXPT + .045\, M_{sus} + .01\, M_{set} \tag{15}$$

PO4

$$M_{PO4}(t) = P_{PO4}(t) \times EXPT + .0045\, M_{sus} + .001\, M_{set} \tag{16}$$

SECTION 4
COMPUTATION OF TREATMENT, STORAGE AND OVERFLOW

PROCEDURE

Computations of treatment, storage and overflow proceed in an hourly step-by-step method throughout a period of rainfall/snowmelt record. For every hour in which runoff occurs the treatment facilities are utilized to treat as much runoff as possible. When the runoff rate exceeds the treatment rate, storage is utilized to contain the runoff. When runoff is less than the treatment rate, the excess treatment rate is utilized to diminish the storage level. If the storage capacity is exceeded, all excess runoff overflows into the receiving waters and does not pass through the storage facility. This overflow is lost from the system and cannot be treated later. While the storm runoff is in storage its age is increasing. Various methods of aging are used including average, first-in: last-out, first-in: first-out, or others, depending on the physical conditions encountered.

The computation of storage and the interplays among rainfall/snowmelt, storage and treatment represent a simplistic approach for dividing a rainfall record into unique events such that the event is defined in terms of the urban system. For example, whether two "storms" are considered as two isolated occurrences or as one large storm is entirely dependent upon how the system will react to them. If the system has not recovered from the first when the second arrives, the two definitely will interact and hence must be considered together. "Events" are defined as beginning when storage is required and continues until the storage reservoir is emptied. All the rainfall occurring within this period is regarded as part of the same event. If precipitation produces runoff that does not exceed the treatment rate, the runoff will pass through the treatment process but will not register as an event. From the standpoint of the urban stormwater system, such precipitation is inconsequential and hence is not part of an "event" even if it should occur immediately preceding an obvious event.

The runoff coming into the storage/treatment system is given by equation (1). The quantity of system overflows are computed using:

$$Q_o = R - Q_T - Q_S \qquad (17a)$$

$$Q_T = \text{minimum of } (R + Q_{s_{t-1}}, T) \qquad (17b)$$

$$Q_s = \text{minimum of } (R - Q_T, S) \qquad (17c)$$

where

Q_o = watershed runoff overflow, in inches;

Q_T = watershed runoff treated, in inches;

Q_s = watershed runoff stored, in inches;

$Q_{s_{t-1}}$ = watershed storage remaining in previous hour, inches;

R = watershed runoff as calculated using equation (1), inches;

T = treatment rate in watershed inches/hour; and

S = storage capacity in watershed, inches.

The quality of system overflows are computed as follows for each pollutant for each hour:

$$M_{po} = M_p (Q_o / R) \quad (18)$$

$$M_{pS/T} = M_p - M_{po} \quad (19)$$

where

M_{po} = total pounds of pollutant overflowing from system;

M_p = total pounds of pollutant p coming into the system; and

$M_{pS/T}$ = total pounds of pollutant p going to storage/treatment.

The program does not model the treatment process but it does compute the quantity of water treated. It is assumed that the pollutants will be reduced to an acceptable level before the storm water is released. The age of pollutant in storage is computed as previously mentioned.

SECTION 5
INPUT AND OUTPUT FOR "STORM"

The basic input data required by STORM and the basic output data generated by the program are illustrated in Figure 9. This section defines the input data requirements more specifically and contains details on STORM output.

INPUT DATA REQUIREMENTS

Hydrogeometric Data

The first step in setting up data for the simulation model is to define the boundaries of the basin which is to be investigated, specifically that area which drains to some specific point of interest such as a receiving water. The size of the area is a computation variable but it should be limited to less than 10 square miles so that travel time in the system can be neglected.

Once the drainage basin boundaries are set the following information is required:

1. Size of the total area of the basin

2. Percent of the total area in each of the following land use groups:

    a. Single Family Residential
    b. Multiple Family Residential
    c. Commercial
    d. Industrial
    e. Open or park

3. Average percent imperviousness of each land use group

4. Feet of gutter per acre for each land use group

5. A runoff coefficient for impervious areas (the usual range is 0.8 to 0.9)

6. A runoff coefficient for pervious areas (the usual range is 0.1 to 0.3)

7. The depression storage available on the impervious areas (usually 0.05 to 0.1 inches).

INPUT

I. LAND USE INFORMATION

Residential
Multiple Family
Commercial
Industrial
Park

A. AREA
B. % IMPERV.
C. RUNOFF COEFF.
D. FT. OF GUTTER/ACRE

II. HYDROLOGIC RECORD OF HOURLY RAINFALL

ANALYSIS

I. RUNOFF

$R = C(I-D)$

where:

$C = \frac{\Sigma C_i A_i}{\Sigma A_i}$

II. QUALITY

$Mp = P(1 - e^{-KR})$

A. SUSP. SOLIDS
B. SETT. SOLIDS
C. BOD
D. NITROGEN
E. PHOSPHORUS

III. STORAGE

$\Delta S = R - T$

OUTPUT

I. STATISTICS BY EVENT

A. RAINFALL
B. STORAGE
C. OVERFLOW
D. TREATMENT
E. QUALITY

II. AVERAGE STATISTICS FOR ALL EVENTS

A. EVENTS/YR.
B. AVERAGES OF A-E ABOVE FOR ALL EVENTS
C. OVERFLOWS/YR. AVERAGES OF A-E ABOVE FOR ALL OVERFLOW EVENTS

FIGURE 9
Input-Output Elements

Determination of the percent of area under the various land uses can be a tedious task. However, most jurisdictions have this information already available in one form or another, or they have maps of sufficient scale that the various land uses can be identified and their areas calculated.

Determination of the average percent imperviousness of each land use group must be done carefully, for this is the most sensitive parameter affecting the amount of storm runoff which comes off a watershed. In particular, impervious surface areas which drain to pervious areas should be excluded from the impervious fraction because runoff from these surfaces will probably be held on the pervious surfaces to which they drain. In this regard, special attention should be given to whether the house gutter drains to pervious land or to the sewer system or gutter. Also, in residential areas where there are parking strips, the sidewalks will most likely drain to the pervious area on either side of the walk. Table 5 may offer some guidance for determining the percent imperviousness for different land uses.

TABLE 5
Percent Imperviousness for
Various Land Uses in the San Francisco Area*

Type of development (1)	Density, in units per acre (2)	Percent impervious: Santa Clara County (3)	Percent impervious: San Francisco Bay Region (4)
Residential:			
Hill areas	0.5- 2	6	8
Low urbanization	3 - 6	10	15
Medium urbanization	7 -10	20	25
Heavy urbanization (apartments)	11 -20	32	40
Industrial:			
Nonmanufacturing		50	60
Manufacturing		40	50
Reserve		20	25
Commercial		50	60
Transporation		70	75
Public buildings		40	50
Public parks		12	12
Agricultural		4	4
Natural watersheds		2	2

*Extracted from Table 1 of Reference 8.

Estimation of the number of feet of gutter per acre is best done from a plat. But if none is available a reasonable estimate can be based on the average size of the block by taking the perimeter of the block times the number of blocks per acre from a street map.

Hydrologic Data

A record of hourly rainfall is required. The rainfall record may be as long or as short as desired but should be of sufficient length to assure that all storms of interest are included in the record. Ten to thirty years of record is desirable. A long raingage record exists for most cities. Where such information is lacking, however, standard hydrologic procedures for areal translation of rainfall records will have to be applied.

Quality Data

The quality data required for the simulation model consists of:

1. The daily rate of dust and dirt accumulation in pounds per 100 feet of gutter for each of the land use areas:

    a. Single Family Residential
    b. Multiple Family Residential
    c. Commercial
    d. Industrial
    e. Open or Park

2. The pounds of each of the following pollutants per 100 pounds of dust and dirt for each land use category:

    a. Suspended solids
    b. Settleable solids
    c. Soluble BOD
    d. Soluble N
    e. Soluble PO4

3. The interval in days between street sweepings for each land use category

4. *Street sweeping efficiency (usual range is .6 to .9).*

Because this data is difficult to obtain, default values are provided in the computer program as follows:

1. Daily Rate of Dust and Dirt Accumulation*

Land Use	Amount of D/D by Land Use, lb./day/100 ft. of Gutter
Single Family Residential	0.7
Multiple Family Residential	2.3
Commercial	3.3
Industrial	4.6
Open or Park**	1.5

2. Pounds of Pollutant in Dust and Dirt*

Land Use	Lbs. of Pollutant/100 lbs. of D/D				
	Sus. Solids**	Sett. Solids**	BOD	N	PO4
Single Family Residential	11.1	1.1	0.5	0.048	0.005
Multiple Family Residential	8.0	0.8	0.36	0.061	0.005
Commercial	17.0	1.7	0.77	0.041	0.007
Industrial**	6.7	0.7	0.3	0.043	0.003
Open or Park**	11.1	1.1	0.5	0.048	0.005

3. *Street Sweeping Interval* 90 days

4. Street Sweeping Efficiency 0.7

OUTPUT FROM "STORM"

The computer program produces four output reports:

1. Quantity Analysis,
2. Quality Analysis,
3. Pollutograph Analysis, and
4. Land Surface Erosion Analysis.

For the quantity and quality analyses, STORM generates statistics by event plus the average statistics for all events. A complete list of the output statistics from the quantity and quality analyses are contained in Table 6.

Tables 7 through 11 are examples of STORM output from the Quantity Analysis, Quality Analysis and Pollutograph Analysis. For details on the output from the Land Surface Erosion Analysis the reader is referred to the program manual [4].

*Data is taken from APWA Chicago Study (See Reference 5).
**Estimated values from other sources.

TABLE 6
"STORM" Output

I. STATISTICS BY EVENTS

A. RAINFALL
1. DURATION OF RAINFALL EVENT
2. HOURS OF RAIN
3. TOTAL RAINFALL

B. STORAGE
1. TIME SINCE LAST EVENT
2. DURATION OF STORAGE
3. TIME TO EMPTY
4. MAXIMUM STORAGE USED

C. OVERFLOW
1. TIME OVERFLOW STARTS
2. DURATION OF OVERFLOW
3. QUANTITY OF OVERFLOW
4. OVERFLOW IN FIRST THREE HOURS

D. TREATMENT
1. DURATION OF TREATMENT
2. QUANTITY TREATED

E. QUALITY (susp. solids, sett. solids, BOD, nitrogen, phosphorous)
1. MASS EMISSION IN RUNOFF
2. MASS EMISSION OF OVERFLOW
3. MASS EMISSION DURING FIRST THREE HOURS OF OVERFLOW

II. AVERAGE STATISTICS (A-E ABOVE)

A. FOR ALL EVENTS
B. FOR ALL OVERFLOW EVENTS
C. EVENTS / YR
D. OVERFLOWS / YR

PAGE 1

SELBY STREET WATERSHED SAN FRANCISCO, CA.
QUANTITY ANALYSIS

TREATMENT RATE = .0100 IN/HR, 37.8 CFS, 24.400 MGD
STORAGE CAPACITY= .1030 INCHES, 31.2 AC-FT, 10.168 MG

FED BLDG, SAN FRANCISCO, CA.
SELBY STREET

EVENT	---D A T E---				HRS NO	-R A I N F A L L-			RUNOFF	HRS TO	--STORAGE--		----O V E R F L O W----					---TREATMENT----		--AGE OF STORAGE---				
	YEAR	MO	DY	HR	STORAG	DURTN	HRS	QUANTY	INCHES	EMPTY	DURTN	MAX	NO	ST	DUR	WASTE	INITL	HRS	QANTY	AGE1	AGE2	AGE3	AGE4	AGE5
****1	********2			*3	*****4	****5	***6	*****7	****7A	*****8	****9	***10	*11	*12	*13	***14	***15	***16	***17	**18	**19	**20	**21	**22
1	64	10	28	16	3422	33	17	1.73	.84	4	37	.10	1	3	9	.47	.07	37	.37	4.9	11.5	35.5	5.4	8.4
2	64	11	1	2	45	3	2	.16	.08	6	9	.05		3	NO OVERFLOW			9	.08	2.1	5.5	7.5	1.8	1.8
3	64	11	2	3	16	6	6	.49	.23	10	16	.10	2	2	5	.06	.06	16	.16	6.1	13.5	14.5	5.2	5.3
4	64	11	8	11	136	26	16	.88	.42	8	34	.10	3	2	5	.08	.05	34	.33	5.0	13.5	32.5	6.5	10.3
5	64	11	9	24	3	20	10	.97	.46	4	24	.10	4	2	4	.22	.20	24	.23	4.3	10.1	22.1	5.6	7.4
6	64	11	11	8	8	1	1	.03	.02	1	2	.00		1	NO OVERFLOW			8	.04	.5	.5	.5	.5	.5
7	64	11	11	12	2	11	6	.36	.18	7	18	.06		3	NO OVERFLOW			19	.18	3.1	7.5	16.5	3.1	4.3
8	64	11	12	7	1	3	3	.11	.04	2	5	.01		2	NO OVERFLOW			5	.04	1.3	3.5	3.5	1.6	1.6
9	64	11	12	18	198	5	3	.14	.07	2	7	.03		1	NO OVERFLOW			8	.07	1.5	3.5	5.5	1.9	2.4
10	64	11	21	20	19	5	4	.24	.10	6	11	.06		3	NO OVERFLOW			11	.10	3.4	7.5	8.5	2.8	3.0

DEFINITIONS OF QUANTITY COLUMN HEADINGS
----

1 EVENT = SEQUENCING NUMBER.
2 DATE = DATE THIS EVENT BEGAN.
3 HR = NUMBER OF HOURS PAST MIDNIGHT THIS EVENT BEGAN.
4 HRS NO STORAG = NUMBER OF HOURS SINCE END OF LAST EVENT, EXCLUDING SUMMER (MORE THAN, 960 HOURS).

5 DURTN = DURATION OF STORM FROM FIRST HOUR OF RAIN TO LAST HOUR OF RAIN.
6 HRS = NUMBER OF HOURS IN WHICH RAINFALL OCCURRED DURING EVENT.
7 QUANTY = AMOUNT OF RAINFALL DURING THE EVENT IN INCHES.
7A RUNOFF INCHES = RUNOFF DURING EVENT IN INCHES.
8 HRS TO EMPTY = NUMBER OF HOURS FROM LAST RAINFALL TO END OF EVENT.
9 DURTN = TOTAL NUMBER OF HOURS STORAGE WAS UTILIZED. IE, LENGTH OF THE EVENT.
10 MAX = MAXIMUM AMOUNT OF STORAGE UTILIZED, IN INCHES.

11 NO = OVERFLOW EVENT SEQUENCING NUMBER.
12 ST = NUMBER OF HOURS ELAPSED BEFORE OVERFLOW STARTED. OR, IF NO OVERFLOW, HOUR OF MAXIMUM STORAGE.
13 DUR = NUMBER OF HOURS IN WHICH OVERFLOW OCCURED.
14 WASTE = QUANTITY OF WATER RELEASED UNTREATED, IN INCHES.
15 INITL = QUANTITY OF WATER RELEASED UNTREATED DURING THE FIRST 3 HOURS OF OVERFLOW.

16 HRS = NUMBER OF HOURS WATER WAS TREATED DURING THE PRESENT EVENT AND SINCE THE PREVIOUS EVENT.
17 QANTY = QUANTITY OF WATER TREATED DURING THE EVENT AND SINCE THE PREVIOUS EVENT.
18 AGE1 = AVERAGE AGE (HOURS) OF TREATED RUNOFF.
19 AGE2 = MAXIMUM AGE (HOURS) OF STORAGE ON FIRST IN, FIRST OUT BASIS.
20 AGE3 = MAXIMUM AGE (HOURS) OF STORAGE ON FIRST IN, LAST OUT BASIS.
21 AGE4 = QUANTITY WEIGHTED AVERAGE AGE (HRS) OF STORAGE ON FIRST IN, FIRST OUT BASIS.
22 AGE5 = QUANTITY WEIGHTED AVERAGE AGE (HRS) OG STORAGE ON FIRST IN, LAST OUT BASIS.

TABLE 7
Example of Quantity Statistics by Event

```
PAGE    1
                                    SELBY STREET WATERSHED   SAN FRANCISCO, CA.
                                                      QUANTITY ANALYSIS
TREATMENT RATE  =  .0100 IN/HR,    37.8 CFS,    24.400 MGD
STORAGE CAPACITY=  .1000 INCHES,   31.2 AC-FT,  10.168 MG                                              FED BLDG, SAN FRANCISCO, CA.
                                                                                                         SELBY STREET

EVENT ---D A T E--- HRS NO -R A I N F A L L- RUNOFF HRS TO --STORAGE-- ----O V E R F L O W---- ---TREATMENT---- --AGE OF STORAGE---
      YEAR MO DY HR STORAG DURTN  HRS QUANTY INCHES  EMPTY DURTN   MAX  NO  ST DUR WASTE INITL  HRS  CANTY AGE1 AGE2 AGE3 AGE4 AGE5
****1 *********2 *3 *****4 ****5 ***6 *****7 ****7A *****8 ****9 ***10 *11 *12 *13 ***14 ***15 ***16 ***17 **18 **19 **20 **21 **22


AVE OF  168 EVENTS   181.7**10.9  7.6     .47     .22     3.8  14.8    .06     2.7*                      15.5    .15  3.1  7.7 12.8  3.5  4.3
AVE OF   69 OVRFLW EVENTS   19.8 13.1     .92     .45     5.7  25.5    .03*    5.3 5.4    .20    .10     26.0    .25  5.2 13.4 23.5  6.1  7.7

* NON-OVERFLOW EVENTS ONLY.
**EXCLUDING 10 DRY PERIODS


AVERAGE ANNUAL STATISTICS FOR  5 YEARS OF RECORD FOR THE PERIOD BEGINNING 641027 AND ENDING 681228
--------------------------------------------------------------------------------------------------

NUMBER OF EVENTS =      33.6

NUMBER OF OVERFLOWS =  13.8.

                                     INCHES
                                     ------

TOTAL PRECIPITATION ON WATERSHED     17.95

TOTAL RUNOFF FROM WATERSHED           7.60     FRACTION OF RAINFALL = .42

OVERFLOW TO RECEIVING WATER           2.70     FRACTION OF RAINFALL = .15,  OF RUNOFF = .36

INITIAL OVERFLOW TO RECIEVING WATER   1.42     FRACTION OF RAINFALL = .08,  OF RUNOFF = .19
```

TABLE 8
Example of Average Quantity Statistics for all Events

PAGE 1

SELBY STREET WATERSHED SAN FRANCISCO, CA.
QUALITY ANALYSIS

TREATMENT RATE = .0100 IN/HR, 37.8 CFS, 24.400 MGD
STORAGE CAPACITY= .1000 INCHES, 31.2 AC-FT, 10.168 MG

FED BLDG, SAN FRANCISCO, CA.
SELBY STREET

EVENT	DATE EVENT BEGAN YR MO DY	HR	RAIN FALL INCHS	STORM RUNOFF INCHS QANTY	STORM RUNOFF TOTAL POUNDS SUSP	SETL	BOD	N	PO4	STORAGE SEQ NO	STORAGE INCHS QANTY	SUSP	OVERFLOW TOTAL POUNDS SETL	BOD	N	PO4	FIRST 3 HOURS OVERFLOW INCH	TOTAL POUNDS SUSP	SETL	BOD	N	PO4
****1	*******2	*3	****4	****5	*****6	****7	****8	****9	**10	*11	***12	****13	***14	***15	***16	**17	**18	***19	**20	**21	**22	**23
1	54 10 28	16	1.73	.84	58378	2150	8134	2849	284	1	.47	27072	1291	3462	1440	144	.07	4248	129	922	264	26
2	64 11 1	2	.16	.08	1741	112	267	97	10		NO OVERFLOW											
3	54 11 2	3	.49	.23	5491	433	702	293	29	2	.06	1317	100	165	70	7	.06	1260	94	157	67	7
4	64 11 8	11	.88	.42	9780	669	1513	548	55	3	.08	1739	125	230	94	9	.05	1073	75	154	59	6
5	64 11 9	24	.97	.46	9153	888	1007	474	47	4	.22	4598	458	490	237	24	.20	4362	429	465	225	22
6	64 11 11	8	.03	.02	134	16	15	6	1		NO OVERFLOW											
7	64 11 11	12	.36	.18	1666	234	206	89	9		NO OVERFLOW											
8	64 11 12	7	.11	.04	310	45	46	17	2		NO OVERFLOW											
9	64 11 12	18	.14	.07	557	73	81	31	3		NO OVERFLOW											
10	64 11 21	24	.24	.10	2360	155	663	162	16		NO OVERFLOW											

TITLE DESCRIPTIONS

1. EVENT = Sequence number
2. DATE = Date this event began
3. HR = Number of hours past midnight this event began
4. RAINFALL = Total quantity of rainfall for this event in inches
5. QANTY = Total quantity of runoff for this event in inches
6. SUSP = Suspended solids
7. SETL = Settleable solids
8. BOD = BOD
9. N = Total nitrogen
10. PO4 = Orthophosphate

(items 6–10: Total lbs in runoff for this event)

11. NO = Overflow event sequencing number
12. QANTY = Total quantity of overflow for this event in inches
13. SUSP =
14. SETL =
15. BOD =
16. N =
17. PO4 =

(items 13–17: Total lbs. in overflow for this event)

18. # = Quantity of overflow during first three hours in inches
19. SUSP =
20. SETL =
21. BOD =
22. N =
23. PO4 =

(items 19–23: Total lbs. in overflow during first three hours)

TABLE 9
Example of Quality Statistics by Events

PAGE 1

SELBY STREET WATERSHED SAN FRANCISCO, CA.
QUALITY ANALYSIS

TREATMENT RATE = .0100 IN/HR, 37.8 CFS, 24.400 MGD
STORAGE CAPACITY= .1400 INCHES, 31.2 AC-FT, 10.168 MG

FED BLDG, SAN FRANCISCO, CA.
SELBY STREET

EVENT	DATE EVENT BEGAN YR MO DY	HR	RAIN FALL INCHS	STORM RUNOFF INCHS QANTY	STORM RUNOFF TOTAL POUNDS SUSP	SETL	BOD	N	PO4	STORAGE OVERFLOW SEQ NO	INCHS QANTY	TOTAL POUNDS SUSP	SETL	BOD	N	PO4	FIRST 3 HOURS OVERFLOW INCH	TOTAL POUNDS SUSP	SETL	BOD	N	PO4
****1	*******2	*3	****4	****5	*****6	****7	****8	****9	**10	*11	***12	****13	***14	***15	***16	**17	**18	***19	**20	**21	**22	**23
AVE OF 168 EVNTS			.47	.22	9110	688	1408	511	51													
AVE OF 69 OVRFLS			.92	.45	18692	1443	2681	1028	103		.20	8663	732	1058	458	46	.10	5950	461	759	318	32

AVERAGE ANNUAL STATISTICS FOR 5 YEARS OF RECORD FOR THE PERIOD BEGINNING 641027 AND ENDING 681228

	SUSP	SETL	BOD	N	PO4
TOTAL POUNDS WASHOFF FROM WATERSHED	308603	23362	48134	17365	1723
TOTAL POUNDS OVERFLOW TO RECEIVING WATER	119551	10098	14595	6325	632
CONCENTRATION OF POLLUTANTS IN OVERFLOW TO RECEIVING WATER (MG/L)	52.12	4.40	6.36	2.76	.28
FRACTION OF TOTAL WASHOFF OVERFLOWING TO RECEIVING WATER	.39	.43	.30	.36	.37
FRACTION OF TOTAL WASHOFF INITIALLY OVERFLOWING TO RECEIVING WATER	.27	.27	.22	.25	.25

TABLE 10
Example of Average Quality Statistics for all Events

PAGE 1

SELBY STREET WATERSHED SAN FRANCISCO, CA.
POLLUTOGRAPH FOR EVENT

TREATMENT RATE = .0100 IN/HR, 37.8 CFS, 24,400 MGD
STORAGE CAPACITY= .1000 INCHES, 31.2 AC-FT, 10,168 MG

FED BLDG, SAN FRANCISCO, CA.
SELBY STREET

									RUNOFF POLLUTANT LOAD, IN LBS/HR					** AVE CONCENTRATION, IN MG/L ******				
EVENT	YR	MO	DY	HR	T(0)	RAINFALL	RUNOFF	CFS-OFF	SUSP	SETL	BOD	N	PO4	SUSP	SETL	BOD	N	PO4
153	68	11	2	6	1	.08	.04	153.8	3592.5	106.7	861.0	231.3	23.0	103.9	3.1	24.9	6.69	.67
153	68	11	2	7	2	.13	.07	290.0	7177.1	207.8	1251.5	414.5	41.3	127.8	3.7	22.3	7.38	.74
153	68	11	2	8	3	.08	.04	153.8	3184.2	103.4	529.9	181.4	18.1	92.1	3.0	15.3	5.25	.52
153	68	11	2	9	4	.05	.03	96.1	1559.1	58.6	256.8	88.6	8.8	72.2	2.7	11.9	4.10	.41
153	68	11	2	10	5	.01	.01	19.2	208.4	11.2	38.7	12.3	1.2	48.2	2.6	8.9	2.85	.28
153	68	11	2	17	12	.04	.01	43.3	538.7	25.3	93.2	31.1	3.1	55.4	2.6	9.6	3.20	.32
153	68	11	2	18	13	.02	.01	38.5	463.4	22.4	78.4	26.6	2.7	53.6	2.6	9.1	3.08	.31
153	68	11	2	20	15	.04	.02	71.3	1009.1	42.2	154.4	56.2	5.6	63.0	2.6	9.6	3.51	.35
153	68	11	2	21	16	.01	.01	19.2	204.0	11.2	33.5	11.6	1.2	47.2	2.6	7.7	2.69	.27
153	68	11	2	22	17	.02	.01	38.5	454.0	22.3	70.0	25.4	2.5	52.5	2.6	8.1	2.94	.29
153	68	11	2	23	18	.01	.01	19.2	202.3	11.1	31.8	11.4	1.1	46.8	2.6	7.4	2.63	.26
153	68	11	2	24	19	.02	.01	38.5	450.1	22.2	66.8	24.9	2.5	52.1	2.6	7.7	2.88	.29
153	68	11	3	1	20	.04	.02	76.9	1083.8	45.2	147.0	58.5	5.8	62.7	2.6	8.5	3.38	.34
153	68	11	3	2	21	.08	.04	153.8	2809.6	100.1	346.0	149.5	14.9	82.4	2.9	10.0	4.32	.43
153	68	11	3	3	22	.08	.04	153.8	2781.5	99.1	318.6	142.4	14.2	79.3	2.9	9.2	4.12	.41
153	68	11	3	4	23	.03	.02	57.7	677.1	32.6	81.0	35.5	3.5	52.2	2.5	6.2	2.74	.27
153	68	11	3	5	24	.07	.04	134.6	2147.3	82.7	240.4	110.6	11.1	71.0	2.7	7.9	3.66	.37

NOTE:

T(0) = Hours since start of storm
RAINFALL = Inches of rainfall during indicated hour
RUNOFF = Inches of runoff during indicated hour
CFS-OFF = Average runoff rate in cfs during indicated hour

TABLE 11
Example of Hourly Quality Statistics

SECTION 6
PLANNING APPLICATIONS

CITY OF SAN FRANCISCO

The City of San Francisco funded the original development of the Quantity Analysis portion of STORM. The purpose of the program was to create a tool that would enable the City to evaluate the effectiveness of various combinations of treatment rate and storage capacity with respect to their ability to reduce combined sewer system overflows. Results from STORM were used as a guide in the initial sizing of facilities for the City's Master Plan [3]. The following paragraphs are abstracted from the Master Plan Report. Additional details are described in References 12 and 13.

The rainfall record used for the analysis was a 62 year U.S. Weather Service record of hourly values of rainfall measured at the Federal Office Building in the City. A runoff coefficient of 0.65 was assumed for the analysis. Table 12 shows the various combinations of treatment rate and storage capacity that were examined, the resulting events per year, overflows per year and average quantity of overflow per year. These data are displayed graphically in Figures 10 and 11, which show the relationship between given combinations of storage and treatment with overflow frequencies and with overflow volumes, respectively.

Application of STORM to the Federal Office Building record with 0 storage and a treatment rate of 0.02 inches per hour provided the baseline or existing condition data. From this computation it was determined that approximately one-third of the runoff is presently treated and discharged by the three water pollution control plants and that the other two-thirds, or about 6.0 billion gallons of runoff per year, overflows without treatment. This volume of overflow occurs during an aggregate average of 206 hours per year. On the average, there are 46 days in the year during which 82 overflows occur.

The storage needed to contain all overflows from the greatest recorded storm utilizing the existing treatment rates would be 240 million cubic feet. This storage volume is then the upper limit of an all-storage scheme and exceeds by a factor of 2 the volume requirement of an all-treatment scheme.

The data presented above was necessarily based on two assumptions: that the runoff loss is 35 percent and that rainfall occurrence is uniform over the City. Each is a significant parameter in determining the total volumes of runoff. At the time the Master Plan was being developed no verified data existed on the losses experienced in the rainfall-runoff process, although some measurements have been made in more recent characterization studies.

TABLE 12
San Francisco Hyetograph Storage/Treatment Analysis

Treatment[1]	Storage Capacity[2]	USWB 62 Yr. Rec. Event/ yr.	Ovrflw/ yr.	Quan/ yr.
.02	.50	38.806	7.710	4.254
	1.00	36.661	2.823	1.907
	1.50	35.726	1.242	.926
	2.00	35.435	.597	.504
	2.50	35.194	.387	.265
	3.00	35.113	.242	.107
	3.50	35.048	.097	.033
	4.00	35.048	.032	.008
.04	.25	42.355	11.726	4.115
	.50	40.226	5.435	2.101
	.75	39.435	2.823	1.125
	1.00	39.113	1.419	.624
	1.50	38.903	.403	.231
	2.00	38.871	.177	.107
	2.50	38.790	.113	.031
	3.00	38.790	.016	.002
.06	.25	37.774	9.323	2.611
	.50	36.855	3.645	1.134
	.75	36.468	1.500	.524
	1.00	36.339	.661	.270
	1.50	36.290	.177	.095
	2.00	36.274	.113	.012
.08	.10	33.016	15.242	3.247
	.25	31.952	7.194	1.694
	.50	31.419	2.371	.633
	.75	31.274	.903	.264
	1.00	31.194	.371	.121
	1.50	31.145	.113	.025
	2.00	31.145	.016	.001
.10	.10	27.484	12.484	2.363
	.25	26.855	5.403	1.121
	.50	26.484	1.597	.369
	.75	26.435	.581	.128
	1.00	26.403	.177	.050
	1.50	26.387	.032	.007

[1]Treatment Rate in inches per hour.
[2]Storage Capacity in inches.

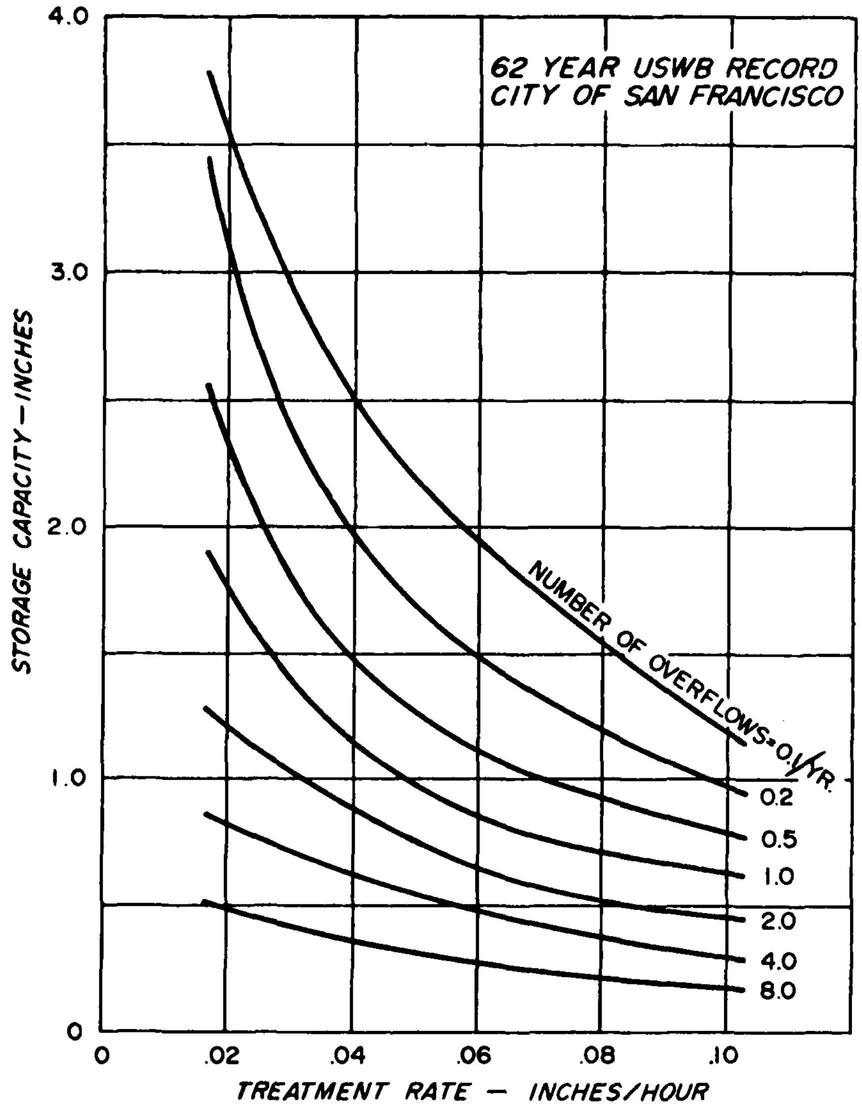

FIGURE 10
Overflow Frequencies

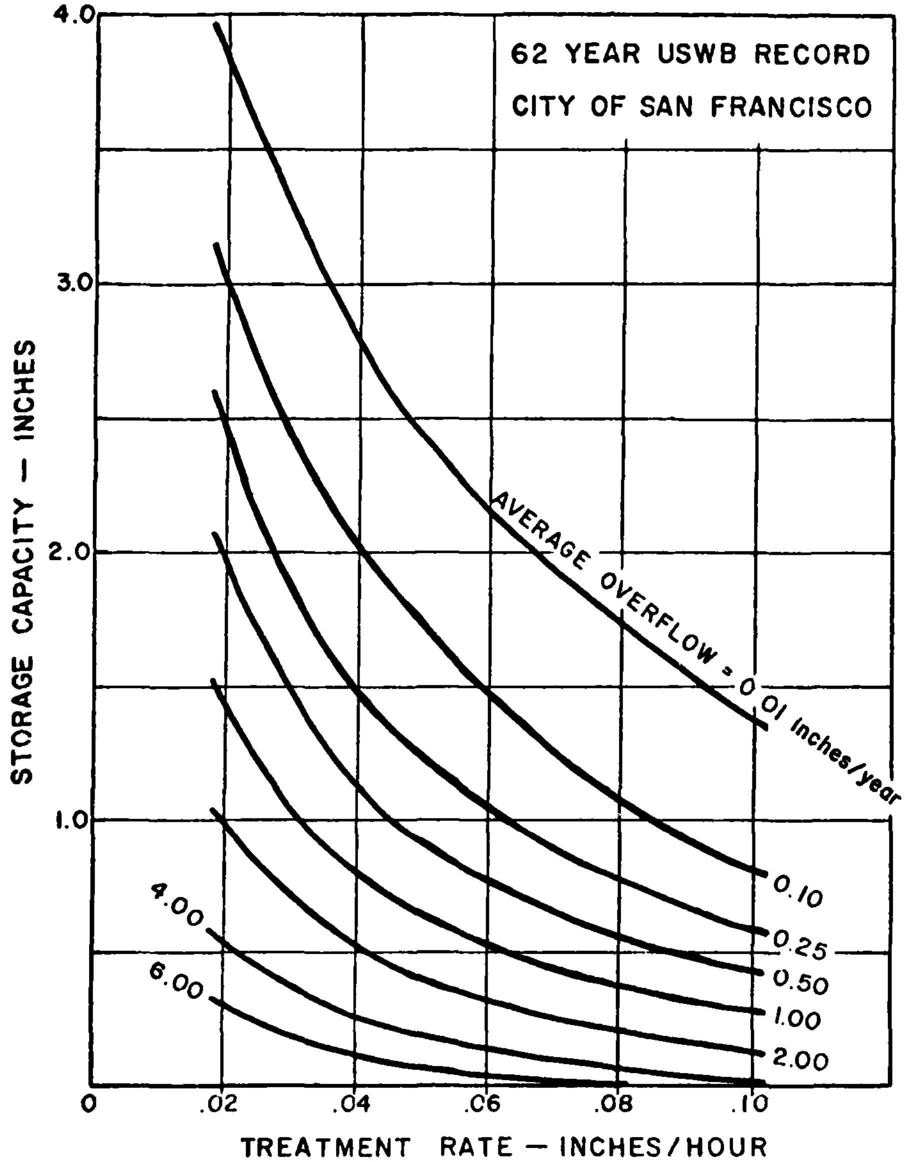

FIGURE 11
Overflow Volumes

Storms monitored during the 1969/1970 rainy season by a system of 19 rain gages distributed over the city showed a 15 percent lower overall average volume of rainfall over the whole city than that indicated by the gage at the Federal Office Building. Because the time correlation for the 19 rain gages which were operational during that season was poor, the above percentage indicates only the extent of spatial variation.

Spatial and temporal differences observed in the occurrence of rainfall led to the conclusion that a system featuring interconnection would result in more efficient utilization of facilities. Further, the use of real-time computer-actuated control, based on sensing storm direction and the likely volumes of rainfall, with a constant concurrent updating of the status of the system, would permit a maximum use of all capacity throughout the system. The result would be the construction of fewer and smaller facilities which would serve the overall system rather than only discrete segments of the system.

Other STORM statistics for the various combinations of storage and treatment include the number of events that would have occurred, the volume of overflows, the duration of overflows, and the number of days of overflows. With the previous assumptions, this data was used for preliminary evaluation of proposed control systems with regard to possible overflow quality and mass emissions of constituents.

The initial sizing of the Master Plan system was based upon the records available from the Weather Service gage. This data represented the best information available at the time and all other data indicated that any design based upon this gage would likely be conservative with regard to size and costs. Refinement of the design will take place as data accumulates from the City's extensive field information collection system.

Figure 12 shows a composite of the effects of various combinations of storage and treatment with regard to the frequency of uncontrolled overflow occurrences. It is apparent that, given a desired frequency of overflow occurrence, increasing the treatment rate decreases the storage requirements and that, for any given storage volume, increasing treatment capacity results in a lower occurrence frequency. Further inspection of the figure also indicates that the law of diminishing returns results in increasingly greater storage requirements for any treatment rate to attain a lower frequency of overflow occurrence. Through the application of cost factors for storage and treatment facilities, optimum design points for minimum cost for various levels of control can be derived.

Sewer System

The present storm sewer design criteria includes the conveyance of a 5-year intensity rainfall without flooding. When rainfall intensity exceeds the design rate, surface transport and flooding can

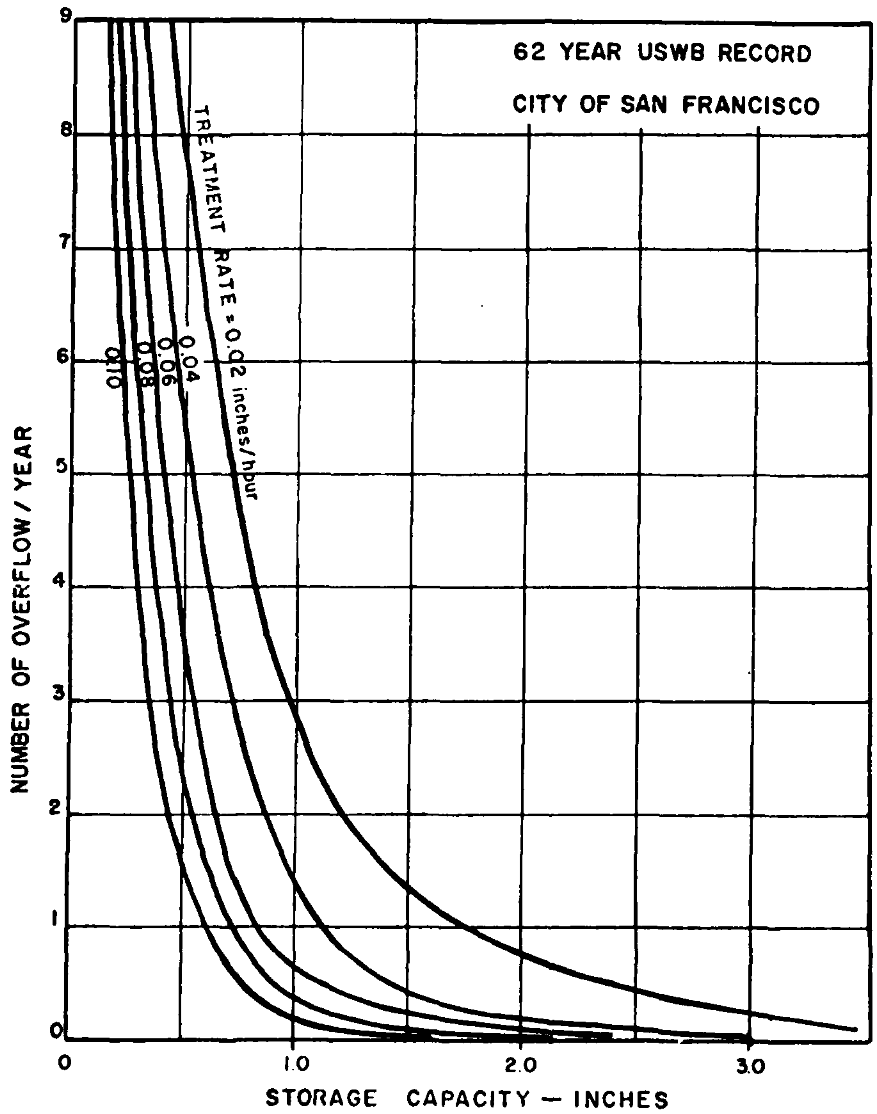

FIGURE 12
Overflow Occurrence Relationships

occur. As may be seen on Figure 13, there are numerous locations in the city where surface waters can accumulate until capacity in the system will accept them. If detention basins were located at these sites with appropriate street drains, surface waters would flow to the basins. Such facilities installed in these locations should provide for greater public protection from the inconvenience of surface ponding.

Another benefit of detention basins to the conveyance system is obtained by limiting the flow to downstream conduits.

The location of stormwater detention or storage basins in any particular sewer system has a beneficial effect on the available downstream conduit transport capacity in terms of historical rates of rainfall. The selection of storage basin locations within any stormwater conveyance system can be made such that the main trunk sewers of the system downstream of the basins will be upgraded with regard to the size of the rainfall that may be conveyed before exceeding sewer capacities. The volume of storage facilities considered must satisfy the following criteria:

1. The storage volumes utilized shall not be less than 1.2 million cubic feet. This restriction stems from the consideration of economics of construction of such basins.

2. The required volume for storage is equivalent to the volume of runoff derived from 1 inch of rainfall on the contributing fraction of the watershed which is not already tributary to the basin. This is based upon the frequency of overflow of such basins which historically would occur when used in conjunction with the next criterion.

3. The evacuation of flow out of storage is continuous and is equivalent to the rate of runoff from a steady state rate of rainfall of 0.10 in/hr from all upstream tributary areas. This criterion, in conjunction with 2 above, provides a storage volume which historically will overflow only one time every five years.

It is estimated that the cost would be $77 million to replace all sewers of inadequate capacity that are larger than three feet in size. The cost of basins will be offset to some degree by the equivalent costs foregone for installing additional or longer sewers in those areas where inadequacies now exist. All conceptual design costs were evaluated with regard to this aspect. Of $150 million required to remove the inadequacy of all sewers, about $50 million could be saved by means of the detention system.

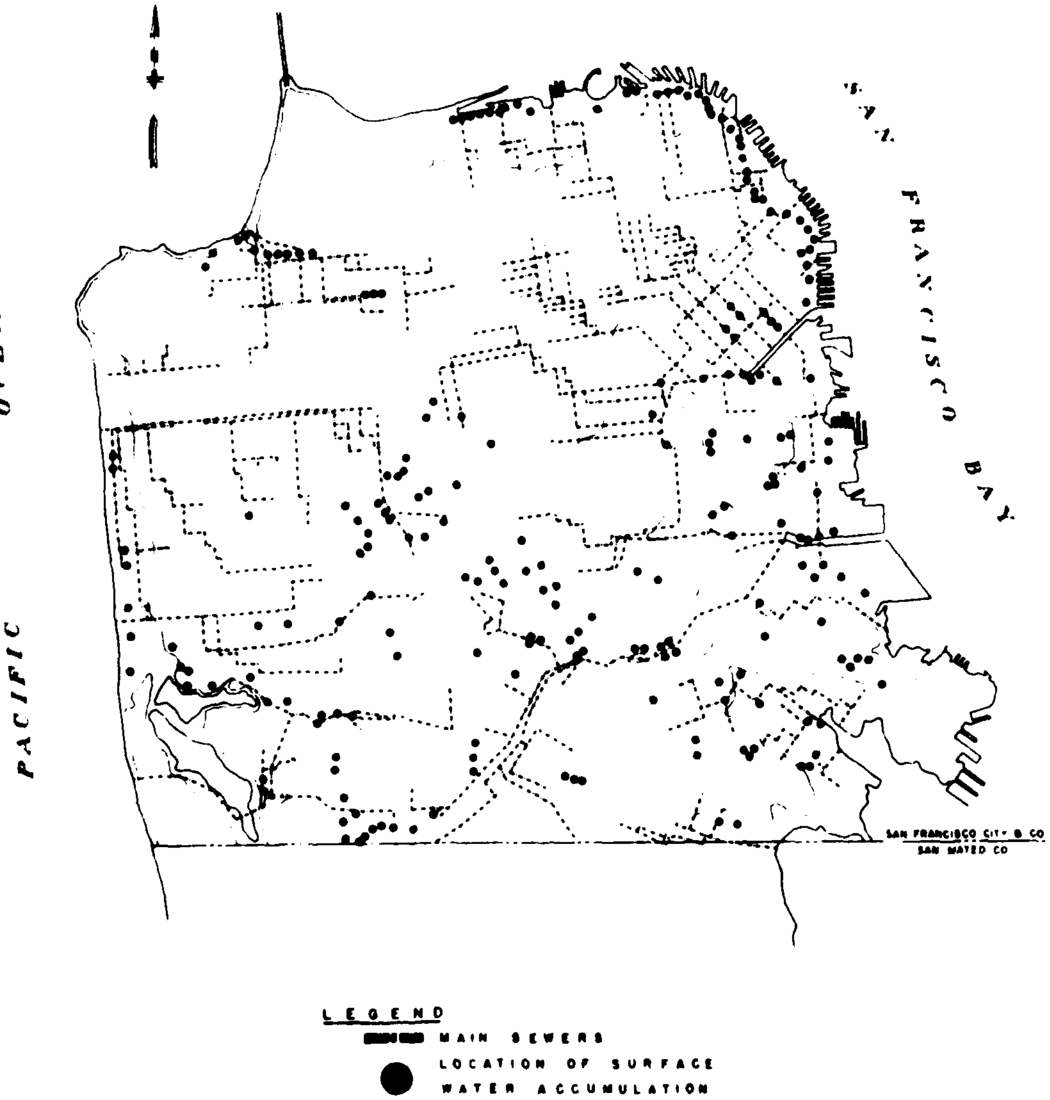

FIGURE 13
Locations of Surface Water Low Points

A further benefit of detention basins is in the potential for flushing the conveyance system with storage flows. This may reduce maintenance costs for lower portions of the system that are in subsidence areas.

EAST BAY MUNICIPAL UTILITY DISTRICT

The East Bay Municipal Utility District, Special District No. 1 (EBMUD, SD1), provides wastewater disposal services to seven cities on the east side of San Francisco Bay, California. Figure 14 shows the location of the service area. The EBMUD system is comprised of a 22 mile interceptor system plus a central treatment plant.

Wet weather inflow/infiltration is a major problem for EBMUD. The source of the problem is the wastewater sewer systems that drain into the interceptor system. Most of these systems are over 30 years old. A number of them have been converted from combined sewers to "sanitary" sewers, and a few combined sewers are still connected to the interceptor system. In addition, there are many illegal connections (especially to roof and yard drains). Present estimates are that 11 percent of the rainfall on the service area appears as inflow/infiltration in the interceptor system causing the system to overflow to San Francisco Bay about 11 times a year.

Reduction of the overflows could be accomplished by reducing extraneous inflows, by providing additional treatment and storage, or through some combination of both. The question was, which particular combination would give the control required and which combination would be the most cost-effective.

It was estimated by the District staff that conversion of the remaining combined sewers to sanitary sewers would reduce the gross inflow/infiltration ratio (i.e., runoff coefficient) from 11 percent to 8 percent. If 80 percent of the direct connections to the sewer system could be eliminated (roof and yard drains, parking lots, catch basins connected in error, etc.) it was estimated that the inflow/infiltration ratio could be reduced another 3 percent, i.e. from 8 percent to 5 percent. Finally, by the additional removal of fifty percent of the percolation infiltration, it was estimated that the inflow/infiltration ratio could be reduced another 2 percent, i.e. from 5 percent to 3 percent.

For purposes of determining what combinations of treatment rate and storage capacity would meet the system requirements, the STORM Quantity Analysis portion was used to process twenty-two and one-half years of hourly rainfall data recorded at the U.S. Weather Service station at Oakland International Airport.

An initial run was made with the STORM model set at existing Special District No. 1 treatment and storage capacities, assumed to be 0.0068 inches/hour and 0.017 inches, respectively, in excess of average

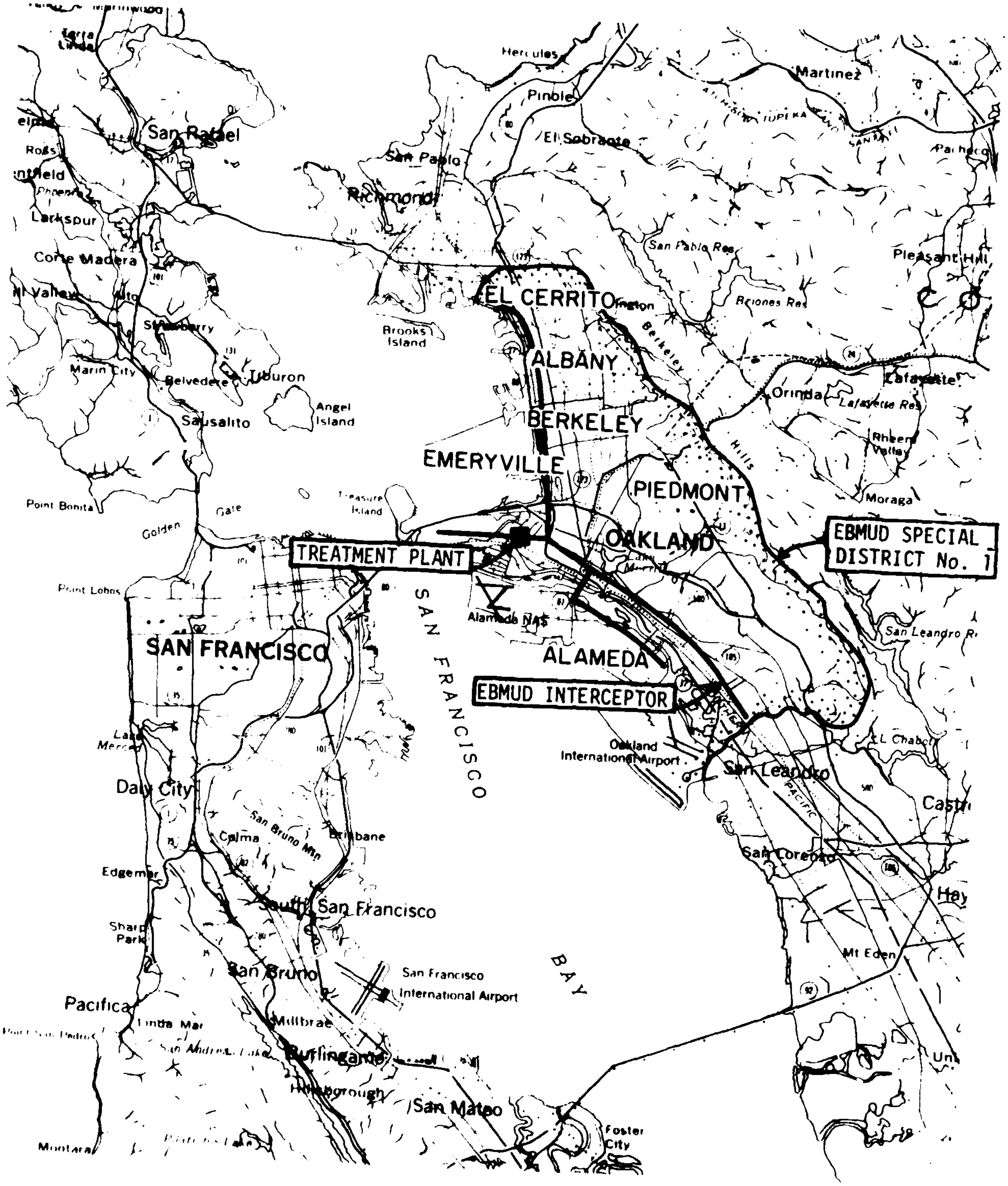

FIGURE 14
Vicinity Map of EBMUD Service Area

dry weather flow requirements. For this run, an existing District-wide gross infiltration rate of 11.1 percent of rain, developed in an earlier study [9], was used. This infiltration rate includes the effect of combined sewers which drain approximately 4 percent of the total area. The run showed an average incidence of 10.9 overflows per year, which is in good agreement with historical data.

All subsequent runs of STORM were based on the assumption that all combined sewers were separated from the sanitary system. Treatment-storage combinations were examined for three alternative infiltration rates (expressed in percent of Oakland Airport rainfall):

1. 8% - Gross Infiltration Ratio without combined sewers

2. 5% - Removal of combined sewers plus 80% of "direct connections"

3. 3% - Additional reduction by removal of 50% of "percolation infiltration."

In order to provide enough points for curve plotting, a total of 49 infiltration-treatment-storage combinations were run as shown in Table 13. Treatment rates ranging from 0.003 to 0.03 inches per hour (107.5 to 1075 MGD) and storage capacities ranging from 0.001 inches to 0.08 inches (1.5 to 120 million gallons) were analyzed.

Table 13 summarizes the events per year, number of overflows per year and quantity of overflow per year for each of the three assumed infiltration rates.

For each of the three infiltration rates, the average number of overflows per year are shown graphically in Figure 15. As expected, the number of overflows decreases as the storage capacity or treatment rate is increased or as infiltration is reduced by upstream extraneous control measures, as represented by the reduction in infiltration rates. Storage required to totally contain the inflow from the 22 year period of rainfall record is shown in Figure 16. It is not possible to recommend the optimum combination of treatment rate and storage based solely on the number of overflows. Nor is this parameter sufficient for use in selecting storms for further analysis in the transport model phase.

The quantity of overflow on an average annual basis is shown in Figures 17, 18, and 19 for each of the assumed infiltration rates. The average quantity of overflow also decreases as the number of overflows decrease. The relationships between quantity and number of overflows are depicted in the figures.

Figures 17, 18, and 19 show the relative effectiveness of treatment and storage in reducing the number and volume of overflows, and will serve as input for further analysis in which the economics of treatment-storage combinations and the overflow criteria likely to be required by the State and Regional Water Quality Control Boards are considered.

TABLE 13
EBMUD Wet-Weather Flow Study

Treatment Rate (inches/hour)	Storage Capacity (inches)	Infiltration Rate = 8%			Infiltration Rate = 5%			Infiltration Rate = 3%		
		Events/year	Overflows/ year	Overflow Quantity per year (inches)	Events/year	Overflows/ year	Overflow Quantity per year (inches	Events/year	Average Overflows/year Number	Average Overflows/year Quantity (inches)
.003	.003							22.182	10.136	.058
	.005							22.000	8.818	.042
	.01							21.818	2.455	.023
	.02							21.818	.682	.011
.006	.003				22.545	13.727	.120			
	.005	33.182	19.318	.336						
	.006				22.136	8.818	.087			
	.01	32.091	12.727	.256	21.909	4.636	.062			
	.02	30.955	6.364	.165	21.864	1.909	.032			
	.03	30.500	4.000	.115	21.864	.727	.021			
	.04	30.227	2.636	.083	21.864	.545	.014			
.01	.001							1.545	1.000	.005
	.003				7.955	4.364	.029			
	.005	18.545	10.409	.131				1.545	.455	.003
	.006				7.909	2.227	.020			
	.01	18.227	6.045	.091	7.864	1.136	.014	1.545	.273	.001
	.02	18.136	2.682	.053	7.864	.364	.008	1.545	.000	.000
	.03	18.045	1.136	.035						
	.04	18.045	.636	.027	7.864	.182	.002			
	.06	18.045	.455	.016	7.864	.045	.000			
	.08	18.045	.273	.010						
.02	.001	4.136	3.500	.037						
	.002							.182	.136	.000
	.003				.636	.545	.005			
	.005	4.136	2.000	.026				.182	.045	.000
	.006				.636	.364	.003			
	.01	4.091	.955	.019	.636	.318	.002	.182	.000	.000
	.02	4.045	.455	.012	.636	.045	.000			
	.03	4.045	.364	.008						
	.04	4.045	.273	.006	.636	.000	.000			
	.06	4.045	.136	.001						
	.08	4.045	.000	.000						
.08	.002	.864	.727	.011						

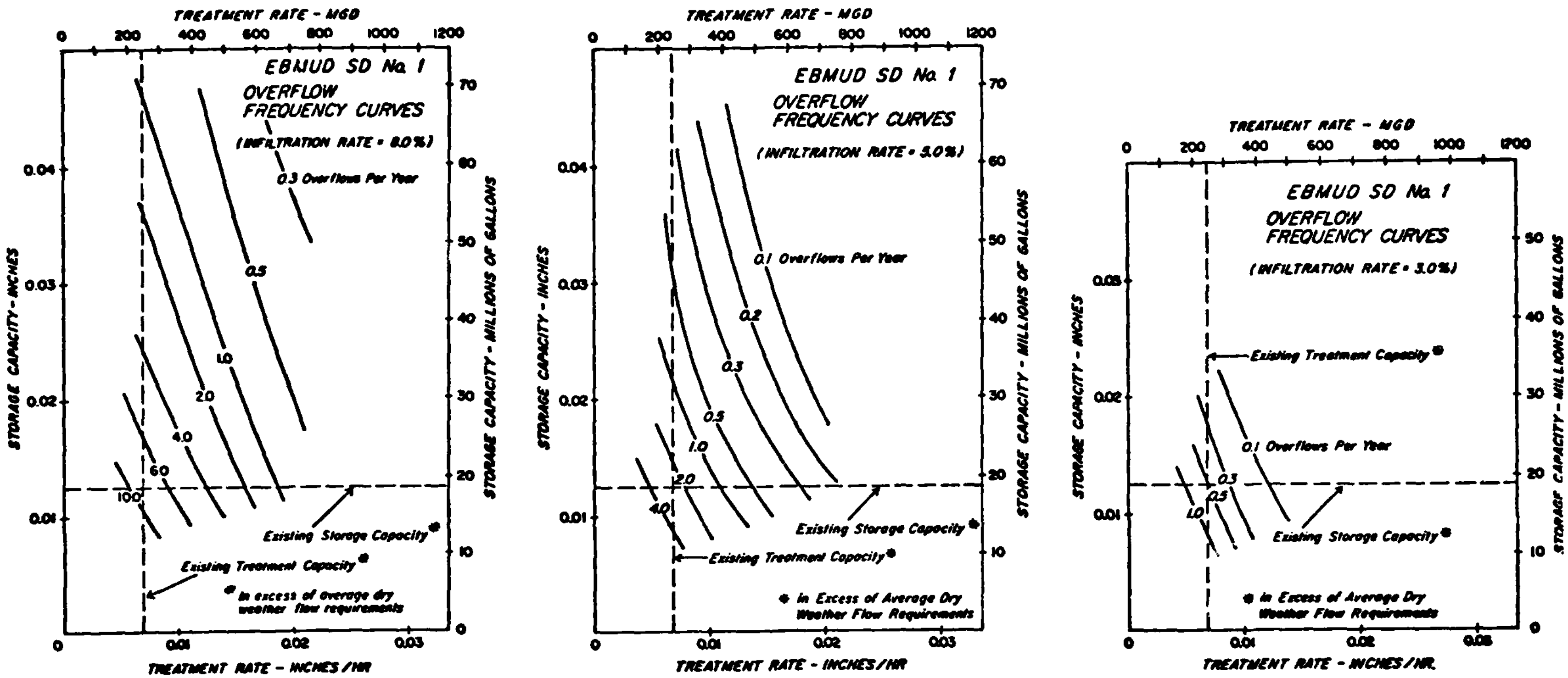

FIGURE 15
Overflows at Various Infiltration Rates

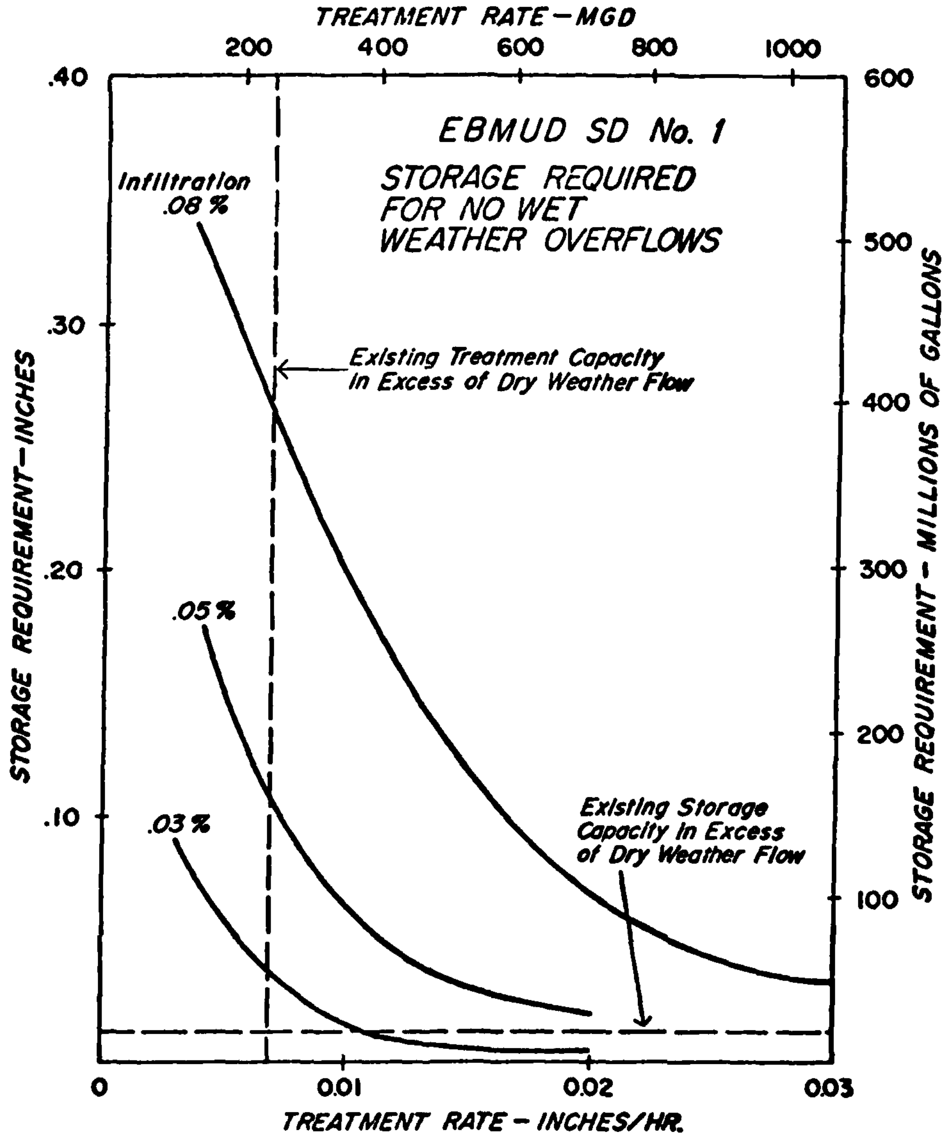

FIGURE 16
Zero Overflows Requirements

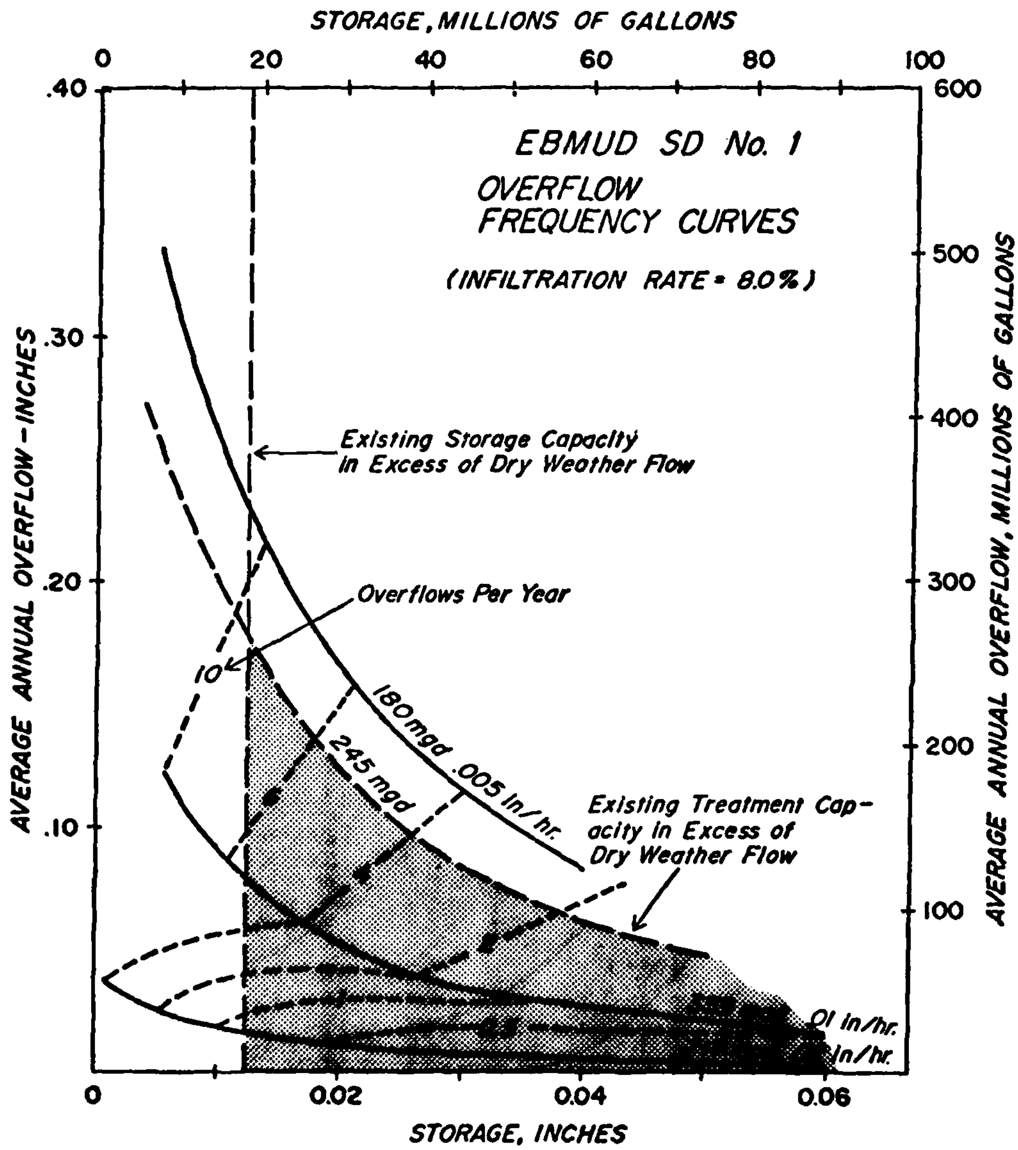

FIGURE 17
Overflow Volumes at 8 Percent Infiltration Rate

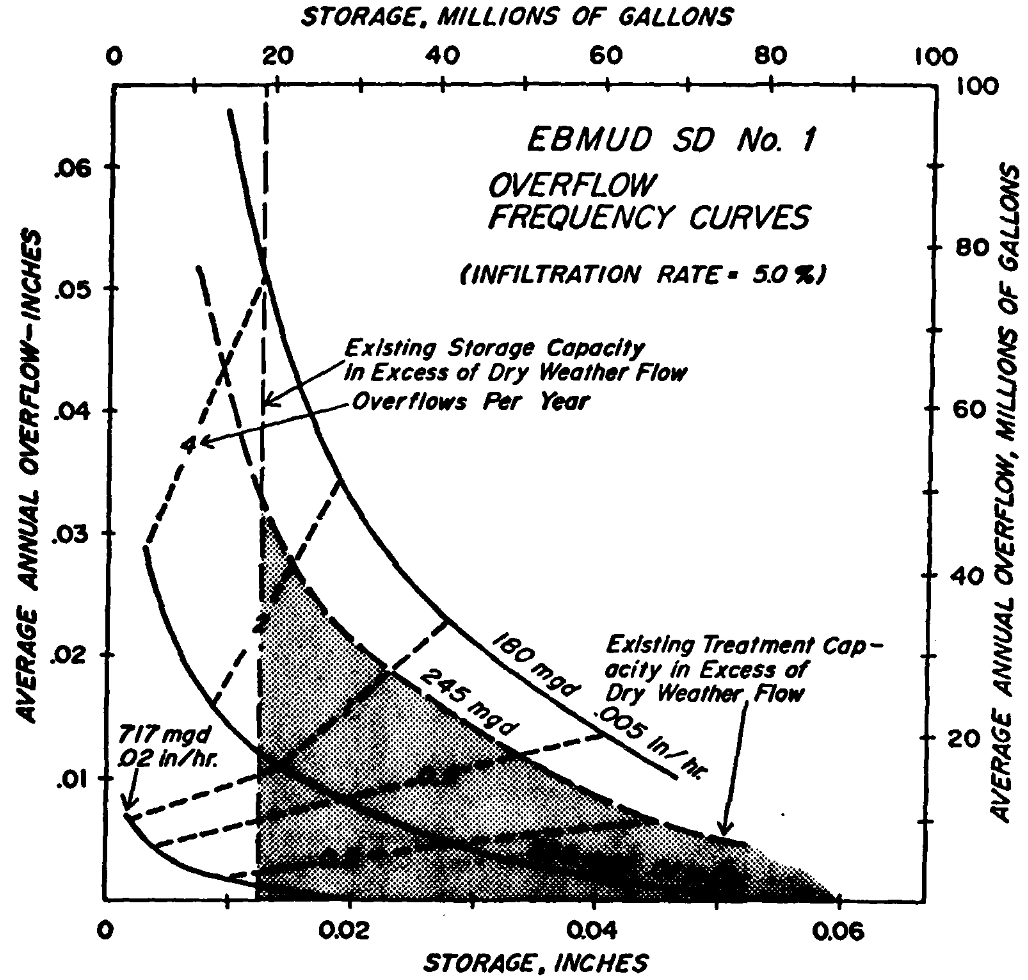

FIGURE 18
Overflow Volumes at 5 Percent Infiltration Rate

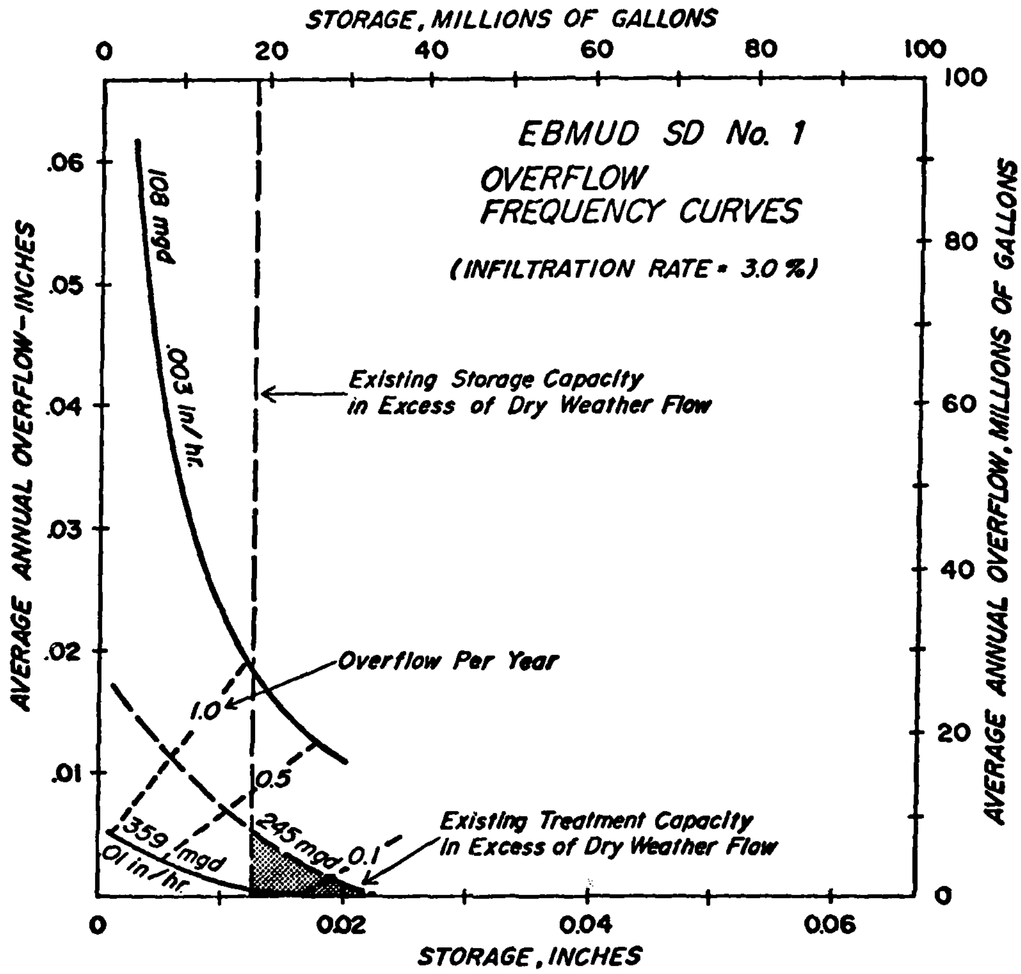

FIGURE 19
Overflow Volumes at 3 Percent Infiltration Rate

SECTION 7
APPLICATION OF "STORM" - EXAMPLES

The purpose of this section is to present some examples of other possible applications of STORM in addition to those described in Section 6. Four applications will be shown:

1. Computation of the quantity of storm runoff by month and for single storm events.

2. Computation of pollutographs for single storm events.

3. Use of STORM to find the most economical treatment-storage combinations that meet system overflow constraints.

4. Analysis of changes in the quantity and quality of urban runoff due to alternative land use management schemes.

A prototype area was selected for these applications of STORM, i.e., the Castro Valley watershed near Oakland, California. Figure 20 shows the USGS map of the area with the watershed boundary and the location of the watershed relative to the San Francisco Bay area. Some land use information can be obtained from the map but an aerial photograph plus ground reconnaissance were necessary to obtain a better understanding of land uses in the basin. Table 14 gives a summary of the estimated hydrogeometric characteristics of the watershed. Runoff statistics for the watershed were generated by processing hourly rainfall data for the 17-month period from November 1971 through March 1973.

COMPUTATION OF THE QUANTITY OF STORM RUNOFF

In the initial application of STORM to Castro Valley, the program was calibrated to give the best comparison between computed and observed values of

1. Average annual precipitation;
2. Average annual runoff;
3. Monthly runoff volumes; and
4. Individual storm event volumes.

It is not appropriate to make comparisons with the instantaneous measurements of discharge because the program computes runoff as hourly volumes only. The hourly volumes should reflect the general shape of the observed hydrograph and its volume, although the

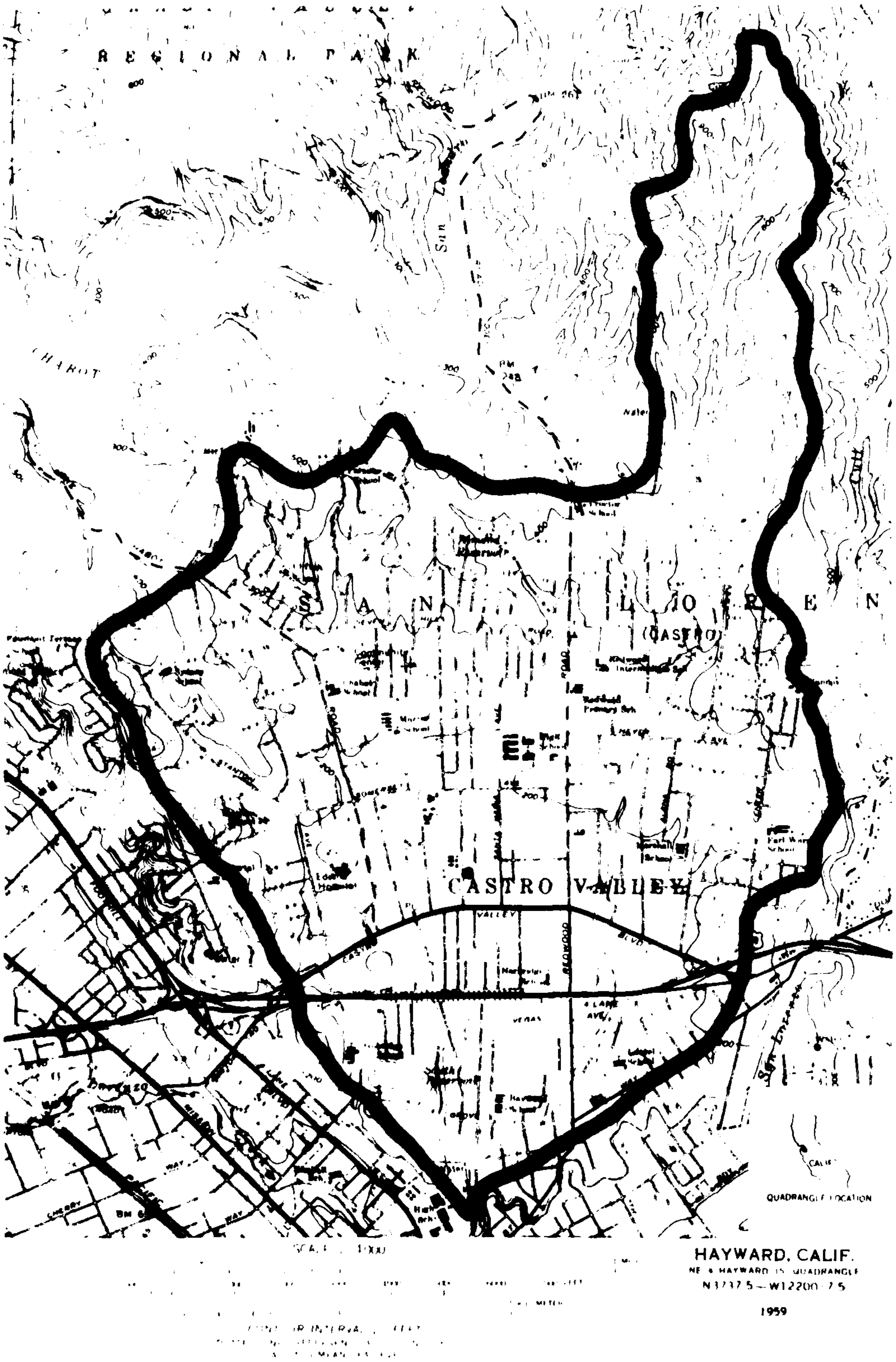

FIGURE 20
Castro Valley Watershed

observed hydrograph will tend to lag behind the computed hydrograph in larger basins where the time of concentration is greater than one hour. The program can be applied to larger basins where this lag problem exists as long as one realizes the impact on the analysis. In storage analyses, however, this problem is generally not critical.

TABLE 14
Hydrogeometric Data

Land Use	Percent of Area	Percent Impervious	Length of Street Gutters
Single Family Residential	70	40	275(ft/ac)
Multiple Family Residential	3	50	430
Commercial	7	80	400
Open or Park	20	2	20

Area of the watershed = 3136 acres
Depression Storage = .10 inch

Depression Storage Recovery, inches/day

January	0.05	July	0.28
February	0.07	August	0.25
March	0.12	September	0.20
April	0.17	October	0.13
May	0.23	November	0.07
June	0.26	December	0.05

Runoff Coefficient for Pervious areas = 0.45
Runoff Coefficient for Impervious area = 0.90

Area weighted basin average runoff coefficient = 0.61

The program parameters which were "tuned" in the calibration process were:

1. Rainfall factor relating basin average rainfall to the gage rainfall;

2. Depression storage and the rate of recovery of depression storage;

3. Imperviousness of the land uses; and

4. Pervious and impervious area runoff coefficients.

The recording rain gage for Castro Valley is centrally located in the watershed and was assumed to reflect basin average precipitation. Calibrated values of the other parameters are those listed in Table 14.

Table 15 shows the computed and observed data for monthly runoff and for total runoff over the 17-month period. Computed average annual rainfall and runoff information is obtained directly from the program's average annual summary. Monthly volumes were computed from the EVENT output. Figures 21 and 22 show the computed and observed hydrograph fit for two events in the 17-month record.

TABLE 15
Comparison of Observed and Computed Monthly Runoff Volumes from Castro Valley, California

Year	Month	Observed Runoff (Inches)*	Computed Runoff (Inches)**
1971	11	.35	.73
	12	1.50	2.29
1972	1	.51	.58
	2	.60	.58
	3	.17***	0
	4	.34	.44
	5	.10***	0
	6	.17	.16
	7	.11***	0
	8	.08***	0
	9	.21	.48
	10	1.01	1.51
	11	2.85	2.82
	12	.91	1.03
1973	1	5.78	4.13
	2	4.34	2.45
	3	2.01	1.71
	TOTAL	21.00	18.90
			+1.70 baseflow
		TOTAL =	20.60

*From USGS Records.
**Does not include baseflow. Baseflow is approximately 0.10 inches per month.
***No rainfall recorded.

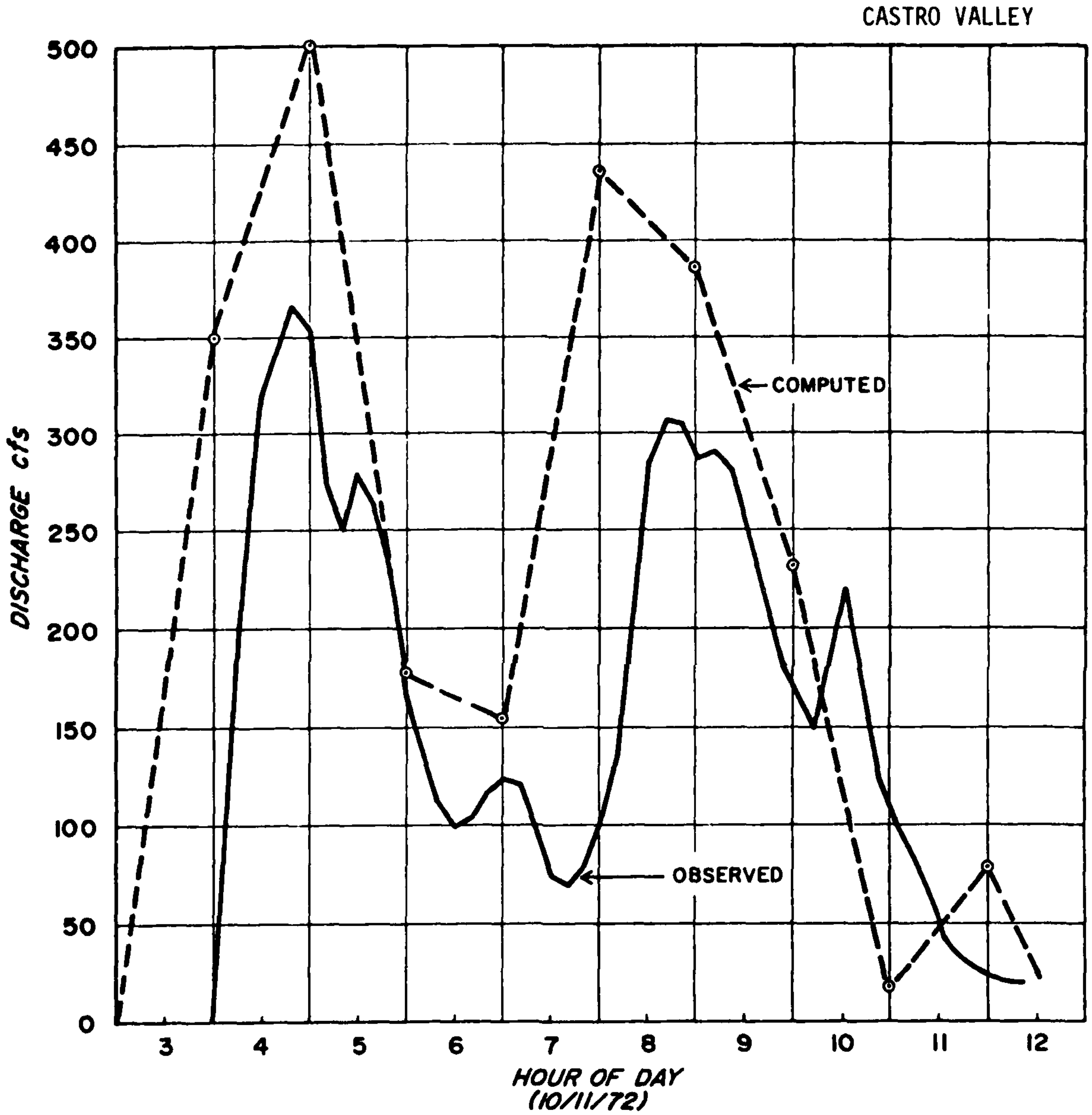

FIGURE 21
Comparison of Observed Hourly Values of Runoff
With Values Computed by "STORM"
November 11, 1972

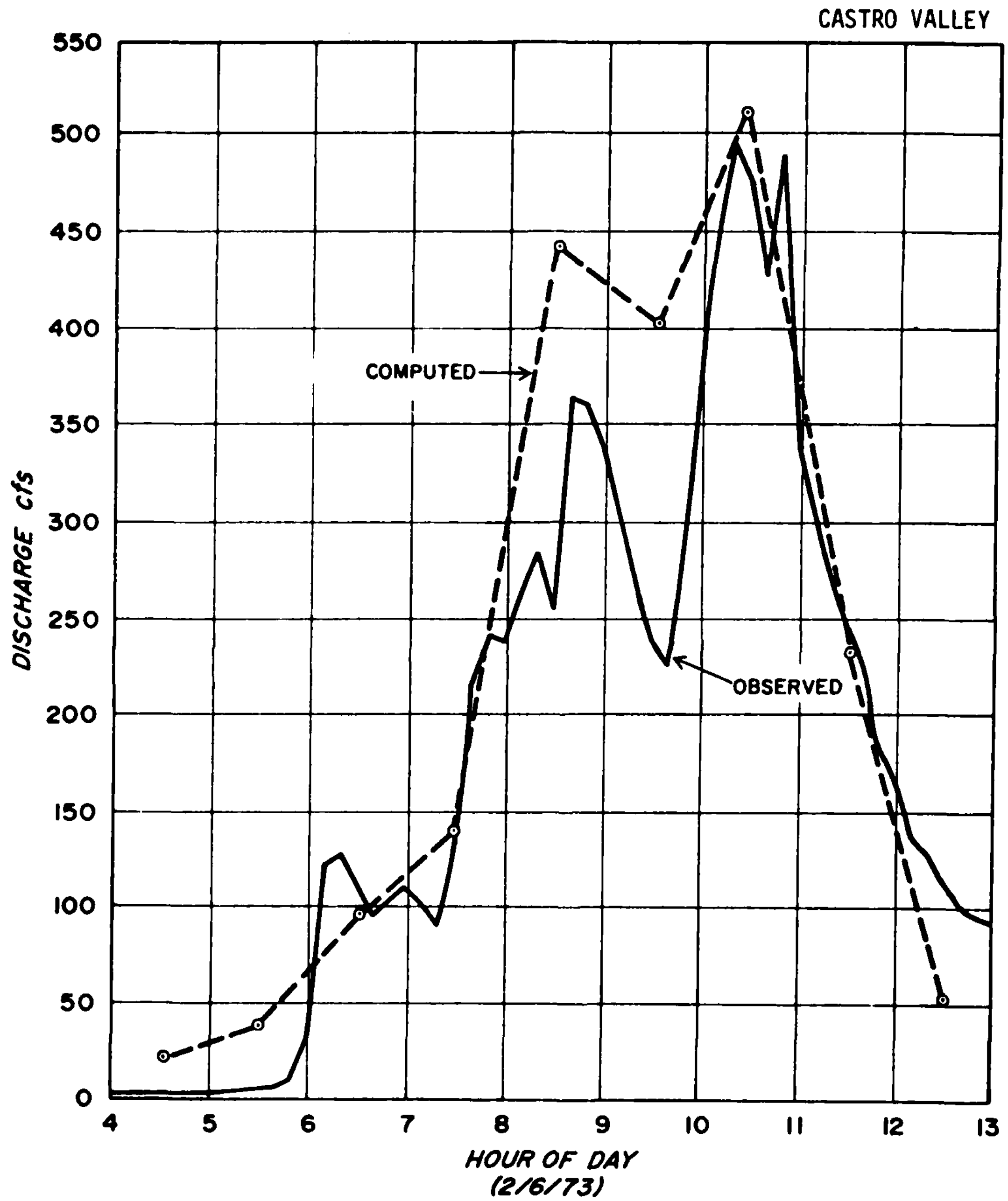

FIGURE 22
Comparison of Observed Hourly Values of Runoff
With Values Computed by "STORM"
February 6, 1973

COMPUTATION OF THE QUALITY OF RUNOFF

The zero storage, zero treatment combination was also used for an initial calibration of the quality portion of STORM. The quality calibration was made difficult because of the lack of adequate data. It is usually not economically feasible to monitor every runoff event, thus monthly or average annual data generally does not exist. In most instances, as was the case for the Castro Valley data, the quality calibration must be made on data from several individual runoff events. However, unless care is taken to obtain a good sampling over the duration of the entire event, the comparison of total amounts of pollutant washoff will not be possible. This was also the case in Castro Valley; consequently, most of the calibration had to rely on a few data points per event. It would be highly desirable to have enough measurements during a runoff event to be able to trace the hourly performance of the pollutant washoff function.

The quality calibration for Castro Valley was made on the basis of comparisons of computed and observed concentrations for individual events. The parameters calibrated were:

1. Dust and dirt accumulation rates;
2. Pollutant composition of the dust and dirt; and
3. The exponent in the pollutant washoff equation.

The initial pollutant loading rates used in the calibration were those from the Chicago APWA study [5] that was discussed in Section 3. These data are programmed as default values to be used if other values for these parameters are not specified as input data. Table 16 shows the calibrated values of the pollutant loading and washoff parameters. A comparison of these values with the default values listed in Section 5 reveals that the Dust and Dirt accumulation rates had to be increased by a factor of two except for the open or park area which was increased by a factor of about six. Pollutant composition of the dust and dirt was also increased by a factor of four for all parameters except suspended and settleable solids.

TABLE 16
Pollutant Loading and Washoff Parameters

Land Use	Dust and Dirt Accumulation lbs/day/100 ft. gutter	Pounds Pollutant per 100 lbs Dust and Dirt: Susp. Solids	Sett. Solids	BOD	N	PO4
Single Family	1.4	11.1	1.1	2.0	.19	.02
Multiple Family	4.6	8.0	.8	1.44	.24	.02
Commercial	6.6	17.0	1.7	3.08	.16	.03
Open or Park	9.2	11.1	1.1	2.0	.19	.02

Street Sweeping Efficiency = 70%
Washoff exponent = 2.0

Comparisons of computed and measured BOD concentrations are shown in Figure 23. Agreement in the first case is very good, however, computed values for the second storm are consistently low. Notice that the first storm occurred in November of 1972 which is the beginning of the winter rainy season. The good agreement in this case indicates that the accumulation of pollutant loads over the dry summer period is being computed well by STORM.

The second comparison shown was for a storm in February which is near the end of the winter. Since the computed values are consistently low, the implication is that the pollutant load on the watershed at the beginning of the storm was too small. This is quite likely the case because during the period between the November storm and the February storm, the computer program has been performing a constant accounting of the pollutant load on the watershed, i.e., how much was there at the beginning of each storm, how much was left at the end of each storm, and how much accumulated between storms. If we assume, on the basis of Figure 23 (the November storm), that the pollutant load at the beginning of the rainy season is correct and that the computation of washoff rate is correct, then the rate of pollutant accumulation (dust and dirt accumulation) on the watershed must be larger for the prototype than the rate being used in the model. As a result, the watershed is being washed overly clean by STORM during the rainy season.

The next step in the calibration procedure, therefore, would be to increase the daily rate of dust and dirt accumulation during the winter period which would result in larger pollutant loads at the end of the rainy season.

STORAGE-TREATMENT ANALYSIS EXAMPLE

The primary purpose of the STORM program is to analyze the effectiveness of storage and treatment facilities for use in controlling the quantity and quality of urban storm runoff. The criteria for control of the storm runoff may be in terms of maximum allowable:

1. Overflow events per year;
2. Volume of overflow per year;
3. Volume of overflow during some design storm event;
4. Pounds of BOD (or other pollutant) overflow per year; and/or
5. Pounds of BOD (or other pollutant) overflow during some design storm event.

It may be possible to achieve the desired control of runoff through a number of different combinations of storage and treatment. A cost analysis is then necessary to determine which storage-treatment alternative achieves the desired control at least cost.

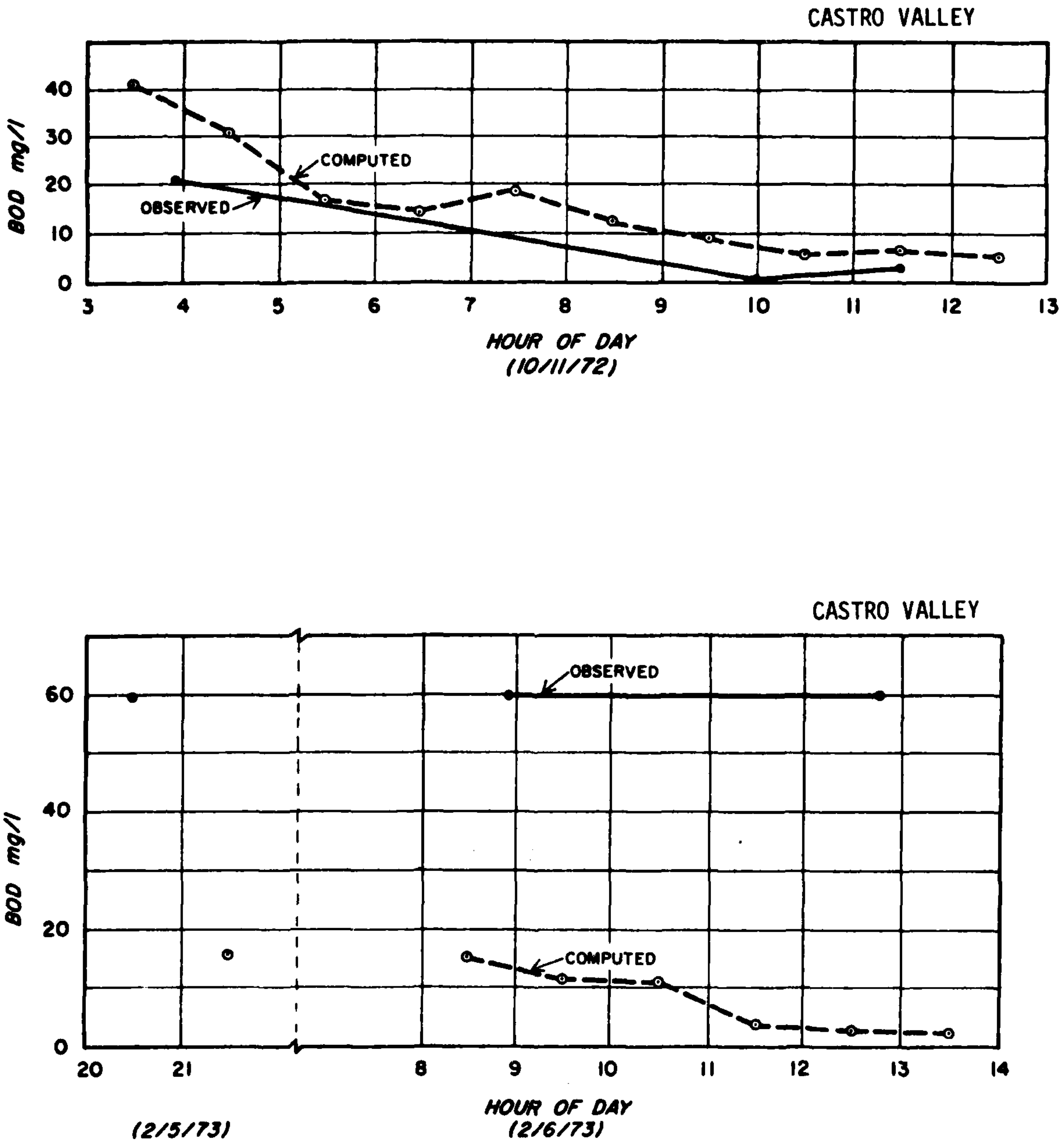

FIGURE 23
Comparison of Observed Hourly values of BOD Concentration With Values Computed by "STORM" November 11, 1972 and February 6, 1973

The decision criteria for the purposes of this hypothetical example are as follows:

1. No more than five overflows per year; and
2. No more than 10,000 pounds of BOD overflow per year.

In order to determine what storage-treatment rate combinations will meet these objectives, the STORM program was run for several different storages for each of several treatment rates. For each storage-treatment combination, information on the average annual number of overflows, inches of overflow, and pounds of BOD (or other pollutant) was obtained directly from the output (see Tables 8 and 10 for example).

This information can be plotted, such as in Figure 10 of Section 6, to enhance the analysis. For this problem, however, it would be better to first plot Number of Overflows/year vs. Storage Capacity and Pounds of BOD Overflow/Year vs. Storage Capacity, both plots showing lines of equal treatment rates. The two plots are shown in Figure 24. Notice on the BOD overflow curves that the overflow frequency is also shown. It can be seen from this figure that overflow frequency is a more severe requirement for the system if its storage capacity is less than 0.3 inches. For greater storage capacities, however, the quality constraint is more limiting. Thus all treatment-storage combinations shown below the shaded line in Figure 25 are acceptable from the standpoint of meeting or exceeding the system performance criteria. However, it can be seen that for a given treatment rate, the smallest allowable storage will be that identified on the shaded performance line in Figure 25. Thus, in our example the most *economical* control system that meets the performance criteria will be one of the following three:

1. Treatment = 0.01 in/hr Storage = 0.46 in
2. Treatment = 0.03 in/hr Storage = 0.28 in
3. Treatment = 0.05 in/hr Storage = 0.20 in

Economic Analysis of these three alternatives would *identify* the most economical system.

LAND USE MANAGEMENT ANALYSIS

Another possible application of STORM is to estimate the impact of proposed land use changes within a watershed on the quantity and quality of urban runoff. To illustrate this use, it was assumed that the upper arm of the Castro Valley watershed (see Figure 20) would be developed. This 470 acre area is presently open space. Under the assumed development plan, single family residential dwellings would be constructed on 67 percent of the area. The remaining 33 percent of the area would be developed as multiple family residences.

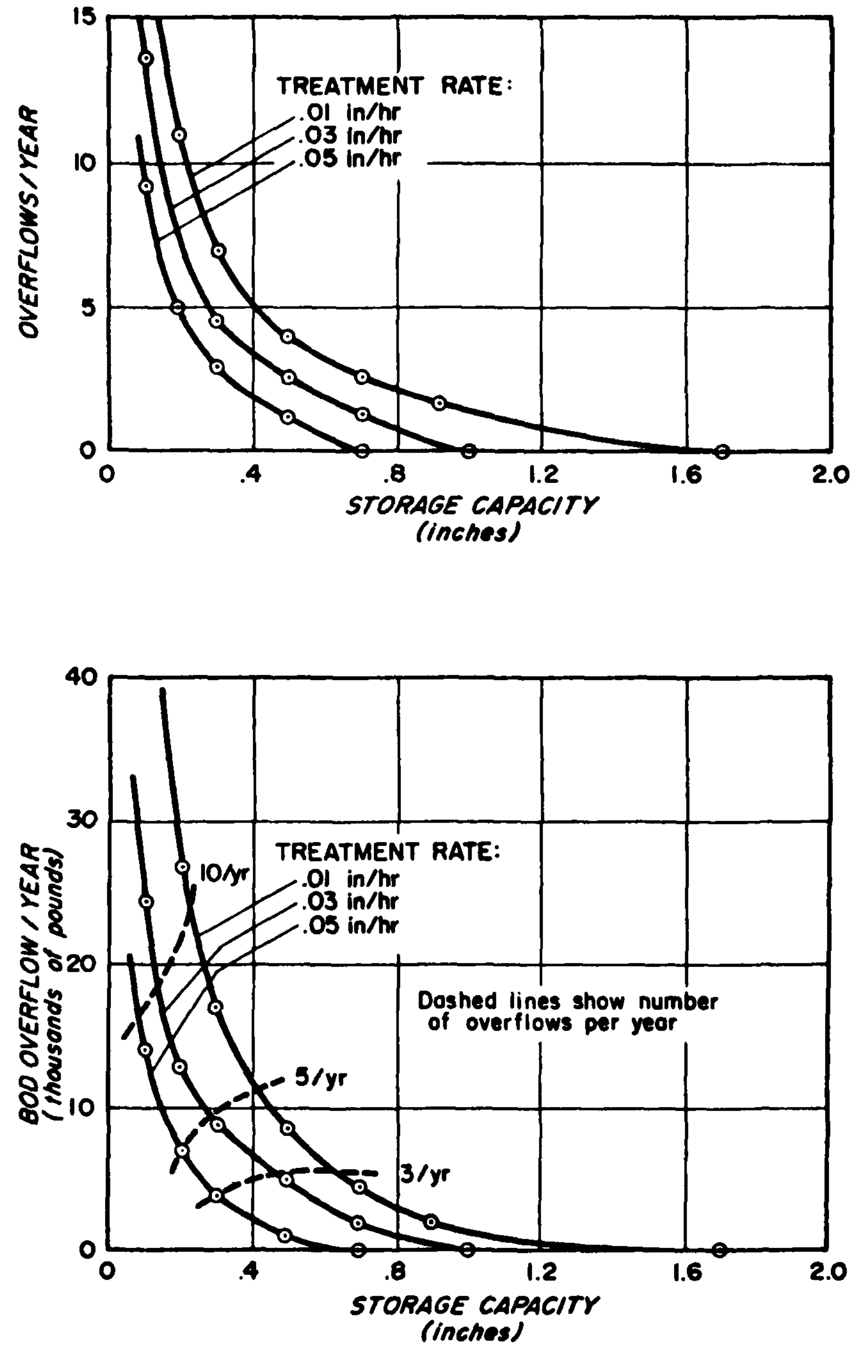

FIGURE 24
Relationship of Overflow Frequency and Pollutant Overflows to Treatment-Storage Alternatives
Castro Valley

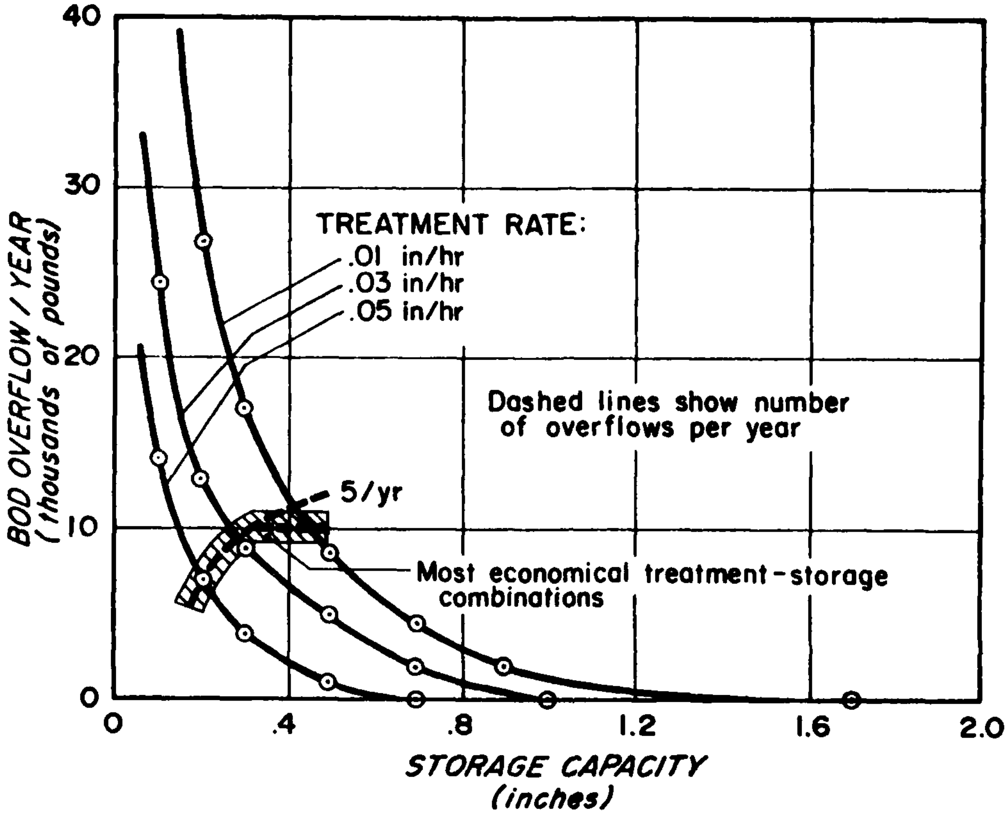

FIGURE 25
Most Economical Treatment-Storage Combinations
To Meet System Overflow Constraints

Table 17 shows the results of applying STORM to the 470 acre subarea in both its present undeveloped state and in the proposed developed state. In the developed state, the annual quantity of runoff can be expected to increase by 40 percent. The annual BOD, on the other hand, will increase more than 400 percent.

The impact of the proposed development on the watershed as a whole is shown in Table 18. As expected, this impact is significantly less. As a result of the proposed development, annual storm runoff from the watershed can be expected to increase by approximately 5 percent. The annual BOD load washed off the watershed will increase approximately 14 percent.

TABLE 17
Effect of Changing Land Use on
Storm Runoff from 470 Acre Subarea

Land Use	Annual Runoff Inches	Annual BOD Load Pounds
Existing 100% open	8.34	5,700
Proposed 67% single family residential 33% multiple family residential	11.72	23,400

TABLE 18
Effect of Changing Land Use of 470 Acre Subarea on Storm Runoff
From Entire Castro Valley Watershed (3140 Acres)

Land Use	Annual Runoff Inches	Annual BOD Load Pounds
Existing 70% single family residential 3% multiple family residential 7% commercial 20% open	11.08	130,500
Proposed 80% single family residential 8% multiple family residential 7% commercial 5% open	11.59	148,300

SECTION 8
TRANSFERABILITY OF WATER QUALITY DATA

VARIED INTERPRETATIONS

The most difficult problem encountered in transferring water quality data measured in one area to another area that has no data is that the data is usually presented in such a way that it is difficult or impossible to separate the hydrologic effects from the pollution data. As was pointed out in Section 3, the common denominator for transferring urban runoff quality data from one area to another is the rate of accumulation of pollutants on the watershed as a function of land use and some length or area parameter, i.e., lbs/year/acre, lbs/day/acre, lbs/day/mile of street, etc. Much of the reported data, however, is in terms of pounds of pollutant washed off the watershed/acre/inch of rainfall (which does not correlate with inches of rainfall), or in terms of mean concentrations of the runoff from the area. If sufficient hydrologic data is presented, this data can be reduced to its basic rate of buildup form, but it is a tedious task.

Even if the data can be reduced, it is likely that it reflects cumulative runoff effects from several different land use areas. In such cases the loading rates for each land use could be derived by developing weighting factors based on the total length of gutters, each land use classification and the APWA data presented in Section 3. An example of this weighting method is detailed below.

Sometimes yearly stormwater mass emissions are reported, i.e., lbs/year of a pollutant discharged from a watershed. Loading rates in terms of land use can also be derived from this type of data using weighting factors.

EXAMPLE OF DERIVATION OF POLLUTANT ACCUMULATION RATES FROM MASS EMISSION DATA

Weighting factors are formed for each pollutant as the product of the D/D rate x pollutants per unit weight of D/D x total gutter length in the land area of the given land use. (See Table 19 for BOD Weighting Factors.)

TABLE 19
BOD Weighting Factors for Reducing Total Mass Emission Rates from a Mixed Land Use Watershed to Rates of Accumulation Per Land Use Area

Land Use	Weighting Factor*
Single Family Residential	$W_1 = 0.7 \times 5.0 \times G_1$
Multiple Family Residential	$W_2 = 2.3 \times 3.6 \times G_2$
Commercial	$W_3 = 3.3 \times 7.7 \times G_3$
Industrial	$W_4 = 4.6 \times 3.0 \times G_4$
Open or Park	$W_5 = 1.5 \times 5.0 \times G_5$

*G is the total length of gutters (1000's of feet) in the portion of the watershed of the given land use type.

To illustrate the use of these factors, assume that it is reported that the BOD mass emission rate from a watershed is 2,500 pounds per month, and that the watershed has the following pertinent features:

Land Use	Area, Acres	Total Length of Gutters, 1000's of feet
Single Family Residential	197	80
Multiple Family Residential	223	100
Industrial	686	160

The BOD weighting factors for this watershed are:

$$W_1 = 0.7 \times 5.0 \times 80 = 280$$
$$W_2 = 2.3 \times 3.6 \times 100 = 830$$
$$W_3 = 4.6 \times 3.0 \times 160 = \underline{2210}$$
$$\text{Total} \quad 3320$$

For a 30-day month, the daily BOD accumulation rate by land use area is thus:

$$\text{Single Family Residential} \quad (2500/30) \times \frac{280}{3320} = 7.0$$
$$\text{Multiple Family Residential} \quad (2500/30) \times \frac{830}{3320} = 20.8$$
$$\text{Industrial} \quad (2500/30) \times \frac{2210}{3320} = \underline{55.5}$$
$$\text{Total} = 83 \text{ lbs/day}$$

We can assume that the APWA values of the amount of pollutant per unit of D/D apply to the area. These values are then used to derive the D/D rates on each watershed. However, recall that the values for BOD, N, and PO4 are only for the soluble fraction of the constituent. Since the model assumes that non-soluble BOD is 10% of the suspended solids load (we neglect the 2% contribution from settleable solids), we must subtract these amounts from the total BOD loads computed above before computing the D/D rate. If the suspended solids loads for the Single Family, Multiple Family and Industrial areas are 23, 47, and 200 lbs/day, respectively, the soluble BOD loading rates are:

Single Family Residential	7.0 - 2.3 = 4.7 lbs/day
Multiple Family Residential	20.8 - 4.7 = 16.1 lbs/day
Industrial	55.5 - 20.0 = 35.5 lbs/day

Finally, dividing these values by the pounds of BOD per pound of D/D and by the total gutter length in each area gives the unit rates of D/D accumulation for the watershed:

Land Use	D/D Accumulation Rate, lbs/day/100 ft. of gutter
Single Family Residential	4.7/0.0050/800 = 1.2
Commercial	15.1/0.0036/1000 = 4.4
Industrial	35.5/.0030/1600 = 7.4

CAVEAT

A substantial amount of data exists on the quality and quantity of urban runoff. References 10 and 11 include fairly complete citations of the data sources that exist. As previously stated, however, much of the data are presented in a form that is inappropriate for translation to other areas.

For data that can be reduced to its basic form (rate of accumulation on the watershed by land use) two cautions are in order. First, much of the reported data is measured in combined sewer systems. Where this is the case, the sewage contribution to the pollution load must first be subtracted from the total load before deriving watershed pollutant accumulation rates. Secondly, "typical" residential and industrial areas in one locality may be atypical in other areas. Before tranferring data from these areas to another locality, the geometric features of the two areas should be compared and (if appropriate) adjustments should be made in the data before applying it to a new area.

Other factors which undoubtedly affect the rate of pollutant accumulation are the general air pollution characteristics of the area and the general climatology. Pollutant accumulation rates are probably much different in industrialized Chicago than in resort towns. They would also be expected to differ between the coastal areas of California and the arid cities of Arizona. No general guidelines can be presented to account for such effects.

SECTION 9
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