EPA-R2-72-068
October 1972

Environmental Protection Technology Series

Storm Sewer Design - An Evaluation of the RRL Method

Office of Research and Monitoring
U.S. Environmental Protection Agency
Washington, D.C. 20460

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Monitoring, Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality Standards.

EPA-R2-72-068
October 1972

STORM SEWER DESIGN - AN EVALUATION OF THE RRL METHOD

By

John B. Stall and Michael L. Terstriep

Project 11030 FLN

Project Officer

Harry C. Torno
Office of Research and Monitoring
Environmental Protection Agency
Washington, D.C. 20460

Prepared for

OFFICE OF RESEARCH AND MONITORING
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price $1.25

EPA Review Notice

ABSTRACT

Storm rainfall and runoff data were assembled from 10 urban basins in the U.S.A. ranging in size from 14 acres to 8 sq mi. The British RRL method of storm drainage design was applied to the 10 basins. The RRL method considers the urban basin to be comprised of the paved area of the basin which is directly connected to the artificial storm drainage system. In 3 of the 10 basins the RRL procedure was deemed to be appropriate and suitable for the design of a storm drainage system within the normal range of frequency of design rainfall events, from 2 to 20-year events. For greater storms and for certain cases within this frequency range, the RRL method breaks down because the runoff Coming from the grassed area of the basin is significant. If the basin is highly steep or if the paved area comprises less than 15% of the total basin, this breakdown occurs. An example is given of the use of the RRL method in the re-design of an existing storm drainage system, as is current practice in Great Britain.

This report is submitted in fulfillment of Project 11030 FLN under the partial sponsorship of the U.S. Environmental Protection Agency.

CONTENTS

FIGURES

TABLES

SECTION I
CONCLUSIONS

1. The RRL method provides an accurate means of Computing runoff from the paved area portion of an urban basin.

2. The RRL method adequately represents the runoff from actual urban basins under the following conditions:
   a. the basin area is less than 5 sq mi,
   b. the directly connected paved area is equal to at least 15 percent of the basin area, and
   c. the frequency of the storm event being considered is not greater than 20 years.

3. The RRL method cannot be used for all urban basins in the United States; the method breaks down when significant grassed-area runoff occurs, which happens if one or more of the following conditions exist:
   a. the directly connected paved area is less than 15 percent of the basin area,
   b. the frequency of the event being considered is greater than 20 years,
   c. the grassed area of the basin has steep slopes and tight soils, regardless of the antecedent moisture condition,
   d. the grassed area of the basin has steep slopes, moderately tight soils, and an antecedent moisture condition of 3 or 4, and
   e. the grassed area of the basin has moderate slopes, moderately tight soils, and an antecedent moisture condition of 4.

4. The principal strength of the RRL method is that, by confining runoff calculations to the paved area of a basin, it utilizes hydraulic functions which are largely determinate such as gravity flow from piain sloping concrete surfaces, gutters, pipes, and open Channels. Physical understanding of these flow phenomena is much greater than the present understanding of the many complex phenomena governing runoff from rural areas such as antecedent moisture conditions, Infiltration, soil moisture movement, transpiration, evaporation, etc.

5. A modification of the RRL method that would provide a function for grassed-area contributions to runoff could be developed into a valuable design tool for urban drainage. This is believed to be possible in spite of the many complexities involved. Further flexibility could be offered by the additional provision for routing surface runoff through surface storage.

6. The input data requirements for use of the RRL method on an urban basin are reasonable for the engineering evaluation of a basin for storm drainage design. The necessary data are no more complex nor elaborate than the data usually compiled for a traditional storm drainage design.

7. It appears that rainfall occurs in greater amounts in the United States than in Great Britain. This may account for the fact that the RRL method is successful and widely used in Great Britain and yet suffers the above-described breakdowns for some of the basins studied in the United States.

8. Better urban rainfall and runoff data are required for proper testing of all mathematical modeis. Research basins that do not have hydraulic problems, such as undersized drains or inadequate inlets, should be selected and instrumented.

SECTION II
RECOMMENDATIONS

1. It is recommended that research and development be carried out to incorporate within the RRL method a series of parameters and functions which would accommodate the runoff from grassed areas within an urban basin and to provide other minor improvements in the RRL method to provide greater flexibility in its application.

2. It is recommended that, until the above improvements are achieved, the method not be promoted as having general applicability for widespread use. This is because the method breaks down for basins where the grassed-area contribution is significant, as shown in this research. If the method can be suitably altered to accommodate grassed-area runoff, then it would be appropriate to carry out further developmental work on the method in order to streamline it as a design procedure.

3. Immediate efforts should be made to establish stations and Instrumentation for the collection of higher quality data on storm rainfall and runoff from urban basins. This is necessary for the adequate testing and calibration of many of the modern existing methods for accommodating urban storm rainfall and runoff. This instrumentation should probably also include water quality parameters.

4. It is recommended that further use and applications be made of total-basin-accounting modeis published and used elsewhere, such as the hydrologic Simulation programming, HSP. The use of such a model in the urban setting offers promise of contributing understanding of all the many complex and critical hydrologic processes in an urban basin.

SECTION III

INTRODUCTION

Need

$2.5 billion per year is the construction cost for storm drainage Systems in urban areas of the United States estimated by the American Public Works Association (1966). This monumental expenditure represents the amount that city dwellers pay in order that storm runoff water can be adequately collected and removed from the rooftops and streets of an urban area and emptied into a convenient natural stream outside of the city limits.

When storm rainfall occurs in a rural area, much of it soaks into the earth; the remainder runs off to the nearest stream. The excess surface runoff may cause some temporary flooding on the land surface along ditches, drainageways, and small stream Channels. When a city is constructed, much of the natural landscape is covered with rooftops, paved streets, and other paved areas. The remaining natural earth is usually covered with grass lawns. Several researchers have shown the effects of urbanization on the storm runoff of a region. Stall and others (1970) showed that the complete transformation of a 3.5 sq mi rural basin in east-central Illinois to an intensely urbanized basin would increase the flood peak by about 4 times for the 50-year recurrence interval. It would increase the mean annual flood by about 8 times.

An artificial storm drainage system for an urban area usually includes a collection network of storm drains consisting of Underground conduits. Engineering design practice in 1972 utilizes almost exclusively the *rational method* for determining the size and hydraulic capacity of these storm drainage Systems. Design practice in 32 cities has been summarized by Ardis and others (1969). The rational method is described in most hydrologic text books and is given by Chow (1964) as being $Q = CIA$ where Q is the peak discharge in cfs, C is a runoff coefficient depending on the characteristics to the drainage basin, I is the rainfall intensity in inches per hour, and A is the drainage area in acres. The term *rational* is used because the units of the quantities are numerically consistent. The method has widespread acceptance but its use still relies heavily on engineering judgment.

Practicing engineers have recognized the need for an improved method for understanding the storm rainfall-runoff process in urban areas. The American Society of Civil Engineers (1969) gave an extremely high priority to the need for better knowledge of the rainfall-runoff-quality process in urban drainage Systems. Under this impetus a number of different models have been developed in recent years for accommodating the storm rainfall-runoff process for an urban region. A critical review of about 12 of these models has been provided by Linsley (1971), who states as one conclusion:

> "The present limited amount of urban hydrologic data is a serious deterrent to development and testing of storm runoff models. It seems unlikely that any significant improvement in current models is possible until more data and better quality data are available."

The Illinois State Water Survey in recent years carried out a major evaluation of the method of storm drainage design developed at the British Road Research Laboratory (called the RRL method) which is described in a later section of this report. Terstriep and Stall (1969) used the RRL method to carry out an analysis of 39 storms on three urban watersheds in the United States and illustrated the general applicability of the method for conditions in this country. It was considered desirable to have additional cases for testing this method. Exploration revealed that some data on storm rainfall and runoff existed for urban areas of the United States. A grant was provided by the federal Environmental Protection Agency to finance part of the cost of the collection of the necessary physical information and rainfall-runoff data and the analysis of these data by the RRL method for about 10 basins in the United States. This activity is described in this report.

All of the basin data, storm drain data, maps, and storm data assembled for this project have been provided to the EPA. Persons interested in obtaining copies of these data for research purposes should contact Harry C. Torno, Staff Engineer, Municipal Pollution Control Section, U.S. Environmental Protection Agency, Washington, D.C. 20460.

Objective

The object of this project has been to provide a catalog of actual applications on about 10 urban basins in the United States of the British Road Research Laboratory method for the design or re-design of storm drainage Systems. This included an evaluation of the applicability of this method for United States conditions. Because the RRL method considers runoff from paved areas only, a secondary objective was to evaluate the influence of grassed-area runoff from typical urban watersheds.

SECTION IV
ASSEMBLY OF DATA

Criteria

Relatively few data exist for storm rainfall and storm runoff measurement from urban drainage basins. The American Society of Civil Engineers recently carried out a study to locate data of this type. As reported by Tucker (1969) there do exist in some cities and other governmental offices throughout the United States some data which seem suitable for hydrologic analysis. The U.S. Geological Survey has emphasized in recent years the measurement of runoff from urban basins. A number of USGS offices were contacted regarding data for this project. Of the 10 basins ultimately studied and reported herein, data for 6 were obtained from the USGS, usually collected in Cooperation with some other agency. In the usual case these urban runoff data had been collected and used for some particular project, but had not been published. A major study by the USGS on the effects of urbanization on floods has been published by Anderson (1970).

In considering basins for this project, priority was given to the following items: 1) basins less than 5 sq mi in size, 2) basins that were intensely urbanized, 3) basins that had extensive storm drainage Systems, 4) basins with a high amount of paved area, 5) long records of rainfall and runoff, 6) the degree of quality of the data on storm rainfall and runoff, 7) the degree of Information available on the storm drainage system, and 8) data which had not already been published in one form or another.

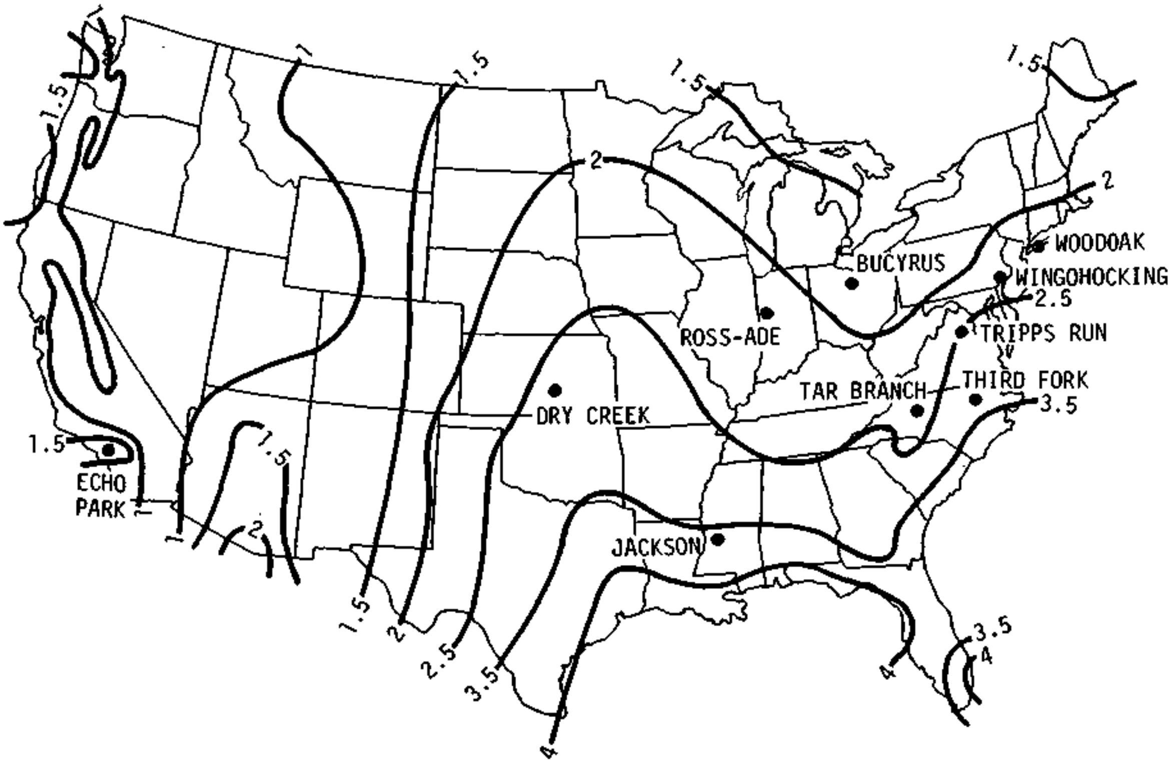


Figure 1. Two-hour storm rainfall in inches expected at a 5-year recurrence interval for mainland United States (U.S. Weather Bureau, 1961)

Another major item in the selection of basins was the effort to provide coverage of a variety of hydrologic regimes in the United States. In order to do this, consideration was given to the variability of storm rainfall within the United States. Figure 1 is a map of the 2-hour storm rainfall in inches expected at a 5-year recurrence interval for mainland United States, as shown by the U.S. Weather Bureau (1961). Although some other combination of duration and frequency could be considered as critical for storm drainage design, it is felt that the 2-hour 5-year storm is one which is certainly in the critical zone as far as storm drainage design is concerned.

The following 10 basins were selected and used: Woodoak Drive basin, Westbury, Long Island, New York; Ross-Ade (Upper) basin, West Lafayette, Indiana; Sewer District No. 8, Bucyrus, Ohio; Echo Park Avenue basin, Los Angeles, California; Crane Creek basin, Jackson, Mississippi; Tripps Run Tributary basin, Falls Church, Virginia; Tar Branch basin, Winston-Salem, North Carolina; Third Fork basin, Durham, North Carolina; Dry Creek basin, Wichita, Kansas; and Wingohocking basin, Philadelphia, Pennsylvania.

Methods

In order to apply the RRL method to a basin it was necessary to obtain street maps, aerial photographs, and the location, size, and slope of the existing storm drainage system. Normally this information was obtained from city officials. In scouting around to locate data suitable for this project, a great number of data collection agencies and cities were contacted. Many leads were obtained from the publication by Tucker (1969). For the more promising basins a letter was written to the data collection agency and to the city outlining the needs of the project, and asking for a description of the exact nature of the data.

The second step was to examine samples of the raingage and streamgage charts to determine the general quality of the data and to determine the minimum time intervals of rainfall and runoff which could be interpreted from the charts. If the data were suitable for the project, arrangements were made to borrow or copy either the charts or any rainfall and runoff data that had already been reduced for the shortest feasible time interval. A detailed inspection trip was made through the basin, and notes were made of the exact drainage pattern. Observations were made of the practice in the disposition of runoff from rooftops and notes were made as to the number or percent of rooftops which emptied onto the driveway or were directly connected to the storm drainage system or to the street by tile drain. Further inspection and notes were made of existing open Channels or drainage ditches, noting the general conditions, shapes, and configurations. An inspection was usually made of the stream gaging Installation and the raingages, to note their general condition, exposure, and setting. Photographs were taken to aid in further Interpretation of the field notes at the office.

In several of the basins a considerable amount of work was entailed in the reading of the raingage charts and recorder charts of flow. This was accomplished as a part of the present project and considerable use was made of the automatic graphical digitizing machine, the model 3400 auto-trol, which was available at the Illinois State Water Survey.

An aerial photograph of each basin was obtained. The principal source of these photos was the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service (ASCS). These aerial photos were used in determining the total amount of the paved area in the basin.

Information has been assembled for every basin to characterize the predominant surface soils. This information was obtained from the federal Soil Conservation Service and followed their designations as hydrologic soil groups:

A. Have low runoff potential, high infiltration rates, consist of sand and gravel,

B. Have moderate infiltration rates and are moderately well-drained,

C. Have slow infiltration rates; have a layer which impedes the downward movement of water, and

D. Have high runoff potential, very slow infiltration rates, clays with a permanent high water table and a high swelling potential.

The antecedent moisture condition used later in this report was determined from Weather Bureau (National Weather Service) Climatological Data. The gage selected for each basin was the nearest Weather Bureau recording gage to the basin. Antecedent moisture conditions were classed in four divisions based on the 5-day antecedent rainfall, as follows: 1, bone dry, 0 rainfall; 2, rather dry, 0 to 0.5 inch; 3, rather wet, 0.5 to 1.0 inch; and 4, wet, over 1.0 inch.

SECTION V
THE ROAD RESEARCH LABORATORY METHOD

Origin

The conception and development of the British RRL method for the accommodation of storm rainfall and runoff for the design and re-design of storm drainage Systems has been the result of an elaborate, varied, and sustained research program. The Road Research Laboratory is an agency of the Ministry of Transport of the British government. In the era after World War II the research personnel of this laboratory recognized the need for better information for the design of storm drainage Systems. The design method being used at that time was the *Lloyd Davies* method which is the British counterpart of the *rational* method. Recognizing the need for observed data on storm rainfall and runoff, suitable measuring equipment was developed. Ultimately, a series of 12 urban basins were selected and instrumented. Storm rainfall and runoff data were collected for 286 storm events on these watersheds during the period 1950-59. These results were analyzed by the rational method and the unit hydrograph method. After recognizing the limitations of these two methods, the new British RRL Hydrograph Method was devised. This research and development has been described by Watkins (1962). Some of the conclusions of this study were:

1. The rational equation is satisfactory as a design method for small areas in which there are no drainage pipes larger than 24 inches in diameter. Here the errors introduced by the rational method are tolerable.
2. The RRL hydrograph method is accurate and reliable for calculating hydrographs for all urban areas.
3. The unit hydrograph method is unsuitable for use in designing urban drainage Systems due to the difficulty of determining the shape of the unit hydrograph.

Having completed this research and having devised the RRL method, the Road Research Laboratory carried out further work to reduce this hydrograph method to an actual design method. Computer programs were written and made available to design engineers at Computing centers. The Road Research Laboratory (1963) later provided a guide for engineers to use in providing input into the Computer program in order to obtain design output. This greatly simplified the use of this design procedure for practicing engineers. It is reported that in Great Britain in 1972 about 80 percent of the design or re-design of storm drainage Systems is carried out by this RRL method.

The Procedure

The dominant feature of the RRL method is that it accommodates runoff only from the paved areas of the basin which are *directly connected* to the storm drainage system. Grassed areas are excluded from consideration as are paved areas which are not directly connected. The principal elements of the procedure are as follows. Equal time increments of rainfall are applied to the directly connected paved area in a small sub-basin of the total urban basin. Next a computation is made of the travel time required for each increment of runoff to reach the inlets at the downstream end of the sub-basin. In this way a surface hydrograph is provided for each sub-basin. These surface hydrographs from each sub-basin are accumulated in a downstream order through the basin. This cumulation of inflow hydrographs is routed through each section of pipe to accommodate the temporary storage within each pipe section. The result is a computed outflow hydrograph from each section of pipe and this is ultimately provided at the outlet of the total basin. The procedure was described by Watkins (1962) and by Terstriep and Stall (1969). In both of these studies storage for the basin was lumped together and the routing was accomplished in one step for the entire basin. A later improvement to the method devised by the British and used in this study provides for multi-step routing of the hydrograph through successive sections of pipe.

The RRL method is applied by first dividing the basin to be studied into sub-basins. A sub-basin is normally a part of the basin contributing to a single inlet or set of inlets into one storm drain pipe. Two physical factors must be evaluated for each sub-basin. First, the paved area directly connected to the storm drainage system must be determined; second, the travel time must be calculated for flows on paved areas and in gutters.

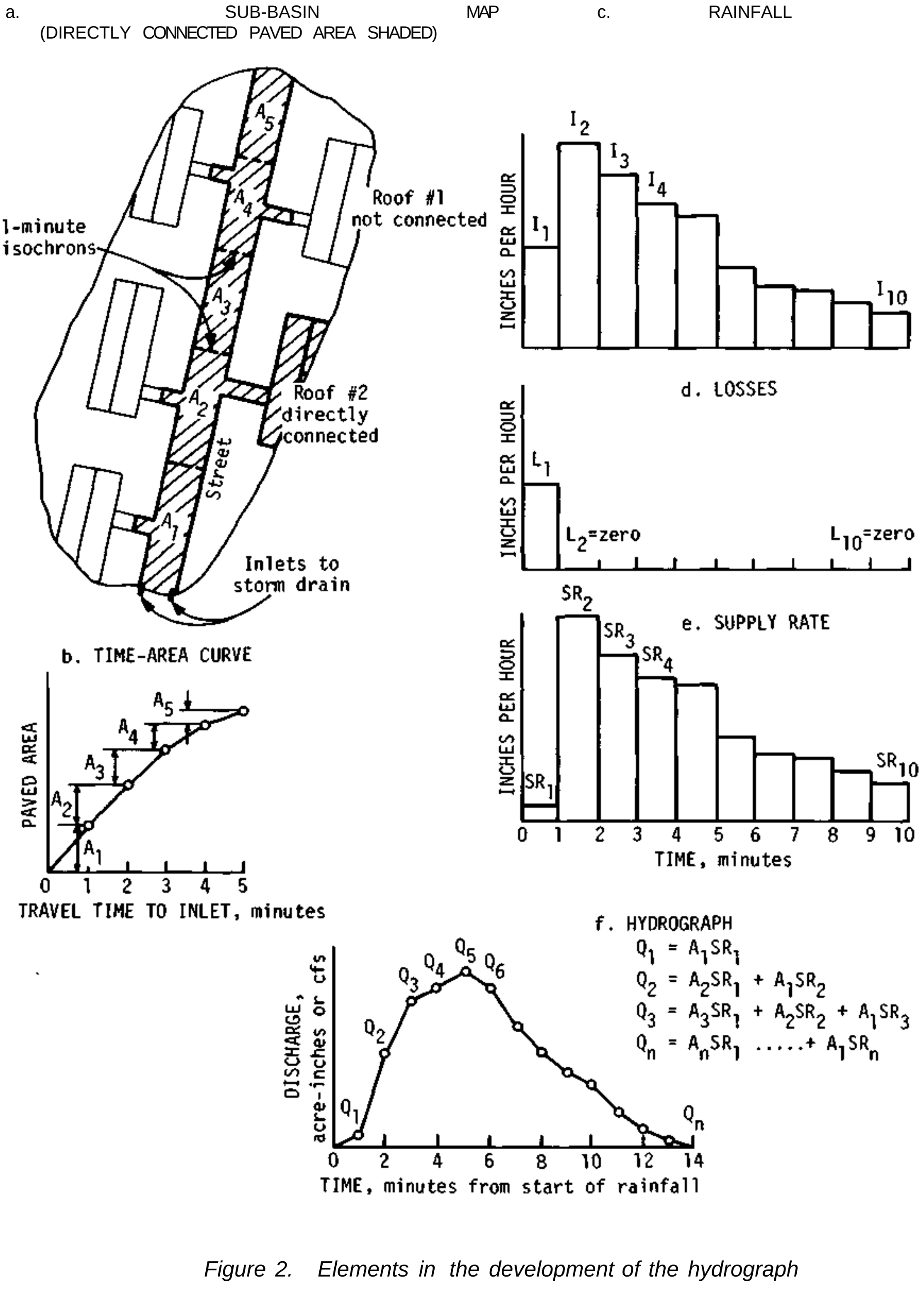
The various elements and steps used in developing a runoff hydrograph for an urban sub-basin are illustrated in figure 2. Extending down the middle of the small sub-basin map (figure 2a) is a city street with a pair of inlets at the lower end which allow water to enter a storm drain pipe. Shown also are rooftops along this city street. The area shaded has been determined by a field survey to be directly connected to the street. In each case about half of the driveway has been considered to be contributing. The flow from roof No. 1 is not connected to the street, but the flow from roof No. 2 reaches the drainage system either by way of the driveway which flows into the street or by a direct Underground connection.

After the directly connected paved area has been determined, calculations are made to determine the time-of-travel for the runoff water from various parts of the paved area to the inlets at the downstream end of the sub-basin. In earlier studies the velocity and travel times for overland flow were based on an equation developed by Hicks (1944) as described by Jens and McPherson (1964). In the present project, travel times were computed in two steps. First, a design flow of 0.5 cfs per acre of paved area was assumed: in a few cases this was increased to 1.0 cfs per acre. This design flow was considered to be flowing down various reaches of street gutters.

The second step was to apply Männing's equation to compute the velocity of flow in the gutter. By this means the travel times were computed for various reaches of the paved area in each sub-basin. These travel times were plotted at various locations on the paved area, and by connecting points of equal travel time a series of isochrons were drawn on the paved area (figure 2a). The directly connected paved area between these isochrons was measured and designated area A1, A2, A3, A4, and A5 as shown in figure 2a. These various areas are accumulated and plotted against travel time to the inlet as shown in figure 2b. This time-area curve shows the amount of paved area within the sub-basin which is contributing water at the inlet at any time after the beginning of runoff. In the Computer program described later, the time-area curve was assumed to be a straight line connecting the origin and the end-point of the curve. The end-point of the curve, as illustrated in figure 2b, represents the travel time of runoff water from the furthest point of the directly connected paved area, and the total amount of the directly connected paved area.

In constructing the hydrograph for each sub-basin the input is the rainfall pattern as a series of intensities of equal duration (figure 2c). The rainfall input can be an actual event or a design storm. The time increment used should be the same as the time interval between the isochrons; this time interval, *At,* is used throughout the computations. In general it should be as short as the quality of rainfall data will allow, except that for very large basins or very long storms it may be more convenient to use a longer *At.*

Shown in figure 2d are the losses for the same time intervals as given for rainfall. For applica-



a. SUB-BASIN MAP (DIRECTLY CONNECTED PAVED AREA SHADED)

c. RAINFALL

d. LOSSES

e. SUPPLY RATE

b. TIME-AREA CURVE

f. HYDROGRAPH

Figure 2. Elements in the development of the hydrograph

tion to a paved area the losses consist of initial wetting and depression storage. These losses are combined and treated as an initial loss to be subtracted from the beginning of the rainfall pattern. In figure 2d the entire initial loss L1 occurs during the first minute or first time interval.

After subtracting these losses from the rainfall pattern, the remainder of the rainfall will appear as runoff from the paved area. This runoff is shown in figure 2e and is referred to as the paved area supply rate; it is also plotted at 1-minute intervals.

The ordinates of the surface hydrograph are developed by applying the supply rate to the time-area curve, which is done by the series shown in figure 2f. The hydrograph developed in figure 2f occurs at the sub-basin inlets illustrated in figure 2a. Such a hydrograph is developed for each sub-basin and becomes an input to the system at a particular point. If the sub-basin in question happens to be at the upper-most end of a series of pipe or open Channel reaches, the hydrograph is entered into the system by routing it downstream to the next input point. If the sub-basin occurs somewhere below the upper end, its hydrograph is combined with the upstream hydrograph and the resulting combined hydrograph is routed downstream to the next input point. If the sub-basin is located at the confluence of two or more pipes, its hydrograph is combined with the converging hydrographs before routing downstream to the next input point.

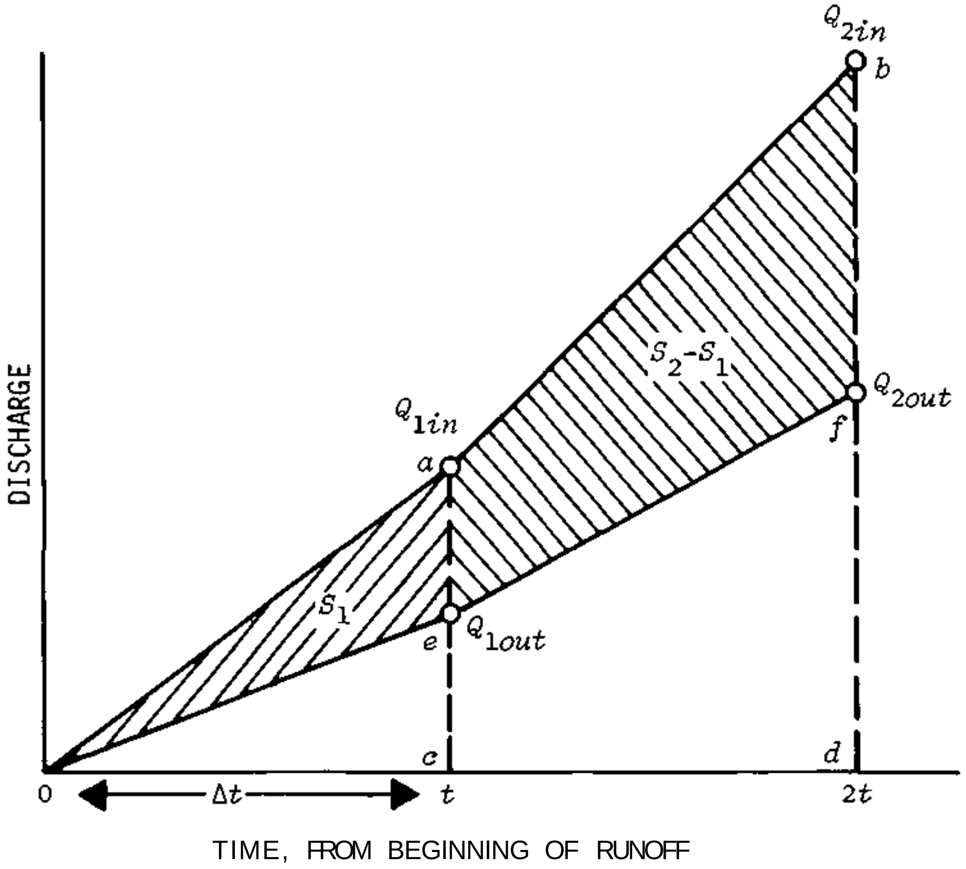


Figure 3. Elements in the storage routing technique

A simple storage routing technique is used to pass the hydrograph from one input point to the next. In order to use this technique a determinate relationship must exist between discharge and storage for the reach of Channel or pipe between the input points. Such a relationship is developed by first using Manning's equation to compute a stage-discharge curve for the cross section in question. Since the length and geometry of the reach are known, the required discharge-storage relationship may be computed by assuming uniform flow in the particular reach. Errors incurred by this assumption are minimized by keeping the time increment and reach length as short as practical.

Figure 3 shows two curves $0Q_{1in}\ Q_{2in}$ which is a section of the inflow hydrograph at the upper end of the reach and $0Q_{1out}Q_{2out}$ which is a section of the outflow hydrograph at the lower end of the reach. Let 51 and *S2* be the total storage at times *t* and *2t* respectively. From figure 3, area 0*ac* = areas 0*ae* + 0*ec* or

$$1/2\,(Q_{1in}\ t) = S_1 + 1/2\,(Q_{1out}\ t) \tag{1}$$

Since Q_{1in} and *t* are known, the right side of equation 1 may be evaluated. Because S_1 is known in terms of Q_{1out} from the discharge-storage relationship described earlier, the equation can be solved for Q_{1out}. For the period *t* to *2t,* area *abdc* = areas *efdc* + *abfe,* or

$$t/2\,(Q_{1in} + Q_{2in}) = t/2\,(Q_{1out} + Q_{2out}) + (S_2 - S_1) \tag{2}$$

$$t/2\,(Q_{1in} + Q_{2in} - Q_{1out}) + S_1 = t/2\,Q_{2out} + S_2 \tag{3}$$

Since the left side of equation 3 is known, the right side may again be solved for Q_{2out} using the discharge-storage relationship. By this step-by-step procedure all ordinates of the downstream or routed hydrograph may be determined.

Computer Program

A Fortran IV program has been developed to perform the Operations just described. The program also provides the summary tables and plotted hydrograph presented in Section VI of this report. The program was written for and run exclusively on the University of Illinois IBM 360/75 and Calcomp Plotter System. The major functions of the program are indicated in the flow diagram of figure 4. Interested persons may contact the Environmental Protection Agency to obtain a listing or program deck for this program.

Application of the RRL Method

Input Format. Figure 5 is a reproduction of the computerized input format for all the data on one basin. Shown is only a skeleton amount of data in order to illustrate the layout of the total input format. The data are for part of the Wingohocking Basin in Philadelphia. Items 1 and 2 and 3 are Computer signals, and item 4 contains the basin name. Item 5 shows the many individual facts regarding the basin parameters which were derived from the various aerial photographs, street maps, and physical inspection of the basin. The data in item 5 comprise the basin data. Item 6 is a Computer signal and item 7 contains physical Information on basin parameters in a particular sub-basin.

Item 8 signals the beginning of storm data and item 9 is the storm identification. Item 10 carries the storm information on base flow, raingage weights, and scale parameters for providing a plotted Output of the storm hydrograph. Item 11 gives the antecedent moisture condition which is used as only a general indication of conditions and is sometimes valuable in the

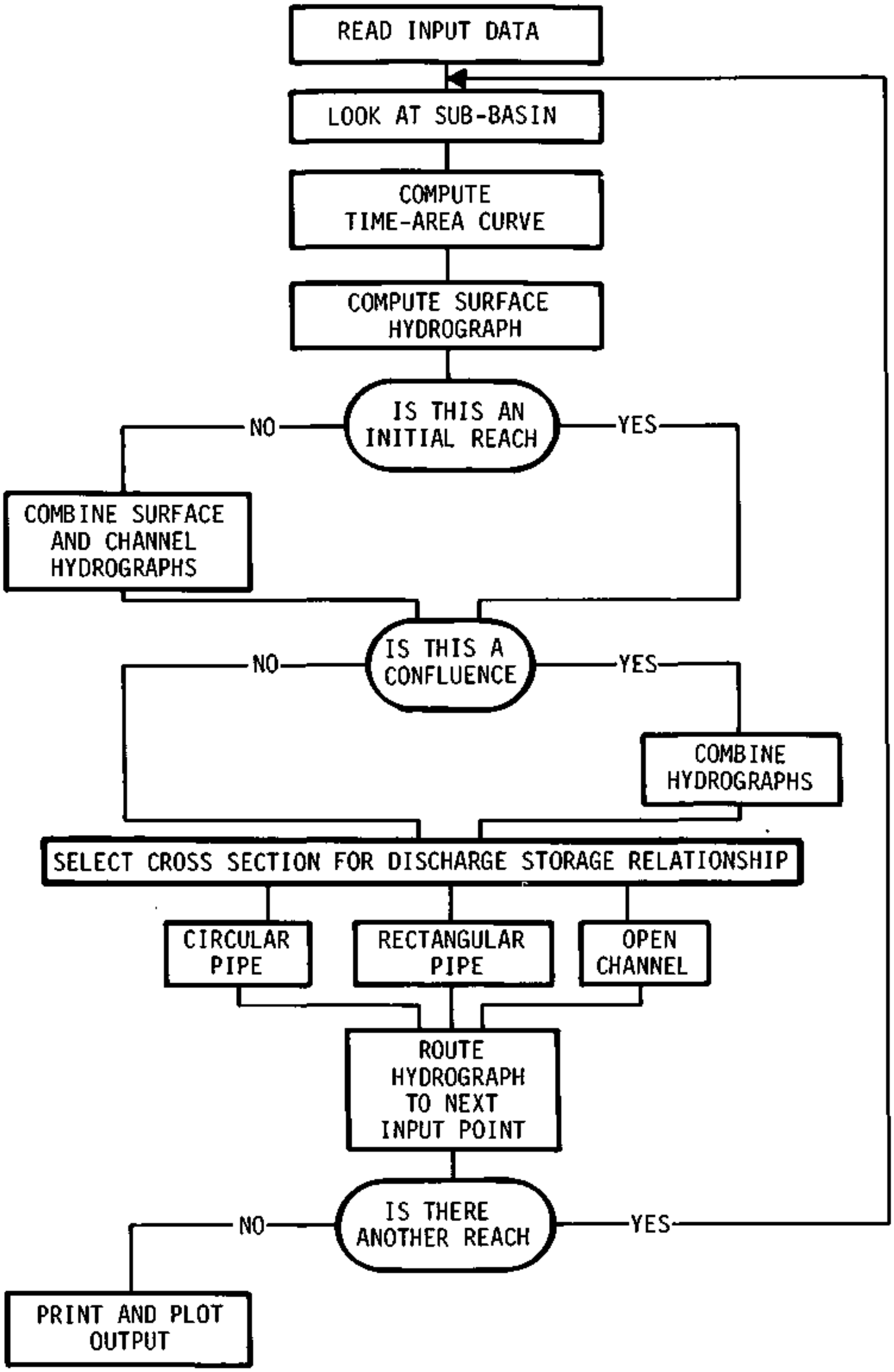
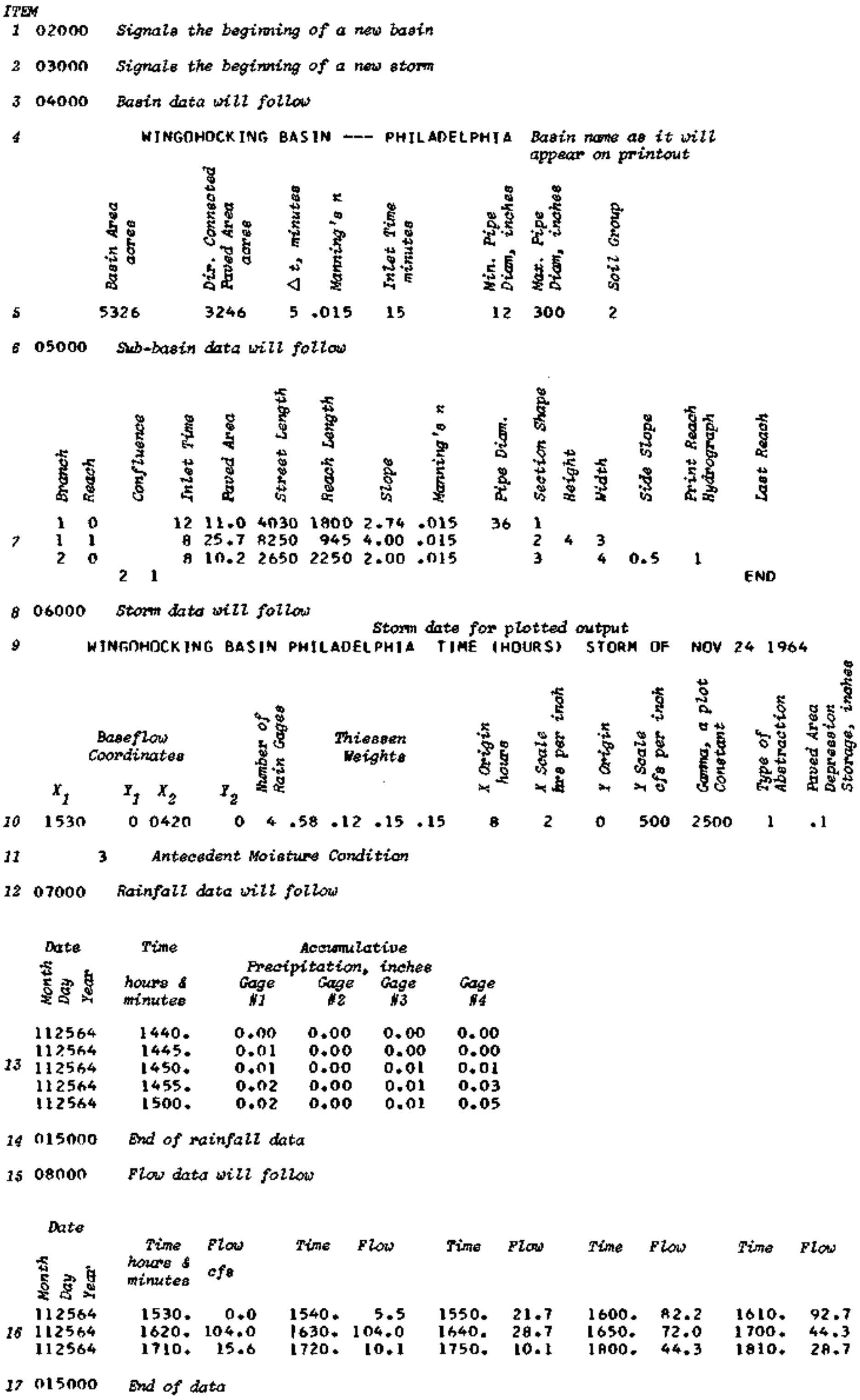


Figure 4. Flow diagram for the Computer program of the RRL method



ITEM

1 02000 *Signals the beginning of a new basin*

2 03000 *Signals the beginning of a new storm*

3 04000 *Basin data will follow*

4 WINGOHOCKING BASIN --- PHILADELPHIA *Basin name as it will appear on printout*

ITEM	Basin Area acres	Dir. Connected Paved Area acres	Δ t, minutes	Manning's n	Inlet Time minutes	Min. Pipe Diam, inches	Max. Pipe Diam, inches	Soil Group
5	5326	3246	5	.015	15	12	300	2

6 05000 *Sub-basin data will follow*

ITEM	Branch	Reach	Confluence	Inlet Time	Paved Area	Street Length	Reach Length	Slope	Manning's n	Pipe Diam.	Section Shape	Height	Width	Side Slope	Print Reach Hydrograph	Last Reach
	1	0		12	11.0	4030	1800	2.74	.015	36	1					
7	1	1		8	25.7	8250	945	4.00	.015		2	4	3			
	2	0		8	10.2	2650	2250	2.00	.015		3		4	0.5	1	
			2 1													END

8 06000 *Storm data will follow*

Storm date for plotted output

9 WINGOHOCKING BASIN PHILADELPHIA TIME (HOURS) STORM OF NOV 24 1964

ITEM	Baseflow Coordinates X_1	Y_1	X_2	Y_2	Number of Rain Gages	Thiessen Weights				X Origin hours	X Scale hrs per inch	Y Origin	Y Scale cfs per inch	Gamma, a plot Constant	Type of Abstraction	Paved Area Depression Storage, inches
10	1530	0	0420	0	4	.58	.12	.15	.15	8	2	0	500	2500	1	.1

11 3 *Antecedent Moisture Condition*

12 07000 *Rainfall data will follow*

ITEM	Date Month Day Year	Time hours & minutes	Accumulative Precipitation, inches Gage #1	Gage #2	Gage #3	Gage #4
	112564	1440.	0.00	0.00	0.00	0.00
	112564	1445.	0.01	0.00	0.00	0.00
13	112564	1450.	0.01	0.00	0.01	0.01
	112564	1455.	0.02	0.00	0.01	0.03
	112564	1500.	0.02	0.00	0.01	0.05

14 015000 *End of rainfall data*

15 08000 *Flow data will follow*

ITEM	Date Month Day Year	Time hours & minutes	Flow cfs	Time	Flow	Time	Flow	Time	Flow	Time	Flow
	112564	1530.	0.0	1540.	5.5	1550.	21.7	1600.	82.2	1610.	92.7
16	112564	1620.	104.0	1630.	104.0	1640.	28.7	1650.	72.0	1700.	44.3
	112564	1710.	15.6	1720.	10.1	1750.	10.1	1800.	44.3	1810.	28.7

17 015000 *End of data*

Figure 5. Input format for RRL method for all basin parameters, storm rainfall, and storm runoff

interpretation of the storm results. Item 12 signals that rainfall data will begin; item 13 gives the actual rainfall data from the various gages. Item 15 signals that flow data will begin, and item 16 provides the actual data on time and discharge amount in cfs. Item 17 is the end of the input data.

Output. The Computer program accomplishes the complete processing of all of the sub-basins by the RRL method, and provides a printed output as well as plotted hydrographs of each storm. As illustrated by table 1 for Woodoak Drive basin presented in the next section, the output includes first (columns 1-7) the identification and observed storm data for each storm on a basin. Column 8 is the observed runoff ratio if runoff had occurred only on the directly connected paved area of the basin. In other words, this method assumes that runoff from the directly connected paved area is virtually 100 percent and that no runoff occurs from any other areas. On the basis of this assumption, the numbers in column 8 should all be 1.00; consequently, the actual values in column 8 give some sense for the precision of the results.

Computed runoff and peak flow results are then presented (columns 9-12). Given along the bottom of table 1 are the number of cases and the average error in the computations of the peaks and of the runoff volume.

The complete graphical results for the application of the RRL method are exemplified by figure 7 for the Woodoak Basin. Included are plots of the observed peaks versus the computed peaks (figure 7a) and the observed runoff volume versus the computed runoff volume (figure 7b) for all of the storms listed in table 1.

Figure 7 illustrates the plotted Computer output showing the goodness-of-fit of the total storm runoff hydrograph as observed and as computed by the RRL method for one storm (October 19, 1966). Such plotted Outputs were obtained for all of the storms, but only a sample plot for one storm is presented in this report for each of the 10 basins.

Layout for Presentation of Basin Results

For each of the 10 basins included in this project, the basin results are presented as an output table similar to table 1 and as a series of graphs similar to that shown in figure 7 for the Woodoak Drive basin. The basins are presented in the following section of the report in increasing order of basin size.

SECTION VI
DESCRIPTION AND RESULTS BY BASINS

Woodoak Drive Basin, Westbury, Long Island, New York

Woodoak Drive basin is a 14.7-acre residential area all of which drains to one set of inlets. Because of its small size and the fact that only one length of pipe exists, it was not necessary to divide the basin into smaller sub-basins. Street slopes are less than 1 percent and yard slopes were estimated to be less than 3 percent. The dominant soil in the area is Haven Loam which is classified in hydrologic group B. The existence of highly permeable gravelly sand at a depth of 2 or 3 feet accounts for the success of recharge basins which are common in this area of Long Island.

Most driveways in the area are paved and are either full-width drives or narrow strips of concrete that accommodate car tires. Roof drains appear to flow onto full-width drives where such drives exist and onto the grass in other cases. The directly connected paved area therefore consists of the streets, all driveway aprons, all full-width driveways, and the front half of roofs located adjacent to full-width drives.

Data. Flow measurements are made at 5-minute intervals by a digital stage recorder located behind a V-notch weir in a 24-inch concrete pipe. The instrumentation, including a water table measuring system, are described in detail by Seaburn (1970). Flow data were provided for this project in printed form with discharge in cfs at 5-minute intervals.

Rainfall is recorded on a weighing-bucket gage located about 300 yards southeast of the basin. Copies of the original weekly charts were provided for this study. The charts were replotted using a larger time scale and read at 10-minute intervals.

Results. There appears to be no significant grassed area runoff from this basin. The permeable soils and flat slopes combine to provide infiltration rates which can accommodate not only the rain falling directly on the grassed area, but also runoff onto grass from the unconnected paved areas. The RRL method works well on this basin.

Table 1. Storm data and results for Woodoak Drive basin

Total Basin Area	Total Paved Area	Directly Connected Paved Area
14.7 acres	4.9 acres	2.85i acres
	33.9 percent	19.4 percent

Observed Storm Data								Computed Results			
Storm (1)	Date (2)	AMC (3)	Rain *inches* (4)	Peak flow *cfs* (5)	Runoff volume *inches* (6)	Runoff ratio (7)	Virtual runoff ratio (8)	Runoff volume *inches* (9)	Error *percent* (10)	Peak flow *cfs* (11)	Error *percent* (12)
1	91466	2	1.42	0.76	0.24	0.17	0.88	0.25	4.7	0.85	12.3
2	92166	I	3.48	5.93	0.75	0.22	1.14	0.64	-15.6	2.53	-57.3
3	101966	2	2.38	1.98	0.45	0.19	1.00	0.43	-4.9	1.35	-31.7
4	102066	4	0.76	1.84	0.14	0.18	0.97	0.12	-11.4	1.27	-30.9
5	42765	3	1.49	0.59	0.20	0.13	0.71	0.26	30.4	0.68	16.0
6	50667	2	0.65	0.53	0.09	0.15	0.77	0.10	9.7	0.69	29.4
7	50767	4	1.13	1.07	0.29	0.26	1.35	0.19	-32.8	0.86	-19.9
8	82567	2	1.74	2.30	0.21	0.12	0.64	0.31	45.1	3.02	31.3
9	82667	4	0.72	2.10	0.10	0.14	0.74	0.12	16.1	2.73	30.2
10	52968	3	3.60	4.00	0.75	0.21	1.10	0.66	-12.2	3.12	-22.9
Mean values						0.18			18.3		28.2

Computed peaks were high in 5 cases, average + error = 23.9 percent
Computed peaks were low in 5 cases, average - error = 52.4 percent
Computed runoff volumes were high in 5 cases, average + error =21.2 percent
Computed runoff volumes were low in 5 cases, average -- error = 15.4 percent

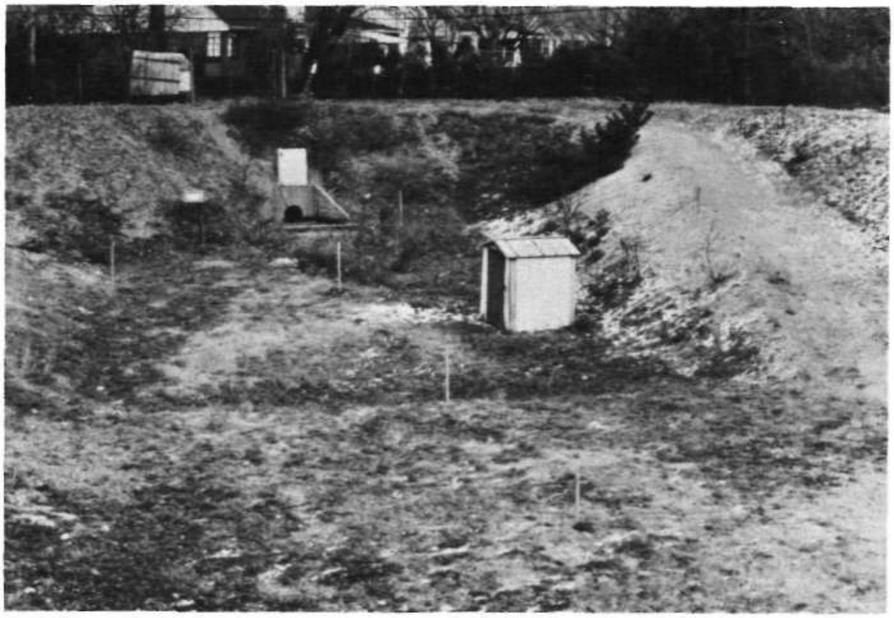


Figure 6. Outlet of the single storm drain in the Woodoak Drive basin

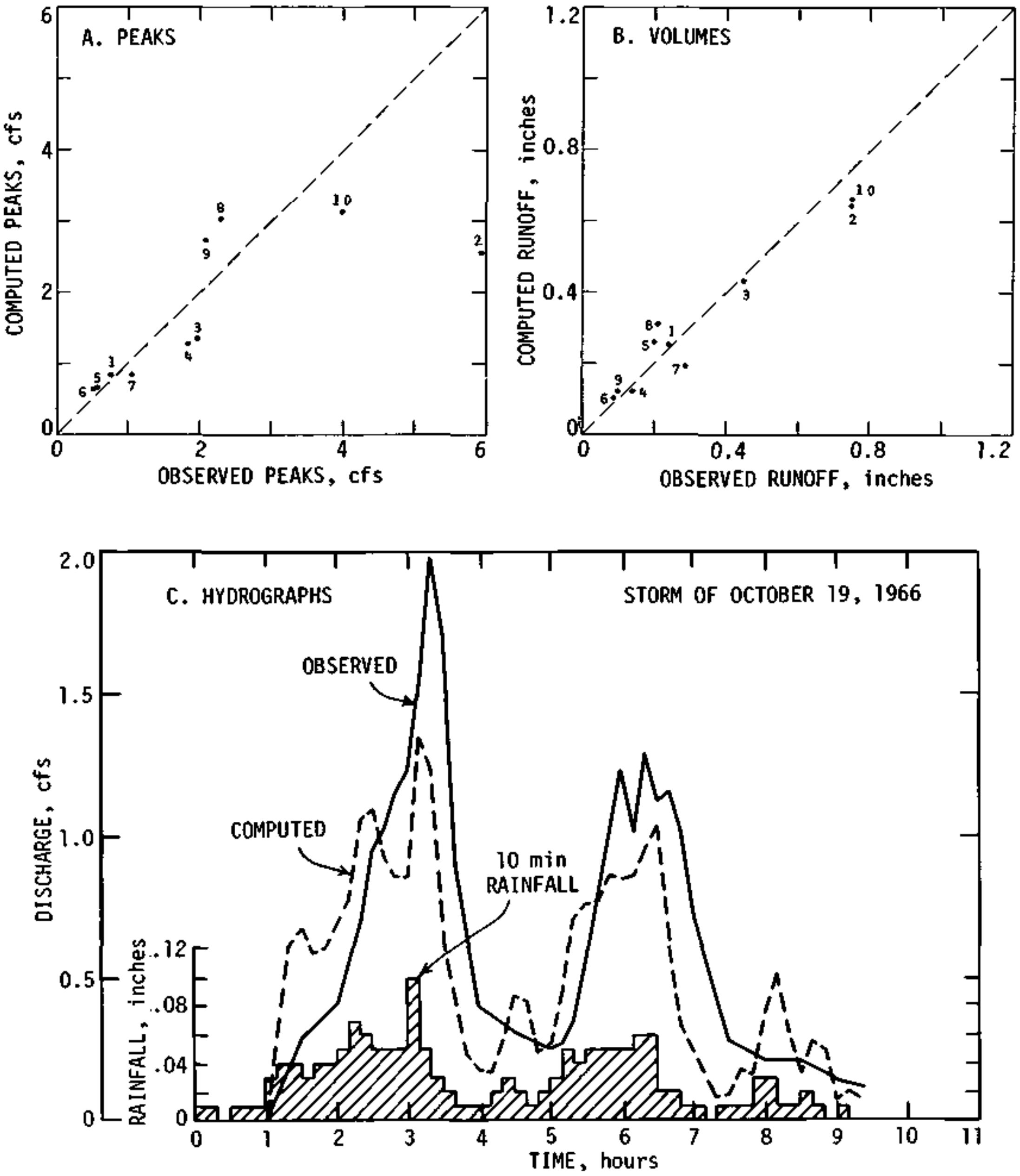
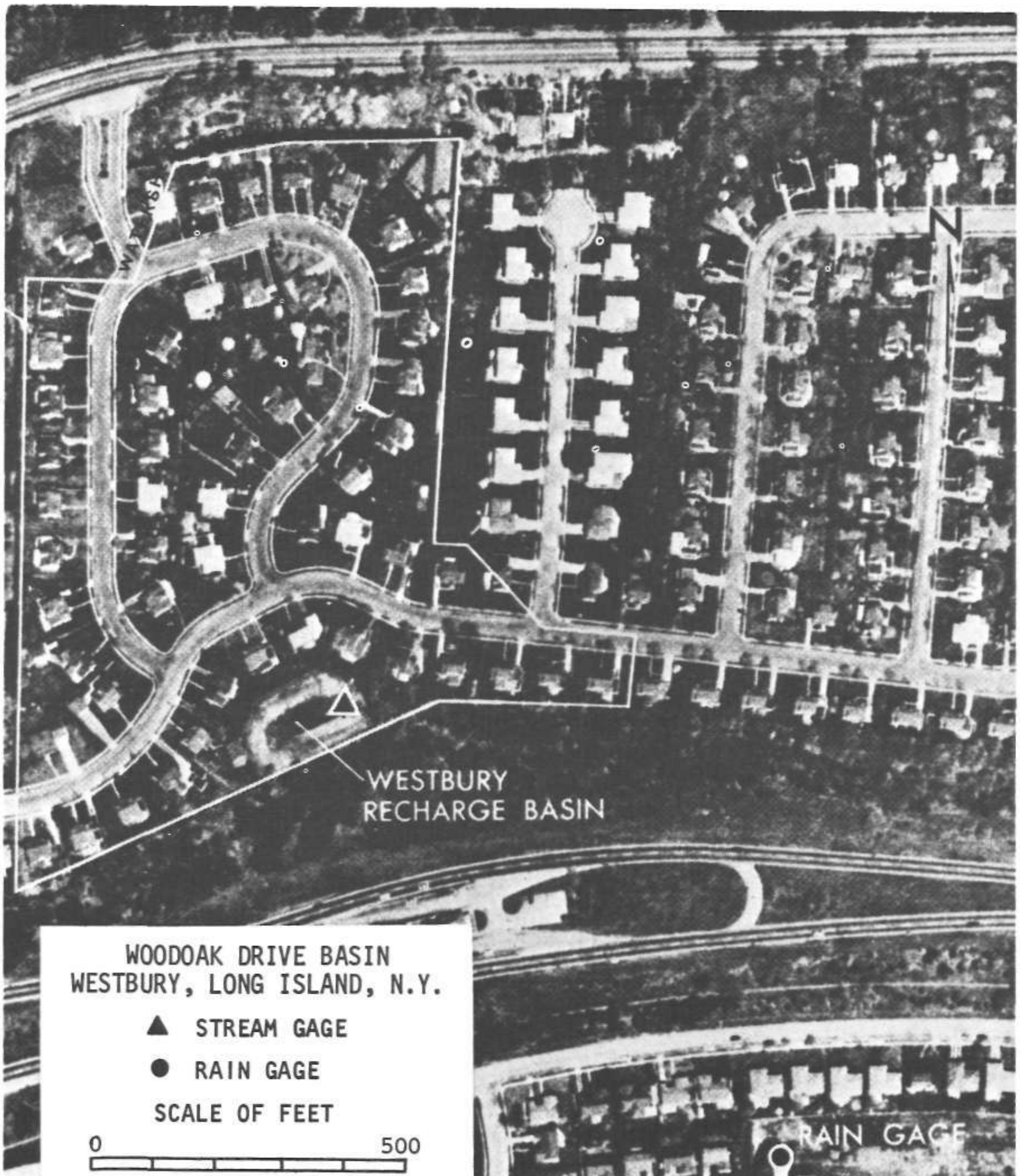


Figure 7. RRL results for Woodoak Drive basin, Long Island, New York



(Photo by Lockwood, Kessler, & Bartlett)

Figure 8. Aerial photo of Woodoak Drive basin

Ross-Ade (Upper) Basin, West Lafayette, Indiana

The Ross-Ade upper basin is one of four research basins established by Purdue University. This basin is entirely residential and relatively uniform in character. The basin has a definite valley-type configuration. Woodlawn Avenue which runs down the center of the valley has slopes of 1 to 3 percent, but some of the side streets are steeper. Yard slopes vary from nearly flat in the upper part of the basin to about 25 percent near the center of the basin. The basin was represented in the model by 12 sub-basins ranging in size from 0.2 to 1.6 acres.

Storm drainage is provided by an interceptor that runs down Woodlawn Avenue. The watershed boundary is difficult to determine. Inlets exist along the watershed boundary that are part of a combined sewer system which does not pass through the gage. If these inlets become inoperative or are overtopped during large storms, runoff can flow into the basin that would otherwise be intercepted by this combined sewer system. Soils in the basin vary from Crosby silt loam of hydrologic group C in the flood plain to Miami silt loam of hydrologic group B on the steeper portions of the basin and Eel silt loam of hydrologic group C on the uplands.

Impervious areas were measured on large-scale aerial photographs. A field survey indicated that about one-half of the roof drains had Underground connections. In the lower portion of the basin it was assumed that these were connected to the storm drain, but in the upper reaches it was assumed that the connections were made to the combined system. The directly connected paved area then consisted of all streets, all driveways, and connected roofs in the lower part of the basin.

Data. A Columbus-type deep-notch weir with a 6-foot crest length provides accurate flow measurement at the gaging site. Stage hydrographs are recorded on a Stevens A-25 recorder with a 20-inch chart. The chart speed of 6 inches per hour allows 1 minute stages to be read. Rainfall is collected by a 16-inch diameter receiver located 8 feet above the ground. The receiver is connected to an 8-inch float Chamber which records rainfall magnified 10 times on the same chart as stage. Temperature is also recorded on these charts. Although the gages are in Operation at the time of this writing, data for the past few years have not been reduced.

Results. Data are limited to the two small storms shown in table 2. For these, the RRL method underestimates peaks and volumes, because of the grassed area contribution caused by steep slopes.

Table 2. Storm data and results for Ross-Ade (Upper) basin

Total Basin Area	Total Paved Area	Directly Connected Paved Area
54.0 acres	13.3 acres	7.8 acres
	24.7 percent	14.4 percent

Observed Storm Data								Computed Results			
Storm (1)	Date (2)	AMC (3)	Rain *inches* (4)	Peak flow *cfs* (5)	Runoff volume *inches* (6)	Runoff ratio (7)	Virtual runoff ratio (8)	Runoff volume *inches* (9)	Error *percent* (10)	Peak flow *cfs* (11)	Error *percent* (12)
1	80267	2	0.37	13.6	0.07	0.19	1.30	0.04	-45.3	8.8	-35.4
2	82667	1	0.14	6.6	0.03	0.20	1.36	0.01	-80.4	2.3	-65.6
Mean values						0.19			62.8		50.5

Computed peaks were high in 0 cases
Computed peaks were low in 2 cases, average -- error = 50.5 percent

Computed runoff volumes were high in 0 cases
Computed runoff volumes were low in 2 cases, average — error = 62.8 percent

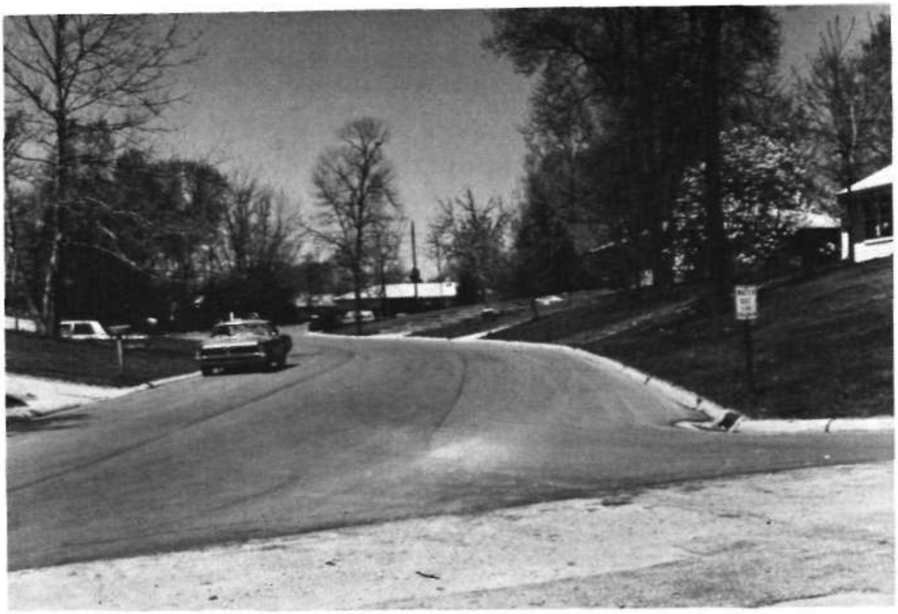


Figure 9. Street view in Ross-Ade (Upper) basin

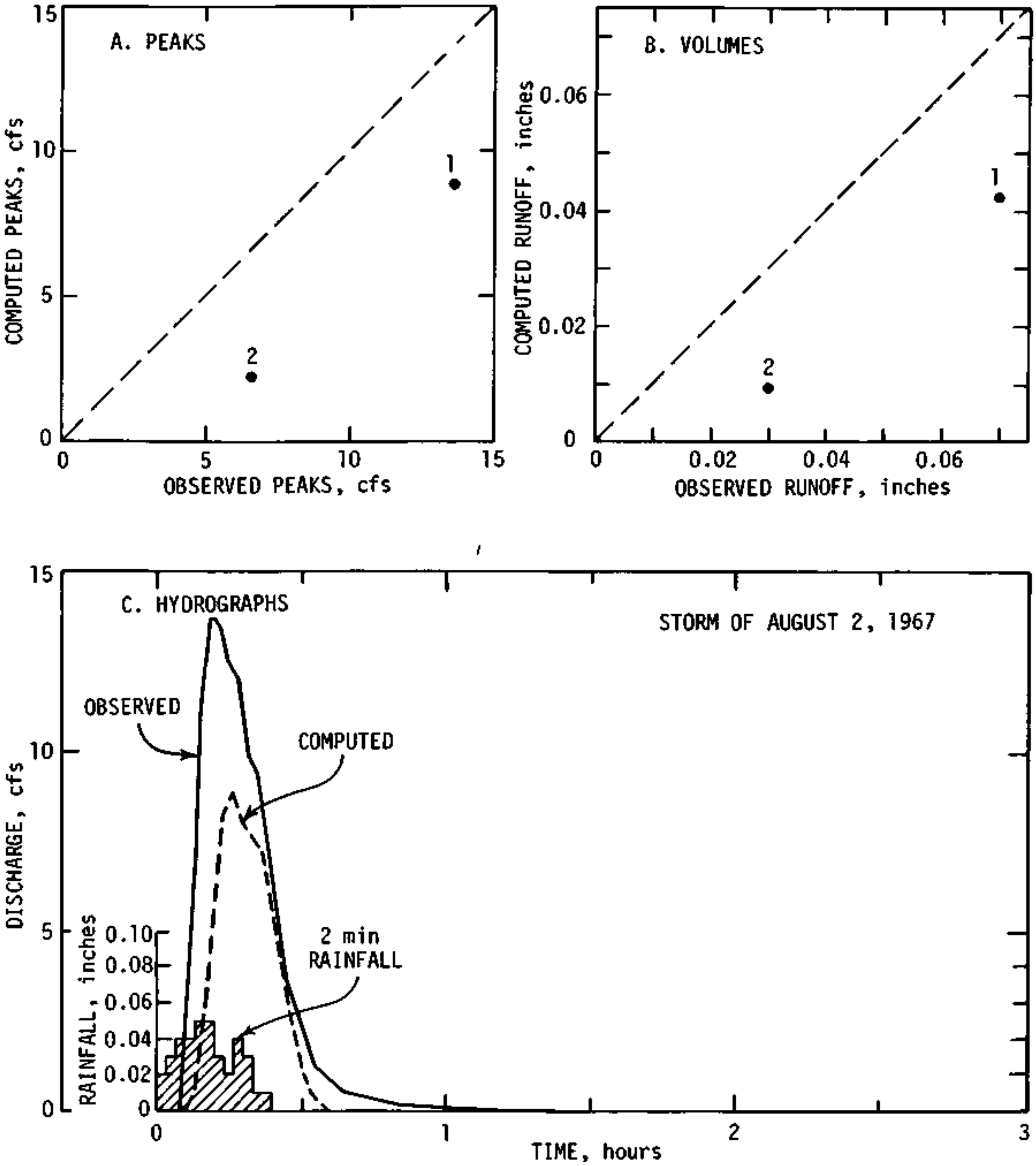
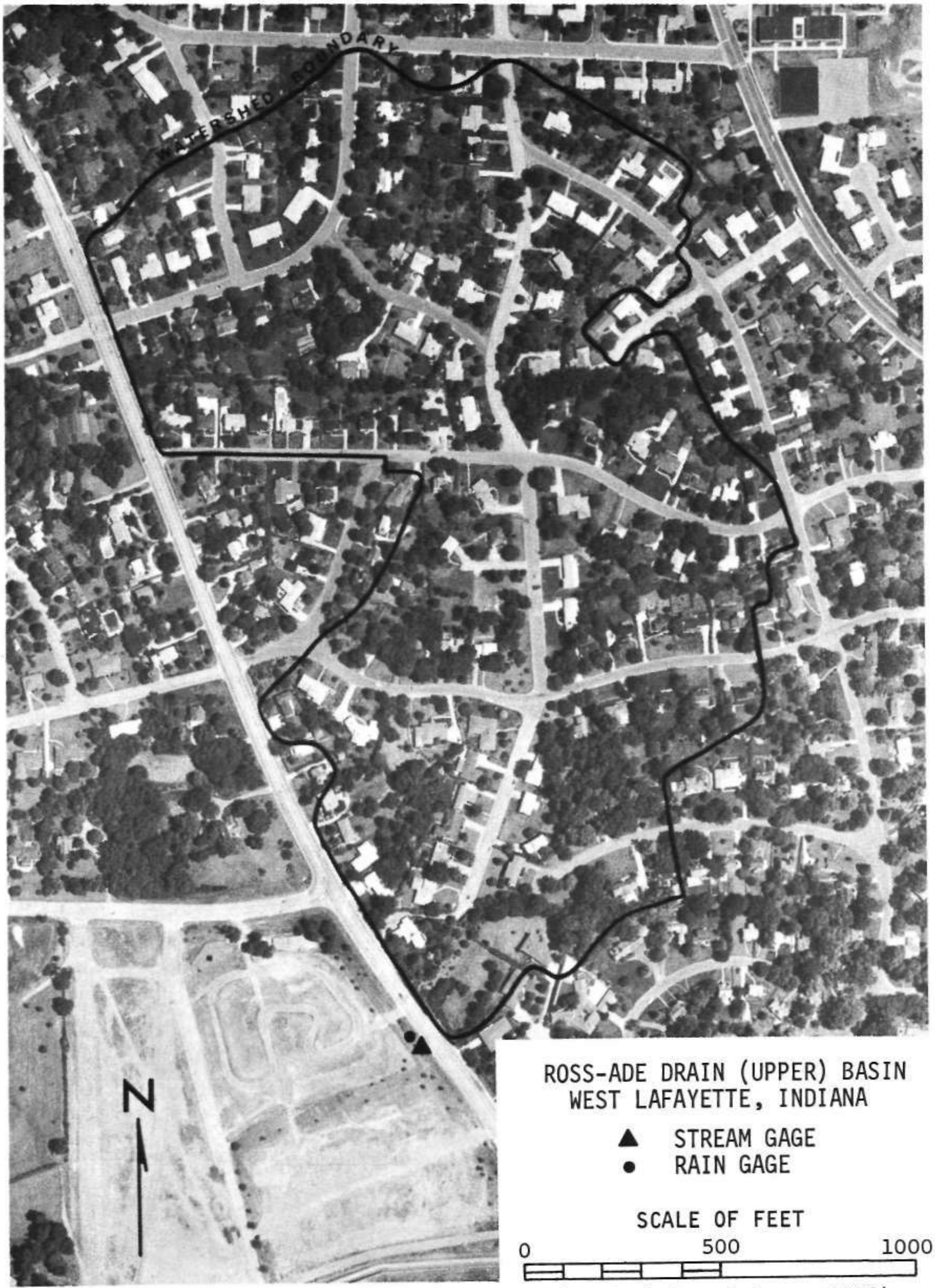


Figure 10. RRL results for Ross-Ade (Upper) basin, West Lafayette, Indiana



(USDA photo of June, 1971)

Figure 11. Aerial photo of Ross-Ade (Upper) basin

Sewer District No. 8 Basin, Bucyrus, Ohio

The 206-acre No. 8 Sewer District basin lies within the older section of Bucyrus, Ohio. Land use varies from residential through commercial and heavy industrial. The entire basin is served by a combined sewer system, but there does not appear to be an adequate number of inlets to drain the basin properly. Dry-weather flow is intercepted above the gage. The combined sewer system is quite extensive and was represented in the model by dividing the basin into 42 sub-basins. With the exception of a few short roadside swales there is no open Channel drainage. Street slopes are generally less than 1 percent and yard slopes less than 3 percent. Principal soils in the area are Bennington Silt loam and Luray silty clay loam. These soils are both classified in hydrologic group C-D.

Determination of the directly connected paved area was complicated by the lack of curb and gutter on many streets in the northern part of the basin. Runoff from many of these streets (figure 12) would apparently find its way into adjacent low-lying yards and vacant lots or be ponded on the street. A sample inspection of roofs during field investigations indicated that about 60 percent of the residential roofs are directly connected to the combined sewer system. The direcdy connected paved area thus consisted of all streets with curb and gutter, a 10-foot strip for streets without curb and gutter, driveways on curb and guttered streets, major buildings, and 60 percent of the residential roofs.

Data. Instrumentation, as described by Burgess and Niple (1969), consisted of a Stevens Type-F stage recorder located behind an 8-foot rectangular weir. The data were provided in the form of plotted discharge hydrographs. Since the distance between the 42-inch outfall pipe and the weir was necessarily small, approach velocities could have had an effect on the measurement of high flows.

Rainfall data were collected on a Bendix weighing-bucket gage with a 24-hour chart. The data received for this study had been digitized and was read at 10-minute intervals.

Results. The runoff ratios of 10 to 15 percent for storms of 1 to 1.5 inches seem reasonable for a basin with 18 percent directly connected paved area. Runoff that might be expected to occur from the relatively tight soils in the basin is delayed by the lack of inlets and the resultant ponding. Infiltration is also enhanced by the ponded conditions.

The storm shown in figure 13 illustrates the problem of the RRL method on this basin. Computed peaks are too quick and too high and flow recedes too quickly. A shortcoming of the RRL method under these conditions is its inability to provide routing through surface storage such as the ponding that occurs on this basin.

Table 3. Storm data and results for Sewer District No. 8 basin

Total Basin Area	Total Paved Area	Directly Connected Paved Area
206 acres	43 acres	37.5 acres
	21 percent	18.2 percent

Observed Storm Data								Computed Results			
Storm (1)	Date (2)	AMC (3)	Rain *inches* (4)	Peak flow *cfs* (5)	Runoff volume *inches* (6)	Runoff ratio (7)	Virtual runoff ratio (8)	Runoff volume *inches* (9)	Error *percent* (10)	Peak flow *cfs* (11)	Error *percent* (12)
1	**32469**	2	**0.31**	**4.4**	**0.03**	**0.10**	**0.58**	**0.04**	**18.4**	**6.1**	**37.7**
2	**40569**	2	**1.47**	**22.8**	**0.16**	**0.11**	**0.58**	**0.25**	**59.1**	**43.6**	**91.5**
3	**51769**	3	**1.37**	**32.4**	**0.16**	**0.11**	**0.63**	**0.23**	**45.7**	**58.8**	**81.4**
4	**61369**	2	**1.20**	**29.5**	**0.18**	**0.15**	**0.83**	**0.20**	**10.6**	**58.3**	**97.7**
5	**71169**	4	**1.55**	**50.8**	**0.20**	**0.13**	**0.70**	**0.26**	**32.0**	**129.5**	**155.0**
6	**71769**	4	**1.01**	**25.8**	**0.15**	**0.14**	**0.79**	**0.17**	**17.1**	**49.9**	**93.4**
7	**72769**	1	**0.40**	**20.9**	**0.05**	**0.12**	**0.67**	**0.05**	**10.4**	**27.5**	**31.7**
8	**80969**	3	**0.51**	**22.7**	**0.07**	**0.14**	**0.78**	**0.08**	**1.8**	**32.4**	**42.7**
9	**81669**	1	**0.70**	**23.1**	**0.10**	**0.14**	**0.80**	**0.11**	**7.6**	**29.9**	**29.6**
10	**90669**	2	**0.23**	**15.9**	**0.02**	**0.09**	**0.52**	**0.02**	**11.0**	**12.8**	**-19.7**
Mean values						**0.12**	**0.69**		**21.4**		**68.0**

Computed peaks were high in 9 cases, average 4 error = 73.4 percent
Computed peaks were low in 1 case, average — errors —19.7 percent

Computed runoff volumes were high in 10 cases, average + error = 21.4 percent
Computed runoff volumes were low iin 0 cases

Figure 12. Flat terrain and indeterminate drainage pattern typical of much of the upstream basin of Sewer District No. 8

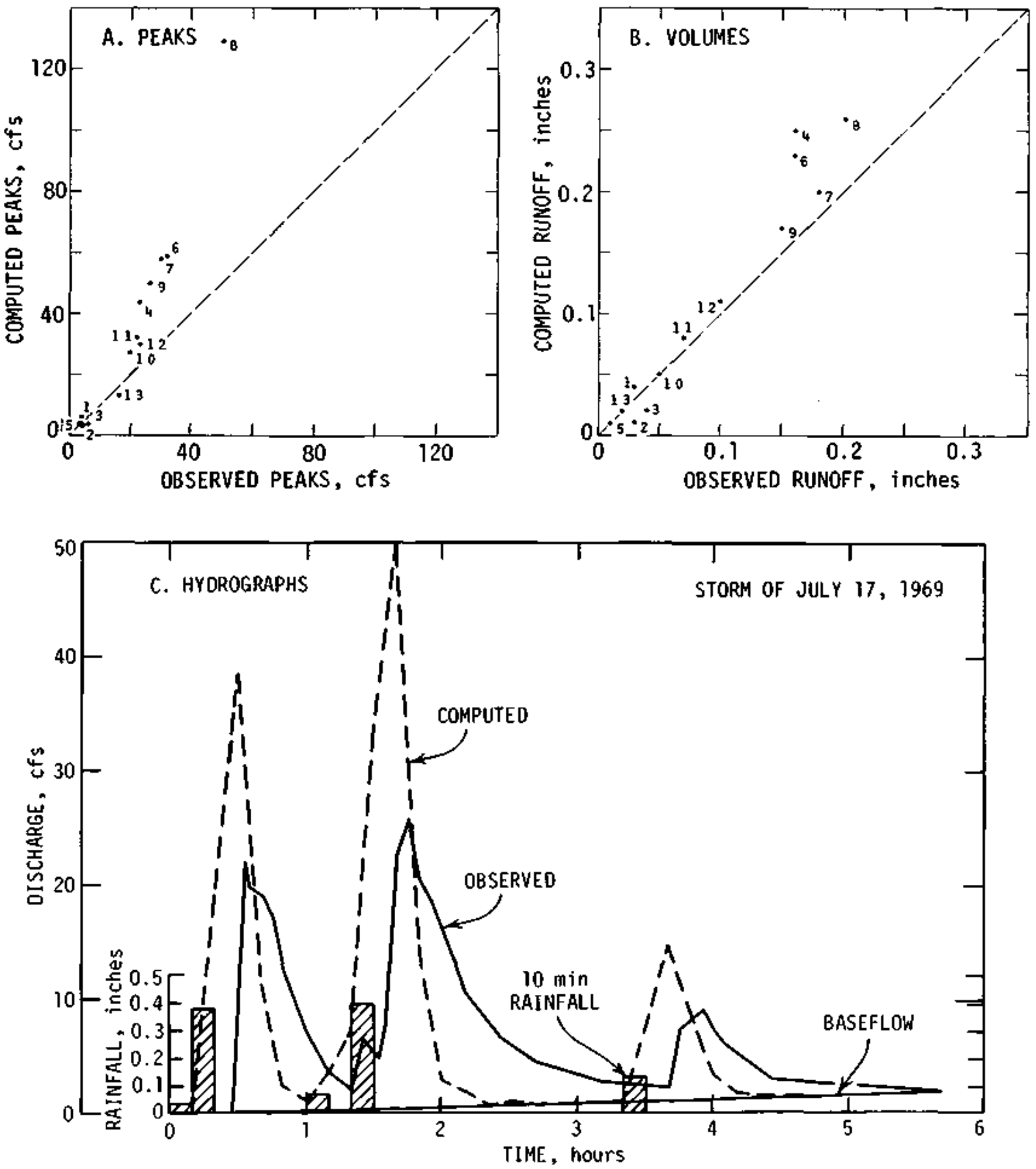
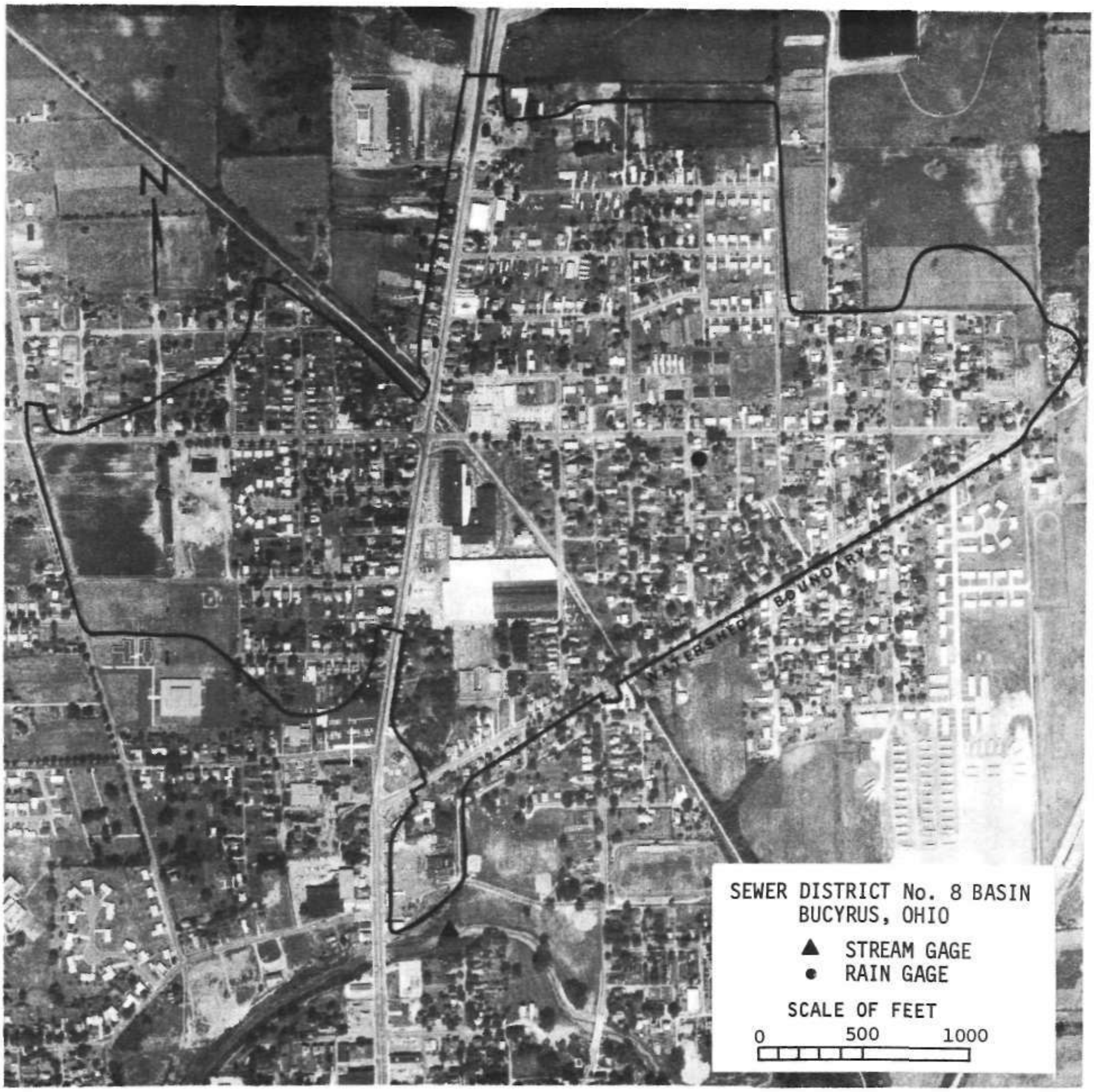


Figure 13. RRL results for Sewer District No. 8 basin, Bucyrus, Ohio



(USDA photos of 1970)

Figure 14. Aerial photo of Sewer District No. 8

Echo Park Avenue Basin, Los Angeles, California

The Echo Park Avenue basin is primarily a residential area with commercial strips along the main streets. The basin has a deep valley configuration. Runoff flows down very steep side streets to an interceptor flowing north-to-south along the center of the valley. Minimum slopes in the basin occur down the center of the valley where they vary from 2 to 4 percent. On the side streets slopes approach 20 percent and on landscaped areas slopes of 30 percent are not uncommon. The dominant soil in the basin according to a 1916 survey is Altamont loam. Under natural, undisturbed conditions, this soil would be in hydrologic group B or C depending on the depth to bedrock and the degree to which the rock is weathered.

Surveys by the City of Los Angeles fixed the total paved area at 136 acres. These surveys showed that 54 percent of the total paved area was in streets and parking, and that the other 46 percent was in roofs. An additional roof survey indicated that 40 percent of the roofs are connected to the streets and 60 percent to the lawns. The directly connected paved area thus consisted of 73 acres of streets and parking (136 × 0.54), and 25 acres of connected roofs [(136-73) × 0.40], for a total of 98 acres.

Data. Stage hydrographs are recorded in a 51-inch concrete storm sewer by the Bureau of Engineering at the City of Los Angeles. The original charts along with a rating table based on Manning's equation assuming uniform flow and a 0.013 "n" value were furnished by the bureau. Crawford (1971) has recently commented on the Echo Park data: "the flow data could be in error by more than 20 percent due to uncertainty in the roughness and the super-critical flow velocities in the sewer."

Rainfall is recorded on a weighing-bucket type gage on a Standard 24-hour chart. These charts were provided by the Bureau of Engineering and were digitized, as a regular part of this project, by the Water Survey Model 3400 auto-trol. A 4-minute time interval was used for rainfall reduction. Because of the short entry times and quick response of this basin, an even shorter time interval would have been desirable.

Results. The RRL method clearly does not apply to this basin. Grassed-area contribution has a significant effect on both the peak and the volume of runoff.

Table 4. Storm data and results for Echo Park Avenue basin

Total Basin Area	Total Paved Area	Directly Connected Paved Area
252 acres	136 acres	97.7 acres
	53.8 percent	38.8 percent

Observed Storm Data								Computed Results			
Storm (1)	Date (2)	AMC (3)	Rain inches (4)	Peak flow cfs (5)	Runoff volume inches (6)	Runoff ratio (7)	Virtual runoff ratio (8)	Runoff volume inches (9)	Error percent (10)	Peak flow cfs (11)	Error percent (12)
1	20358	2	0.66	275	0.29	0.45	1.15	0.22	-26.9	161	-41.6
2	20458	4	1.10	260	0.56	0.51	1.31	0.38	-31.1	137	-47.4
3	21958	1	3.43	295	1.43	0.42	1.08	1.28	-10.7	207	-30.0
4	21262	4	0.68	234	0.42	0.61	1.59	0.22	-46.6	110	-53.4
5	21962	4	1.54	204	0.68	0.44	1.14	0.55	-18.3	104	-49.3
6	20963	1	2.38	170	0.73	0.31	0.79	0.87	19.3	85	-49.9
7	12164	2	1.06	178	0.41	0.38	0.99	0.37	-9.7	93	-47.9
8	12264	4	0.54	187	0.25	0.47	1.22	0.17	-33.5	74	-60.6
9	40865	4	1.11	182	0.44	0.39	1.01	0.39	-11.0	101	-44.2
10	40965	4	1.30	199	0.74	0.57	1.47	0.46	-37.9	89	-55.6
11	111967	1	0.88	260	0.49	0.55	1.42	0.30	-38.3	125	-51.9
12	112067	4	0.49	284	0.31	0.62	1.61	0.15	-51.0	155	-45.5
13	12669	4	0.85	187	0.56	0.66	1.69	0.29	-48.4	85	-54.5
14	20669	2	1.01	240	0.60	0.59	1.53	0.35	-41.9	104	-56.4
15	21569	2	1.00	196	0.45	0.45	1.16	0.35	-23.4	105	-46.4
16	22569	4	1.33	146	0.84	0.63	1.63	0.47	-43.9	65	-55.2
17	30470	4	1.35	147	0.55	0.41	1.06	0.48	-13.3	90	-38.6
18	122170	4	1.35	116	0.24	0.18	0.46	0.48	100.9	91	-21.3
Mean values						0.48			30.3		47.2

Computed peaks were high in 0 cases
Computed peaks were low in 18 cases, average —error = —47.2 percent
Computed runoff volumes were high in 2 cases, average + error = 60.1 percent
Computed runoff volumes were low in 16 cases;, average — error = —30.4 percent

Figure 15. Street view in Echo Park Avenue basin

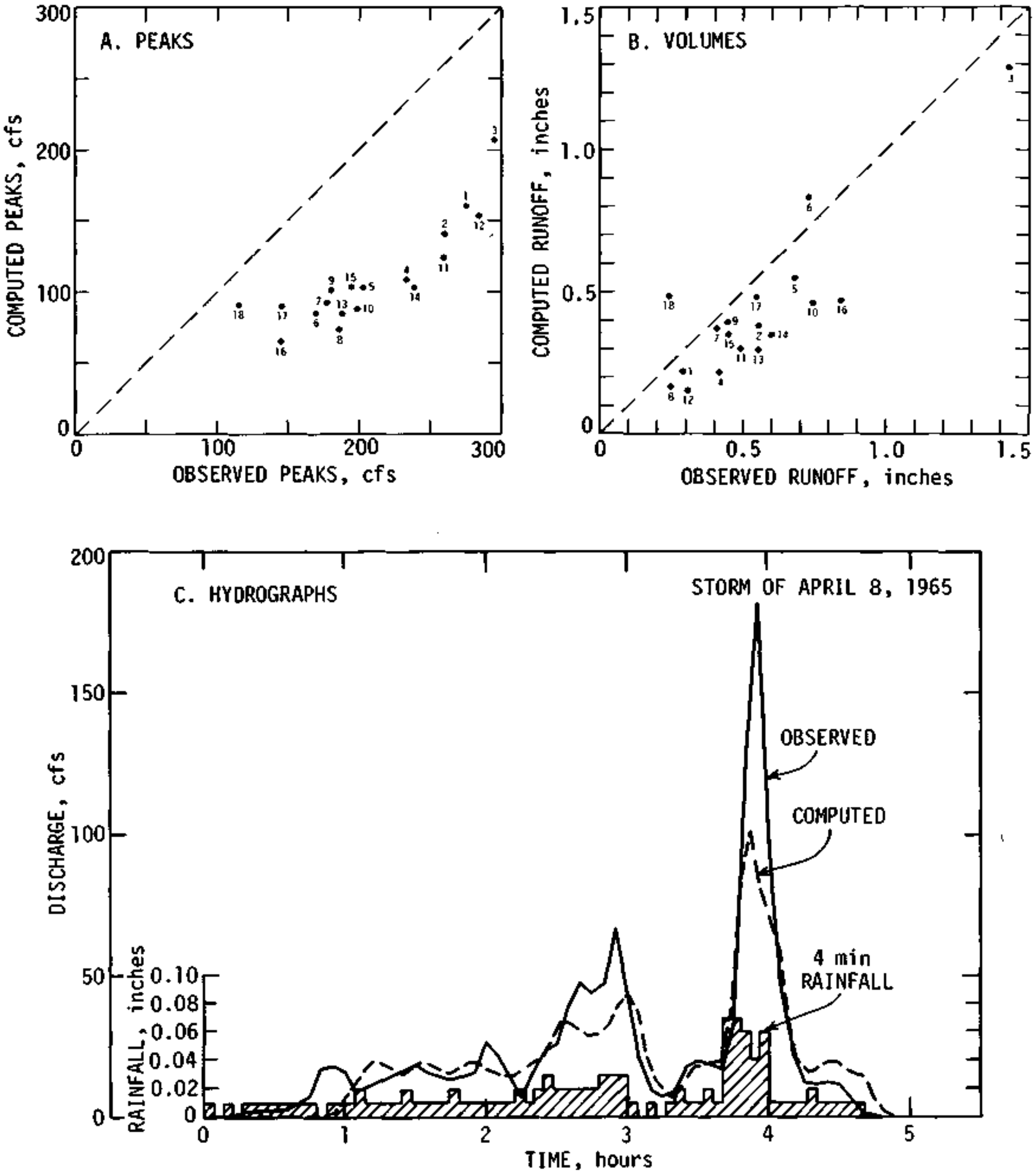


Figure 16. RRL results for Echo Park Avenue basin, Los Angeles, California

(Photo by Geotronics, Long Beach, California, 1968)

Figure 17. Aerial photo of Echo Park Avenue basin

Crane Creek Basin, Jackson, Mississippi

The Crane Creek basin is a 273-acre residential area. Two large schools, a church, and an apartment complex have a significant effect on the paved area runoff. There are large open areas around the schools and in the flood piain in the lower part of the basin. Street slopes range from 1 to 30 percent and yard slopes vary from 2 to 6 percent. The drainage system as represented in the model has 11 open channel reaches with a total length of 5700 feet and 15 closed conduits with a total length of 6800 feet. The primary soil in the basin is a Loring silt loam which is classified in hydrologic group C. In the flood piain area, Falaya series soils of hydrologic group D should be expected.

The absence of curb and gutter on many streets complicate the determination of directly connected paved area. All such streets have well-maintained roadside ditches and conceivably the contributing roadway could include everything between the centerline of the ditches. For this study, however a 20-foot strip of contributing area was used for streets without curb and gutter. In addition to the streets, all major buildings, parking lots, and an approximation of residential driveways were included in the directly connected paved area. Residential roofs generally drain onto grass.

Data. The instrumentation for this basin is typical for a USGS installation. One digital recorder provides stage hydrographs at a rated culvert on Crane Creek. Another digital recorder provides rainfall at the same site. The recorders operate from the same clock at 5-minute intervals. Rainfall and discharge data were provided in both tabular and plotted form for this study.

Urban runoff effects for several basins in Jackson have been published elsewhere by Wilson (1968).

Results. The RRL method seriously underestimates peak flow and runoff volumes on this basin. A substantial amount of grassed-area runoff occurs both from yards and from the large open areas. This is substantiated by the fact that the 8 storms which fall lowest on the two plots (figures 19a and b) occurred when the soil was saturated, an antecedent moisture condition of 4.

Table 5. Storm data and results for Crane Creek basin

Total Basin Area	Total Paved Area	Directly Connected Paved Area
273 acres	65.5 acres	39.7 acres
	23.9 percent	14.5 percent

Observed Storm Data								Computed Results			
Storm (1)	Date (2)	AMC (3)	Rain *inches* (4)	Peak flow *cfs* (5)	Runoff volume *inches* (6)	Runoff ratio (7)	Virtual runoff ratio (8)	Runoff volume *inches* (9)	Error *percent* (10)	Peak flow *cfs* (11)	Error *percent* (12)
1	51565	2	0.38	39	0.07	0.18	1.34	0.04	-42.9	38	-2.1
2	62465	2	1.44	106	0.24	0.17	1.24	0.18	-27.0	91	-14.3
3	62565	4	0.78	65	0.15	0.20	1.42	0.09	-43.1	35	-46.1
4	72465	2	2.00	161	0.42	0.21	1.51	0.25	-39.6	127	-20.8
5	81265	4	1.81	149	0.47	0.26	1.88	0.23	-50.5	157	5.5
6	82065	2	0.64	30	0.08	0.12	0.89	0.07	-13.0	46	55.2
7	91065	1	1.74	78	0.25	0.15	1.06	0.21	-16.0	53	-31.7
8	91165	4	1.27	253	0.54	0.42	3.06	0.16	-70.6	108	-57.3
9	92265	3	0.58	20	0.04	0.07	0.47	0.06	59.9	54	166.4
10	100665	2	1.14	70	0.16	0.14	1.04	0.13	-17.6	81	15.2
11	10466	4	1.79	60	0.46	0.26	1.87	0.22	-53.3	32	-47.5
12	20166	4	0.45	23	0.08	0.17	1.22	0.05	-40.0	26	11.1
13	22666	3	0.65	22	0.13	0.20	1.46	0.07	-48.2	15	-33.1
14	30366	4	0.57	137	0.29	0.50	3.65	0.06	-78.3	64	-53.4
15	42066	2	3.23	154	0.70	0.22	1.58	0.41	-41.7	112	-27.2
16	42666	4	1.09	116	0.38	0.35	2.55	0.13	-66.2	53	-54.1
17	52366	4	1.16	248	0.56	0.26	3.49	0.15	-73.2	87	-64.9
Mean values						0.23			45.9		41.5

Computed peaks were high in 5 cases, average + error = 50.7 percent
Computed peaks were low in 12 cases, average — error = 37.7 percent
Computed runoff volumes were high in 1 case, average + error = 59.9 percent
Computed runoff volumes were low in 16 cases, average — error = 45.1 percent

Figure 18. Ditch along street in Crane Creek basin

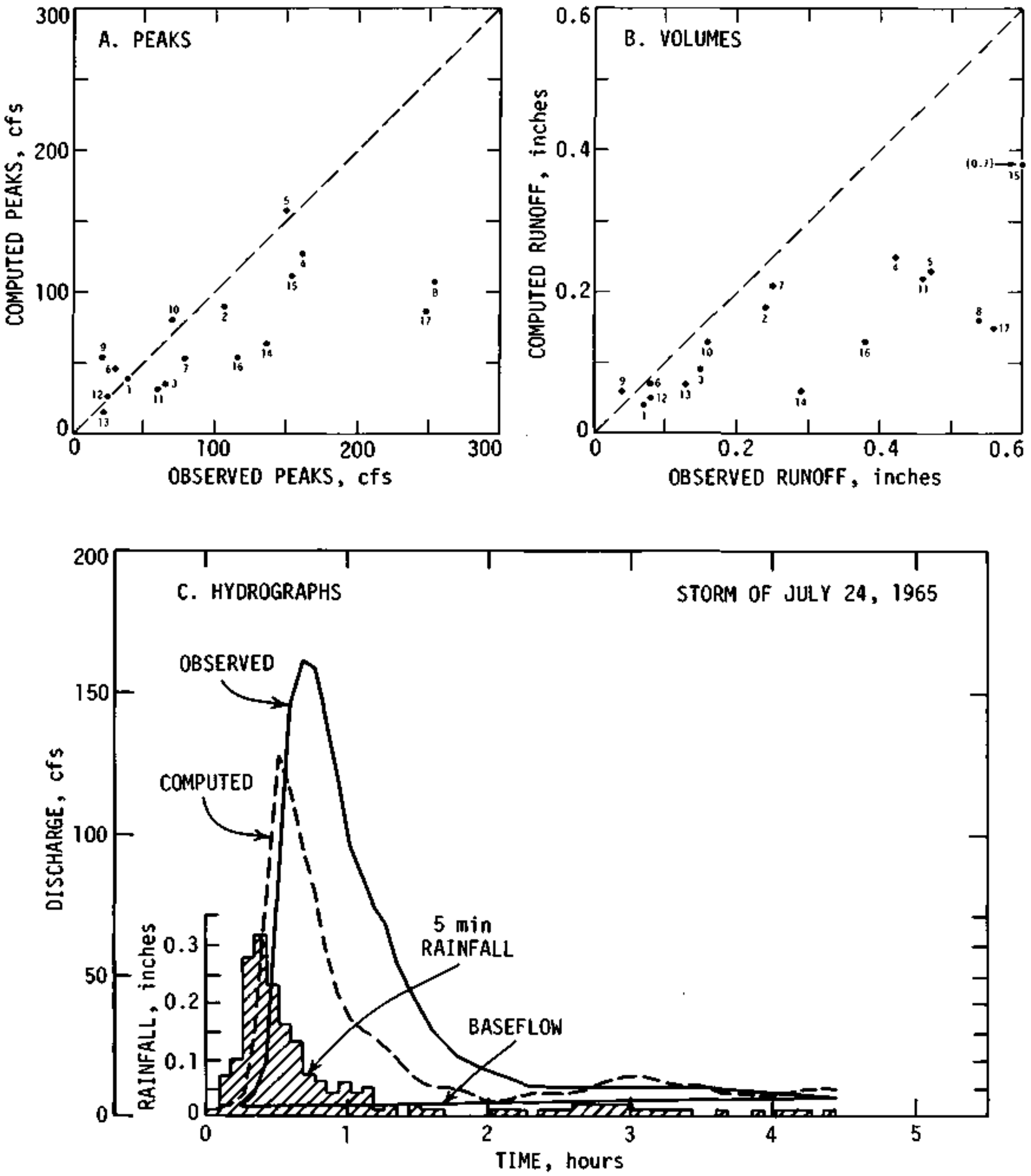
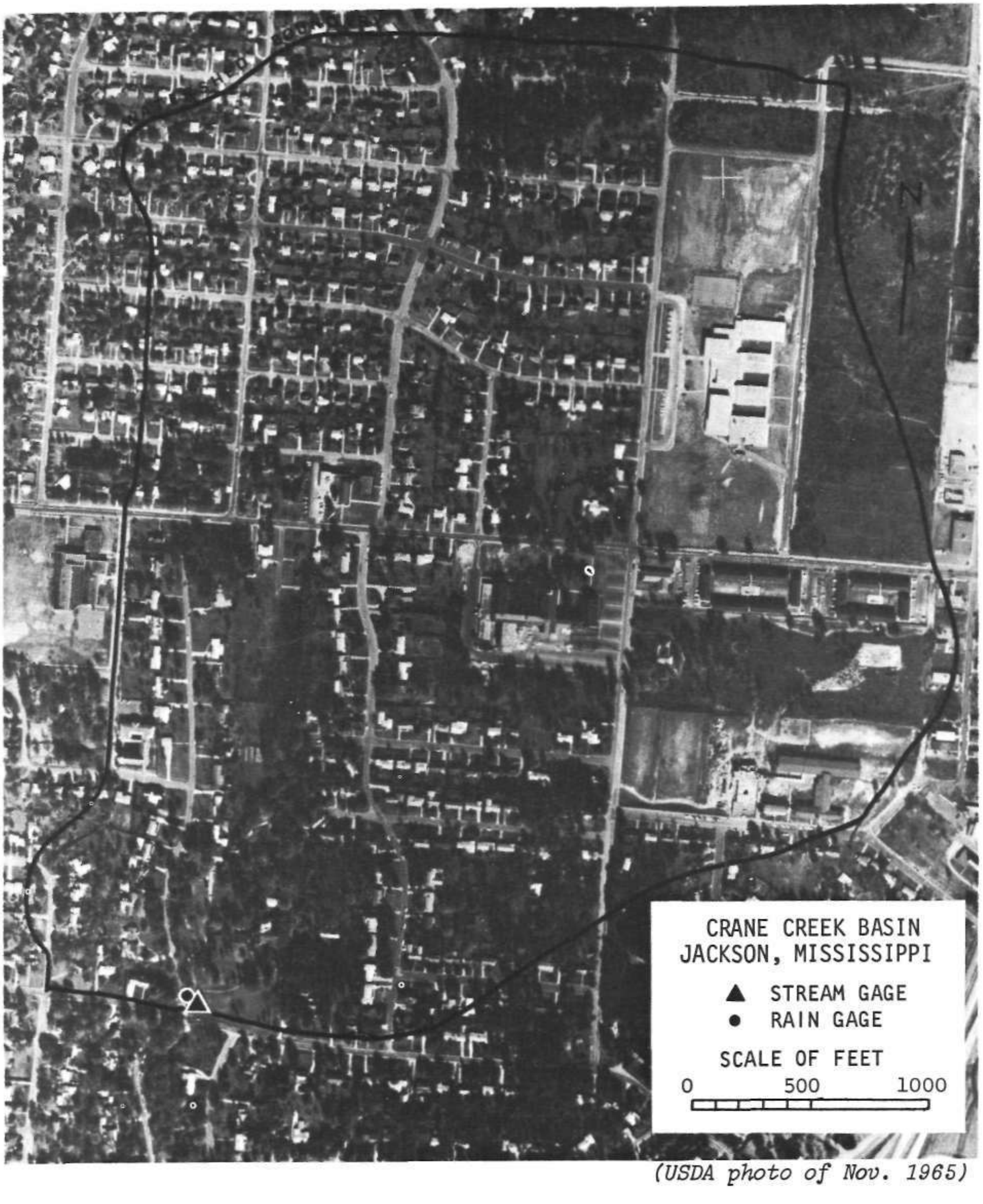


Figure 19. RRL results for Crane Creek basin, Jackson, Mississippi



(USDA photo of Nov. 1965)

Figure 20. Aerial photo of Crane Creek basin

Tripps Run Tributary Basin, Falls Church, Virginia

Tripps Run is primarily a residential basin, but there is a significant amount of commercial development adjacent to U.S. Route 50 which crosses the basin in an east-west direction. North of Route 50 the residential area is relatively dense compared with the large lots and open areas to the south. The streets south of Route 50 are asphalt strips laid on existing grade without curb and gutter or roadside ditches, as illustrated in figure 21. Of the 15 reaches used to represent the drainage system, 5 were open channels with a combined length of 2370 feet and 10 were closed conduits with a combined length of 8325 feet. Storm drain information was difficult to obtain. In several locations missing data had to be filled with what seemed appropriate. Street slopes in the basin vary from 1 to 6 percent and yard slopes vary from 3 to 10 percent. Dominant soils in the general area of the basin are Appling and Louisburg in hydrologic group B and Colfax in hydrologic group C.

The directly connected paved area includes all of the streets, all of the commercial area, and driveways in the residential areas.

Data. The USGS provided the data for this study in the form of original charts from a Stevens graphical stage-recorder located on a rated culvert. The recorder was equipped with a second pen that recorded blips from a tipping bucket raingage on the same chart. The time scale of 0.2 inches per hour was adequate to define the stage hydrographs but not for accurate timing of bucket tips. The 0.1 inch tipping bucket was a further limitation on this data. Since it was recognized that a different interpretation of the rainfall between bucket tips was possible, the most intense storms from the available data were read at 10 minute intervals.

Results. The RRL method does not work on this basin. There is a significant amount of grassed-area contribution to runoff. The fact that the prediction of peak values is slightly better than the prediction of runoff volumes shows the influence of the concentrated paved areas in the commercial zone.

Table 6. Storm data and results for Tripps Run Tributary basin

Total Basin Area	Total Paved Area	Direcdy Connected Paved Area
322 acres	100 acres	56.9 acres
	31.0 percent	17.7 percent

Observed Storm Data								Computed Results			
Storm (1)	Date (2)	AMC (3)	Rain *inches* (4)	Peak flow *cfs* (5)	Runoff volume *inches* (6)	Runoff ratio (7)	Virtual runoff ratio (8)	Runoff volume *inches* (9)	Error *percent* (10)	Peak flow *cfs* (11)	Error *percent* (12)
1	62963	1	2.75	225	0.78	0.28	1.61	0.47	-39.4	101	-55.1
2	81963	2	2.55	219	0.58	0.23	1.28	0.44	-23.6	155	-29.2
3	82063	4	2.45	285	1.23	0.50	2.85	0.42	-66.0	174	-38.9
4	60265	3	0.85	47	0.08	0.09	0.52	0.14	76.4	68	44.3
5	81865	2	0.85	131	0.17	0.20	1.15	0.13	-22.5	125	-4.9
6	82665	3	1.35	203	0.30	0.22	1.24	0.22	-24.2	210	3.3
7	100765	1	3.10	221	1.00	0.54	1.83	0.54	-46.2	90	-59.1
8	82467	4	2.55	312	2.27	0.44	5.03	0.44	-80.7	92	-70.7
9	102567	1	0.90	62	0.17	0.14	1.10	0.14	-18.1	84	36.0
Mean values						0.29			44.1		37.9

Computed peaks were high in 3 cases, average + error = 27.9 percent
Computed peaks were low in 6 cases, average - error = 43.0 percent

Computed runoff volumes were high in 1 case, average + error = 76.4 percent
Computed runoff volumes were low in 8 cases, average — error = 40.1 percent

Figure 21. Typical large lawns in the downstream portion of Tripps Run Tributary basin

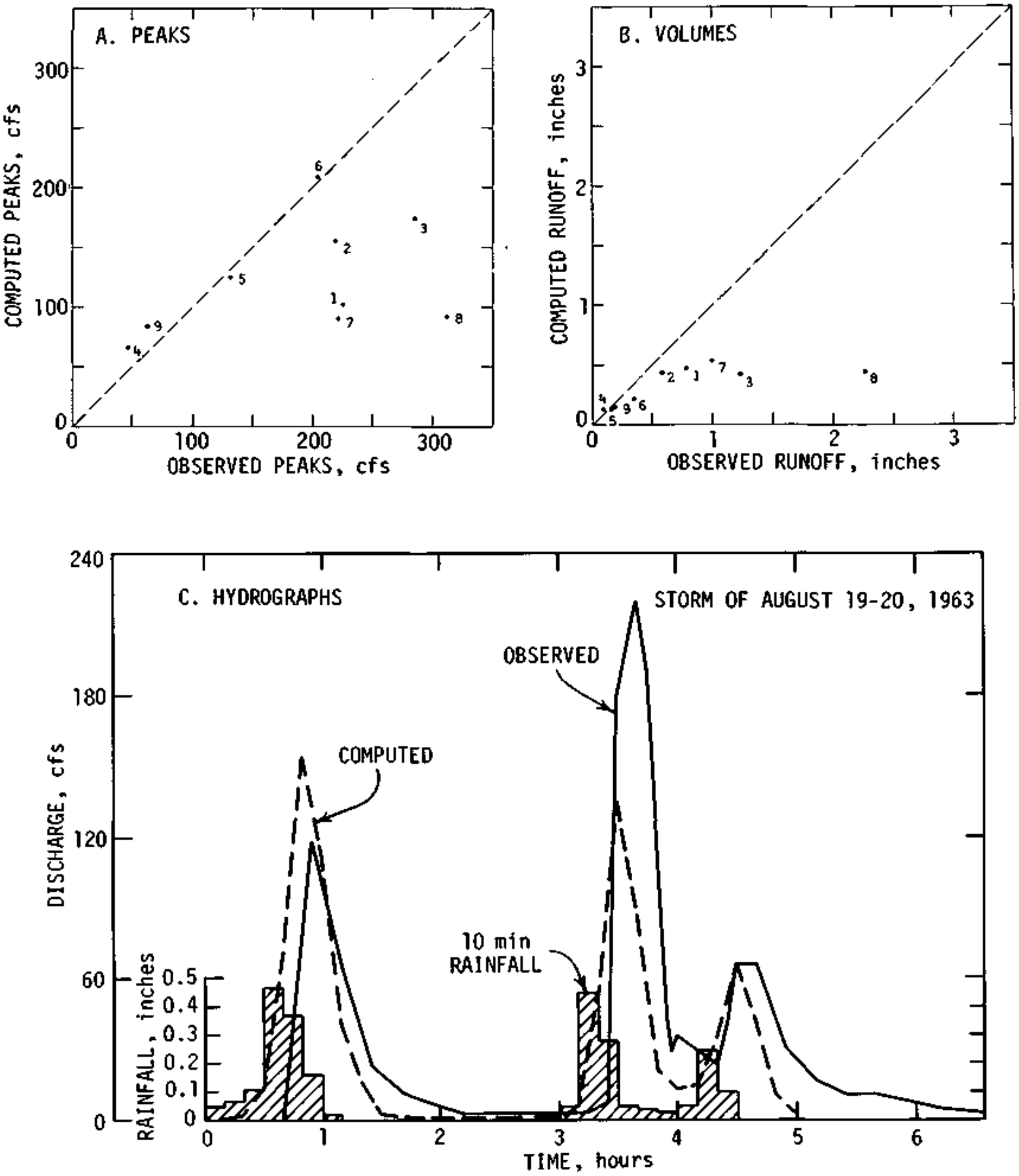
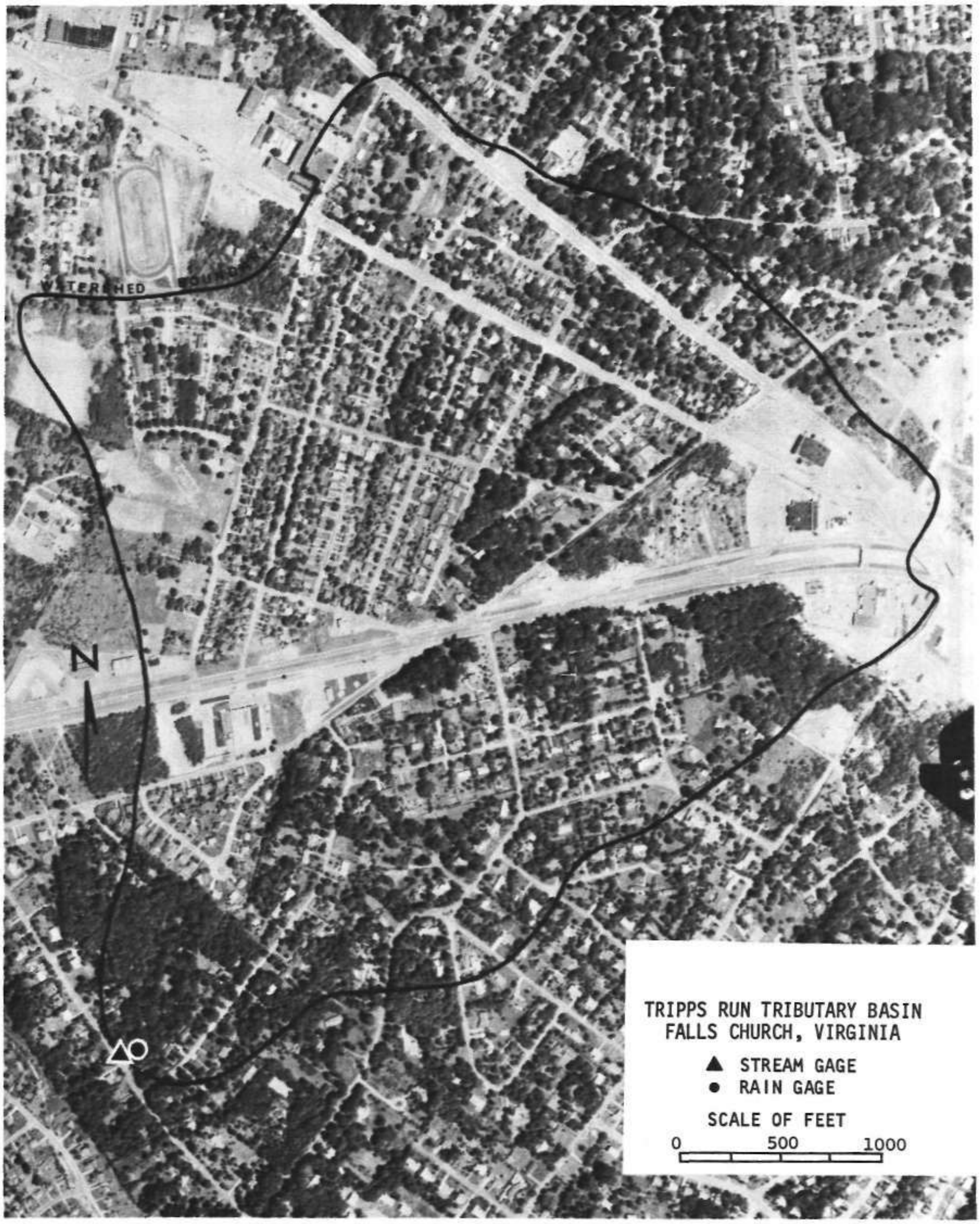


Figure 22. RRL results for Tripps Run Tributary basin, Falls Church, Virginia



(USDA photo of May 25, 1962)

Figure 23. Aerial photo of Tripps Run Tributary basin

Tar Branch Basin, Winston-Salem, North Carolina

A large part of downtown Winston-Salem and major industrial areas lie within the boundaries of the Tar Branch basin and account for the high percentage of paved area. The remainder of the basin is light commercial or residential. In order to represent the extensive storm drainage system in reasonable detail, 103 sub-basins were used. Of the 103 reaches, 15 were open Channels with a combined length of 7200 feet. Pipes in the system ranged from 10 inches up to 72 inches in diameter. Information on the drainage system was not complete, and storm drain slopes were assumed to be the same as street slopes in many cases. Street slopes are highly variable. In the downtown area they are gentle; but range up to 10 percent in other parts of the basin. Yard slopes are also variable ranging from 3 to 10 percent. The dominant soil in the basin is a Pacolet fine sandy loam which in the undisturbed state is in hydrologic group B.

The directly connected paved area consists of all of the downtown commercial area, all other streets, and other major buildings and parking lots. Residential roofs are not generally connected to the drainage system and private driveways are usually not paved.

Data. The Instrumentation on this basin was the USGS Standard installation for urban basins. Two digital recorders punch the rainfall and stage synchronously at 5-minute intervals. In this case the instruments are located on an open Channel above a rated culvert. For this study the rainfall and the discharge were both provided in tabular form at 5-minute intervals.

Results. There is no significant grassed-area runoff contribution from the Tar Branch basin. The RRL method works well because of the large percentage of paved area and because of the permeable soil.

Table 7. Storm data and results for Tar Branch basin

Total Basin Area	Total Paved Area	Directly Connected Paved Area
384 acres	227 acres	195 acres
	59 percent	51 percent

Observed Storm Data								Computed Results			
Storm (1)	Date (2)	AMC (3)	Rain *inches* (4)	Peak flow *cfs* (5)	Runoff volume *inches* (6)	Runoff ratio (7)	Virtual runoff ratio (8)	Runoff volume *inches* (9)	Error *percent* (10)	Peak flow *cfs* (11)	Error *percent* (12)
1	62668	2	0.67	265	0.34	0.51	1.00	0.29	-15.0	302	13.9
2	71268	2	1.42	397	0.69	0.48	0.95	0.67	-3.1	540	36.0
3	101868	4	2.88	175	0.71	0.25	0.49	1.41	97.8	299	70.9
4	61169	4	3.03	945	1.97	0.65	1.28	1.48	-24.9	713	-24.5
5	61569	4	2.22	171	0.46	0.21	0.41	1.06	127.8	335	96.2
6	61869	4	0.38	210	0.12	0.31	0.61	0.15	29.9	260	23.8
7	62169	2	0.82	316	0.33	0.40	0.78	0.37	12.0	456	44.4
8	72869	2	1.38	290	0.53	0.39	0.76	0.59	11.1	297	2.5
9	61370	3	2.05	857	1.80	0.88	1.73	0.98	-45.6	686	-20.0
10	121867	1	1.00	97	0.43	0.43	0.85	0.45	5.0	60	-38.4
11	31668	4	1.14	132	0.32	0.28	0.54	0.53	66.7	129	-2.2
12	42368	2	0.52	73	0.10	0.20	0.38	0.21	110.4	79	7.7
13	41569	2	0.88	71	0.30	0.34	0.67	0.39	32.2	91	28.7
14	52769	3	1.22	105	0.41	0.33	0.66	0.56	38.7	165	56.9
15	60969	2	0.71	134	0.13	0.18	0.35	0.31	147.6	219	63.2
16	80369	3	0.43	80	0.07	0.17	0.35	0.17	123.3	96	19.6
17	121069	4	1.23	82	0.31	0.25	0.50	0.57	83.4	66	-20.1
Mean values						0.37			57.3		33.4

Computed peaks were high in 12 cases, average + error = 38.6 percent
Computed peaks were low in 5 cases, average — error = —21.0 percent
Computed runoff volumes were high in 13 cases, average + error = 68.1 percent
Computed runoff volumes were low in 4 cases, average — error = —22.2 percent

Figure 24. Typical houses and street in the Tar Branch basin

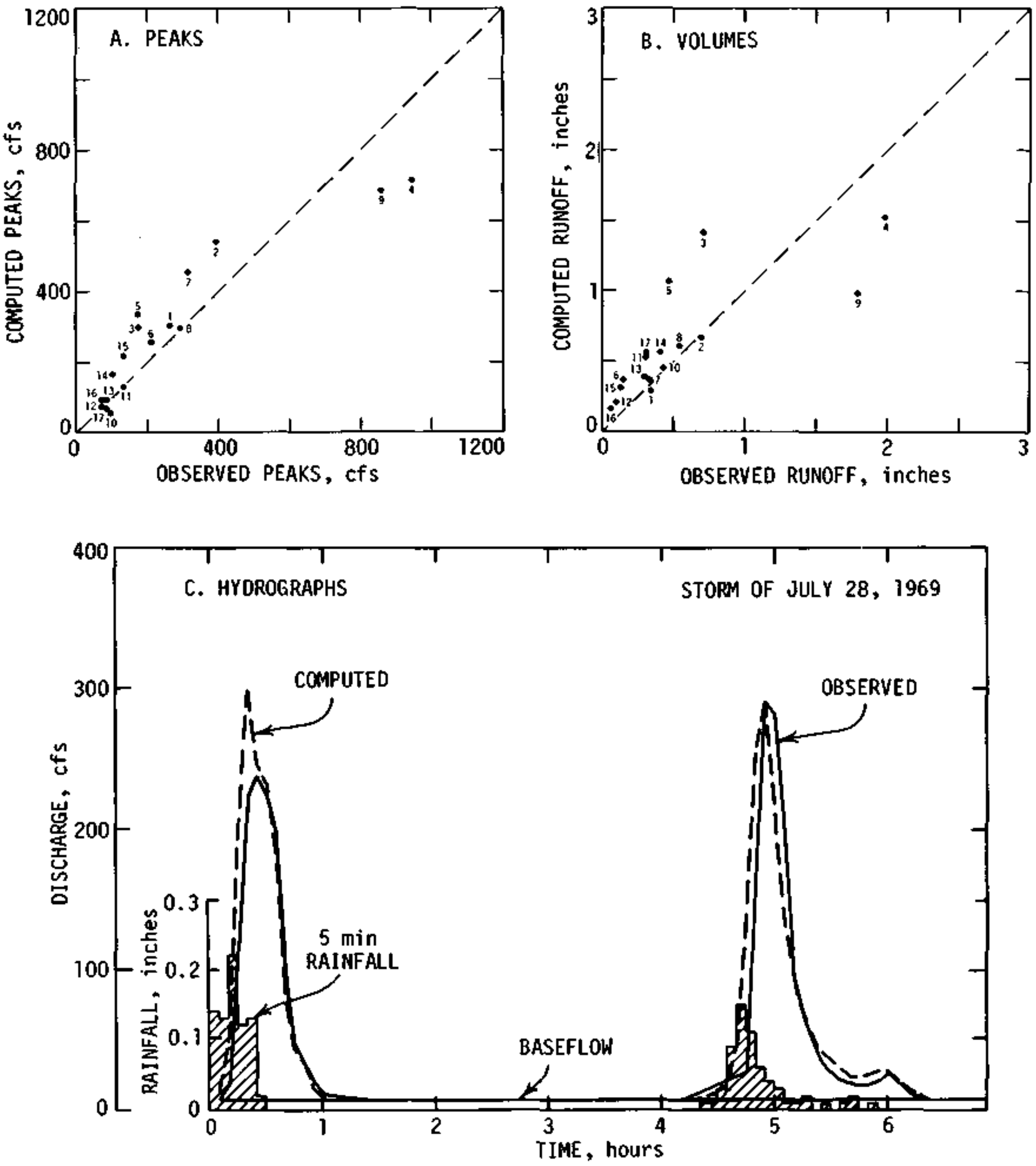


Figure 25. RRL results for Tar Branch basin, Winston-Salem, North Carolina

(USDA photo of Oct. 1966)

Figure 26. Aerial photo of Tar Branch basin

Third Fork Basin, Durham, North Carolina

The Third Fork basin contains a variety of land uses. There is a high-density commercial area and a significant industrial area along the northern watershed boundary. The residential area, which makes up most of the basin, is itself highly variable ranging from simple frame homes on dirt streets to homes on large lots. Surrounding the channel in the southern part of the basin are over 100 acres of open park area. Soils in the flood piain are primarily Cangaree loams. Although these are classified in hydrologic group B, the high water table in this area could add significantly to the runoff potential. Upland soils consist of White Store soils and are classified in hydrologic group D. With the exception of a few pipes in the upper reaches of the basin, all drainage is by open Channel. Of the 39 reaches used to describe the storm drainage system, only 8 are closed conduits. Street and Channel slopes are moderate, ranging from less than 1 to about 5 percent. Yard slopes range from 5 to 10 percent.

The total paved area of the basin was determined by zoning out the 100-percent paved areas and the park areas, and measuring sample blocks in the remaining area. The residential area was divided into 3 zones; low income, middle income, and high income. It was assumed that zero, 10 percent, and 12.5 percent, respectively, of these roof areas were connected to the storm drainage system. In the areas where paved streets did not exist a 15-foot strip was assumed to be connected to the system. The directly connected paved area thus consisted of 147 acres of commercial area, 126 acres of streets, and 20 acres of residential roofs and driveways.

Data. This is a Standard USGS installation. Two digital recorders operating from the same clock punch the stage hydrograph and the rainfall at 5-minute intervals. The stage hydrograph is recorded at a rated culvert section in an open channel. For this study both rainfall and discharge were provided in tabular form at 5-minute intervals.

Results. The RRL method works on small storms but underestimates large storms. Much of the directly connected paved area is in the upper reaches of the basin. Flood runoff from this area flows downstream through an earth Channel. For small storms the flood peak reaches the gage later than it would if the paved area were evenly distributed or located in the lower portions of the basin. The RRL method correctly reproduces this delayed peak for small storms.

For big storms a large grassed-area contribution is generated in the lower part of the basin and arrives at the gage at about the same time as the delayed paved-area contribution. The RRL method which ignores the grassed-area contribution thus seriously underestimates both the peak and the volume of runoff.

Table 8. Storm data and results for Third Fork basin

Total Basin Area	Total Paved Area	Directly Connected Paved Area
1075 acres	397 acres	293 acres
	37 percent	27 percent

Observed Storm Data								Computed Results			
Storm (1)	Date (2)	AMC (3)	Rain *inches* (4)	Peak flow *cfs* (5)	Runoff volume *inches* (6)	Runoff ratio (7)	Virtual runoff ratio (8)	Runoff volume *inches* (9)	Error *percent* (10)	Peak flow *cfs* (11)	Error *percent* (12)
1	60969	2	0.64	77	0.15	0.23	0.83	0.14	-1.7	86	12.0
2	61569	4	1.80	500	0.79	0.44	1.61	0.46	-42.3	324	-35.2
3	72869	3	0.97	485	0.33	0.35	1.27	0.23	-31.2	202	-58.3
4	80169	3	0.72	137	0.19	0.26	0.97	0.17	-12.4	151	9.9
5	80369	4	0.83	593	0.48	0.58	2.14	0.20	-59.5	279	-52.3
6	80469	4	0.50	199	0.19	0.38	1.40	0.11	-43.7	131	-34.0
7	81369	3	0.53	120	0.17	0.31	1.15	0.11	-31.2	128	6.4
8	81569	3	1.96	1700	1.39	0.71	2.60	0.50	-63.9	1021	-39.9
9	90269	1	0.73	593	0.32	0.43	1.59	0.17	-46.4	346	-41.7
10	91769	1	1.36	732	0.37	0.27	1.00	0.34	-8.9	646	-11.8
11	92469	4	0.60	217	0.31	0.52	1.90	0.13	-57.2	81	-62.5
12	121069	3	1.05	205	0.36	0.34	1.26	0.25	-29.3	183	-10.9
13	122169	1	0.83	105	0.27	0.32	1.18	0.19	-27.2	87	-17.3
14	122569	3	0.73	116	0.32	0.44	1.62	0.17	**-48.0**	75	-35.1
15	21670	1	2.11	245	1.01	0.48	1.75	0.53	-46.9	159	-35.3
Mean values						0.40			36.7		31.2

Computed peaks were high in 3 cases, average + error = 9.4 percent
Computed peaks were low in 12 cases, average — error = —36.2 percent
Computed runoff volumes were high in 0 cases
Computed runoff volumes were low in 15 cases, average — error = —36.7 percent

Figure 27. Open channel which is representative of most of the drainage in Third Fork basin

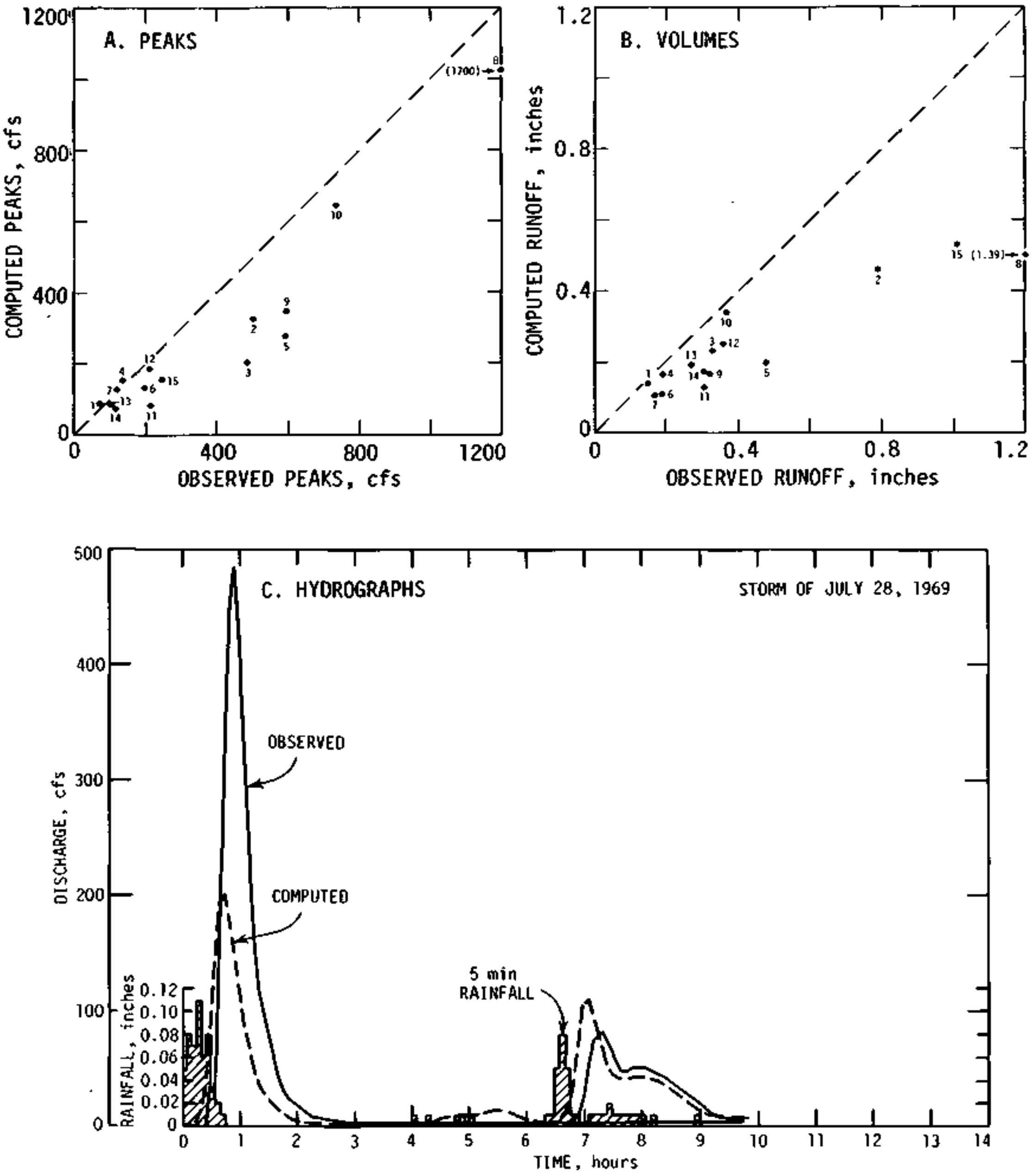


Figure 28. RRL results for Third Fork basin, Dur harn, North Carolina

(USDA photo of Oct. 1966)

Figure 29. Aerial photo of Third Fork basin

Dry Creek Basin, Wichita, Kansas

This is primarily a residential basin with a few strips of commercial area. There is no Underground storm drainage in the basin. Runoff is transported via streets to either the East or West Branches of Dry Creek. The East Branch has had some improvement but is essentially a natural stream. The West Branch flows for much of its length through specially modified street cross sections which are in effect a concrete canal. This is illustrated in the photo in figure 30. As a result, flow down the West Branch is much faster than flow down the East Branch. Street slopes are quite flat, averaging less than 0.5 percent. Yard slopes vary from 2 to 8 percent. Dominant soils in the area are Dale silt loam and Farnum loam, both classified in hydrologic group B. There is a small area of Bethany silt loam in the upper reaches of the basin which is in hydrologic group C.

Twenty-three sample blocks were used to determine the paved area of the basin. The directly connected paved area includes all of the streets, major buildings and parking lots, and 25 percent of the remaining paved area.

Data. Both rainfall and stage data on this basin are collected by digital punch-type recorders located on a rated bridge-opening on Dry Creek. A graphical stage recorder originally installed was found impractical because of the rapid changes in stage. The data provided for this project were for 1964 through 1969, but only the 1964-1965 data were used because, after a dry period during 1966-1967, there appeared to be a shift in the rating curve. This shift has been fairly well documented by the USGS personnel, but there is still some question about the 1968-1969 data.

Results. There is no significant grassed-area runoff from this basin. Although the results are erratic the RRL method does seem to apply. The flat slopes and relatively permeable soil are factors which favor the RRL method.

Table 9. Storm data and results for Dry Creek basin

Total Basin Area	**Total Paved Area**	**Directly Connected Paved Area**
1882 acres	**583 acres**	**365 acres**
	31 percent	**19 percent**

Observed Storm Data								**Computed Results**			
Storm (1)	Date (2)	AMC (3)	Rain *inches* (4)	Peak flow *cfs* (5)	Runoff volume *inches* (6)	Runoff ratio (7)	Virtual runoff ratio (8)	Runoff volume *inches* (9)	Error *percent* (10)	Peak flow *cfs* (11)	Error *percent* (12)
1	50564	2	0.72	250	0.15	0.21	1.07	0.12	-21.0	219	-12.6
2	80964	4	2.20	365	0.34	0.15	0.80	0.40	17.4	355	-2.6
3	82764	4	1.88	580	0.39	0.21	1.07	0.34	-13.1	645	11.3
4	91964	4	0.56	226	0.11	0.19	1.00	0.09	-19.0	175	-22.7
5	22865	2	0.60	212	0.15	0.25	1.32	0.09	-39.1	155	-26.7
6	51365	2	2.38	608	0.55	0.23	1.18	0.43	-20.9	522	-14.1
7	52465	4	0.74	148	0.08	0.11	0.58	0.12	45.7	210	41.9
8	70965	3	1.68	505	0.56	0.33	1.71	0.30	-46.0	351	-30.4
Mean values						0.21			27.8		20.3

Computed peaks were high in 2 cases, average + error = 26.6 percent
Computed peaks were low in 6 cases, average — error = 18.2 percent
Computed runoff volumes were high in 2 cases, average + error =31.6 percent
Computed runoff volumes were low in 6 cases, average — error = 26.5 percent

Figure 30. View of street typical of those which carry most surface runoff in the Dry Creek basin

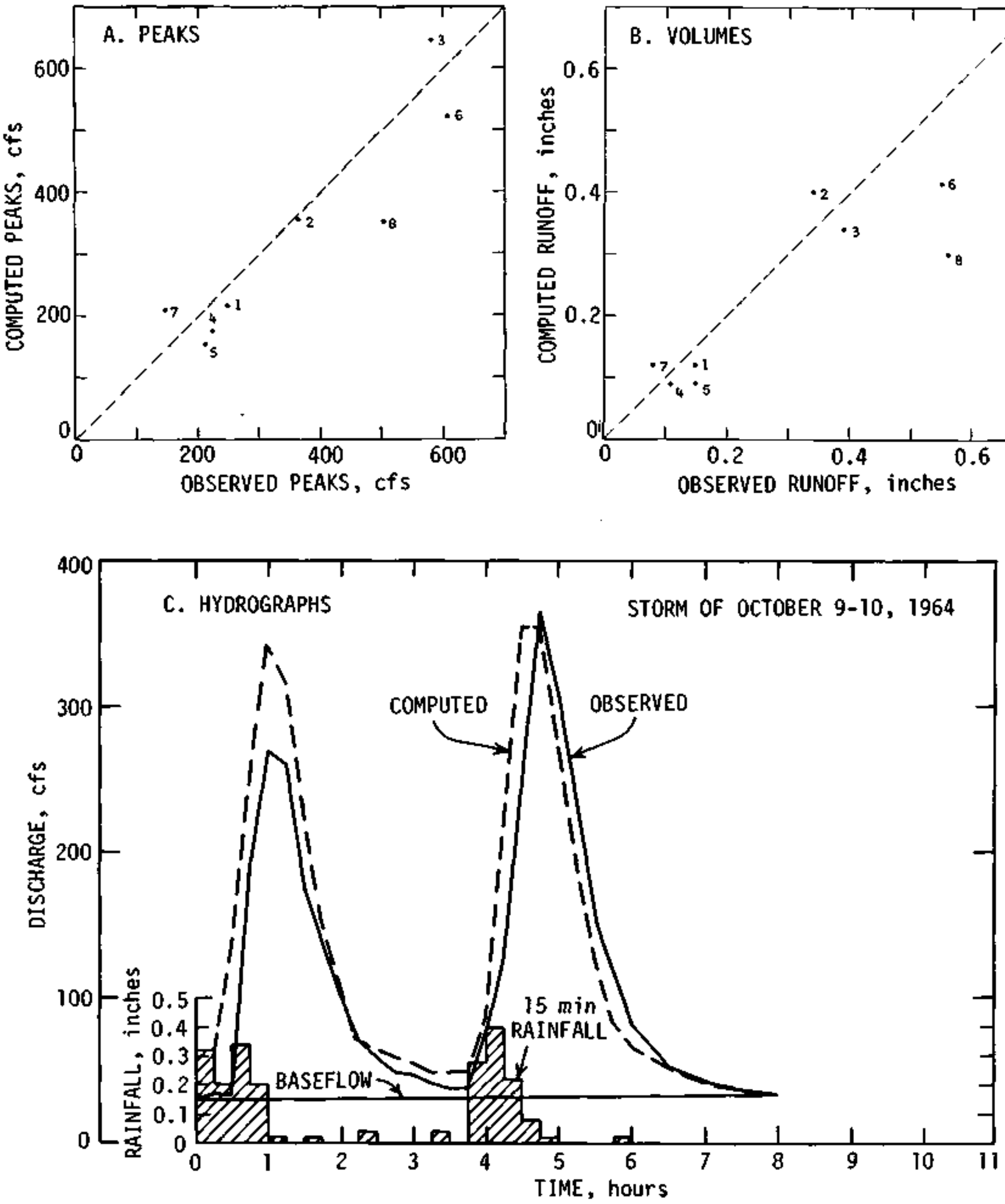


Figure 31. RRL results for Dry Creek basin, Wichita, Kansas

(USDA photo of June, 1970)

Figure 32. Aerial photo of Dry Creek basin

Wingohocking Basin, Philadelphia, Pennsylvania

Wingohocking is the largest and the most highly urbanized basin in this report. There are a few areas of separate single-family residences in the basin, but row-houses are by far the most common. Extensive commercial and industrial areas also exist in the basin. There are no open Channels. An extensive combined sewer system with arch-shaped pipes up to 21 by 24 feet provides storm drainage. A sanitary interceptor sewer picks up dry weather flow just above the gage. The basin is represented in the model by 128 separate sub-basins ranging in size from 1.2 to 117 acres. Street slopes generally range from 0.5 to 2 percent and yard slopes from 3 to 10 percent. Soils in the area are either in the Chester Complex group which is classified 85 percent hydrologic group B and 15 percent C-D, or Howell Complex which is classified 75 percent hydrologic group B and 25 percent C-D.

Paved areas were based on studies previously made by the city of Philadelphia and confirmed during this study by measuring sample blocks on aerial photographs. All of the paved areas in the basin, including residential rooftops, are directly connected to the drainage system.

Data. The flow measurement program, as described by Tucker (1969), was established by the U.S. Public Health Service in 1963. A graphical stage recorder was installed 450 feet upstream from a low broad crested weir. The weir, which itself is 87 feet above the outfall, was rated by a physical model built and tested at Swarthmore College in 1964. The Research and Development unit of the Philadelphia Water Department took over the gage in July of 1967 and again built a model of the weir at the city's Northeast Water Pollution Control Plant. For use in this project discharge hydrographs were provided in digital form.

The city also operates a network of recording raingages. Four of these gages were used for the Wingohocking basin. These are shown on the accompanying map as 1, Roosevelt; 2, Heintz; 3, Queen Lane; and 4, Harrowgate. All of the raingages were of the weighing-bucket type. As a part of this project the original raingage charts were digitized for 5-minute intervals with the Water Survey's auto-trol model 3400 X-Y digitizer.

Results. Both peaks and volumes are overestimated by the RRL method for storms occurring between 1964 and 1967. The runoff ratios for these storms seem to be quite low for a basin which is 61 percent paved. The method works satisfactorily on the 1968 storms which have an average runoff ratio of 0.72.

Table 10. Storm data and results for Wingohocking basin

Total Basin Area	rotal Paved Area	Directly Connected Paved Area
5326 acres	3246 acres	3246 acres
	61 percent	61 percent

Observed Storm Data								**Computed Results**			
Storm (1)	Date (2)	AMC (3)	Rain *inches* (4)	Peak flow *cfs* (5)	Runoff volume *inches* (6)	Runoff ratio (7)	Virtual runoff ratio (8)	Runoff volume *inches* (9)	Error *percent* (10)	Peak flow *cfs* (11)	Error *percent* (12)
1	42764	2	1.02	470	0.27	0.26	0.43	0.55	107.2	849	80.6
2	42964	3	1.00	860	0.37	0.37	0.61	0.54	45.9	1400	62.8
3	92864	4	1.26	1145	0.38	0.31	0.50	0.70	81.5	1690	47.6
4	112564	2	1.41	1960	0.36	0.26	0.43	0.79	116.5	2225	13.6
5	71165	2	2.52	1860	0.89	0.35	0.58	1.46	64.2	2583	38.9
6	80465	2	1.02	789	0.31	0.30	0.50	0.58	86.6	1124	42.5
7	80965	4	1.97	1960	0.50	0.25	0.42	1.13	124.6	3301	68.4
8	82165	3	1.16	800	0.31	0.27	0.43	0.64	106.9	1308	63.5
9	92465	1	1.22	1570	0.39	0.32	0.52	0.67	72.3	3101	97.5
10	100765	1	1.11	880	0.26	0.23	0.38	0.61	137.1	1667	89.5
11	70267	3	1.38	2325	0.70	0.51	0.83	0.77	10.6	2967	27.6
12	72967	3	1.20	1587	0.50	0.41	0.67	0.66	33.7	2692	69.6
13	80967	3	1.34	2640	0.35	0.26	0.43	0.74	112.7	3928	48.8
14	61268	4	3.23	5248	2.72	0.84	1.38	1.88	-30.8	3680	-29.9
15	72468	3	1.68	3402	1.20	0.71	1.17	0.95	-20.5	2806	**-17.5**
16	80168	2	1.31	3402	0.80	0.61	1.00	0.72	**-9.2**	3417	0.5
Mean values						0.39			72.5		49.9

Computed peaks were high in 14 cases, average + error = 53.7 percent
Computed peaks were low in 2 cases, average — error = 23.7 percent
Computed runoff volumes were high in 13 cases, average + error = 84.6 percent
Computed runoff volumes were low in 3 cases, average — error = 20.2 percent

Figure 33. Typical row-houses in the Wingohocking basin

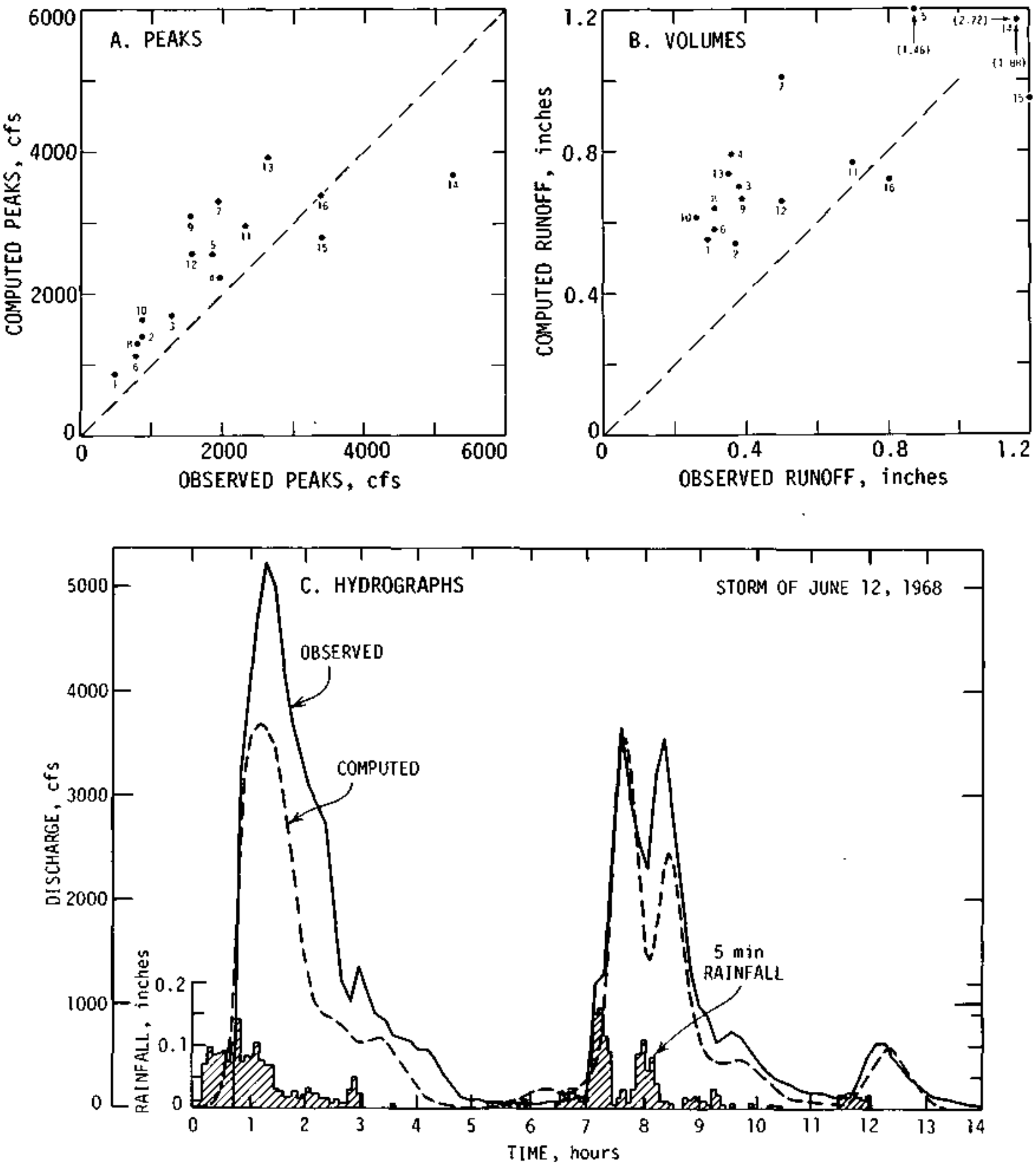


Figure 34. RRL results for Wingohocking basin, Philadelphia, Pennsylvania

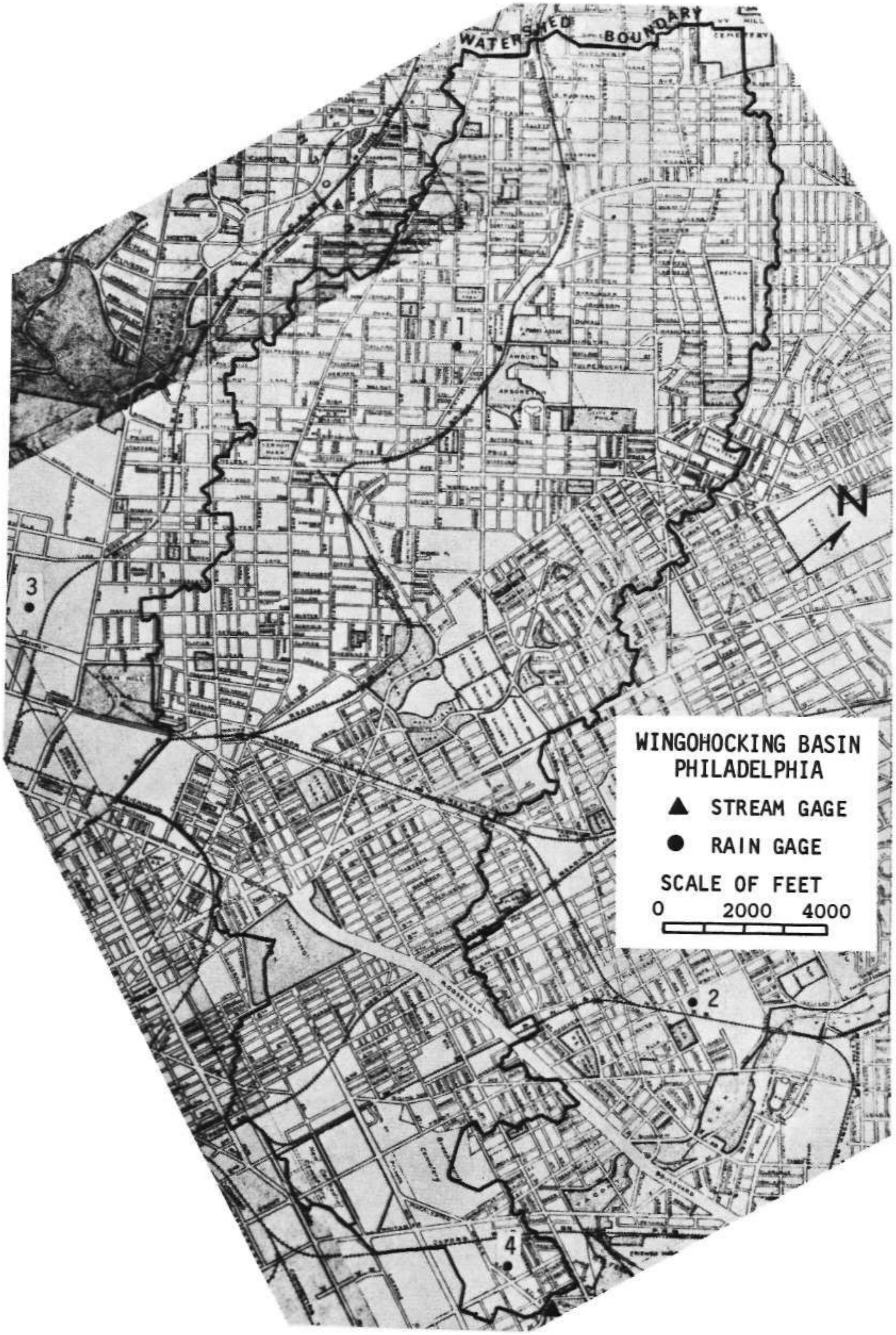


Figure 35. Street map of the Wingohocking basin

SECTION VII
OVERALL RESULTS

General

The results and basic parameters for the 10 basins used in this study are presented in table 11. Columns 9 and 10 show the number of storms for which the computed peak was higher and lower, respectively, than the observed peak. Column 11 gives the difference between the observed and computed peaks expressed as a percent of the observed peak and averaged without regard to sign for all storms in the basin. The last three columns give a similar summary for the computed runoff.

The 10 basins fall into three classifications with regard to the RRL method. The first includes the 3 basins on which no significant grassed-area runoff was present and on which the RRL method does apply. These basins are Woodoak Drive, Tar Branch, and Dry Creek. These basins have in common flat to moderate slopes and soils in hydrologic group B. The weighted average errors for all of the storms in this group are 28.9 percent for the peaks and 39.4 percent for the runoff volumes. These percentage values are influenced greatly by large percentage errors in relatively small peaks and runoff volumes.

In the second class, computed peaks and runoff volumes are much lower than the corresponding observed values. The RRL method does not apply because significant grassed-area runoff occurs from these 5 basins. Included in this group are Ross-Ade, Echo Park, Crane Creek, Tripps Run, and Third Fork. These basins have in common moderate to steep slopes and soils in hydrologic groups C or D. The weighted average errors are 40.4 percent for peaks and 39.4 percent for the runoff volumes for the storms on these 5 basins having significant grassed-area runoff.

The third classification includes 2 basins: Sewer District No. 8 and Wingohocking. For these basins the RRL overestimates peaks and runoff volumes. Surface ponding is known to be a problem on both of these basins and would appear to be the reason for the overestimates by the RRL method. There is no provision in the RRL method for attenuating the surface hydrograph because of ponded conditions before the runoff reaches the inlet. Although this is a shortcoming of the method, it should be pointed out that even if such a procedure were available the evaluation of these flooded conditions would be subjective at best.

Table 11. General results for the RRL method on all basins

		Total paved area		Dir. connected paved area				Computed peaks			Computed runoff		
Basin	Basin area					Hydrologic soil group	Basin slope	No. high	No. low	Mean absolute error	No. high	No. low	Mean absolute error
	acres	*acres*	*percent*	*acres*	*percent*					*percent*			*percent*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Woodoak Drive	14.7	4.9	33.9	2.8	19.4	B	flat	5	5	28.2	5	5	18.3
Ross-Ade (Upper)	54.0	13.3	24.7	7.8	14.4	B-C	steep	0	2	50.5	0	2	62.8
Sewer Dist No. 8	206	43	21.0	37.5	18.2	CD	flat	9	1	68.0	10	0	21.4
Echo Park Avenue	252	136	53.8	97.7	38.8	B-C	steep	0	18	47.2	2	16	30.3
Crane Creek	273	65.5	23.9	39.7	14.5	CD	mod	5	12	41.5	1	16	45.9
Tripps Run Trib.	322	100	31.0	56.9	17.7	B-C	mod	3	6	37.9	1	8	44.1
Tar Branch	384	227	59.0	195	51.0	B	mod	12	5	33.4	13	4	57.3
Third Fork	1075	397	37.0	293	27.0	B-D	mod	3	12	31.2	0	15	36.7
Dry Creek	1882	583	31.0	365	19.0	B-C	flat	2	6	20.3	2	6	27.8
Wingohocking	5326	3246	61.0	3246	61.0	B-D	mod	14	2	49.9	13	3	72.5

During the evaluation of these results considerable emphasis was placed on the plotted results and the general shape and fit of the computed and observed hydrographs. It is difficult to describe objectively the overall fit of the computed hydrographs for all of the storms on a basin. In a number of basins excellent reproductions of the entire observed hydrograph tend to be obscured by the average percentage errors reported in table 11.

Overall, it is the authors' judgment that the RRL method is satisfactory for describing runoff characteristics of an urban basin that is smaller than about 5 square miles, and has a paved area directly connected to the storm drainage system of at least 15 percent of the basin area. This applicability is limited to the normal design storms for storm drainage Systems, storms having frequencies from 2 to 20 years.

Rainfall Intensity in Britain and America

The British RRL method was devised in Great Britain and is extensively used today in all of Britain for the routine design or re-design of storm drainage System. The research described in this report, however, indicates that for some basins in the United States the storm runoff cannot be predicted merely by Computing the runoff from the paved area of a basin that is directly connected to the storm drainage system. This difference suggests that the rainfall regime in the United States may be more severe.

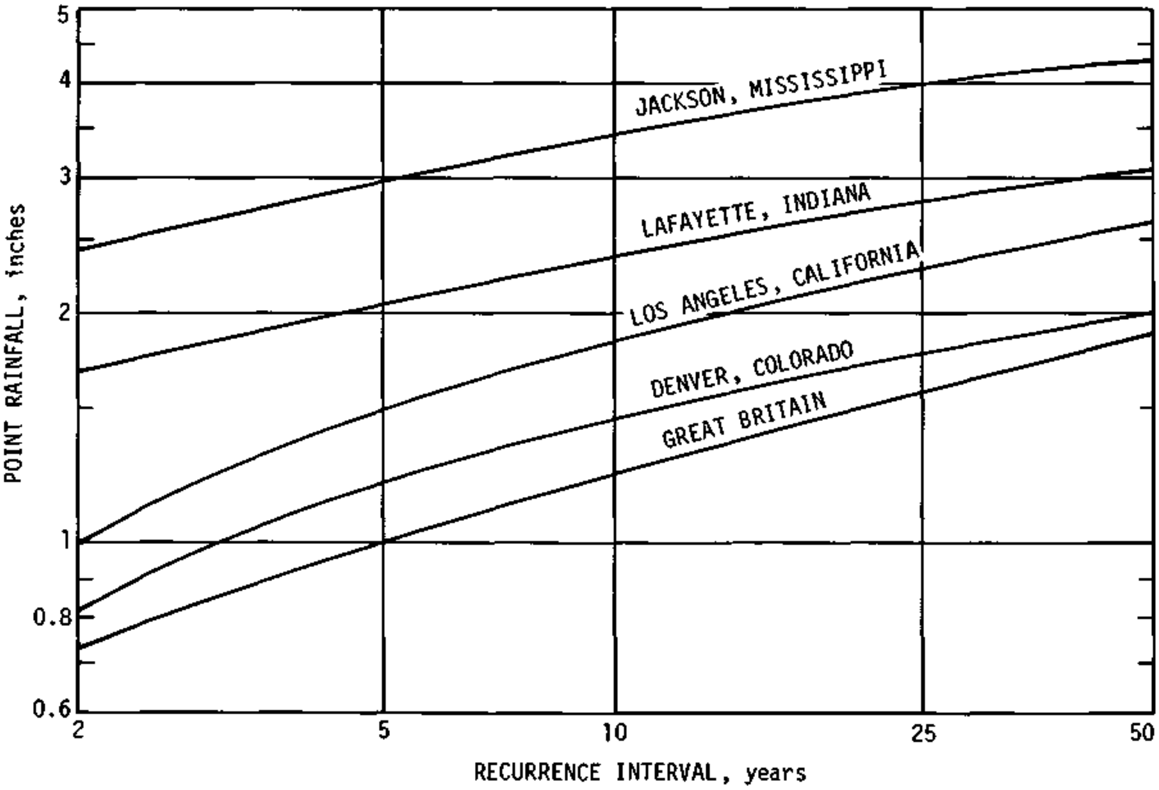


Figure 36. Frequency curves of 2-hour point rainfall in Great Britain and for four locations in the United States

Figure 36 shows a series of point rainfall frequency curves for 2-hour storms which are important for the urban runoff application. The curves show the comparison of British and American conditions. The curves for the United States were derived from the maps of Technical Publication 40 of the U.S. Weather Bureau (1961). The Great Britain curve was published by Watkins (1962) and represents the Bilham formula for interpretation of a wide range of heavy rainfalls recorded throughout Great Britain.

It is readily noted that the Great Britain curve is lower than all of the curves for the United States. This may be a significant indication that rainfalls in the United States which are critical for storm drainage design are greater in amount than those that generally occur in Great Britain.

Other Urban Hydrologic Models

A number of existing modeis for the urban rainfall-runoff process are noted here. These accomplish a variety of purposes; the RRL method is not a duplication of any of these. The effect of urban development and drainage improvement on runoff has been shown by James (1965) for a 43.8 square mile basin in California using the Stanford Watershed Model.

A major storm water management model has been published by Metcalf and Eddy Inc. and others (1971). This model was devised for the EPA by a triumvirate of Metcalf and Eddy Inc., the University of Florida, and Water Resources Engineers, Inc. The 4-volume report describes the model which accommodates rainfall, runoff, and water quality.

An hydrologic model to accommodate the rainfall-runoff process for an urban basin has been devised by the St. Paul Metropolitan Sewer Board (1971). The Chicago method of storm drainage design has been described by Tholin and Keifer (1960). The University of Cincinnati (1970) has derived an urban rainfall-runoff-quality model. Brater (1968) provided a better understanding of urban runoff processes.

The value of the total-basin-water-accounting procedure called Hydrocomp Simulation Programming, HSP, has been shown by Crawford (1971) in its application to urban hydrology.

SECTION VIII
RE-DESIGIM OF A STORM DRAINAGE SYSTEM

One object of this project has been to illustrate how the RRL method could be utilized to re-design a storm drain system. All of the basins included in this project were inspected as to the suitability of the RRL method for the re-design of the existing storm drainage system. For only 3 basins was the RRL method valid, as has been described in the preceding section. Of these, the Dry Creek basin was omitted because there are no existing storm drainage pipes in the basin. The remaining 2 basins, Woodoak Drive and Tar Branch, were selected for this analysis. A relatively good fit was obtained by the RRL method to the observed storms on both of these basins. Also good information on the existing storm drainage system is available. Tar Branch basin contains considerable existing artificial storm drainage.

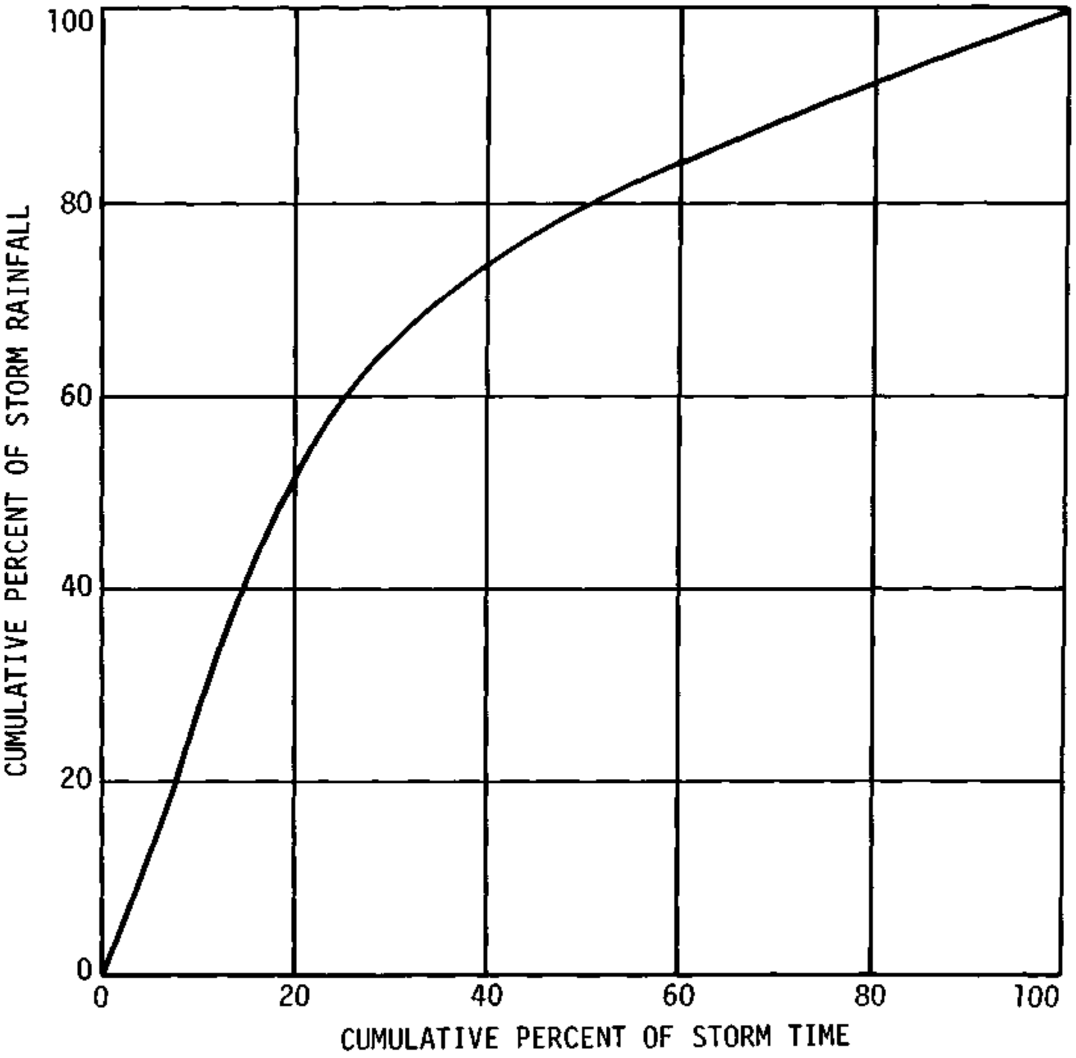


Figure 37. Time distribution of storm rainfall, median curve for point rainfall (Huff, 1967)

In order to re-design a storm drain system, an applicable *design storm* is required. In this case use has been made of the map on storm rainfall frequency shown in figure 1. This map shows that the 5-year 2-hour storm rainfall amount would be 2.25 inches for Woodoak Drive and 2.40 inches for Tar Branch.

Illinois studies have provided considerable information on the time distribution of rainfall (Huff, 1967). The use of this time distribution in urban studies has been demonstrated by Stall and others (1970). Further, a complete discussion of the occurrence of storm rainfall and its many dimensions has been provided by Stall and Huff (1971). Primarily on the basis of these published papers and the descriptions of the storm rainfall phenomena, a time distribution for storm rainfall was selected and used in this study. This time distribution (Huff, 1967) is shown in figure 37. This graph is the median curve for the distribution of storm rainfall within thunderstorms for which the majority of the rainfall occurred during the first quartile of the storm time. The first quartile storm was shown by Huff to be the most common type in Illinois. Also the curve in figure 37 represents the distribution of storm rainfall at a point.

This time distribution was used to provide a cumulative mass curve for the 2-hour 5-year storm rainfall amounts for Woodoak Drive and Tar Branch (table 12). Column 1 is the cumulative storm time at 5-minute intervals from 0 to 120 minutes. These are the incremental values needed for the distribution of the design rainfall for both basins and they are converted into percent of storm time in column 2. The values from the curve in figure 37 are read and given in column 3 as cumulative amount of storm rainfall. These cumulative amounts are then applied to the rainfall totals for the two basins. The last value in columns 4 and 5 (2.25 and

Table 12. The 5-year 2-hour design storms for Woodoak Drive basin. Long Island, and Tar Branch basin, Winston-Salem

Cumulative storm time		Cumulative percent of storm rainfall	Design rainfall	
minutes (1)	*percent* (2)	(3)	Woodoak *inches* (4)	Tar Branch *inches* (5)
0			0	0
5	4.2	10	0.22	0.24
10	8.3	21	0.47	0.50
15	12.5	33	0.74	0.79
20	16.7	44	0.99	1.06
25	20.8	52	1.17	1.25
30	25.0	59	1.33	1.42
35	29.2	64	1.44	1.54
40	33.3	68	1.53	1.63
45	37.5	72	1.62	1.73
50	41.7	75	1.69	1.80
55	45.8	78	1.76	1.87
60	50.0	80	1.80	1.92
65	54.2	82	1.84	1.97
70	58.3	84	1.89	2.02
75	62.5	85	1.91	2.04
80	66.7	87	1.96	2.04
85	70.8	88	1.98	2.11
90	75.0	90	2.02	2.16
95	79.2	92	2.07	2.21
100	83.3	94	2.11	2.26
105	87.5	95	2.14	2.28
110	91.7	97	2.18	2.33
115	95.8	98	2.21	2.35
120	100	100	2.25	2.40

2.40 inches) is the design amount for the basin.

In order to re-design the storm drainage system for these two basins, the two design storms (table 12) were applied to the basins with the existing pipes and storm drainage system. A design version of the RRL program was used. In cases where a pipe section was not large enough to accommodate the design flow, the computer automatically specified one size larger pipe and recomputed that section until an adequate pipe size was obtained.

This process was carried out for the Woodoak Drive basin, which is a small basin with only one section of storm drain pipe. This one pipe was found to be adequate to carry the flow from the 5-year design storm, so no re-design was needed or accomplished.

For the Tar Branch basin, the re-design process did provide considerable results. Figure 38 shows a street map of a part of the Tar Branch basin identifying the various reaches (upstream reach 1-0 to downstream reach 1-8) of existing storm drains. Table 13 gives the results of the re-design of these reaches. If the design peak flow in column 6 exceeds the capacity of the existing pipe in column 5, the ratio of the two flows, called the surcharge ratio, is given in column 7.

Table 13 shows that the design flow exceeded that of the existing pipe for 8 of the 26 reaches of pipe in the Tar Branch basin. For these 8 pipe sections the design program was written to select the next available pipe size larger than the existing pipe. This pipe was tested for its capacity to carry the design flow. If not large enough, a still larger pipe was selected until one adequate to carry the design flow was found. The re-designed pipe sections and their capac-

Table 13. Results of the RRL method re-design of the storm drainage system for Tar Branch basin

Physical data			**Existing pipe**		**5-year design**		**Required pipe**	
Reach (1)	Length *feet* (2)	Slope *percent* (3)	Diam *inches* (4)	Capacity ***cfs*** **(5)**	Design peak *cfs* (6)	Surcharge ratio (7)	Diam *inches* (8)	Capacity ***cfs*** **(9)**
1-0	**330**	**2.4**	**18**	**14.1**	**15.0**	**1.06**	**21**	**21.3**
1-1	**200**	**2.5**	**18**	**14.4**	**21.1**	**1.47**	**21**	**21.7**
1-2	**250**	**4.8**	**18**	**19.9**	**26.2**	**1.32**	**21**	**30.1**
2-0	**259**	**4.7**	**10**	**4.1**	**3.5**			
3-0	**260**	**4.7**	**18**	**19.7**	**9.9**			
3-1	**410**	**4.7**	**24**	**42.5**	**14.3**			
1-3	**238**	**3.5**	**24**	**36.6**	**57.2**	**1.56**	**30**	**66.4**
4-0	**240**	**4.5**	**18**	**19.3**	**8.6**			
4-1	**300**	**2.0**	**18**	**12.9**	**15.7**	**1.22**	**21**	**19.4**
1-4	**430**	**5.0**	**open channel**		**86.9**		**33**	**102.0**
5-0	**300**	**9.5**	**15**	**17.2**	**6.3**			
1-5	**350**	**5.0**	**36**	**129.2**	**99.8**			
1-6	**400**	**5.0**	**36**	**129.2**	**103.6**			
6-0	**350**	**5.0**	**18**	**20.3**	**15.2**			
6-1	**300**	**9.5**	**18**	**28.0**	**32.7**	**1.17**	**21**	**42.3**
6-2	**390**	**3.5**	**24**	**36.6**	**47.9**	**1.31**	**27**	**50.2**
6-3	**325**	**7.0**	**24**	**51.8**	**63.0**	**1.22**	**27**	**71.0**
6-4	**300**	**7.0**	**open channel**		**64.7**		**27**	**71.0**
1-7	**150**	**0.9**	**open channel**		**167.0**		**57**	**187.0**
7-0	**410**	**6.5**	**18**	**23.2**	**13.4**			
7-1	**360**	**8.5**	**18**	**26.5**	**15.1**			
8-0	**240**	**7.5**	**18**	**24.9**	**9.7**			
8-1	**350**	**2.5**	**18**	**14.4**	**11.2**			
8-2	**260**	**5.0**	**18**	**20.3**	**13.4**			
1-8	**500**	**2.5**	**60**	**356.7**	**202.6**			

Figure 38. Reach identifications for a portion of Tar Branch Basin, Winston-Salem

ities for the 8 pipes are given in columns 8 and 9 of table 13.

The results in table 13 can be further interpreted as to the degree that the pipe system is inadequate. For example, for reach 1-0 the surcharge ratio is 1.06 meaning the design flow is only 6 percent greater than pipe capacity. For reach 1-3, however, the surcharge ratio is 1.56 which depicts a relatively important deficiency. The re-design suggests that a 30-inch pipe is needed to replace the 24-inch pipe in the existing system. The open Channels shown on three reaches have been replaced in the re-design by appropriate circular pipes.

SECTION IX
ACKNOWLEDGMENTS

Michael L. Terstriep, Associate Engineer of the Illinois State Water Survey, has been the principal professional person carrying out this project, and John B. Stall, Engineer, has been director. The work has been carried out as a part of their regular work in the Water Survey Hydrology Section, H. F. Smith, Head. The entire work has been under the general supervision of Dr. William C. Ackermann, Chief. Robert A. Sinclair, Systems Analyst, provided the programming expertise for this project. The drafting has been carried out by John W. Brother, Jr., and William Motherway, Jr., of the Research Support Group. Mrs. J. Loreena Ivens, Technical Editor, reviewed the final report and contributed much to its value. John Lichter worked on the project as an Engineering Assistant part-time while a student in Sanitary Engineering at the University of Illinois. The total effort of the Water Survey comprised 70 percent of the project budget.

An amount equivalent to 30 percent of the budget of this project was provided to the Illinois State Water Survey as a Research and Development Grant from the federal Environmental Protection Agency, designated as Project 11030 FLN. During most of the project, George A. Kirkpatrick was Project Officer of the EPA, a role later assigned to Harry C. Torno. The aid and counsel of both these Project Officers is gratefully acknowledged.

Help and advice to the project personnel were provided by L. Scott Tucker of the American Society of Civil Engineers, who had earlier compiled a report (Tucker, 1969) listing various sources of rainfall-runoff data on urban basins.

A considerable amount of the data used in this project was obtained from various offices of the U.S. Geological Survey. The data used here were usually of the type collected by the USGS for their own analysis for other projects.

The data for the Woodoak basin near Westbury, New York, were provided by the USGS. In a paper by Seaburn (1970) the instrumentation was described, as well as the results of urbanization on runoff. Gerald E. Seaburn was helpful in providing the data and taking photos of the basin.

Data for the Ross-Ade basin were provided by Professor Jacques W. Delleur, Professor of Hydraulic Engineering in the Civil Engineering Department at Purdue University, and Dr. Ramachandra A. Rao, Associate Professor.

For the basin of Sewer District No. 8 in Bucyrus, Ohio, the primary information was obtained from Richard Noland of the Consulting engineering firm of Burgess and Niple, Ltd. of Columbus, Ohio. The firm had earlier provided a special report on this basin for the federal EPA; see Burgess and Niple, Ltd. (1969).

Data for the Echo Park Avenue basin in Los Angeles were provided by the Department of Public Works, Mr. Lyall A. Pardee, City Engineer. Special help and advice were provided by Irving R. Cole, Head of the Division of Storm Drainage Design in the Bureau of Engineering, and by Walter R. Naydo of the same Division.

Data for the Crane Creek basin were provided by personnel of the USGS District Office in Jackson. The special help of Kenneth V. Wilson and James Hudson is especially acknowledged. Data for the Tripps Run basin in Falls Church were provided by the Fairfax Sub-District Office of the USGS with the special help of Pat L. Soule.

Data for the Tar Branch basin in Winston-Salem and the Third Fork basin in Durham were provided by personnel of the Durham District Office of the USGS with the special help of Arthur L. Putnam. For the Third Fork basin, information on existing storm drainage was provided by Larry S. Kerr, Street Engineer, City of Durham.

The data for Dry Creek basin in Wichita were provided by David Richards of the USGS District Office in Lincoln, Nebraska, and the personnel of the Sub-District Office in Wichita.

Data for the Wingohocking basin in Philadelphia were provided by personnel of the Research Division of the Water Department, City of Philadelphia, Joseph V. Radziul, Chief; William Green, of the Planning Division also provided help.

SECTION X
REFERENCES

American Public Works Association, *Urban Drainage Practices, Procedures, and Needs,* Special Report 13, Chicago (1966).

American Society of Civil Engineers, *Water and Metropolitan Man,* New York (1969).

Anderson, Daniel G., *Effects of Urban Development on Floods — Water in the Urban Environment,* U. S. Geological Survey Water Supply Paper 2001-C (1970).

Ardis, Colby V., Kenneth J. Dueker, and Arno T. Lenz, "Storm Drainage Practices of Thirty-two Cities," *ASCE Journal of the Hydraulics Division, 95,* No. HY1, (January 1969).

Brater, E. F., "Steps Toward a Better Understanding of Urban Runoff Processes," *Water Resources Research, 4,* No. 2, pp 335-347 (April 1968).

Burgess and Niple, Ltd., *Stream Pollution and Abatement from Combined Sewer Overflows, Bucyrus, Ohio,* Federal Environmental Protection Agency Water Pollution Control Series 11024 FKN (1969).

Chow, Ven Te, *Handbook of Applied Hydrology,* McGraw-Hill Book Co., Inc., New York, pp 14-17(1964).

Crawford, N. H., *Studies in the Application of Digital Simulation to Urban Hydrology,* U. S. Office of Water Resources Research Contract Report 14-31-0001-3375, Washington, D.C., 100 pp (1971).

Hicks, W. I., "A Method of Computing Urban Runoff," *American Society of Civil Engineers Transactions, 109,* pp 1217-1253 (1944).

Huff, F. A., "Time Distribution of Rainfall in Heavy Storms," *Water Resources Research, 3,* No. 4, pp 1007-1019 (1967).

James, L. Douglas, "Using a Digital Computer to Estimate the Effects of Urban Development on Flood Peaks," *Water Resources Research, 1,* No. 2, (1965).

Jens, Stifel W., and W. B. McPherson, "Hydrology of Urban Areas," Section 20 in *Handbook of Applied Hydrology,* edited by Ven Te Chow, McGraw-Hill Book Co., Inc., New York (1964).

Linsley, Ray K., *A Critical Review of Currently Available Hydrologic Models for Analysis of Urban Stormwater Runoff,* Office of Water Resources Research, Washington, D.C. (1971).

Metcalf and Eddy, Inc. University of Florida, and Water Resources Engineers, Inc., *Storm Water Management Model,* 4 volumes, Federal Environmental Protection Agency Water Pollution Control Research Series 11024DOC (1971).

Road Research Laboratory, *A Guide for Engineers to the Design of Storm Sewer Systems,* Road Note 35, London (1963).

Seaburn, G. E., *Preliminary Results of Hydrologic Studies at Two Recharge Basins on Long Island, New York,* U. S. Geological Survey Professional Paper 627-C, 17 pp (1970).

St. Paul (Minnesota) Metropolitan Sewer Board, *Dispatcbing System for Control of Combined Sewer Losses, Part II, Mathematical Model,* Federal Environmental Protection Agency Water Pollution Control Research Series 11020FAQ, p 121 (1971).

Stall, John B., and Floyd A. Huff, *The Structure of Thunderstorm Rainfall,* Illinois State Water Survey Reprint 165, Urbana, 30 pp (1971).

Stall, John B., Michael L. Terstriep, and F. A. Huff, *Some Effects of Urbanization on Floods,* Illinois State Water Survey Reprint 133, Urbana (1970).

Terstriep, Michael L., and John B. Stall, "Urban Runoff by the Road Research Laboratory Method," *ASCE Journal of the Hydraulics Division, 95,* No. HY6, pp 1809-1834 (November 1969).

Tholin, A. L., and C. J. Keifer, "The Hydrology of Urban Runoff," *American Society of Civil Engineers, Transactions, 125,* p 1308 (1960).

Tucker, L. Scott, *Availability of Rainfall-Runoff Data for Sewered Catchments,* American Society of Civil Engineers Urban Water Resources Research Program, Technical Memorandum No. 8, New York, 43 pp (1969).

U. S. Weather Bureau, *Rainfall Frequency Atlas of the United States,* Technical Paper No. 40, Washington, D.C. (1961).

University of Cincinnati, *Urban Runoff Characteristics,* Federal Environmental Protection Agency Water Pollution Control Research Series 11024DQU (1970).

Watkins, L. H., *The Design of Urban Sewer Systems,* Road Research Technical Paper No. 55, Dept. of Scientific and Industrial Research, London, Her Majesty's Stationery Office (1962).

Wilson, K. V., *A Preliminary Study of the Effect of Urbanization on Floods in Jackson, Mississippi,* U. S. Geological Survey Professional Paper 575D, pp 259-261, Washington, D.C. (1968).

SECTION XI
GLOSSARY OF TERMS

Design Area — The paved portion of a basin from which runoff water can reach the gage without first passing over grassed area. This term is synonymous with the directly connected paved area.

Design Storni — A rainfall pattern of specified amount, intensity, duration, and frequency.

Directly Connected Paved Area — The paved portion of a basin from which runoff water can reach the gage without first passing over grassed area.

Entry Time — The time in minutes for runoff water to flow from the most remote point on the directly connected paved area to a specified inlet.

Reach — The smallest subdivision of the drainage system consisting of a uniform length of open Channel or Underground conduit.

Sub-Basin — A physical division of a larger basin which is associated with one reach of the storm drainage system.

SELECTED WATER RESOURCES ABSTRACTS
INPUT TRANSACTION FORM

1. Report No.

2.

3. Accession No.
W

4. Title
STORM SEWER DESIGN — AN EVALUATION OF THE RRL METHOD

5. Report Date

6.

8. Performing Organization Report No.

7. Author(s)
John B. Stall and Michael L. Terstriep

10. Project No.
EPA 11030 FLN

9. Organization
Illinois University, Urbana, Illinois 61801,
Illinois State Water Survey

11. Contract/Grant No.

13. Type of Report and Period Covered

12. Sponsoring Organization

15. Supplementary Notes
Environmental Protection Agency report number EPA-R2-72-068, October 1972.

16. Abstract

Storm rainfall and runoff data were assembled from 10 urban basins in the U.S.A. ranging in size from 14 acres to 8 sq mi. The British RRL method of storm drainage design was applied to the 10 basins. The RRL method considers the urban basin to be comprised of the paved area of the basin which is directly connected to the artificial storm drainage system. In 3 of the 10 basins the RRL procedure was deemed to be appropriate and suitable for the design of a storm drainage system within the normal range of frequency of design rainfall events, from 2 to 20-year events. For greater storms and for certain cases within this frequency range, the RRL method breaks down because the runoff coming from the grassed area of the basin is significant. If the basin is highly steep or if the paved area comprises less than 15% of the total basin, this breakdown occurs. An example is given of the use of the RRL method in the re-design of an existing storm drainage system, as is current practice in Great Britain.

17a. Descriptors
*Storm drains, *storm runoff, rainfall-runoff relationships, closed conduit flow, sewers, hydrographs, surface drainage, peak discharge, surface runoff, urbanization, design flow.

17b. Identifiers

17c. COWRR Field & Group 02E

18. Availability

19. Security Class. (Report)

20. Security Class. (Page)

21. No. of Pages

22. Price

Send To:

WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D. C. 20240

Abstractor John B. Stall

Institution

ENVIRONMENTAL PROTECTION AGENCY
Publications Distribution Section
Route 8, Box 116, Hwy. 70, West
Raleigh, **North** Carolina 27612

Official Business

POSTAGE AND FEES PAID
ENVIRONMENTAL PROTECTION AGENCY

EPA-335

Special Fourth-Class Rate
Book

If your address is incorrect, please change on the above label; tear off; and return to the above address.
If you do not desire to continue receiving this technical report series, CHECK HERE ☐ ; tear off label, and return it to the above address.