WISSAHICKON CREEK, PENNSYLVANIA
A CASE STUDY IN THE APPLICATION OF STORM (Storage, Treatment, Overflow, and Runoff Model)

William N. Fitch, John L. Matticks and Robert S. Taylor, Jr.
Water Resources Engineers, Inc., Springfield, Virginia

INTRODUCTION

As water pollution control regulations require higher and higher levels of removal of sewered municipal and industrial point sources of pollution, a logical question is what pollutants reach streams from unsewered areas or from storm runoff. This study was performed in order to provide an estimate of the urban stormwater component of currently uncollected nonpoint pollution. The results will be used to determine if more detailed evaluations are necessary in order to define pollutant generation and to preserve overall water quality in the receiving streams for both storm and non-storm events.

This work is one element in the development of The Comprehensive Water Management Program for Southeast Pennsylvania (including the City of Philadelphia) undertaken in 1973 by the Pennsylvania Department of Environmental Resources. Water Resources Engineers performed this study under a subcontract to Chester Betz Engineers of Plymouth Meeting, Pennsylvania.

STUDY AREA

The Wissahickon Creek flows southeasterly from its headwaters near Lansdale, Pennsylvania through the several subdivisions of northwestern Philadelphia to its confluence with the Schuylkill River. The portion of the basin studied extends from the headwaters to a point approximately 17 miles downstream near the Montgomery County/Philadelphia County boundary. The downstream point is the U.S. Geological Survey surface water gaging station number 1-4739.5 (Wissahickon Creek at Bells Mill Road, Philadelphia, Pennsylvania). This station is about one and one-third miles south of the Philadelphia County border. Figure 1 depicts the study area and shows its geographic location within the State of Pennsylvania.

The availability of land use data and surface water measurements were the two determinants that influenced the definition of study area boundries. Land use data is available for all but that portion of the study area that lies within Philadelphia County. The homogenity of the study area permitted extrapolation of the relative percentages of land use by category in Montgomery County to this portion of Philadelphia County in order to provide estimates of the watershed land use.

To a lesser degree, the location of U.S. Weather Service precipitation stations influenced site selection. The stations at Sellersville, Phoenixville and North Philadelphia, Pennsylvania all yield hourly rainfall data. These stations all lie outside the study area and form more or less an equilateral triangle with the centroid of the triangle near the centroid of the study area.

STORMWATER MODEL (STORM)

STORM (Storage, Treatment, Overflow Runoff Model) was developed by WRE for its work in San Francisco, and it has subsequently been adapted by the Corps of Engineers, through its Hydrologic Engineering Center in Davis, California, and distributed widely throughout the United States. Present users include the American Public Works Association, the Environmental Protection Agency, the American Society of Civil Engineers, the Corps of Engineers, and a number of state and local agencies. It is also used by several universities as part of their teaching program.

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 may be completely contained within storage so that no untreated storm water 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.

It would seem reasonable, therefore, to assume precipitation cannot be considered without the system; a storm cannot be defined by itself, but must be defined in light of the urban storm water facilities. It is for this reason that an approach was developed that would not only recognize the properties of duration and intensity, but would also consider storm spacing and the capacity of the urban storm water system.

Figure 2 shows, pictorially, the interrelationships of the seven stormwater elements considered in this approach to estimating storm water runoff quality and quantity. In this approach rainfall washes dust and dirt and the associated pollutants off the watershed to the treatment-storage facilities where as much storm water runoff as possible is treated and released. Runoff exceeding the capacity of the treatment plant is stored for treatment later. If at some point the storage facilities become inadequate to contain the runoff, the untreated excess is wasted through overflow directly into the receiving waters.

For a given rainfall/snowmelt record, the quantity, quality, and number of overflows will vary as the treatment rate, storage capacity, and land use is changed.

STORM is a relatively simple model, its data requirements are actual rainfall, usually at hourly intervals, and land use information. The model computes the runoff, also on an hourly basis, and determines the concentration of five constituents of water quality in the runoff. In its present form, it considers BOD, suspended solids, total solids, nitrogen and phosphorus, but the structure of *STORM* permits this list to be modified when field data are sufficient to warrant it.

The effects of storage and treatment on the amount, distribution and quality of runoff are determined by *STORM*. Storage may be either manmade facilities or it may be the result of runoff control measures.

Finally, *STORM* performs a series of simple statistical computations on the output, so that the results of long simulations, involving hundreds of storm events, can be examined. In typical usage, something between ten and one hundred years of data are input to *STORM;* the user would be inundated with results if he tried to analyze each storm. The model output provides a way around this situation.

A simple example is illustrated in Figure 3, which shows the results obtained for Castro Valley, California. It shows the production of BOD for a number of treatment rates and storage capacities, and superimposed, the number of overflows from the sewer system to be expected. All of these results are for a single land use pattern, because Castro Valley is an already developed area. However, the figure demonstrates the response of the system to real rainfall data and shows how waste loads are produced by the model.

As will be seen, *STORM* can be utilized to forecast the average annual water quantity and quality of the Wissahickon. In addition to that to be described, *STORM* can be applied to: (1) Computation of the quantity of storm runoff by month; (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; and, (4) Analysis of changes in the quantity and quality of urban runoff due to alternative land use management schemes.

Data input requirements to *STORM* are encompassed in three broad classifications of:

(1) Hydrogeometric data;
(2) Hydrologic data; and,
(3) Quality data.

Data requirements have been summarized under each of these topical headings below:

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 small areas 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)

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 rain gage record exists for most cities. Where such information is lacking, however, standard hydrologic procedures for a real 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)

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 1.

PROGRAM OPERATION

STORM has been documented by the Hydrologic Engineering Center, Army Corps of Engineers, Davis, California and is available to the public. (1) The reader is referred to this program manual for a detailed discussion of program operation and specifications. Highlights of the program requirements, and computational procedure have been extracted from this manual and are presented below:

Hardware And Software Requirements

STORM has been written for the IBM 360/50, UNIVAC 1108, and CDC 6600 or 7600 computer systems. It requires about 40,000 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.

Computational Procedure

A summary of the computational procedure is shown in Figure 4. Some of the computations may be bypassed depending upon the program options specified. The first block of Figure 4 where "basic data" are read includes information on:

Job specifications,
Hourly precipitation records } available on magnetic
Daily temperature record, } tape from the National Weather Service
Land use data including runoff parameters,
Pollutant accumulation and washoff data, and
Land surface erosion data.

DATA DEVELOPMENT

Having defined the watershed boundaries, the requisite data is obtained and organized for use with *STORM*. The following paragraphs discuss data development by category.

Hydrologic Data

Precipitation data are available from the three U.S. Weather Bureau Service Stations at Sellersville, Phoenixville and North Philadelphia Airport. The Sellersville station was selected as the primary source because of its proximity to the watershed. Hourly rainfall values are available for the station from 1 October 1964 to 30 September 1970 with only minor lapses. Information from the adjacent stations was used to augment the missing Sellersville data.

The U.S.G.S. surface water station number 1-4739.5 supplied runoff information. Records from October 1965 to September 1969 were readily available for use in this study.

The overlap in rainfall and runoff records permitted modeling four years of coincident rainfall-runoff data. This information is sufficient to allow adjustment of the runoff coefficients which in turn permitted calibrating the model to reproduce historic stormwater outflows from the study area.

Hydrogeometric Data

This data was a little more difficult to organize for use with the model. Existing land use is available by demand centers prepared by Delaware Valley Regional Planning Commission. Unfortunately these demand centers do not exactly correspond to the boundaries of the Wissahickon watershed. Adjustments had to be made to many of the existing centers and additional areas added to land use data in order to correctly define the watershed. Also, the land use data, as it was supplied to WRE, had a separate category for all transportation related facilities including all streets and roads. This created a problem. All work that relates land use to runoff potential has not broken out streets. Therefore, it is necessary to reallocate the street areas to each of the five land use types included in the analysis. This is accomplished using the relationships WRE had developed from experiences on other similar watersheds. Table 2 shows the final land data developed for the Wissahickon Basin.

The model also required the estimation of the percent of each land use area that is impervious to rainfall. Fortunately, WRE has just completed an analysis of this variable on another watershed study in the Washington, D.C. area. Because the two areas exhibit similiar suburban development characteristics the values from that study are adopted for use in the Wissahickon Basin. Table 3 presents the pertinent data on impervious areas that are used in this analysis.

Two other classes of information are needed to fulfill the data requirements of *STORM*, depression storage and monthly evaporation rates. Depression storage is evaluated based on an area-weighted-average by land use type of the data presented in Table 4. The average monthly evaporation rates are developed by using information supplied by the National Weather Service.

QUALITY DATA

Ideally, water quality data is gathered or field sampling is performed on a storm event basis for all water quality parameters of interest. The procurement of this data permits the adjustment of the model for water quality prediction. However, the application of the model *STORM* to this basin was not intended to rigidly forecast water quality, but to demonstrate the ability of the model to predict the same where data is available. Since the accurate prediction of water quality was not within the scope of the study, a first approximation of the quality of stormwaters was acceptable. Accordingly, use was made of existing data and model coefficients from other studies to simulate the water quality parameters in the Wissahickon watershed. Some minor adjustments were made to these adopted water quality parameters to account for the large amount of rural open space in the basin. These adjustments are discussed in the subsequent paragraph.

MODEL ADJUSTMENTS

Adjustment of the model *STORM* is accomplished in two steps to assure its ability to reproduce the events as they occur in the field. The first step of the adjustment uses the rainfall-runoff data to calibrate the hydrology of the basin. Four years of coincident records of rainfall at Sellersville and runoff measured at the Bells Road U.S.G.S. station are used to calibrate the model. Hourly rainfall records at Sellersville from 1 October 1965 to 1 October 1969 are supplied to the model. The runoff coefficients are adjusted until the average yearly runoff volume measured at the U.S.G.S. gage is predicted by the model. The gage at Bells Road recorded an average of 15.06 inches of runoff for the period of record used. The base flow is estimated to be 3.84 in/yr for the same period. Therefore, 11.22 in/yr of direct runoff is accounted for at the gage and the calibrated *STORM* model produces an average of 11.37 in/yr of direct runoff. This is a very close agreement of total runoff volumes. Selected storms are analyzed for peak flows using the model and the flow records. Figure 5 is a plot of the results of this comparison. Considering the relatively large size of the basin and the use of only one rain gage that isn't located in the basin, the results are reasonably good. This figure illustrates a very simplified hydraulic model's ability to estimate hydrograph peaks.

Having the hydrologic portion of the model reasonably reproducing the annual rainfall-runoff process in the basin, the water quality simulations are performed. As explained previously, the water quality portion of the model is not calibrated from field data, but model coefficients from other watersheds of similar characteristics are used for the analysis. However, in the case of the rural open space land use category an adjustment is made to the model to produce expected average annual loads from that type of land use. Data are obtained from a yet to be published U.S. Environmental Protection Agency report on average annual loads for nonpoint source runoff for rural areas. The open space land use category is modeled separately and adjusted until the average annual loads for all water quality parameters are in the range reported in this recent study. Having adjusted the runoff loads from the open space area, the model is then used to simulate the nonpoint source pollutional loads for the entire Wissahickon watershed.

MODEL RESULTS

Table 5 presents the information obtained from the simulation of the nonpoint loads from the Wissahickon Watershed. These values are presented as average annual loads for the four years of record simulated. These values are certainly of a significant magnitude and must be considered in any water quality management plan. Perhaps, even more significant is the peak hourly loads produced from the period of record. Table 6 shows these peak hourly pollutional loads that resulted from a peak flow of nearly 6,000 cfs on 27 January 1967. This storm happened to occur after a fairly long dry spell and exhibited an intense rainfall in the very first hour of the rainfall. These two occurrences combine to produce large concentration of pollutants with large flow volumes that cause these very large peak loads. These loads could be somewhat reduced by the routing that exists in the basin that is not reproduced accurately by the model.

It is extremely important to remember that this model has not been calibrated for water quality using measured field data. Coefficients used in the model for pollutional buildup and runoff from the watershed were adopted from previous studies and recent literature articles.

But these pollutant loads are of significant magnitude to warrant further evaluation. The purpose of this study was to estimate the relative magnitude of nonpoint loads so that they could be compared with point loads. The comparison will be accomplished in latter phases of the overall study and is not yet complete.

The final answer in evaluation of the relative importance of nonpoint loads can only be determined by the water quality response of the receiving stream. The Biochemical Oxygen Demand of the materials washed off the watershed during the peak hours of the 27 January 1967, storm is approximately equal to the raw organic load of 90,000 people for a day. A shock loading of this magnitude to a small stream will have an important effect.

The annual average nonpoint storm wash resulted in a BOD loading of 441,000 pounds per year or 1208 pounds per day average. A urban population of approximately 48,000 produces a similar amount of wastes if the wastes receive secondary treatment.

The annual loadings do not appear significant but the peak loading should be examined in more detail. In particular a monitoring for the mainstem of the Wissahocken should determine if poor water quality results from these storm events.

REFERENCES

1. *Urban Storm Water Runoff STORM,* Generalized Computer Program, 723-S8-L2520, Hydrologic Engineering Center, U.S. Army Corps of Engineers, May 1974.

2. *Water Pollution Control Federation, Design & Construction of Sanitary & Storm Sewers.*

LIST OF FIGURES

LIST OF TABLES

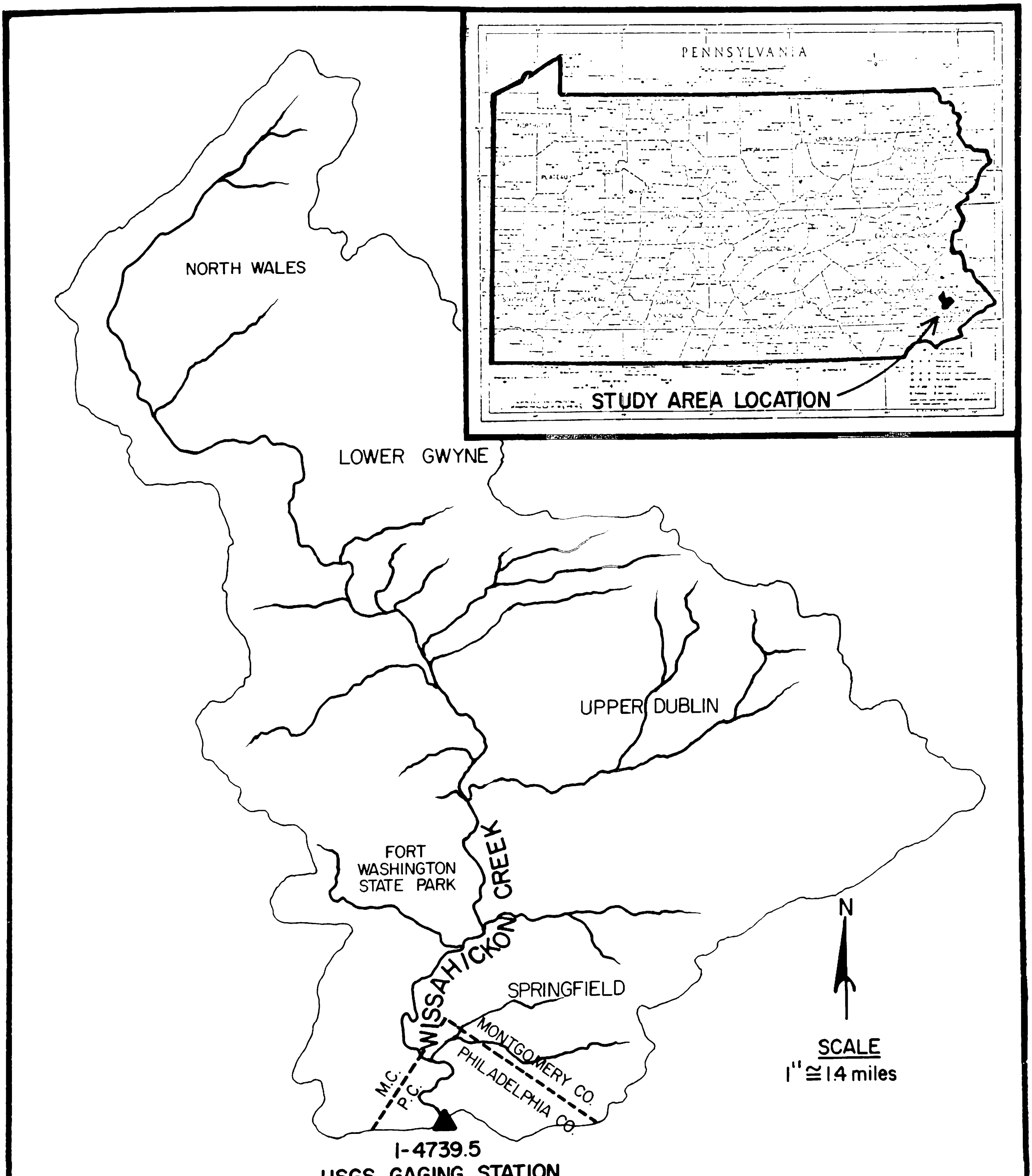


Figure 1

WISSAHICKON CREEK STUDY AREA

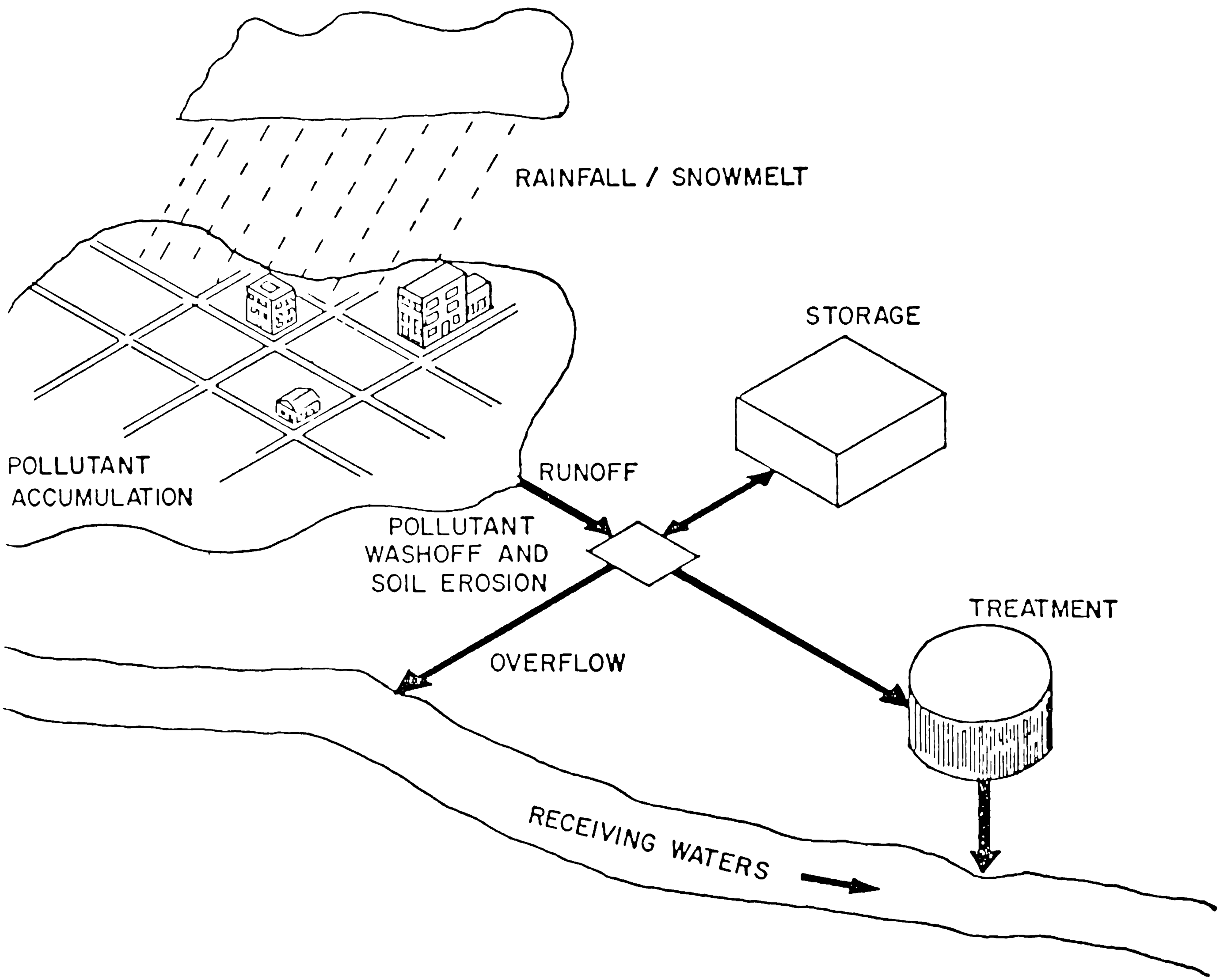


FIGURE 2

CONCEPTUALIZED VIEW OF URBAN SYSTEM
USED IN STORM

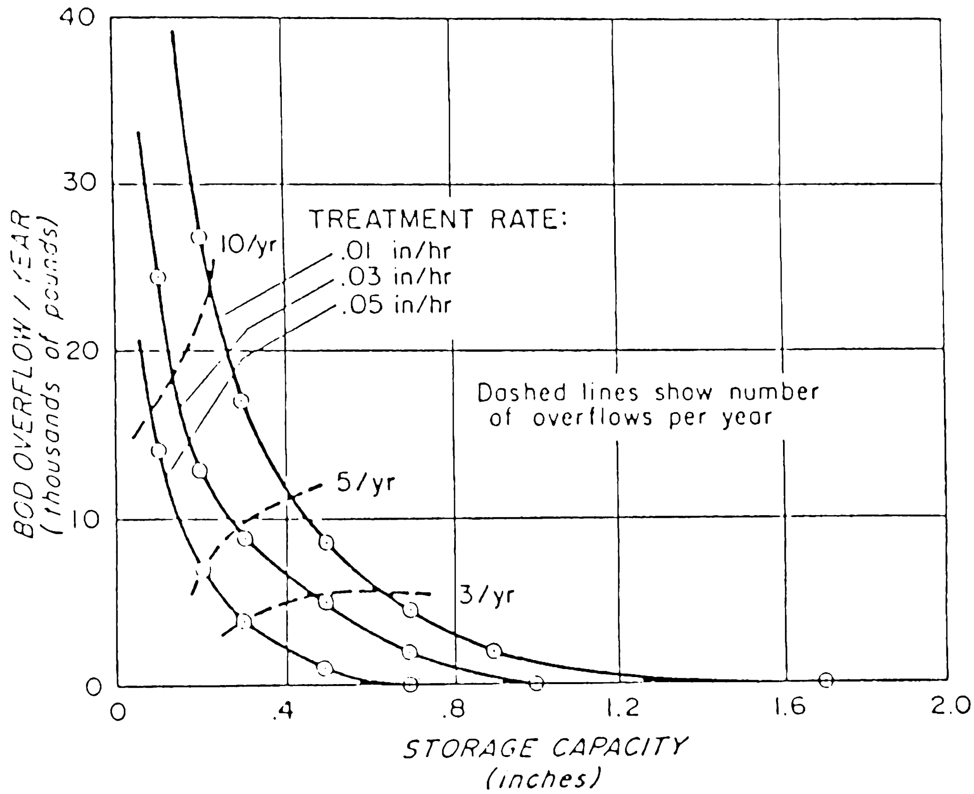
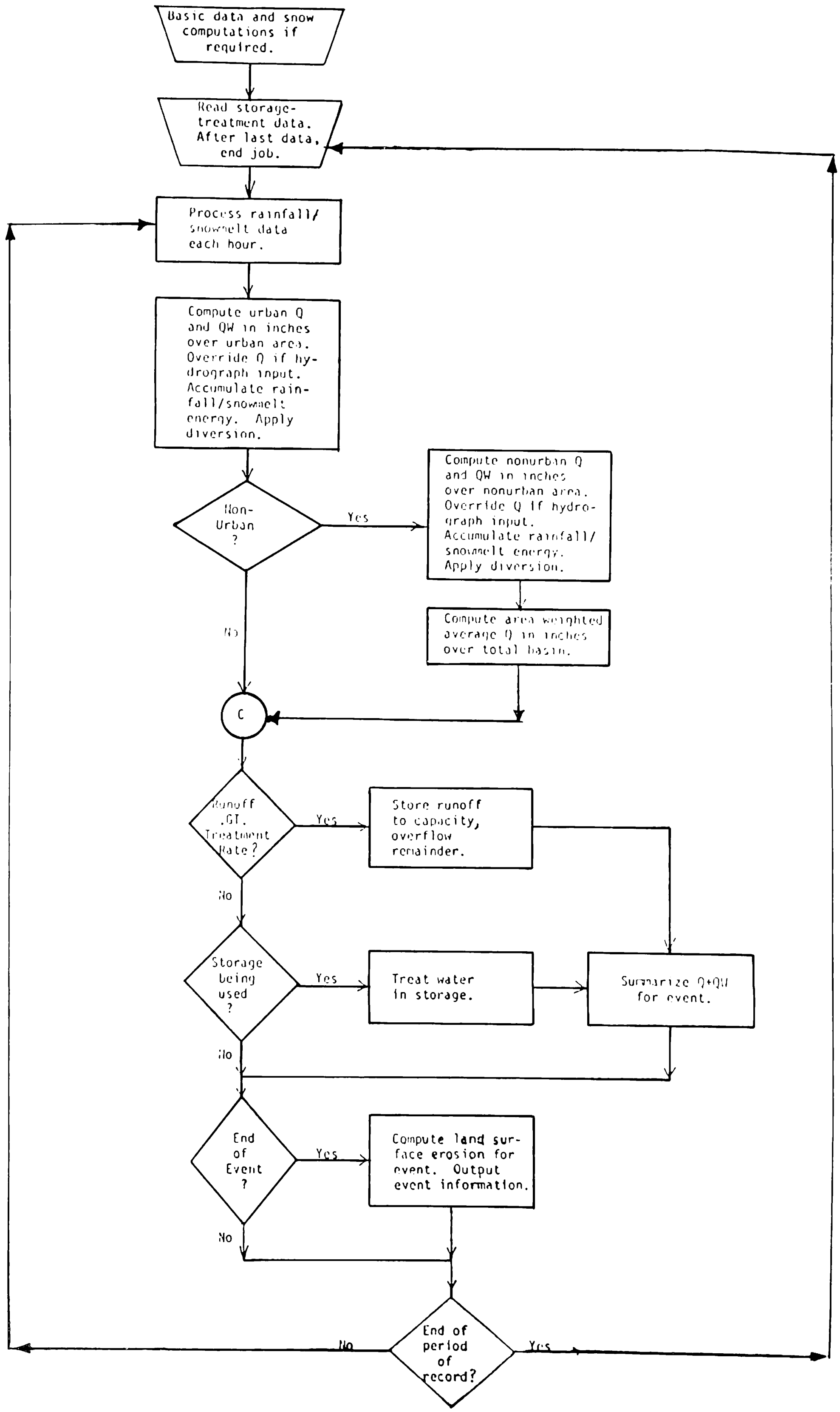


Figure 3

Application of STORM Model
Castro Valley, California

Figure 4 Computational Procedure Flow Chart



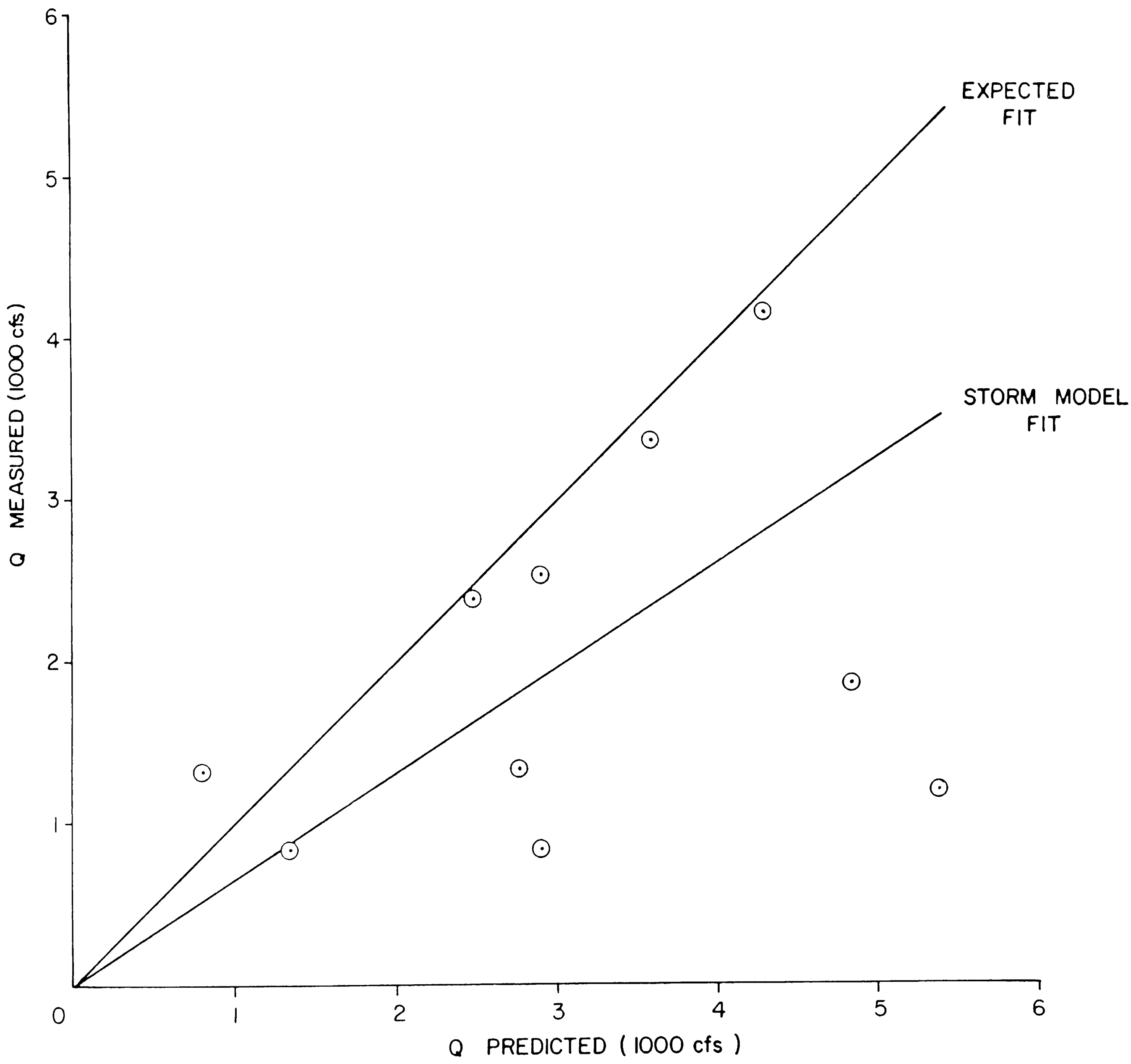


FIGURE 5

WISSAHICKON CREEK PREDICTION OF HYDROGRAPH PEAKS AT USGS GAUGE NO. 1-4739.5 BY "STORM" MODEL

TABLE 1
"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

TABLE 2

LAND USES

WITHIN WISSAHICKON WATERSHED

AT USGS GAGE 1-4739.5

Demand Center[1]	Single Residential	Multi Residential	Industrial	Commercial	Open	Total (Acres)	Total (MI^2)
WRE 1	62	0	0	0	0	62	
WRE 2	99	2	2	11	74	188	
103F460-03	55	18	0	0	18	91	
-17	258	57	32	55	37	439	
-22	520	7	16	143	1026	1712	
-23	1044	69	37	185	687	2022	
-24	1005	25	16	114	758	1918	
-25	166	3	41	55	782	1047	
-26	354	6	93	118	1711	2282	
-27	86	1	23	29	415	554	
-28	1728	14	163	268	3411	5584	
-29	1173	88	9	392	410	2070	
-30	684	21	68	110	1383	2266	
-31	246	73	52	102	80	553	
-32	909	58	51	98	2325	3440	
-33	411	5	30	39	1253	1738	
-38	321	6	17	26	1015	1385	
-39	444	21	12	46	1337	1862	
-40	21	0	5	5	239	270	
-42	623	57	344	100	2118	3242	
-43	221	50	27	47	32	376	
-44	125	12	0	35	485	657	
Phil. Co.	309	16	8	42	204	579	
Total (Acres)	10864	609	1046	2020	19800	34338	53.6

[1]Numbers correspond to Delaware Valley Regional Planning Commission nomenclature

TABLE 4

VALUES OF DEPRESSION STORAGE (2)

Land Use	Depression Storage (in)
Forest Litter	0.30 in
Good Pasture	0.20 in
Smooth Cultivated Land	0.05-0.10 in
Urban Areas (Moderate Grade)	
Pervious Surfaces	0.10 in
Impervious Surfaces	0.05 in
Lawns	0.10 in

TABLE 3

LAND USE/IMPERVIOUS AREA CORRELATIONS

Land Use	No. of Areas Evaluated	Total Area Evaluated (1000 ft²)	Size (1000 ft²)		% Impervious Streets Only			% Impervious Streets, Drives, Walks, Parking			% Impervious Streets, Drives. Walks, Roofs, Parking		
			Min.	Max.	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
Single Family	73	23,490	100.7	1116	4.4	20.2	12.6	8.0	28.6	13.8	13.2	52.9	24.3
Medium Density Residential	15	3,305	60.2	397	7.5	19.6	11.3	12.2	61.9	23.2	19.2	65.0	34.2
High Density	46	20,356	112	2000	5.4	36.3	11.8	11.9	62.9	31.6	30.9	71.0	47.8
Schools	9	8,339	165.5	1900	3.8	13.5	5.9	14.9	36.5	20.5	23.2	49.4	30.8
Industrail	5	1,417	143	483	42.	85.1	62.6	76.	96.6	87.3	86.9	97.6	92.6
Commercial	15	4,339	86.3	1800	15.3	97.2	44.	61.2	99.6	78.2	64.7	99.7	82.8
Vacant	--	--	--	--	--	--	8.0	--	--	8.0	--	--	8.0
TOTAL	163	61,246											

TABLE 5

AVERAGE ANNUAL POLLUTION LOADS

Parameter	1000 lbs/yr	Runoff Concentration (mg/l)
Suspended Solids	2993	33.9
Settable Solids	276	3.1
BOD	441	5.0
Total Nitrogen	164	1.9
Orthophosphate (PO_4)	17	0.2

TABLE 6

PEAK HOURLY LOADS

STORM OF JANUARY 27, 1967

Parameter	1000 lbs/hr	Runoff Conc. (mg/l)
Suspended Solids	143	118
Settleable Solids	9.7	8.0
BOD	22.5	18.6
Total Nitrogen	7.9	6.6
Orthophosphate (PO_4)	0.8	0.7