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COMPUTER SIMULATION OF URBAN RUNOFF CHARACTERISTICS WITHIN SALT LAKE COUNTY

by

Robert Newman Parnell, Jr.

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil Engineering

Approved:

UTAH STATE UNIVERSITY
Logan, Utah

1971

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Robert N. Parnell, Jr.

Robert Newman Parnell, Jr.

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PARTIAL LIST OF SYMBOLS

A	Area
a_i	Impervious area
b	Channel width
C_f	Percentage impervious cover
F	Mass infiltration
f	Instantaneous capacity rate of infiltration
f_c	Average minimum infiltration rate over the entire catchment area
f_o	Average maximum infiltration rate over the entire catchment area
IC	Initial conditions on the integration amplifiers
i	Rate of precipitation
i_2	Rate of outflow after losses are deduced from rainfall, i
i_{cc}	Capacity rate of inflow into interception storage
K_f	Decay parameter for infiltration
L_f	Characteristic impervious length factor
L_m	Mean characteristic impervious length
L	Length of flow
n	Manning's roughness coefficient
P	Cumulative precipitation
P_e	Rate of rainfall excess
Q	Rate of runoff
Q_c	Analog computer value representing cubic feet/sec

PARTIAL LIST OF SYMBOLS (Continued)

Q_i	Rate of inflow into the upstream section of a channel
Q_o	Rate of outflow from the downstream section of a channel
Q_p	Peak discharge
Q_T	Total volume of outflow, ac-ft
S	Catchment area storage or slope
S_d	Depression storage expressed as a mean depth over the entire catchment area
S_I	Volume of interception storage capacity expressed as an average depth over the entire catchment area, inches
T_L	Lag time for channel routing
t_R	Rise time of hydrograph during overland flow-inlet time
σ_c	Capacity rate of inflow into surface depression storage

ABSTRACT

Computer Simulation of Urban Runoff Characteristics Within Salt Lake County

by

Robert Newman Parnell, Jr., Master of Science

Utah State University, 1971

Major Professor: Dr. J. Paul Riley
Department: Civil Engineering

A hybrid computer program is developed to simulate the outflow hydrographs of two urban watersheds located within Salt Lake County, Utah. The gaged outflow of the watersheds provided a checkpoint for comparing the observed and the simulated final outflow hydrographs.

The outflow hydrographs for each subzone of the two watersheds were obtained by abstracting interception, infiltration and depression storage from each subzone hyetograph. The outflow of the subzones were routed to the Jordan River, the final outflow point of the two watersheds. The final hydrographs of the watersheds were combined and compared with the gaged flow.

The uniquenesses of this systems model are the flexibility in varying hyetographs, variable loss rates, combination of subzone hydrographs, and the combination of watershed hydrographs. Subzone hydrographs can also be plotted for visual inspection as well as obtaining numerical values. With a variety of input and output data, designers and planners can visually perceive urban runoff characteristics. The systems model should be a tool used by those interested in urban runoff characteristics.

(123 pages)

CHAPTER I

INTRODUCTION

Because of the rapid urban development in recent years and the associated property damage potential, the hydrology of urban watersheds has gained increased importance. The American Public Works Association (1966) estimated that flood damages to both real and personal property within urban areas of the United States currently exceed \$1 billion per year. Estimates of expenditures before the year 2000 for storm drainage facilities to serve the rapidly-expanding urban population exceed \$25 billion. Demographers predict a population of 320 million persons within the United States by the year 2000, with over 90 percent expected to reside in urban areas occupying only a few percent of the total national geographic area (ASCE Urban Hydrology Research Council, 1968).

The increased importance of urban hydrology is well-recognized by today's planners. Such awareness results from the rapid growth of the nation's urban areas and, in many cases, the drainage problems associated with this growth as indicated by appropriation requests for expensive structures. Because drainage structures are costly to install and maintain, economics has motivated the search for better and more efficient hydrologic analysis and more efficient design schemes.

An urban watershed may be defined as a catchment area in which the natural stream channels are supplemented with or replaced by a system of artificial drainage works including paved gutters and storm sewers. Although it is difficult to describe the usual urban drainage system in quantitative terms, a systematic approach to the particular hydrologic problems associated with an urban watershed requires some form of descriptive quantification. This process involves the development of an adequate mathematical description of the various hydrologic processes and a practical method of incorporating the mathematical equations into a model which simulates the physical system. In this study a model of this nature is applied to a particular drainage area in Salt Lake County, and the model is used to examine the effect of hydrologic parameters on the urban drainage system.

Objectives

The objective approach to this problem is to select a highly-urbanized area and to evaluate the effects that various urban parameters have on the urban flood hydrograph. Specific objectives of this study are:

1. To develop a systems model utilizing the urban hydrology simulation model developed at the Utah Water Research Laboratory.

2. To calculate the urban watershed parameters needed in the simulation model.

3. To include storage considerations for the temporary storage of portions of the watershed subzone discharge.

4. To synthesize urban outflow hydrographs with the calculated input parameters.

5. To design the systems model such that it will accommodate an economic analysis for hydraulic design within the watershed.

Organization of the Study

The report is organized into six chapters. A review of urban watershed modeling studies is given in the remainder of this chapter. Chapter II illustrates the watershed study area while Chapter III gives the development of the hydrologic model. Computer programming is discussed in Chapter IV. Application of the model to the watersheds is the subject of Chapter V which also with outflow hydrographs gives the results followed by a discussion. Finally, Chapter VI gives the summary and recommendations of this study.

Runoff Considerations

Although rainfall is described as a stochastic process, rainfall excess that becomes runoff from the urban watershed can be described mathematically. Useful and reasonably accurate results are possible though some simplifications are necessary to derive and solve the mathematical equations. A mathematical model of the runoff process takes into account the total rainfall less the various losses to obtain net rain. This net rain eventually collects and becomes surface outflow. Losses entail evapotranspiration, interception, infiltration, and surface depression storage. In the urban model, the time considered is too short for evapotranspiration to become a significant factor and for groundwater to enter the runoff flows; therefore, these processes are not included. A schematic diagram of the hydrologic processes is shown in Figure 1. 1. The dotted line indicates the parameters considered in this study.

The amount of rainfall loss to interception, infiltration, and surface depression storage is not easily measured and can vary from storm to storm, season to season, and year to year. Further factors complicating the rate of runoff supply are the spatial and time distribution of rainfall as well as the antecedent conditions within the given watershed.

The same abstractive runoff processes operate on both rural and urban watersheds. The difference being that urban watersheds are covered with significant quantities of impervious area which alter the operation of the abstractive processes of a natural watershed. Of primary importance is the increase in total volume of runoff due to decreased infiltration, gutter and storm drain systems, and main channel improvements that change inlet time and lag time on an urban watershed.

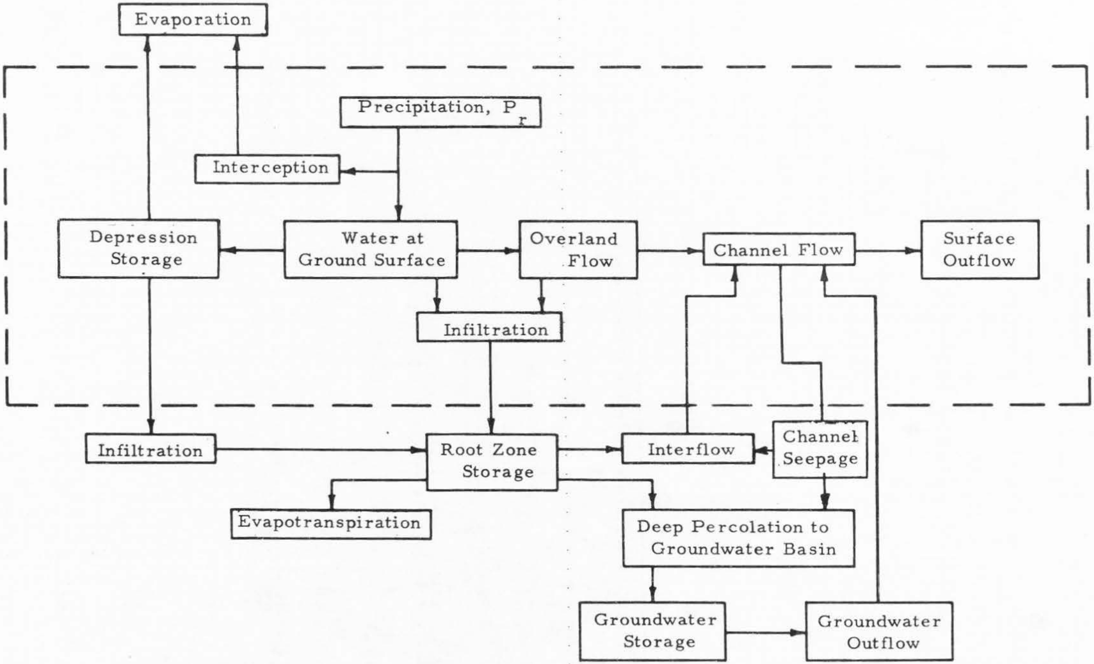

Evaporation
Precipitation, P_r
Interception
Depression Storage
Water at Ground Surface
Overland Flow
Channel Flow
Surface Outflow
Infiltration
Infiltration
Root Zone Storage
Interflow
Channel Seepage
Evapotranspiration
Deep Percolation to Groundwater Basin
Groundwater Storage
Groundwater Outflow

Figure 1.1 Schematic diagram to obtain surface outflow. The dotted line indicates the parameters considered in this study.

Numerous studies have been conducted in which the objective was to investigate the changes due to urbanization in the runoff process of a rural watershed. Following is a list of the major effects of urbanization taken from Crippen and Waananen (1969) and Espey, Morgan, and Masch (1965):

1. Greater total volume of runoff due primarily to a decrease in infiltration.
2. Higher peak discharge for a given storm input.
3. Higher frequency of flood peaks as a direct result of Number 2.
4. Shorter rise time; artificial channelization causes a much quicker response to rainfall excess.
5. Marked increase in sediment production during construction phases of urban development.

Review of Urban Watershed Modeling Studies

A review of the literature, pertinent to the fields of hydrologic modeling and storm drainage systems for urban areas, shows the overwhelming interest in urban drainage systems and in economic studies of urban flooding. Universities and private investigators have conducted and published the results of considerable research. A selection of literature and pertinent topics follows.

Recent studies investigating the nature of the hydrologic effects of urbanization and development on watersheds have provided feedback useful in approaching hydraulic design and subsequent economic analysis. Varied approaches have been taken to relate urbanization and watershed responses. The use of the unit hydrograph method, after chronologically abstracting losses, is widely accepted. Studies on a microscopic scale, involving the application of overland flow equations to small impervious areas, were also made. Statistical analysis of runoff and urban watershed parameters provide other avenues of investigation. The major part of urban hydrology research has dealt with the evaluation of urbanization effects on the hydrograph characteristics of lag time and peak discharge.

Tholin and Keifer (1960) made a detailed study of rainfall-runoff relationships in urban areas based on a "Design Storm" of three hours duration. The "Chicago Hydrograph Method" of sewer design evaluates the physical effect of rainfall abstractions and flow detentions on the hydrographs of sewer supply and sewer outflow. Various types of uniform land use, ranging from suburban residential to industrial and commercial, were analyzed to determine their influence on the infiltration capacity of pervious areas; depression storage; overland flow detention; detention in gutters; and detention in lateral sewer systems. In evaluating the land use characteristics in terms of pervious and impervious areas several simplifying assumptions were introduced.

Utilization of the Stanford Watershed Model in studies where a complete water budget is of interest has produced some significant results. This digital computer model is based on a system of equations used to keep a running tabulation of all water entering the watershed as inflow or precipitation, stored within the watershed and leaving the watershed as runoff, subsurface outflow, or evapotranspiration (Crawford and Linsley, 1962).

James (1965) used the Stanford Watershed Model to develop a long-term continuous hydrograph, between 1905 and 1963, for Morrison Creek, Sacramento County, California, which drains 72.7 square miles. By varying constants which describe the physical conditions within the watershed, a number of continuous hydrographs were developed. Synthesis of hydrographs for any combination of urbanization, channel improvement, and precipitation input could, thereby, be produced.

James attempted to relate the independent variables (urbanization, channelization, and tributary area) with the dependent observed flood peaks. A trial and error procedure was used to determine the 32 constants and 3 arrays necessary to describe the watershed characteristics for the digital program. In his models, the inputs altered to represent changes in the degree of urbanization were:

1. Advance of the time-area histogram of inflows to reflect the probable installation of storm sewers;
2. Increase in the impervious area;

3. Decrease in maximum hourly interception and depression storages because of the reduction in undrained natural depressions with increase in urbanization;
4. Reduction in upper zone soil moisture storage;
5. Reduction in overland flow delay; and
6. Reduction in interflow delay.

James concluded from his study that impervious cover and channelization are the most important parameters of urbanization affecting the runoff process in a watershed.

Dempsey (1968), using the Stanford Model and James' values for a typical urban area land use breakdown, proceeded to run an economic analysis for Morrison Creek, California, and Pond Creek, Kentucky. To do so he first required an average of structure value assessments from the Jefferson County tax records. Eighteen sample properties were selected on a random basis and categorized according to residential, commercial, or industrial land use. The structural value and the acreage of each property were tabulated. The market values were divided by the acreages so as to get a structure value in dollars per acre. The values per acre for properties in each category were averaged to get values for residential, commercial, and industrial properties. Urban and agricultural damages were considered for various frequencies of flooding. The damage sustained was assessed according to the depth of flooding. Channel improvements were considered and incorporated into the degree of protection and flood frequencies. Using a discount rate, an economic analysis was made for various flood frequencies related to depth-damage parameters.

Viessman (1966) considered the design of a storm drainage system a twofold problem: (1) individual runoff inputs must be determined at each inlet or group of inlets; and (2) these inputs must then be routed and combined in the storm sewers, enabling outflow hydrographs to be synthesized at any point of interest. His study is limited, specifically, to the determination of runoff hydrographs for small (0. 4 to 1. 0 acre) impervious urban inlet areas. In small urban areas (up to several acres in size) the drain can be considered to act as a linear reservoir. The hydrology of these small areas is exceedingly important, as most composite urban drainage areas can be broken up into a subset of smaller areas usually tributary to the storm water inlets. Thus, if the runoff hydrograph at each inlet within an urban drainage area can be predicted adequately, then routing of the various inlet flows would produce the desired outflow hydrograph.

In his study Viessman used the following method of analysis:

1. The rainfall excess was determined by considering the same losses as are present in a rural watershed. Because the study areas were all 100 percent impervious, infiltration and interception were neglected, and depression storage accounted for all abstractive losses.

2. The drainage area was considered a linear reservoir with the storage, S, directly proportional to the outflow. In mathematical terms, $S = kq$. The continuity equation is:

$$i - q = \frac{ds}{dt} \tag{1.1}$$

in which

i = inflow rate (effective precipitation)

q = outflow rate (rate of runoff)

The outflow rate, q, is given by the following expression:

$$q = q_{max} \exp(-\tau/k) \tag{1.2}$$

in which

$$q_{max} = i\,(1 - e^{-1/k}) \tag{1.3}$$

in which

k = parameter indicating lag time

$\tau = t - 1$

3. Synthesis of the total runoff hydrograph by the unit hydrograph method.

Willeke (1966) hypothesized that a linear storage system could be used to transfer the time distribution of effective precipitation into the time distribution of runoff. If this idealization is sufficiently accurate, then the lag time of the watershed would be the only parameter needed to describe the characteristics of the linear storage system.

Willeke used a two-part procedure for the hydrograph synthesis on small urban catchment areas. First, the effective precipitation pattern was determined by using the phi-index method. Second, effective precipitation was routed through reservoir storage by the Muskingum formula using coefficients based on $x = 0$ and $k =$ lag time.

Evidence presented showed that the lag time, defined as the time between centers of mass of effective precipitation and runoff, was essentially constant for small urban watersheds. There were few significant correlations between lag time and storm magnitude. These findings tend to support the hypothesis of linearity.

Espey et al. (1965) undertook a study to evaluate the various effects of urbanization on the hydrologic characteristics of a small urban watershed located within Austin, Texas. A linear regression analysis of data from 24 urban and 11 rural watersheds was used to derive equations which would evaluate the past rural conditions and predict future urban conditions for the Waller Creek watershed. The effects or urbanization on the discharge hydrograph include a decrease in hydrograph rise time, as well as increases in peak discharge and unit yield (in/mi^2).

Narayana et al. (1969) devised a watershed model for an analog computer simulation of the runoff characteristics of an urban watershed for the Waller Creek experimental watershed near Austin, Texas. He found that the watershed coefficients of the equivalent rural watershed depended upon urban parameters which vary from year to year. These watershed coefficients were represented by interception storage capacity,

S_I, the maximum infiltration capacity role, f_a, the minimum infiltration capacity rates, f_c (and the exponential decay factor in Horton's infiltration equation, k_f), the depression storage capacity, S_D, and the rise time of the unit hydrograph, t_R. He simulated some 48 storms on the watershed and, by a regression analysis, derived the watershed coefficients based upon urban parameters of percent impervious area, C_f, and characteristic flow length, L_f. His study assumed the watershed as one catchment area.

Evelyn et al. (1970) expanded on the Narayana et al. (1969) model by dividing the Waller Creek watershed into subzones and calculating the new percent impervious area and the characteristic flow length. He also devised a method of routing the subzone flows to the final outflow point.

Several conclusions reached on the urban hydrology literature reviewed are:

1. The unit hydrograph method is at present the most versatile approach to hydrograph synthesis.
2. More research investigating the effects of intermingling pervious and impervious areas is needed.
3. More climatologic and hydrologic data are needed for more conclusive results in statistical studies.
4. Accurately describing the abstractive loss processes of interception, infiltration, and depression storage is the

most difficult aspect of urban watershed modeling, as these losses are interrelated and depend on many variables.

5. Watershed modeling studies are giving good results where a sufficient quantity and quality of data are available to verify the model.

The analog computer simulation model for urban hydrology developed by Narayana et al. (1969) and the modification by Evelyn et al. (1970) forms the foundation of the present study.

CHAPTER II

DESCRIPTION OF THE WATERSHED STUDY AREA

The urbanized area of Mill Creek and Big Cottonwood is within Salt Lake County, Utah. This area was selected for study because it is subject to frequent storm runoff which exceeds the existing drainage system capacity and results in flood damage. The U. S. Department of Agriculture has aerial photographs of this area with flights in June and July 1965. Most of the climatologic, hydrologic, and geologic data pertaining to the area are published in the form of annual reports or are in the files of public offices and can be used in the application of the watershed model.

The Watersheds

Mill Creek and Big Cottonwood Creek are located within Salt Lake County, near Salt Lake City, Utah, and both are tributaries to the Jordan River (Figure 2. 1). The drainage area above Mill Creek is 21. 7 square miles, and the drainage area above Big Cottonwood Creek is 50. 0 square miles. These drainage areas lie in the Wasatch Mountains above the study area. The urban drainage area of Mill Creek and Big Cottonwood Creek within the area studied are 14. 8 and 23. 3 square miles, respectively, and extend from the foot of the

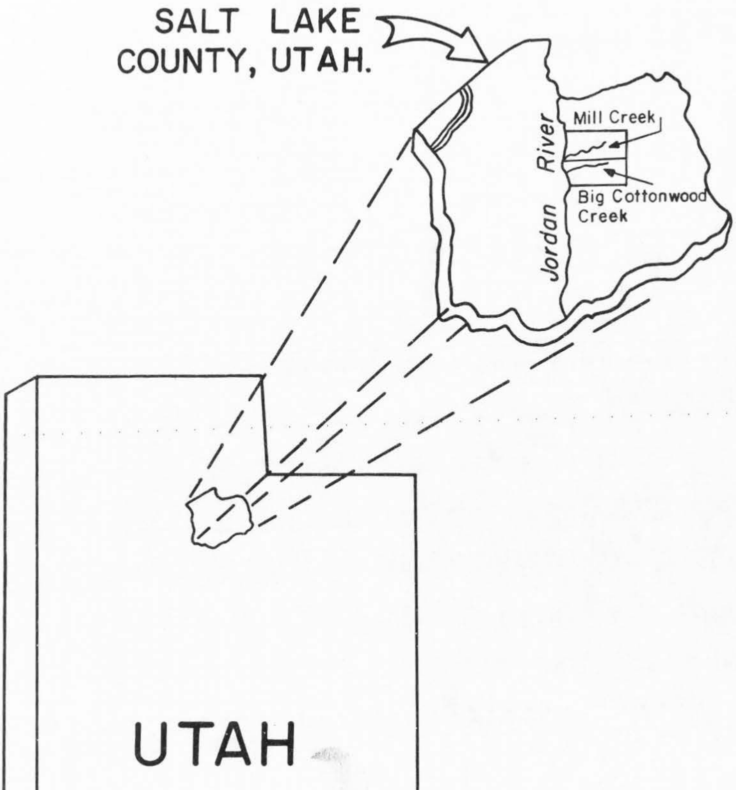

SALT LAKE
COUNTY, UTAH.
Jordan River
Mill Creek
Big Cottonwood
Creek
UTAH

Figure 2.1. The watershed within Salt Lake County, Utah.

Wasatch Mountains to the Jordan River. The Jordan River flows northward into the Great Salt Lake.

Geography

The urban watershed is situated west of the Wasatch Mountains and extends westward to the Jordan River, northward to Interstate 80, and southward almost to Little Cottonwood Creek, a total area of 38 square miles.

Topography

Storm and flood waters flow by gravity from the Wasatch Mountains toward the Jordan River (Figure 2. 2). The rapid runoff of storm and flood waters from steep grades creates a problem of control in ditches, curbs, and gutters on the flatter areas due to the volume of water that must be conveyed to the Jordan River. Storm water collects and passes off quickly from the steeper slopes onto the flatter areas, adding to the burden of collecting and passing storm water which originates on these flatter areas. The watershed of interest is predominantly residential, with various patches of commercial and light industrial complexes.

Climate

The Salt Lake City area has temperate, semi-arid climate with a temperature range from a $-20^{\circ}F$ to a high of $105^{\circ}F$. Precipitation varies with elevation, with normal annual values of 16 inches at Salt

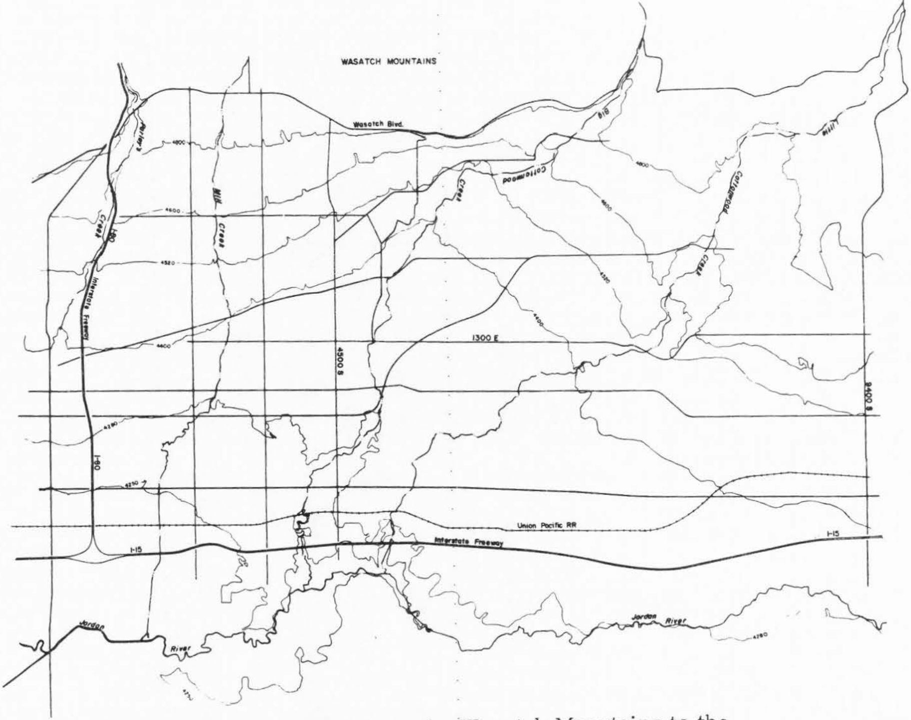

WASATCH MOUNTAINS
Wasatch Blvd.
Parleys
Creek
Mill
Creek
Cottonwood
Creek
Cottonwood
Creek
Mill
I-80
Interstate Freeway
I-80
1300 E
4500 S
9400 S
Union Pacific RR
I-15
Interstate Freeway
I-15
Jordan
River
Jordan
River
4800
4600
4520
4400
4280
4250
4800
4600
4520
4400
4280

Figure 2.2. Topography from the Wasatch Mountains to the Jordan River.

Lake City to 40 inches at higher elevations in the mountains. Rain may come in a low volume steady fall over a period of many hours, or it may come as a high intensity short duration storm causing heavy flow from a concentrated or a relatively large area. The Weather Bureau (National Weather Service) has maintained continuous records at Salt Lake City for more than 85 years which gives general background information.

Geology

As the steep slopes of the mountains merge with the upper planes of the valley, rocks, and gravel are overlain with sand and soil. Vegetation of the scrub oak variety abounds with some grasses. This type of soil has considerable absorptive quality for storm water. Floor runoff or high velocity flows of storm water tend to cut and gulley this type of soil formation. Once disturbed in grading, trenching, or other movement, this area becomes highly vulnerable to washing and displacement, and when water is applied to the surface it cannot be readily absorbed. In the lower plane of the watershed, the soil becomes heavier and more compact. Its absorptive ability lessens and there is the tendency for more but slower runoff to occur. In depressions, there is ponding rather than absorption by the soil.

Instrumentation

The watershed's basic instrumentation data were obtained from six precipitation stations and six gaging station (Figure 2. 3). Of these

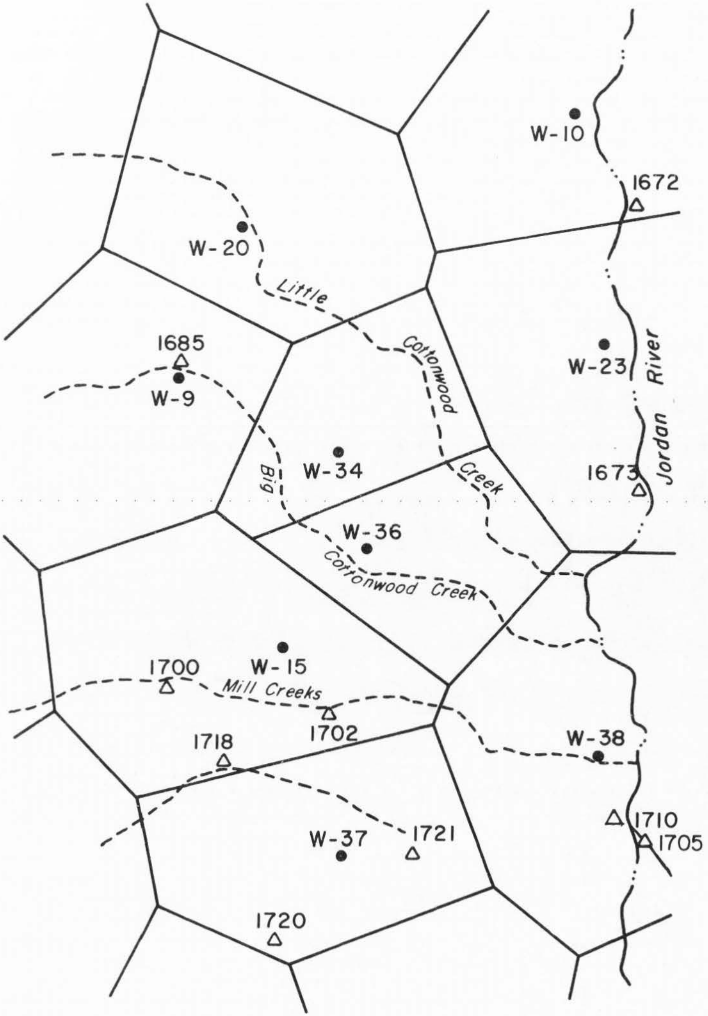

W-10
1672
W-20
Little
Cottonwood
1685
W-9
W-23
River
Jordan
W-34
Big
Creek
1673
W-36
Cottonwood Creek
W-15
1700
Mill Creeks
1702
1718
W-38
1710
1705
W-37
1721
1720

Figure 2.3. Instrumentation of the watersheds.

data, two gaging stations were on Mill Creek, two were on Big Cottonwood Creek, and two were on the Jordan River. Three non-recording precipitation stations were in the Mill Creek watershed and three were in the Big Cottonwood Creek watershed, with one station being used jointly in the Thiessen network analysis.

Drainage conditions

All storm water which falls within the watershed must flow in existing natural water courses, man-made water courses, or follow the curbs and gutters to the Jordan River. One important factor affecting the runoff is the present barriers to flow, notably railroads and highways. Runoff reaching these barriers will pass through existing culverts or drains, change direction of flow, or build-up and form ponds.

The existing pattern of residential streets acts as collecting drains, and the drainage pattern follows the layout and slope of the streets. Other minor diversions which are present within the study area are irrigation canals and storm sewers.

CHAPTER III

THE HYDROLOGIC MODEL

The research undertaken in this study makes use of the urban watershed model developed at the Utah Water Research Laboratory by Narayana et al. (1969) and used by Evelyn et al. (1970). Their digital computer programs used to calculate input data were modified to reflect the conditions within Salt Lake County, Utah, and also to make the programs generally more flexible and readily adaptable to a hybrid system.

Modeling Procedure

Narayana et al. (1969) sought to accurately describe the runoff process of a small urban watershed by developing an adequate mathematical model which could be programmed on an analog computer for verification. Evelyn et al. (1970) applied the Narayana et al. (1969) mathematical model to subzones of the watershed in Austin, Texas. A summary of the original procedure and back-up data needed for the mathematical model is necessary as a supporting foundation.

The Narayana et al. (1969) modeling procedure is outlined as follows:

1. Identification and definition of measurable urban parameters. (These are coefficient of impervious cover and characteristic impervious length factor.)

2. Mathematical description of the various phases of the runoff process in terms of the physical characteristics of the watershed.
3. Verification of the mathematical model on an analog computer by simulation of several recorded runoff events.
4. Determination of the watershed coefficients from model verification and relating them to the corresponding urban parameters.
5. Prediction of future urban parameters and determination of the corresponding watershed coefficients. The watershed coefficients are dependent on the urban parameters.

Subsequent use of the verified model would then require knowledge of the two urban parameters and precipitation. The estimated urban parameters must, of course, represent the same time period as the precipitation values represent.

Utilizing the functional relationship developed in step 4 between watershed coefficients and urban parameters, the values of watershed coefficients are determined from any given set of urban parameters. By applying these watershed coefficients, the outflow hydrograph can be predicted for any storm.

Urban Parameters

The most difficult part of hydrograph synthesis in urban areas is the accurate determination of the abstractive processes of interception, infiltration, and depression storage. Therefore, the selection of parameters, which are readily measured yet capable of providing a representative index of the various rainfall losses, is the most crucial decision in striving for good model simulation. The percentage impervious cover and the characteristic impervious length factor have been chosen as parameters which represent the watershed processes and which are easily identified without special skills.

Computation of urban parameters

Initial decisions in this procedure involve the determination of the spatial unit size. Narayana et al. (1969) chose the entire watershed as the primary catchment area. Evelyn et al. (1970) found that the synthesis of outflow hydrographs at selected locations within a basin dictated that a smaller subwatershed or subzone be chosen as the primary catchment area. The outflows from the subzones are routed and combined to determine the outflow hydrograph at the specified point. A smaller unit of spatial integration would be the urban block and would allow one to synthesize storm inlet hydrographs. An efficient procedure given by Evelyn et al. (1970) for the computation of the urban parameters, which are subsequently used in calculating the watershed coefficients, is outlined and used in this study.

I. Divide the watershed into a number of subzones (Figure 3.1).

  A. Factors influencing the number of subzones and their boundaries are:

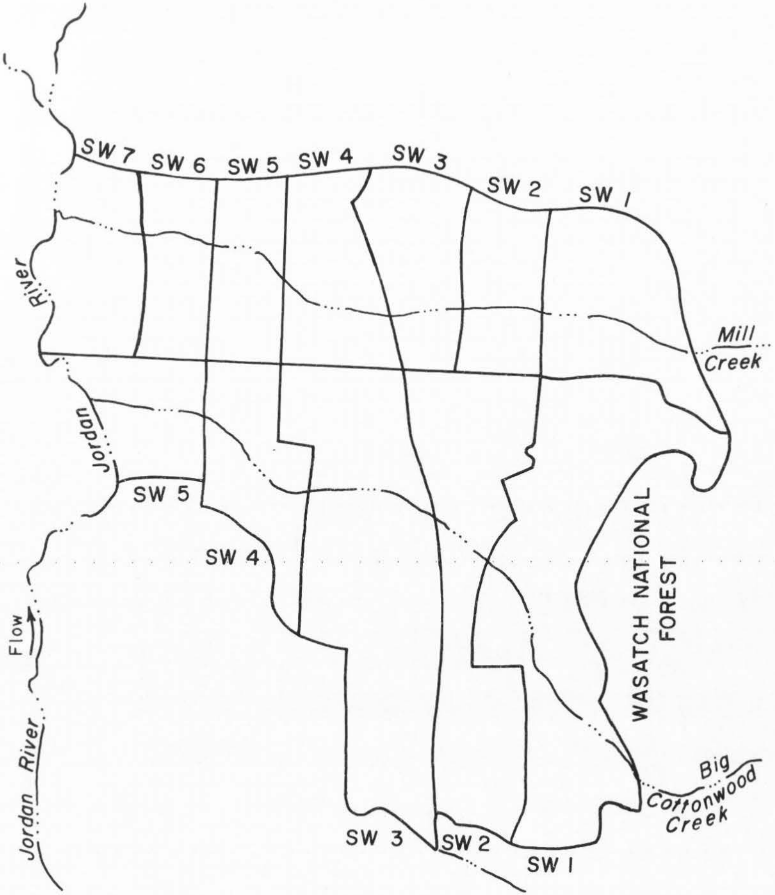

SW 7
SW 6
SW 5
SW 4
SW 3
SW 2
SW 1
River
Mill Creek
Jordan
SW 5
SW 4
WASATCH NATIONAL FOREST
Flow
Jordan River
Big Cottonwood Creek
SW 3
SW 2
SW 1

Figure 3.1. Dividing the watershed into subzones.

1. Natural topography and street configurations.
2. Location of rainfall and streamflow gages.
3. Objectives of study, i. e., different boundaries might be chosen for investigations of storm characteristics, of land use studies, and of design of flood control structures.
4. Location and direction of diversions.

B. The concept of the subwatershed model requires that all outflow from a subzone exit through one point. Although this condition may not be satisfied completely, it should be adhered to as closely as possible.

II. Determine the impervious cover of roads, buildings, parking lots, and sidewalks. First, the use of large aerial photographs (in the present study, aerial photos had a scale of 1" = 400') greatly reduces the work involved in that minimal enlargement and tracing of details is necessary. The personnel gathering data can work directly on the aerial photographs, delineating boundaries, subzones, and units within subzones by different color wax pencils which can be erased if necessary. Second, although the procedure outlined catalogs the areal extent of roads, buildings, parking lots, and sidewalks separately for each unit considered, the important parameter is the total impervious area. The separation of impervious cover into individual types was deemed a beneficial feature even though it somewhat increases the amount of work necessary in gathering data. This feature allows a researcher or designer more flexibility in relating each individual type of impervious cover to the runoff characteristics of the watershed. The cataloging of each unit is also available when an economic analysis is commenced. The following procedure determines several average values of impervious cover which greatly reduce later computations.

A. Choose a number of residential blocks which provide a representative sample of each type of block within the watershed.
    1. Carefully measure the precise amount of each type of impervious cover for each block. The total area of the block was considered from the area enclosing the midpoints of the intersections of the adjacent roadways (Figure 3. 2). Measurements were best taken with a scale and rotometer. For large areas utilizing a large scale aerial-photo, the planimeter was advantageous.
    2. Calculate the percentage impervious area for each individual type of surface for each block.
    3. Average the results of all the blocks to obtain a mean impervious area for residential houses. Garage roofs, driveways, and home sidewalks

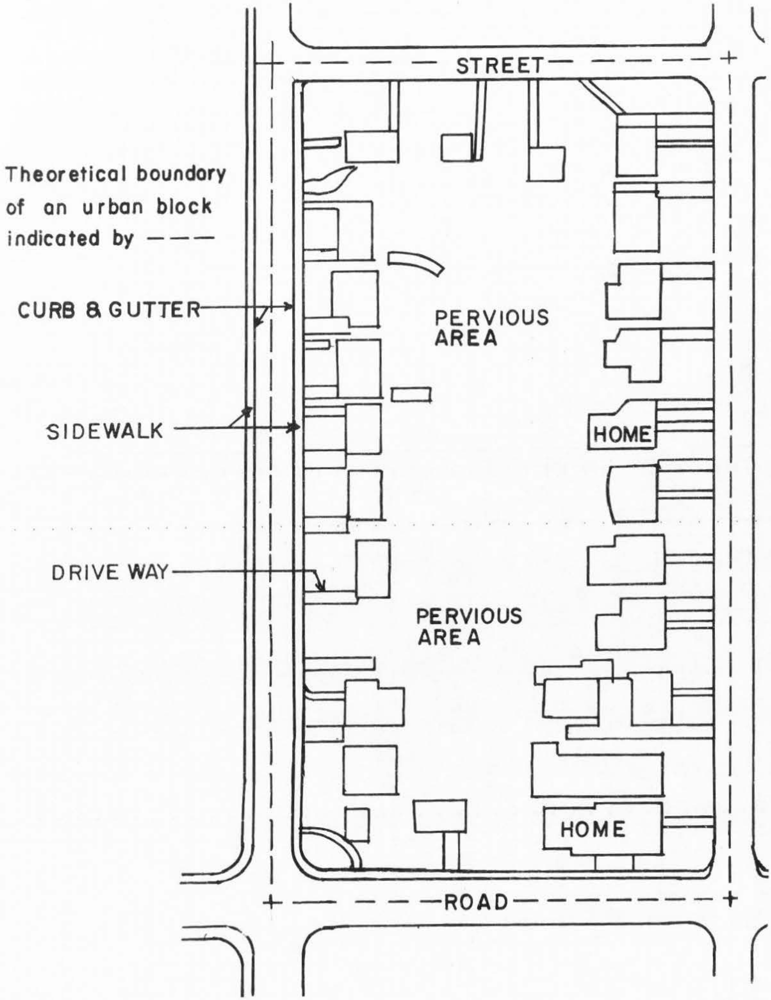

STREET
Theoretical boundary of an urban block indicated by ---
CURB & GUTTER
SIDEWALK
DRIVE WAY
PERVIOUS AREA
PERVIOUS AREA
HOME
HOME
ROAD

Figure 3.2. Typical urban residential block showing the pervious and the impervious areas.

were counted as residential houses. (An average residential home equal to 2400 ft^2 was used in this study. This value of 2400 ft^2 was obtained using a statistical analysis on the blocks sampled.)

4. In the same manner an average value for the width of residential streets and for thoroughfares was obtained. Freeways and main highways should be calculated individually.

B. Divide the primary catchment area into units based on the following criteria (Figure 3. 3).

  1. The amount of impervious cover and its distribution should be nearly homogeneous within the unit.
  2. The geometric center of the unit can be found from visual inspection. The geometric center of the unit was considered the point from which all runoff from the unit originates.

C. Analyze each unit within the basin to determine the percentage impervious cover.

  1. Using a rotometer, the length of all roads within a unit were rolled off. The resultant length multiplied by the road width equaled the area of the roadway.

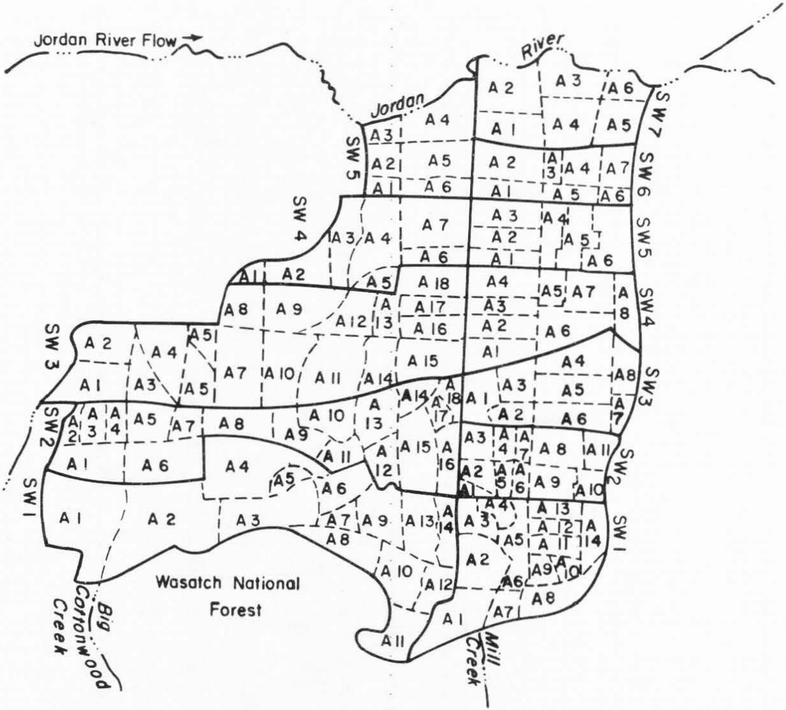

Jordan River Flow →
Jordan
River
SW 1
SW 2
SW 3
SW 4
SW 5
SW 6
SW 7
Wasatch National Forest
Big Cottonwood Creek
Mill Creek

Figure 3. 3. Dividing the subzone into smaller spatial units.

2. Parking lot areas were determined either by measuring their dimensions and multiplying or by use of a planimeter.
3. The area of buildings equaled the number of residential homes times the average roof area plus the larger roof structures such as industrial plants, hospitals, and churches.
4. The sidewalk cover was obtained by multiplying the sidewalk width by the length. The length can generally be found at the time of measuring street lengths.

III. Determination of the characteristic impervious length factor was made by using the following formula. (Reference is made to Figure 3.4.)

$$L_f = \frac{L_m}{L} \tag{3.1}$$

in which

$$L_m = \frac{\Sigma\, a_i l_i}{\Sigma\, a_i} \tag{3.2}$$

a_i = the impervious area of the i^{th} unit

l_i = the length of drainage from the geometric center of the i^{th} unit to the final discharge point of the subzone

L = the maximum length of flow draining from the subzone

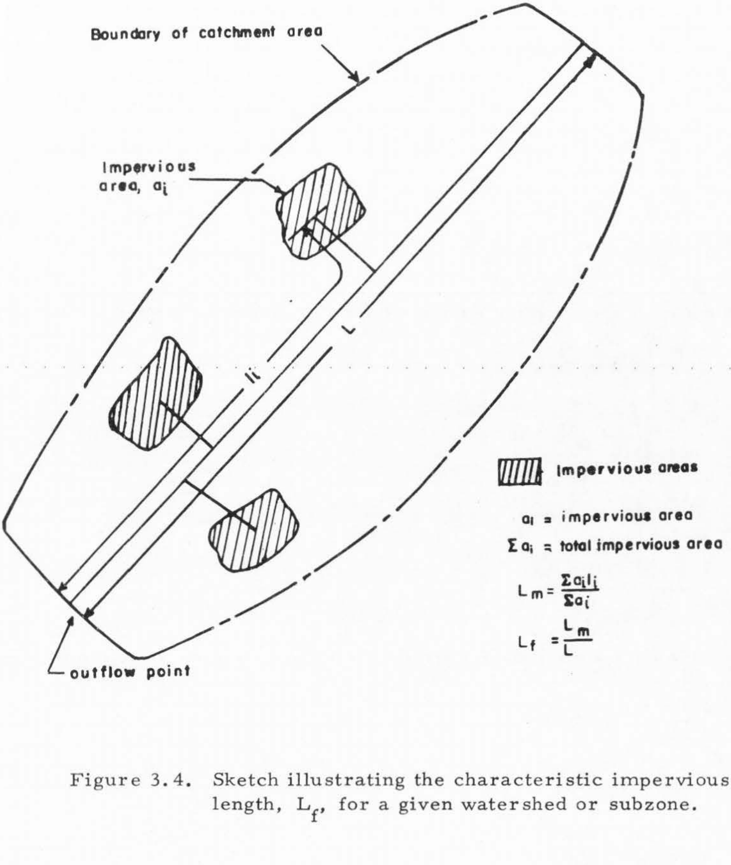

Boundary of catchment area
Impervious area, a_i
L
l_i
Impervious areas
a_i = impervious area
Σa_i = total impervious area
$L_m = \frac{\Sigma a_i l_i}{\Sigma a_i}$
$L_f = \frac{L_m}{L}$
outflow point

Figure 3.4. Sketch illustrating the characteristic impervious length, L_f, for a given watershed or subzone.

A contour map was required to determine the paths of drainage. U.S.G.S. quad sheets are excellent for most purposes and with a little field observation directions of flow at street intersections were obtained.

Summary of calculated urban parameters

Aerial photos within Salt Lake County for the Mill Creek and Big Cottonwood watersheds for the year 1965 were used to determine the urban parameters.

Table 3.1 shows the form of the data collected. The raw data were input to a computer program (Appendix A) to total the impervious categories and to calculate the impervious length factor and the percent impervious cover.

Having determined the urban parameters, the watershed coefficients were obtained for each subzone from the regression equations. These urban parameters are tabulated in Table 3.2 for the urban watershed of Mill Creek and Big Cottonwood Creek.

Justification for using an impervious area of 2400 ft^2 for an average urban unit results from the subjective sampling from aerial photographs of 21 residential blocks in the two urban watersheds. A mean residential home and mean driveway value were calculated for each block. The mean values were then entered into a statistical computer program which computed a mean residence area of 1833.2 ft^2 and a mean driveway area of 553.6 ft^2, to total 2486.8 ft^2 for an average urban unit. Confidence limits

Table 3.1. Sample form of data collected and calculations. Mill Creek SW-1

```
A     AREA    ROADS    HOMES   SIDEWALK PARKLOT   BUILD   IMPAREA  LENGTH   SUMS
       MSF      KSF      KSF     KSF       KSF      KSF      KSF     KF
 1     1.2    744.0    465.6      .0        .0       .0    1209.5     1.4  1693.4
       1.9     62.0     38.8      .0        .0       .0
 2     6.7    432.0    792.0    14.4     282.5    534.5    2155.3     1.4  3017.5
      10.8      6.4     11.5      .2       4.2      9.4
 3     3.5    432.0    328.8     7.2      91.5     73.8    *933.3     2.2  2053.2
       5.6     12.3      9.3      .2       2.6      2.1
 4     3.0    162.0    112.8     6.0      34.0     51.0     365.8     1.0   365.8
       4.3      5.4      3.7      .2       1.1      1.7
 5     9.2    770.0   1017.6    13.5     283.0    100.5    2184.5     1.0  2184.5
      14.9      8.3     11.0      .1       3.0      1.0
 6     3.7    469.0    549.0      .0        .0       .0    1018.0     1.2  1221.5
       6.0     12.6     14.8      .0        .3       .0
 7     7.2    600.0    732.0     8.4      28.0    252.0    1620.3     1.4  2268.5
      11.7      8.3     10.1      .1        .3      3.5
 8     4.9    932.0    542.4     3.6      87.0     40.0    1604.9     3.4  5456.9
       7.9     19.0     11.0      .1       1.7       .8
 9     2.2    224.0      7.2      .0        .0      3.0     234.2     3.0   702.6
       3.5     10.1       .3      .0        .0       .1
10     2.5    330.0    256.8      .0        .0       .0     586.8     4.2  2464.5
       4.0     13.2     10.2      .0        .0       .0
11     4.1    448.0    542.4      .0     286.0     88.0    1364.3     3.6  4911.8
       6.6     10.9     13.2      .0       6.9      2.1
12     3.4    292.0    364.8     4.0     282.0    140.0    1082.7     3.2  3464.9
       5.5      8.5     10.7      .1       8.2      4.1
13     2.8    430.0    554.4      .0     131.5     23.5    1139.3     3.2  3646.0
       4.5     15.3     19.8      .0       4.6       .8
14     7.1    218.0    369.6     6.0        .0       .0     593.6     5.2  3086.7
      11.5      3.0      5.2      .1        .0       .0
      61.5                                                           36538.5
PERCENT IMPERVIOUS AREA=    .2616       IMPERVIOUS  LENGTH FACTOR=  .2467
```

Table 3.2. Summary of the urban parameters.

Mill Creek							
	SW_1	SW_2	SW_3	SW_4	SW_5	SW_6	SW_7
C_f	.262	.220	.271	.026	.250	.273	.093
L_f	.477	.552	.629	.690	.682	.638	.706

Big Cottonwood Creek					
	SW_1	SW_2	SW_3	SW_4	SW_5
C_f	.118	.167	.117	.154	.320
L_f	.623	.489	.438	.401	.669

of 95 percent yielded values of a residence between 1716.9 ft^2 and 1949.4 ft^2 and driveways between 476.6 ft^2 and 630.6 ft^2. The upper and lower limits could range between 2193.5 ft^2 and 2580.0 ft^2, respectively.

For economic and time considerations, individual residence and driveway values were not calculated for each subzone as the additional refinement would not be significant. Individual measurement of the larger buildings, parking lots, and roadways, masks any small error in average residence and driveway values.

Determination of Rainfall Excess

Precipitation

The initial step in any watershed modeling procedure is to determine representative storm hyetographs or collect precipitation data for the catchment area under investigation. By applying the isohyetal or Thiessen's techniques to a raingage network, the areal distribution of precipitation can be determined. The Thiessen network was used in the present study, and the calculations for the storm hyetograph were made by the computer program in Appendix B.

The precipitation inputs consisted of non-recording gage daily totals correlated, by ratio, with data from the "Hourly Precipitation Data," published by the U. S. Department of Commerce. This hourly precipitation and the raingage totals for each storm were the input to the WATMOD program, and the daily totals from the non-recording stations were proportioned to the total of the recording gage. The time distribution of the two gage types were assumed to be equal, although in reality for convective storms, this may not occur. The precipitation for each storm was calculated in 30-minute time periods to correspond to the regression equations for the watershed coefficients.

The 30-minute precipitation was then used in the Thiessen network analysis to obtain the areal distribution over the urban watershed for the interval. The areal distribution of precipitation was then transferred to the analog computer where it was used by the watershed model.

Figure 3.5 illustrates the precipitation network used, the Thiessen polygon network, and the subzone boundaries. The calculations for the Theissen network analysis are contained in the WATMOD program in Appendix B. Sample input and output data are also given.

Figure 3.6 shows the isohyetal lines and the precipitation station totals for a storm that was used in this study. The isohyetal charts were not always available, therefore, recourse was made to the Thiessen method to determine areal distribution of precipitation.

The total precipitation values calculated for the subzones by the Thiessen method closely approximated the total precipitation values calculated by the isohyetal method for data of 1968. Several reasons for the two methods not being exactly equal are: 1) The isohyetal lines were drawn using the six stations used by the Thiessen method plus other precipitation stations that were not published but were used by

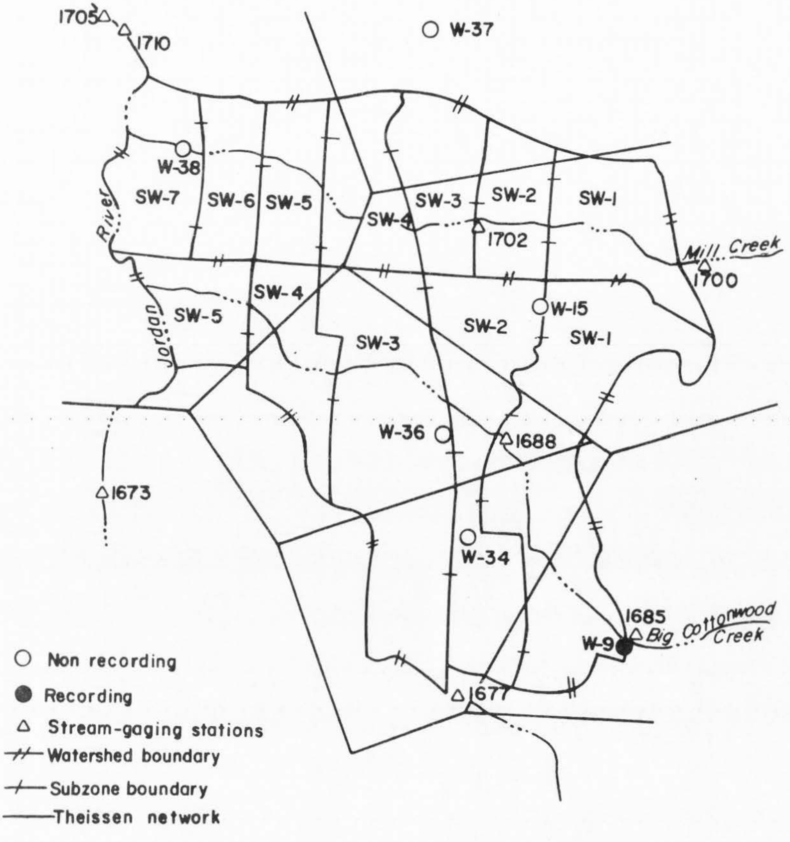

1705
1710
W-37
W-38
SW-7
SW-6
SW-5
SW-4
SW-3
SW-2
SW-1
1702
Mill Creek
1700
River
Jordan
SW-5
SW-4
SW-3
SW-2
W-15
SW-1
W-36
1688
1673
W-34
1685
Big Cottonwood Creek
W-9
1677
○ Non recording
● Recording
△ Stream-gaging stations
Watershed boundary
Subzone boundary
Theissen network

Figure 3.5. The Thiessen network over the watershed and the location of instruments.

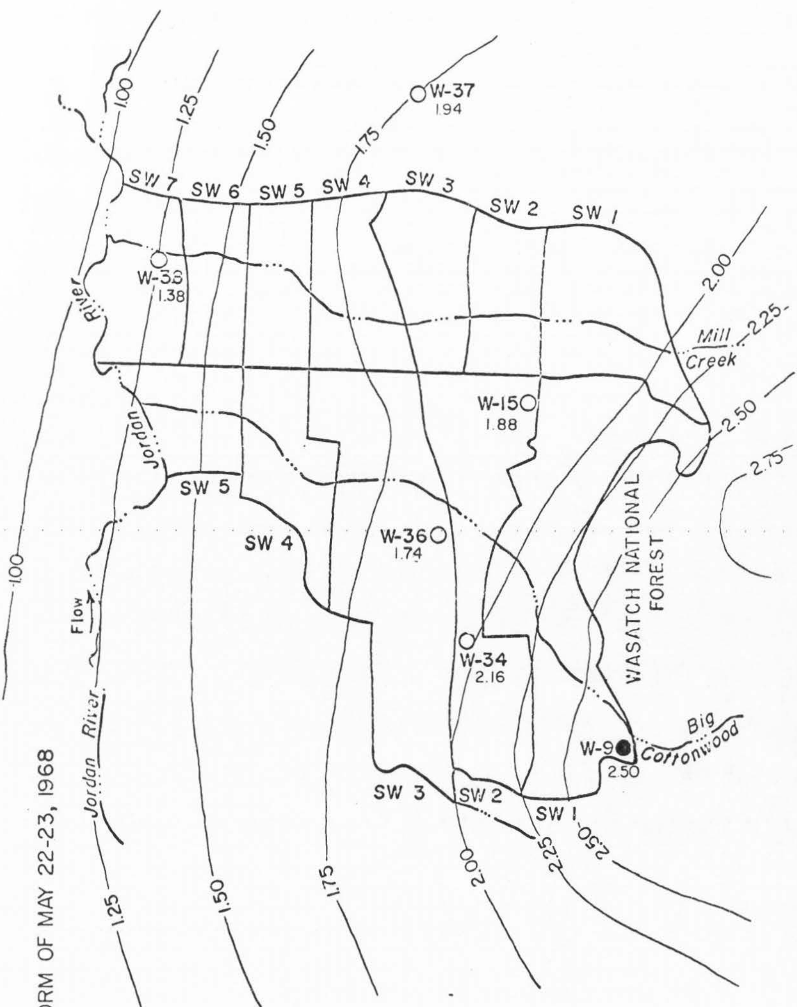

STORM OF MAY 22-23, 1968
W-37
1.94
W-38
1.38
W-15
1.88
W-36
1.74
W-34
2.16
W-9
2.50
SW 7
SW 6
SW 5
SW 4
SW 3
SW 2
SW 1
SW 5
SW 4
SW 3
SW 2
SW 1
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
Jordan River
Flow
Mill Creek
Big Cottonwood
WASATCH NATIONAL FOREST

Figure 3. 6. Isohyetal lines for the event of May 22-23, 1968.

another study for the purpose of gathering information for composing the isohyetal charts. 2) Several subzones had two or more isohyetal lines cross the subzone, while other subzones had no isohyetal lines crossing the subzone. 3) The isohyetal lines were drawn with 0.25 inch intervals and the precipitation station data were recorded to the nearest 0.01 inch.

Numerical comparisons for the 12 subzones were made and although the isohyetal method gave the graphical trend of a storm, the Thiessen method gave satisfactory values. The Thiessen method yielded 1.89 inches versus 2.00 inches by the isohyetal method for subzone 1 of the Mill Creek watershed. However, not all of the calculated Thiessen values were low, as the Thiessen values were both higher and lower relative to the isohyetal method. For example, subzone 3 of Mill Creek had a value of 1.91 inches by the Thiessen method and a value of 1.85 inches by the isohyetal method. Many of the compared values were extremely close. For example, subzone 2 of Mill Creek yielded a Thiessen value of 1.89 inches compared to 1.90 inches by the isohyetal method. The greatest difference between the two methods was 0.21 inch higher by the isohyetal method at subzone 5 of Mill Creek with an average difference of 0.02 inch high by the isohyetal method for the two watersheds for the 1968 data comparison.

Interception

Rainfall excess is calculated by subtracting losses, such as interception, from the precipitation reaching the ground or vegetative cover. The rate of interception was assumed to reduce exponentially with an increase in interception storage and can be expressed as

$$i_{cc} = ie^{-P/S_I} \tag{3.3}$$

in which

i_{cc} = capacity rate of inflow into interception storage

i = rate of precipitation

P = cumulative precipitation

S_I = volume of interception storage capacity expressed as an average depth over the catchment area

with the actual interception rate defined by

$$i_{ca} = i \text{ for } i > i_{cc}$$

and (3.4)

$$i_{ca} = i_{cc} \text{ for } i < i_{cc}$$

In order to generate the function ie^{-P/S_I} the following procedure is adopted. Let $i = 1.0$, the analog voltage in machine units, then $y = 1.0\, e^{-P/S_I}$.

Then the value to be integrated is

$$\frac{dy}{dt} = -\frac{1}{S_I}\frac{dp}{dt}(e^{-P/S_I})$$

and by substituting (3.5)

$$\frac{dy}{dt} = -\frac{i}{S_I}y$$

The precipitation after satisfying interception can be expressed by the following equation

$$i_1 = i(1 - e^{-P/S_I}) \quad (3.6)$$

. . . .

The major portion of moisture accumulated in interception storage is lost through evaporation. However, this evaporation loss does not form a significant mechanism of the runoff process for short duration storms.

Infiltration

The second loss considered was infiltration loss. Narayana et al. (1969) chose Horton's equation which expressed infiltration capacity as a function of time

$$f = f_c + (f_o - f_c)e^{-k_f t} \quad (3.7)$$

in which

f = instantaneous capacity rate of infiltration

t = time measured from the beginning of the infiltration curve

f_c = constant rate at which f is approached asymtotically with time

f_o = initial rate at $t = 0$

K_f = positive coefficient depending upon the soil characteristics

in which

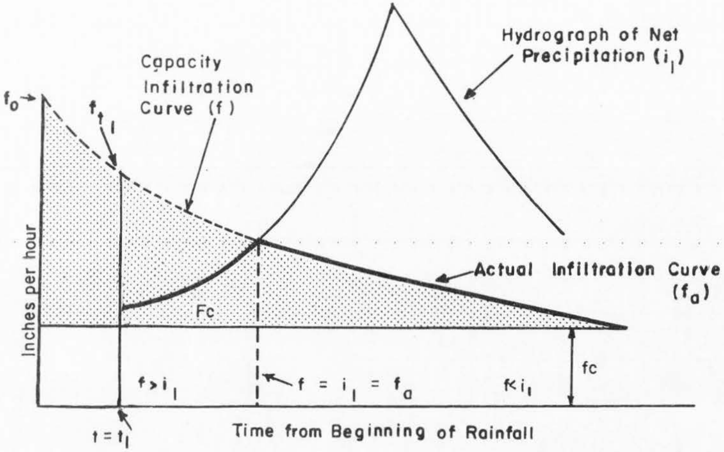
$$f_a = i_1 \text{ for } i_1 < f$$

and (3.8)

$$f_a = f \text{ for } i_1 > f$$

As indicated by Figure 3.7, the actual infiltration rate, f_a, curve follows the hydrograph of net precipitation, i_1, until the net rainfall intensity (rainfall less interception) exceeds the infiltration rate capacity curve.

The initial infiltration capacity rate, depending on the antecedent soil moisture, is located at a value, f_{t_1}, which is less than the maximum of the capacity rate curve and is located by sliding the curve to the right. The actual value of f_{t_1} depends upon the prevailing soil moisture status.


Hydrograph of Net Precipitation (i_1)
Capacity Infiltration Curve (f)
f_o
f_{t1}
Inches per hour
Actual Infiltration Curve (f_a)
Fc
fc
$f > i_1$
$f = i_1 = f_a$
$f < i_1$
$t = t_1$
Time from Beginning of Rainfall

$$K_f = \frac{fo-fc}{F_c}$$

Figure 3.7. Typical infiltration rate curve.

Surface depression storage

The third loss considered was surface depression storage. The capacity rate of inflow into depression storage is expressed by the following equation

$$\sigma_c = i_2 e^{-(P_1 - F)/S_d} \tag{3.9}$$

in which

$i_2 = i_1 - f$ = net rate of precipitation after satisfying interception and infiltration

P_1 = accumulated rainfall having satisfied interception storage

F = accumulated infiltration loss

S_d = total volume of available depression storage (expressed as mean depth over the entire catchment area)

σ_c = capacity rate of inflow into depression storage

in which

$$\sigma_a = i_2 \text{ when } \sigma_c > i_2$$

and (3.10)

$$\sigma_a = \sigma_c \text{ when } \sigma_c < i_2$$

Watershed Coefficients

The watershed coefficients, based on the regression equations of interception, maximum and minimum infiltration rates, depression storage, and time of rise describe the fundamental hydrologic behavior of a watershed. A sixth coefficient was the lag time, T_L, for each section of channel within the subwatershed model.

Narayana et al. (1969) developed a series of regression equations which related the five watershed coefficients to the urban parameters. Forty-eight storms over a ten-year period were simulated on another urban watershed model. The values of the watershed coefficients were adjusted for each storm until the best results were obtained between computed and observed storms. The order of matching computed to observed storm hydrograph characteristics was: (1) peak discharge, (2) rise time, (3) total volume of outflow, and (4) total duration of outflow.

Knowing both the watershed coefficients and the urban parameters for each year of study, the following multiple regression equations were developed for the Waller Creek watershed, Austin, Texas. All but one of these regression equations as applied to the present urban watershed study within Salt Lake County.

$$S_I = -0.780 - 0.214C_f + 2.476L_f \tag{3.11}$$

$$f_o = 2.029 - 2.986C_f - 1.141L_f \tag{3.12}$$

$$f_c = 1.066 - 1.222C_f - 0.973L_f \tag{3.13}$$

$$S_d = -1.069 + 0.580C_f + 2.679L_f \tag{3.14}$$

$$t_R = 52.26 - 83.70C_f + 75.60L_f \tag{3.15}$$

Equations (3.11) through (3.14) were utilized to determine S_I, f_o, f_c, and S_d; however, the use of Equation (3.15) was inappropriate for determining the rise time in the subwatershed model. Clearly, the rise time is a function of the absolute areal extent of the catchment area. In Equation (3.15), t_R is a function of a constant and two ratios which do not account for the length of travel of water draining from the catchment area. To provide an estimate of rise time, Evelyn et al. (1970) made recourse to the regression equation of Espey et al. (1965) for the 30-minute unit hydrograph of urban watersheds in the southwestern United States. This equation uses the channel length and its slope, besides the two urban parameters.

The actual computations of the watershed coefficients from the urban parameters were accomplished using the digital computer program in Appendix B. Table 3.3 summarizes the watershed coefficients calculated for the two watersheds within Salt Lake County, utilizing the Narayana et al. (1969) regression equations and the Espey et al. (1965) regression equation.

Hydrograph of rainfall excess

The hydrograph of rainfall excess is computed by chronologically deducting the losses due to interception, infiltration, and depression

Table 3.3. Watershed coefficients.

Mill Creek

	SI (In)	SD (In)	f_o (In/Hr)	f_c (In/Hr)	t_r (Min)
SW_1	.34	.36	.70	.28	7.
SW_2	.53	.53	.74	.26	7.
SW_3	.71	.77	.50	.12	6.
SW_4	.92	.79	1.16	.36	28.
SW_5	.85	.90	.50	.09	10.
SW_6	.74	.79	.48	.11	7.
SW_7	.94	.87	.94	.26	17.

Big Cottonwood Creek

	SI (In)	SD (In)	f_o (In/Hr)	f_c (In/Hr)	t_r (Min)
SW_1	.73	.66	.96	.31	12.
SW_2	.73	.66	.96	.31	12.
SW_3	.27	.17	1.17	.49	15.
SW_4	.17	.09	1.11	.48	13.
SW_5	.80	.91	.30	.02	9.

storage from the hydrograph of precipitation in compatible, finite, time increments. The schematic flow chart of this procedure along with the various equations developed so far are presented in Figure 3.8. These equations are programmed on the analog computer to obtain the hydrograph of rainfall excess.

Overland-Channel Routing

Narayana et al. (1969) adopted the linear procedure of "storage routing" wherein the storage effects (overland and channel components) of the catchment area are accounted for by the characteristic time of the catchment area.

The general continuity equation for any linear storage system is

$$P_e - Q = \frac{dSt}{dt} \tag{3.16}$$

in which

P_e = rainfall excess rate

Q = runoff rate

St = catchment area storage (overland and channel components)

Catchment area storage was considered as directly proportional to the outflow rate

$$St = t_R Q \tag{3.17}$$

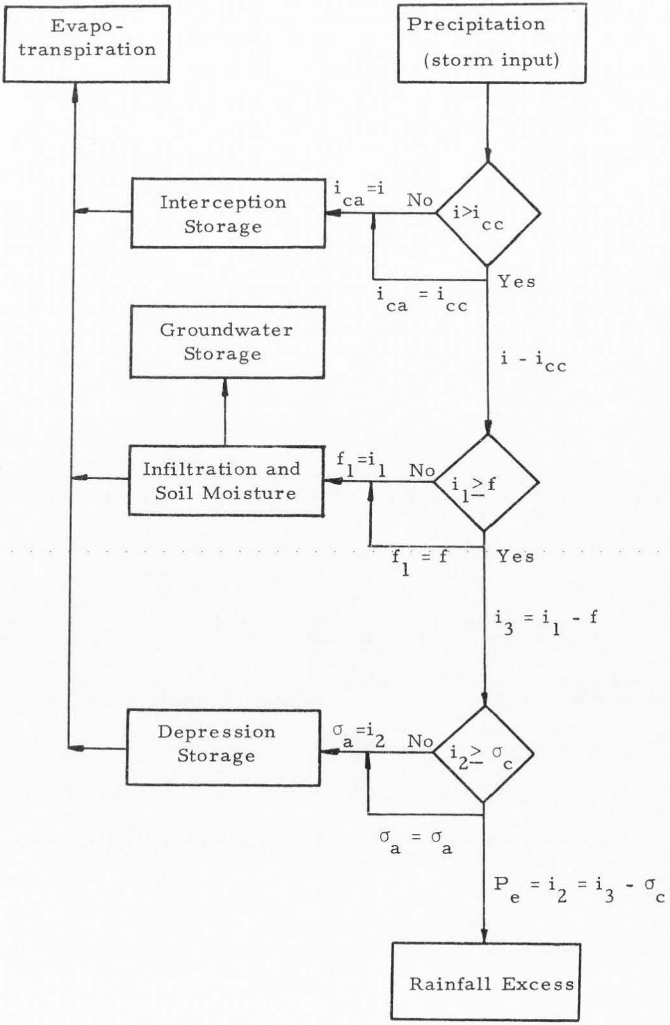

Evapo-transpiration
Precipitation (storm input)
Interception Storage
$i_{ca} = i$
No
$i > i_{cc}$
Yes
$i_{ca} = i_{cc}$
$i - i_{cc}$
Groundwater Storage
Infiltration and Soil Moisture
$f_1 = i_1$
No
$i_1 \geq f$
$f_1 = f$
Yes
$i_3 = i_1 - f$
Depression Storage
$\sigma_a = i_2$
No
$i_2 \geq \sigma_c$
$\sigma_a = \sigma_a$
$P_e = i_2 = i_3 - \sigma_c$
Rainfall Excess

Figure 3.8. Schematic flow chart for obtaining hydrograph of rainfall excess.

in which

t_R = the proportionality factor approximated by the hydrograph rise time

Using the equation derived by Espey et al. (1965), for 30-minute unit hydrographs of urban watersheds, the rise time is expressed as a function of the channel length and the mean slope of the catchment area. Hence,

$$P_e - Q = t_R \frac{dQ}{dt} \tag{3.18}$$

The outlet Q for a single catchment area is obtained by solving this differential equation.

Subwatershed Model

A concept of the urban watershed model as applied to a subzone or subwatershed is essential at this point. The Narayana et al. (1969) original model was confined to simulating the runoff from an entire watershed at its final outflow point. Evelyn et al. (1970) subdivided that watershed and applied the model. The outflows of each subwatershed were routed together to produce the outflow at selected points. The Evelyn et al. (1970) method was used in the present study.

Channel Routing

The outflow hydrographs at the discharge points of each subzone are produced by applying the urban watershed model on a subzone level.

This discharge combines with the outflow from the downstream catchment area. A technique of channel routing was devised by Evelyn et al. (1970) to combine each subzone discharge to produce the final hydrograph of the entire basin.

The method used was similar to the overland-channel routing method of Narayana et al. (1969). The channel or storm drain is assumed to be a linear storage reservoir. Hence,

$$Q_i - Q_o = \frac{dSc}{dt} \tag{3.19}$$

and

$$Sc = T_L Q_o \tag{3.20}$$

in which

Q_i = rate of inflow into the upstream section of channel (Figure 3.9), in this instance the upstream section, which coincides with the upstream boundary between subzones

Q_o = rate of outflow from the downstream section of channel which coincides with the boundary between the two adjacent downstream subzones

Sc = instantaneous volume of channel storage

T_L = proportionality factor between S and Q_o which represents the time lag of water flowing between upstream and downstream channel sections

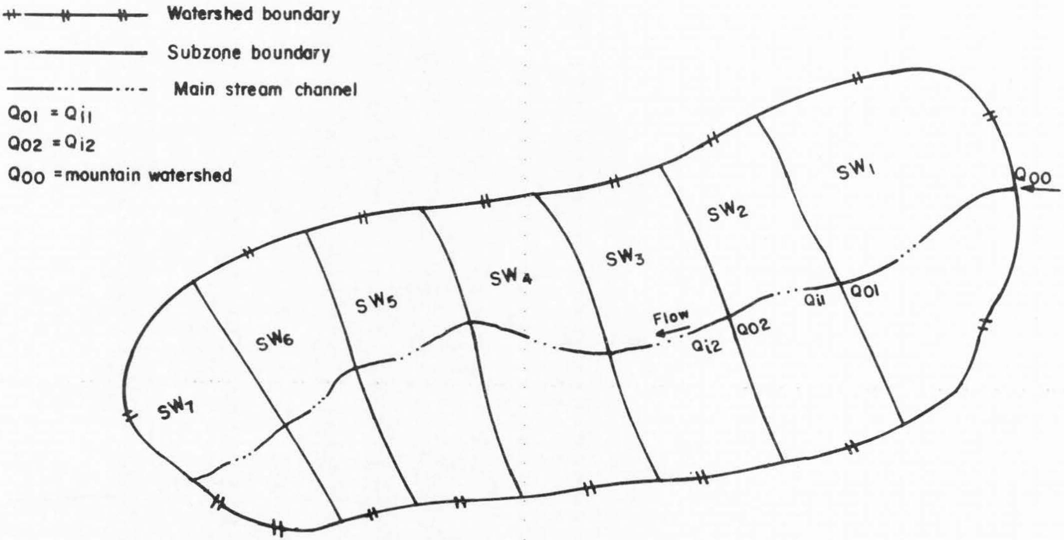

Watershed boundary
Subzone boundary
Main stream channel
Qo1 = Qi1
Qo2 = Qi2
Qoo = mountain watershed
SW1
SW2
SW3
SW4
SW5
SW6
SW7
Qoo
Qi1
Qo1
Flow
Qi2
Qo2

Figure 3.9. Schematic diagram of an urban subwatershed model.

The resulting equation after substituting Equation (3.20) into Equation (3.19) is

$$Q_i - Q_o = T_L \frac{dQ_o}{dt} \tag{3.21}$$

Derivation of Lag Time

The use of a linear storage system analogy for channel routing in the subwatershed model necessitated the derivation of an expression for the characteristic lag time in Equation (3.21).

A rectangular channel cross-section was assumed throughout the watershed in order to simplify the analysis. Appropriate parameters of diameter and depth of flow can be substituted for a storm drainage system.

b = channel width in feet

and

y = depth of flow in feet

therefore

$A = by$ = cross-sectional area of flow

and

$$P = b + 2y \approx b = \text{the wetted perimeter of flow} \tag{3.22}$$

Manning's open channel flow equation is

$$Q = VA = 1.49 \frac{AR^{2/3}S^{1/2}}{n} \tag{3.23}$$

in which

Q = discharge in cfs

S = channel slope in ft/ft

n = Manning's roughness coefficient

R = hydraulic radius = A/P

$R^{2/3} = (A^{2/3})/(P^{2/3}) \approx y^{2/3}$

Therefore,

$$Q = 1.49 \frac{(by)\, y^{2/3} S^{1/2}}{n} = 1.49 \frac{bS^{1/2}}{n} (y^{5/3})$$

Solving for y as a function of Q

$$y = f(Q) = \left(\frac{n}{1.49\, bS^{1/2}}\right)^{3/5} Q^{3/5} \tag{3.24}$$

$$y = KQ^{3/5} \tag{3.25}$$

in which

$$K = \left(\frac{n}{1.49\, bS^{1/2}}\right)^{3/5} \tag{3.26}$$

The following derivation leads to an expression for T_L as a function of instantaneous discharge, a quantity readily obtained from the analog circuits.

$$T_L = \frac{\text{distance}}{\text{velocity}} = L\frac{A}{Q} = L\frac{by}{Q} \tag{3.27}$$

Substituting Equation (3.25) into Equation (3.27)

$$T_L = \frac{L\ bKQ^{3/5}}{Q}$$

$$T_L = L\ bKQ^{-2/5} \tag{3.28}$$

An expression for lag time, T_L, (Equation 3.28) is given in terms of readily obtained channel parameters or storm drain design parameters. Dividing Equation (3.28) by 60 gives T_L in minutes.

Assuming a linear distribution of inflow into the channel or the storm drain system along its length, then a reasonable expression for Q within a subzone is given by the following

$$Q = \frac{Q_i + Q_o}{2} \tag{3.29}$$

The Narayana et al. (1969) study did not use a lag time concept since that study had one composite watershed and did not require routing upstream outflow through downstream subzones. The Evelyn et al. (1970) study utilized a subzone approach and a lag time parameter. This parameter was reduced to a constant based on subzone characteristics and a variable related to individual storm peak discharge. The discharge for each subzone was determined by assuming that the outflow for each subzone was proportional to the area drained, and, therefore, the lag time parameter for each subwatershed could be expressed in terms of the peak discharge at the last subzone outflow point. The lag time parameter used by Evelyn et al. (1970) gave satisfactory results. This lag time parameter, in essence, gave an attenuation effect to the outflow hydrographs and increased the recession time. The time of the peak discharge was not shifted.

In the present study, each subzone discharge was determined and used to calculate the lag time parameter for each corresponding subzone. The calculations for Equations (3. 26) and (3. 28) were made by the digital computer using the physical characteristics of the subzones (Table 3. 4), and subsequently scaled for input to the analog model. The lag time parameter is also used to calculate the shift in unit time periods due to channel routing effects. This unit time shift is found by dividing the lag time parameter into the time scale and then rounding to the nearest integer. The routing of the upstream hydrograph through the lower subzone channel is then delayed as calculated to yield a lateral shift for time of peak discharge. This process is followed for each subzone.

Table 3.4. Physical characteristics of the subzones of Mill Creek and Big Cottonwood Creek.

Sub-zone	Area (miles^2)	Length of Channel within subzone d (feet)	width* b (feet)	slopes ft/ft*	Mannings n*
SW_1	2.20	9200	30	.0370	.030
SW_2	1.95	5600	30	.0228	.030
SW_3	1.94	4400	30	.0284	.030
SW_4	2.49	7400	30	.0250	.030
SW_5	2.02	5400	30	.0018	.030
SW_6	1.70	4400	30	.0043	.030
SW_7	2.53	6000	30	.0017	.030
	14.83				
SW_1	6.86	9800	30	.0586	.030
SW_2	5.37	3800	30	.0036	.030
SW_3	7.29	8800	30	.0057	.030
SW_4	2.61	9600	30	.0052	.030
SW_5	1.18	8600	30	.0020	.030
	23.31				

*Average values for the subzones

CHAPTER IV

THE COMPUTER MODEL

This section discusses the separate digital and analog computer programs that were used in this urban watershed model study. The digital computer programs were written in standard FORTRAN IV language for the EAI 640 system and are given in Appendix A and Appendix B with sample input and output data. The analog programs are shown as schematic diagrams.

Digital Programs

The first program is used for calculating the urban input parameters, C_f and L_f, and is called URBPAR (Urban Parameters). The second program, WATMOD (watershed Model), calculates the values needed by the analog computer, controls the analog computer, and prints both input and output data.

Program URBPAR

The URBPAR program represents the solution of Equations (3.1) and (3.2) for the characteristic impervious length factor and the ratio of the impervious cover to the total area which is the percentage impervious cover. These values are illustrated in Figure 3.4. The program iteratively computes these watershed characteristics for each subzone within the catchment area. The characteristic impervious length factor and the percent impervious cover are subsequently used by the WATMOD program. A general flow diagram of URBPAR is shown in Figure 4. 1. The program is given in Appendix A.

Program WATMOD

The WATMOD program is by far the most important of the two digital programs (Figures 4. 2 and 4. 3). This program, given in Appendix B, calculates the precipitation inputs in equal time intervals from precipitation given in non-equal time increments and also calculates precipitation distribution from non-recording precipitation stations based on the total storm precipitation and the time distribution from a recording precipitation station.

The equal time interval precipitation is then used in a Thiessen network analysis to determine the areal distribution of rainfall over the watershed. This becomes the precipitation input to the analog computer.

Watershed coefficients, which are used by the analog model, are calculated by the subroutined ANALOG of the WATMOD program (Figure 4. 3) utilizing regression equations based on the two urban parameters C_f and L_f. These watershed coefficients are then scaled for magnitude and transferred to the analog computer where the corresponding attenuators (pots) are automatically set.

The digital computer, before transferring the precipitation to the analog, checks a logic voltage from the analog which is essence acts as

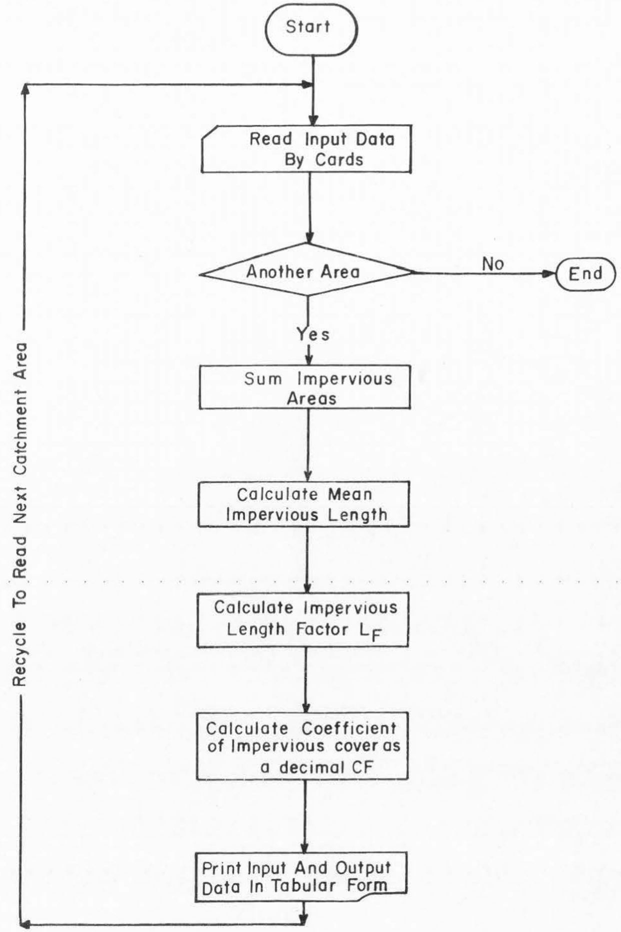

Start
Read Input Data By Cards
Another Area
No
End
Yes
Sum Impervious Areas
Calculate Mean Impervious Length
Calculate Impervious Length Factor L_F
Calculate Coefficient of Impervious cover as a decimal CF
Print Input And Output Data In Tabular Form
Recycle To Read Next Catchment Area

Figure 4.1. Flow diagram of URBPAR program for the digital computer.

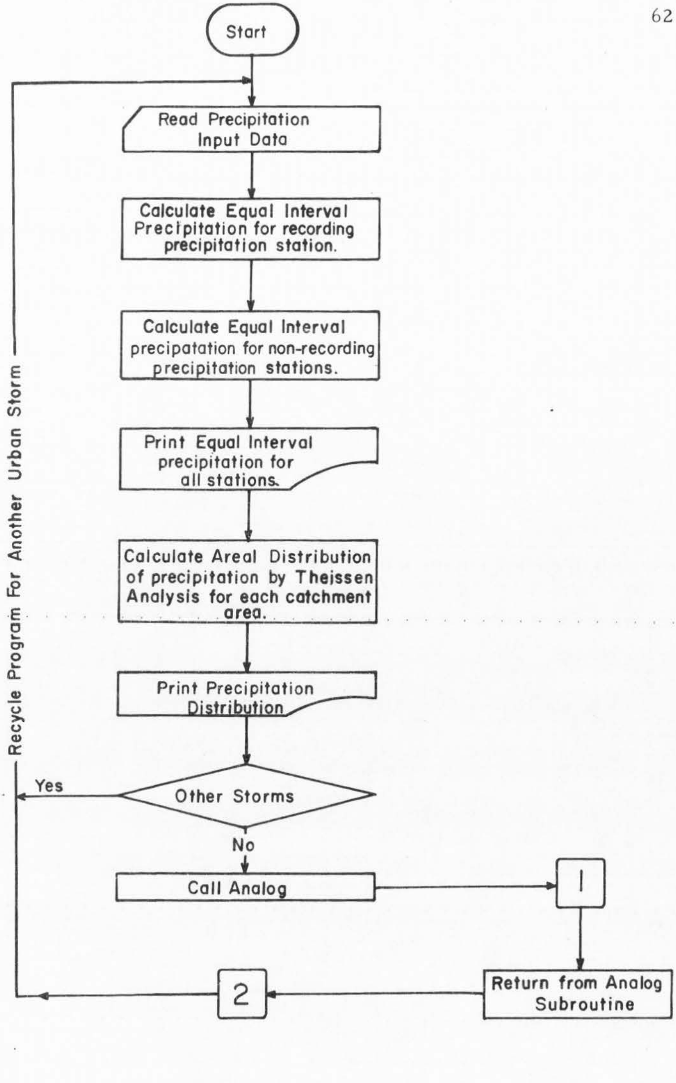

Start
Read Precipitation Input Data
Calculate Equal Interval Precipitation for recording precipitation station.
Calculate Equal Interval precipatation for non-recording precipitation stations.
Print Equal Interval precipitation for all stations.
Calculate Areal Distribution of precipitation by Theissen Analysis for each catchment area.
Print Precipitation Distribution
Other Storms
Yes
No
Call Analog
1
Return from Analog Subroutine
2
Recycle Program For Another Urban Storm

Figure 4. 2. Flow diagram of the WATMOD program.

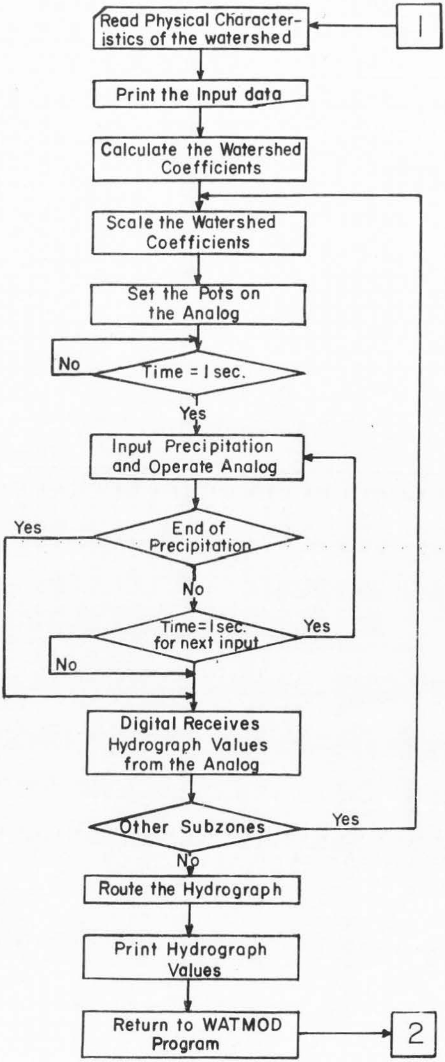

Read Physical Characteristics of the watershed
1
Print the Input data
Calculate the Watershed Coefficients
Scale the Watershed Coefficients
Set the Pots on the Analog
No
Time = 1 sec.
Yes
Input Precipitation and Operate Analog
Yes
End of Precipitation
No
Time=1 sec. for next input
Yes
No
Digital Receives Hydrograph Values from the Analog
Other Subzones
Yes
No
Route the Hydrograph
Print Hydrograph Values
Return to WATMOD Program
2

Figure 4.3. Flow diagram of WATMOD subroutine program analog.

an internal time clock to insure proper input timing. This logic voltage comes in high and low square waves at one second intervals of time. The logic voltage is checked and when proper, the digital computer sends to the analog one value of equal interval precipitation per second (Figure 4.4). This precipitation is then used by the analog computer to calculate the runoff from the watershed.

After the analog computer has made the calculations, the values are transferred to and stored in the memory of the digital computer. In the meantime, another second of time will have elapsed and the digital computer, after checking the logic voltage, will send to the analog another precipitation value.

The iterative cycle is completed for each catchment area, and the runoff is routed to the outflow point. Each catchment area has this iterative operation performed and the resulting runoff summed and the volume of flow calculated. By the use of an X-Y plotter, a visual hydrograph can be drawn. The visual hydrograph is discussed in Chapter 5.

Analog Program

The EAI 580 analog computer was used in this study as part of the hybrid system. The iterative capability of the hybrid computer allows various combinations of input parameters to be readily tried, and parameter effects to be visually displayed. Thus, the effects on the outflow combinations of urban parameters and precipitation

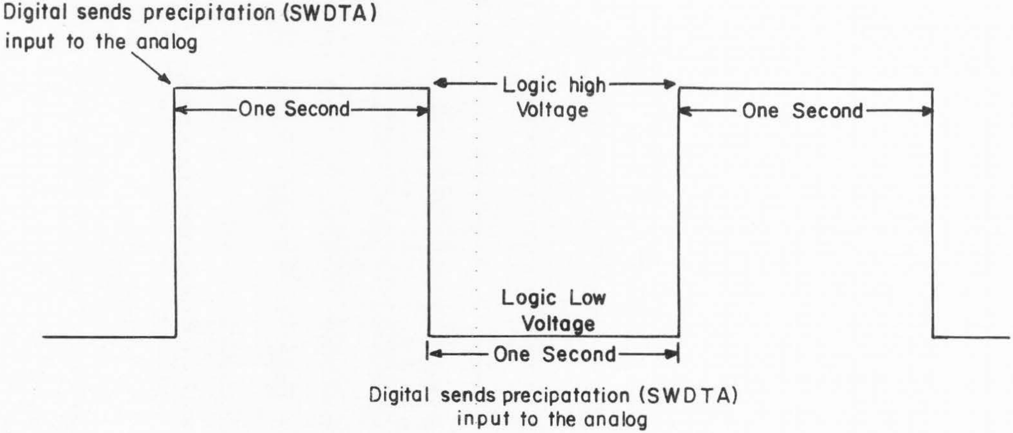

Digital sends precipitation (SWDTA) input to the analog
One Second
Logic high Voltage
One Second
Logic Low Voltage
One Second
Digital sends precipatation (SWDTA) input to the analog

Figure 4.4. Time of precipitation inputs.

can be observed. This can be a great aid in design and economic studies.

Programming the analog computer consists of properly interconnecting a system of electrical components to simulate linear and nonlinear mathematical equations. The basic mathematical operations which the analog computer can be programmed to perform are: integration, multiplication, division, and summation. The proper interconnections of components permit a wide range of mathematical equations to be simulated. Synthesis of the mathematical equations describing the urban watershed on the analog computer is referred to as the analog model.

The analog computer program, illustrated in Figure 4.5, represents the mathematical simulation of the runoff process for the watersheds within Salt Lake County, Utah. The basic program is discussed as follows.

Precipitation

The precipitation that has occurred during a particular storm or precipitation generated by a random process (stochastic precipitation) is the input variable for a given set of urban conditions.

The input for each period was determined from precipitation records and calculated in equal intervals as previously described by the digital computer program in Appendix B.

The precipitation was subsequently scaled for input into the analog model by dividing the inch/time by the appropriate scaling factor

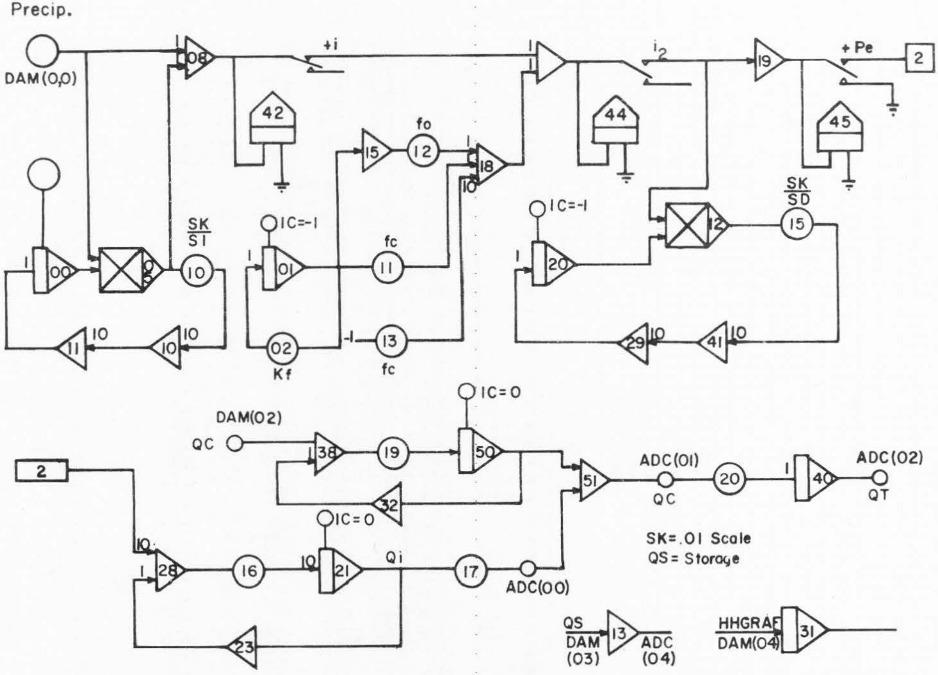

Precip.
DAM(0,0)
08
+i
42
fo
15
12
18
10
44
i2
19
+ Pe
2
45
SK/SD
IC=-1
20
12
15
10
41
29
SK/SI
IC=-1
00
10
01
fc
11
10
11
02
Kf
-1
13
fc
IC=0
DAM(02)
QC
38
19
50
32
51
ADC(01)
QC
20
40
ADC(02)
QT
SK=.01 Scale
QS= Storage
2
IC=0
10
28
16
21
Qi
17
ADC(00)
23
QS
DAM
(03)
13
ADC
(04)
HHGRAF
DAM(04)
31

Figure 4.5. Schematic diagram of the analog computer program.

of 1 inch equal to 1 machine unit. This assumed that the precipitation input would not exceed the computer capability and values less than 1 would be the input. This precipitation then had losses subtracted from it to arrive at excess precipitation.

Interception

The expression for capacity rate of inflow into interception storage is given by Equations (3. 3) and (3. 4). A comparator and a switch after amplifier 08 assures the conditions given by limiting passage of a positive voltage. Referring to Figure 4. 6, this circuit generates the desired result at summing amplifier 08 when the proper antecedent value is set.

The initial condition on integrator 0 can be set to either -1 to represent a dry watershed or to 0 to represent a recent storm which has satisfied the interception storage. Potentiometer, 01, was introduced between a -1 source and the initial condition on integrator 00 which enables any intermediate value of capacity interception rate to properly represent various antecedent conditions.

Infiltration

The infiltration capacity rate is given by Equation (3. 7) along with the conditions defined by Equation (3. 8) and assured by a comparator and a switch after amplifier 09 as represented by Figure 4. 7. The output of summation amplifier 09 is f, the desired results of Equation (3. 7).

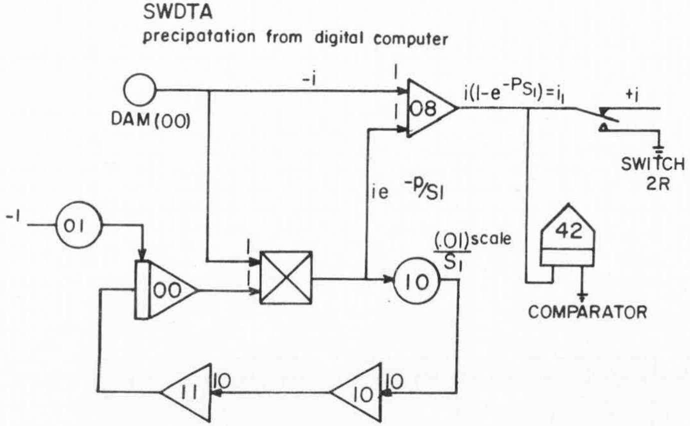

SWDTA
precipatation from digital computer
-i
1
i(1-e^-Ps1)=i1
+i
DAM(00)
1
08
SWITCH
2R
ie -P/S1
-1
01
(.01)scale
S1
42
1
1
00
10
COMPARATOR
11
10
10
10

Figure 4.6. Analog circuit for generating the expression for interception rate.

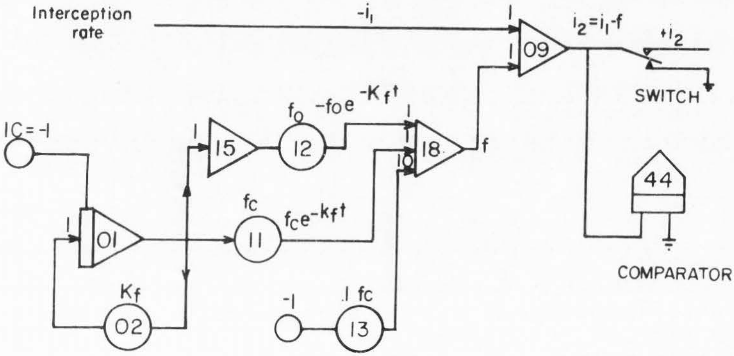

Interception rate
-i1
1
i2=i1-f
+i2
1
09
SWITCH
f0
-foe^-Kft
1
IC=-1
1
15
12
1
18
f
10
44
fc
fce^-kft
1
01
11
COMPARATOR
Kf
-1
.1 fc
02
13

Figure 4.7. Analog circuit for generating the expression for infiltration rate.

Depression Storage

The rate of inflow into depression storage is given by Equation (3. 9) along with conditions defined by Equation (3. 10). The analog program for these expressions is given by Figure 4. 8. This circuit is similar to Figure 4. 6 since Equations (3. 9) and (3. 3) are similar.

Overland-Channel Routing

The expression that governs the routing of rainfall excess as given by Evelyn et al. (1970) is Equation (3. 18).

The circuit diagram to solve for dQ/dt in Equation (3. 18) is shown by Figure 4. 9. Potentiometer 17 is equal to the area of the respective subwatershed divided by the total area of the watershed. If the catchment area being modeled is an entire watershed, then the potentiometer is set at 1. 0, as was done by Narayana et al. (1969).

Channel Flow Routing

The expression developed for channel flow routing, Equation (3. 21), is solved by the analog circuit in Figure 4. 10.

The Outflow Hydrograph

The graphical representation of precipitation excess with respect to time is called a hydrograph. By connecting an X-Y plotter to the output of the analog circuit, various combinations of hydrographs are

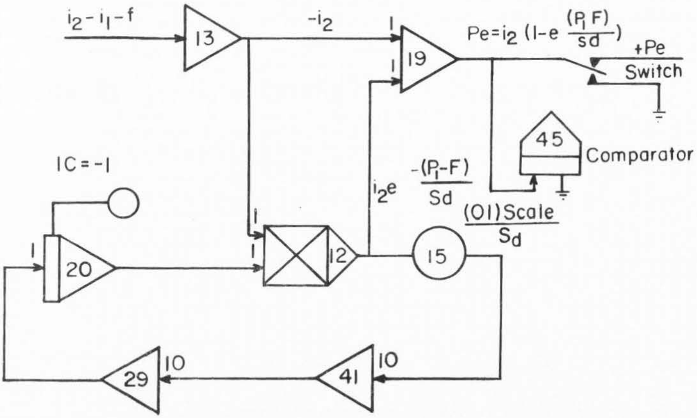

i2 - i1 - f
13
-i2
1
1
19
Pe=i2 (1-e (P1 F)/sd)
+Pe
Switch
45
Comparator
IC = -1
1
20
1
1
12
i2e
-(P1-F)/Sd
(01)Scale/Sd
15
10
29
10
41

Figure 4. 8. Analog circuit for generating the expression for inflow rate into depression storage.

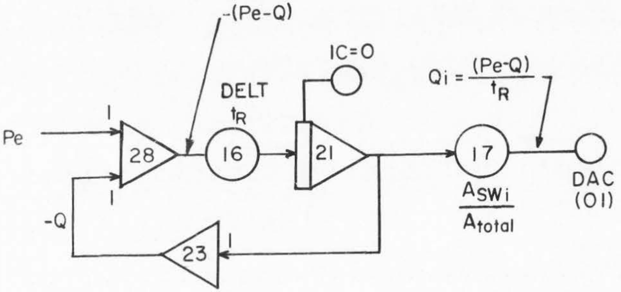

-(Pe-Q)
IC=0
Qi = (Pe-Q)/tR
DELT
tR
Pe
1
28
16
21
17
1
-Q
ASWi/Atotal
DAC
(01)
23
1

Figure 4. 9. Analog circuit for obtaining the subwatershed outflow hydrograph t_R is the time of rise of storm drain inlet time.

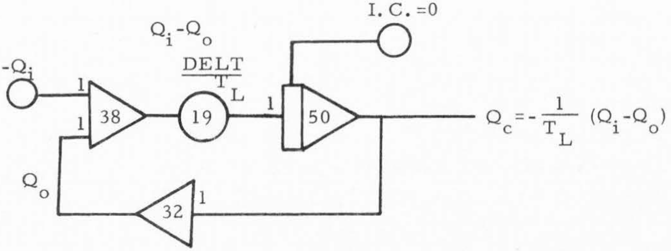

I. C. =0
$Q_i - Q_o$
$-Q_i$
DELT
T_L
1
1
38
19
1
50
$Q_c = -\frac{1}{T_L}(Q_i - Q_o)$
Q_o
32
1

Figure 4.10. Analog circuit for channel routing.

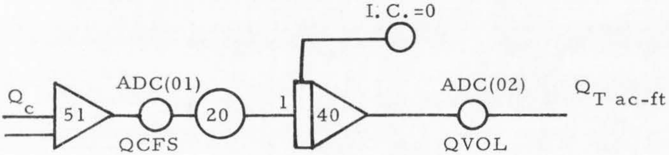

I. C. =0
Q_c
51
ADC(01)
QCFS
20
1
40
ADC(02)
QVOL
Q_T ac-ft

Figure 4.11. Analog circuit for scaling the final outflow and total volume of outflow.

possible. By connecting the Y terminal of the plotter to the output of amplifier 21, and the X terminal to a time reference, the hydrograph of an individual subzone is obtained. By connecting the Y terminal to the output of amplifier 51, the total outflow of the current subzone plus the routed effect of all upstream subzones is obtained. The output of amplifier 40 will yield the total volume of flow (Figure 4.11).

The graphical representation of rainfall called a hyetograph is obtained by connecting the Y terminal to the upper input of amplifier 28 and the X terminal to a time reference. Precipitation excess is plotted from the input of amplifier 28. Some of these hydrographs are shown in the next chapter.

Time Scaling

The time scale of 1 second of computer time equal to 30-minutes of physical time reflects the choice made by Narayana et al. (1969) and Evelyn et al. (1970). The statistical equations for the unit hydrograph characteristics were developed for 30-minute durations by Narayana et al. (1969) and Espey et al. (1965), and this time of 30-minute periods permits the direct use of the Narayana et al. (1969) watershed coefficients and the rise time of Espey et al. (1965) as the characteristic time in routing precipitation excess. This time scale of 1 second equal to 30-minutes of real time works quite well with the present inputs and the anlog computer.

Amplitude Scaling

The choice of a proper amplitude scale factor for a problem is as important as the choice of time scale. Ideally, a problem should be scaled to keep the output voltage as high as possible without exceeding the maximum voltage range of the computer (± 1 machine unit = ± 10 volts) or allowing the output voltage to drop into the "noise" range.

Richardson (1971) estimated return periods for short-duration precipitation in Utah and found that for a return period of 100 years and a duration of 30 minutes the recording gage at Cottonwood Weir would show 0.89 inch of precipitation. Since this was less than 1.00 inch per 30 minutes, a scale factor of 1.0 was used, and the actual storm values from the recorded data were used. In the event that one hour intervals are used, the scale factor should be increased to about 1.13, since for one hour duration and a return period of 100 years, Richardson (1971) obtained a precipitation value of 1.13 inches/hour.

The watershed coefficients for surface depression storage and interception storage were scaled, since their units were also in inches. The scale factor used was identical to the precipitation scale factor. The watershed coefficients for time of rise and lag time were not magnitude scaled but were time scaled since their units were in minutes. To convert minutes to 30-minute intervals, the coefficients were divided into the time unit of DELT of the digital program. This general procedure will allow variable time to be used without changing the program. This will allow longer or shorter time intervals to be used, for example, time intervals of 15 minutes or less for storm sewer systems.

Table 4.1 summarizes the potentiometer settings used in the watershed model. The "pot number" refers to the potentiometer number used in Figures 4.1 through 4.7.

Table 4.1. Summary of the attenuators (pot) settings on the analog computer.

Program Section	Pot Number	Variable	Units	Remarks
Interception	01*		Constant	Antecedent soil condition (0 to 1.0)
	10	S_I	Inches	(.01) SCALE/S_I
Infiltration	02*	K_f	Constant	Assumed equal to 0.5
	11	f_c	In/hr	F_c/SCALE x DELT/60
	12	f_o	In/hr	F_o/SCALE x DELT/60
	13	f_c	In/hr	F_c/SCALE x DELT/60 x .10
Depression storage	15	S_d	Inches	(.01) SCALE/S_d
Subwatershed outflow hydrograph	16	t_R	Minutes	DELT/t_R
	17	APOT	Constant	Subzone area/watershed area
Channel routing	19	T_L	Minutes	DELT/T_L
Total volume of the outflow	20		Constant	

*Pots are not set automatically by the WATMOD program, but are hand set for each run.

DELT = time interval
SCALE = scaling value to keep pot settings less than 1.0000

CHAPTER V

APPLICATION OF THE MODEL

The application of the watershed model to the two urban watersheds of Mill Creek and Big Cottonwood Creek, within Salt Lake County, Utah, is discussed in this chapter. The input data, the methods of operation with their inherent flexibility, and the types of output data are presented.

Input Data

Precipitation data for each of six different storms were obtained in the form of daily totals for the five non-recording precipitation stations. The storms studied were in 1965, 1966, and 1968. The gage total for each precipitation station for the individual storm was punched on computer cards. The hourly precipitation for the recording station was also punched on computer cards. The time of the beginning of the storm and the time interval desired for the equal interval precipitation was punched on computer cards. These data were then used to calculate the equal time interval precipitation for the five non-recording precipitation stations based on the ratio of the recording station total catch to the non-recording station total catch. From these data, the Thiessen network analyses was computed. These analyses yielded the precipitation hyetograph for each subzone within the urban watershed.

The surface inflow to the urban watersheds was obtained from strip chart information for the gaging stations immediately upstream from each watershed. Using rating tables, the strip chart information was converted into cubic feet per second flow with respect to time. This yielded the hydrographs for the contribution to the first subzone of the urban watershed. The gaging station above Mill Creek watershed (1700) and the station above Big Cottonwood Creek (1685) were maintained by the City of Salt Lake, which made available most of the records for the storms considered. The hydrograph for each of the mountain watersheds was put on computer cards to be used as input data for its respective watershed. This discharge from the mountain watershed would subsequently be routed through the urban watershed.

The urban parameters of percentage impervious cover and the characteristic flow length were punched on computer cards to be used in the initial estimation of watershed coefficients for each subzone of each watershed.

The urban characteristics, consisting of Manning's roughness coefficient, CN, channel width, B, average channel slope, S, channel length, CL, area, A, and allowable upstream discharge after storage considerations, CFS, were punched on computer cards for each subzone in both watersheds.

The direction and the operation of the computer was controlled by card input. The urban watershed selection was by a variable named ID. ID equaled 1 for Mill Creek and 2 for Big Cottonwood Creek.

KOUNT controlled the combining of the final outflow hydrograph for the two watersheds. KOUNT equaled -1 for the hydrograph combination, +1 for the regression equations, and 0 for sensitivity. LD equaled 0 to calculate the precipitation for a composite watershed made up of all the watershed subzones. LD equaled 1 for calculating the equal interval precipitation values and corresponding Thiessen network analyses. LD equaled 2 to suppress printing precipitation values but to continue all other calculations. LD equaled a negative number to do all calculations and printing except calculations for a composite or single watershed. RSG equaled 1 for routing upstream mountain watershed hydrographs. Storage considerations were controlled by the variable CFS.

Methods of Operation

Composite watershed

The urban watershed model was applied to different spatial arrangements. In the first case each watershed was treated as a single watershed with the surface input hydrograph routed downstream through the watershed. Individual computer runs were made for Mill Creek and then for Big Cottonwood Creek. The final outflow hydrographs were combined to become the simulated contribution of the two watersheds to the Jordan River.

Subzone approach

In the second case, the model was used on a subzone basis with inputs to each subzone. The accumulated runoff from each subzone included its contribution plus the addition of the routed upstream flow. Storage considerations were also taken into account. The outflow hydrographs of the two watersheds were combined to represent the total discharge to the Jordan River.

Storage considerations

Two alternative plans for storage were considered in this study. Plan A had no provisions for temporary storage other than in the main channel or in the storm sewers, and the discharge was routed to the Jordan River through the downstream subzones. This small storage consideration was accomplished using the attenuation effect of the watershed coefficients for T_R and T_L. Plan B employed temporary storage at the upper end of some subzones. If no temporary storage was desired, the discharge could by-pass the assumed storage location and allow the full flow to be routed downstream. The Plan B storage would still have the attenuation effect and lag time effect regardless of temporary storage.

The model was operated using temporary storage within each subzone. The discharge above a given value of CFS was stored as QS within that subzone. The remaining discharge was routed and combined with the individual subzone contribution. The volume of flow stored was calculated for the assumed stored flow and the subzone hydrograph.

Sensitivity analyses

A sensitivity analysis is performed by changing one system variable while holding the remaining variables constant and noting the changes in the model output functions. If small changes in a particular system parameter induce large changes in the output or response function, the system is said to be sensitive to that parameter. Thus, through sensitivity analyses it is possible to establish the relative importance with respect to system response of various system processes and input functions. This kind of information is useful from the standpoint of system management, system modeling, and the assignment of priorities in the collection of field data.

Output Data

The model was used to test the system response to a variety of input data to illustrate the effects a parameter change would have on the whole system. Output data were obtained for numerous combinations of parameters and of subzones.

Digital output

The digital computer gave numerical values for input precipitation in equal time intervals for each subzone, the watershed coefficients that were utilized by the analog computer, the subzones discharge, the accumulated discharge of the subzone discharge plus the routed upstream discharge, the stored discharge, the volume of discharge, and the combined watershed hydrograph.

Analog output

The analog computer output was obtained in graphical form to illustrate the input precipitation, the precipitation excess, the subzone hydrograph, the routed upstream hydrograph contribution to the subzone total discharge, the hydrograph at the subzone discharge point, and the combined watershed hydrograph. It should be noted that the analog computer is very versatile in graphical display since any analog parameter can be plotted. Additional values calculated by the analog and not transferred to the digital are the precipitation losses incurred due to surface depression, infiltration, and interception losses.

Economic Applications

The stage or gage height for a particular flood peak is the distance from a datum point to the water surface. For a given cross-sectional area (measured section) and discharge, the stage can be calculated. For a given frequency of flooding, there corresponds to it a given peak discharge to design for. At a specified location for this given discharge, the gage height can be found and subsequently the depth of inundation for agricultural, commercial, or residential properties.

Depth-damage curves

Economic evaluation of the damages for a given depth can be formulated using depth-damage curves based upon a flood return period. These curves can be calculated using field values determined from previous floods or derived using estimated damages for a given frequency inundation.

From estimated damages for a given return period of a flood, an annual savings in dollars could be expected if a system were designed that would lower the depth of flooding or eliminate flooding altogether. The annual cost of the system installed would offset partial annual estimated savings from flood damages. The starting point in this economic analysis begins with the stage discharge-relationship where economic values are based on either the return period (frequency) for a given discharge, a discharge, or the stage of that discharge. The hydrologic and hydraulic aspects of an economic analysis are generally the controls for economic benefits.

The watershed model presently gives discharge both in the form of a graph and numerical ordinates with time as the abscissa. From this hydrograph setup, the peak discharge within any subzone can be found and the depth of inundation can be found, such as at bridge crossings. The cross-sectional data for depth of flow could be either input to the computer program, and the computer programmed to calculate the stage and depth of flooding; or the stage can be found manually by graphical techniques.

Results and Discussion

The results and discussion in this chapter indicate the usefulness of the systems model as applied to the two urban watersheds within Salt Lake County, Utah. Each watershed was modeled as a composite of the subzones of that watershed and then was modeled utilizing the subzone approach. Watershed coefficients were calculated for each of the subzones using the regression equations. Graphical results were obtained as well as a digital computer printout. The event of May 22-23, 1968, is presented since this storm had the highest total precipitation.

The upstream runoff mountain watersheds gaged inflow into each of the two urban watersheds was routed through each subzone and added to the runoff of that subzone. The final hydrograph for each watershed was combined with the other watershed hydrograph to yield the two watersheds contribution to the Jordan River. Considerations for both types of storage were made.

Mill Creek

The urban watershed of Mill Creek has seven subzones for which urban parameters were calculated by the regression equations. The urban parameters were summarized earlier in Table 3.2. The watershed coefficients calculated were given in Table 3.3. It should be noted that the minimum infiltration capacity, F_c, as calculated for each subzone in inch/hour was larger than the precipitation input after abstractions for depression storage and interception losses. The F_c value was converted into inch/30 minutes by to correspond to the 30-minute time interval used in this study. It was found that by initially setting F_c, to 0.01 inch/hour as an initial estimate and retaining the other watershed coefficients at the value calculated by the regression equations, runoff would occur.

The watershed coefficients, as initially calculated, abstracted all the precipitation input to the watershed subzones and the composite watershed; therefore, no runoff occurred. With no runoff occurring, the maximum discharge was equal to zero and the lag time parameter, which is divided by the discharge, became infinity. No changes were made in the regression equations to directly calculate a lower F_c value. Instead, F_c was arbitrarily set equal to 0.01 with the other parameters unchanged; and the values as the initial watershed coefficients were read directly into the computer. The lag time was initially estimated to be less than the time of rise.

These combinations of parameters yielded the initial runoff hydrograph for each subzone for the event of May 22-23, 1968. The Thiessen network analyses for the input precipitation are presented in Table 5.1. Tables 5.2 through 5.8 represent the digital output of the runoff and include the watershed coefficients used. Figure 5.1 is the graphical results from the analog computer and illustrates the input precipitation hyetograph, the excess precipitation, and the various combinations of hydrographs. Storage considerations, alluded to as Plan B for temporary

Table 5.1

```
INPUT DATA FOR WATROD CONTROLLING PROGRAM
COTTONWOOD WEIR (W-9) IS THE RECORDING RAIN GAGE USED IN THIS RUN MAY 22-3,1968
                          1    7    8    2
          2.50 1.94 1.88 1.74 2.10 1.39
175022/05/68      1968     1232.
     .30      .00   53.00      .40  120.90      .74  180.44      .08  244.00     1.10
  300.00     1.30  360.00     1.60  420.70     1.88  480.09     2.00  540.00     2.20
  600.00     2.49  840.00     2.30 1500.00     2.50

 COTTONWOOD WEIR (W-9) IS THE RECORDING RAIN GAGE USED IN THIS RUN MAY 22-3,1968
THE THIESSEN NETWORK ANALYSIS
        SW1     SW2     SW3     SW4     SW5     SW6     SW7     SW8     SW9     SW10
         .18     .15     .15     .13     .11     .11     .11
         .15     .15     .15     .13     .11     .11     .11
         .11     .11     .11     .10     .08     .08     .08
         .11     .11     .11     .10     .08     .08     .08
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .11     .11     .11     .10     .08     .08     .08
         .11     .11     .11     .10     .08     .08     .08
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .07     .07     .07     .06     .05     .05     .05
         .03     .03     .03     .03     .02     .02     .02
         .03     .03     .03     .03     .02     .02     .02
         .03     .00     .00     .00     .00     .00     .06
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .00     .00
         .00     .00     .00     .00     .00     .02     .00
         .00     .00     .00     .00     .00     .03     .00
         .00     .00     .00     .00     .00     .00     .00
TOTALS  1.84    1.80    1.91    1.49    1.39    1.39    1.30
```

Table 5.2

```
COTTONWOOD WEIR (W-9) IS THE RECORDING  COTTONWOOD WEIR (W-9) IS THE RECORDING


WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA       1968
     BI(IN)        SD(IN)       FO(IN/HR)    FC(IN/HR)        TR(MIN)      TL(MIN)
      P-10          P-15          P-12        P-11,,13          P-16          P-19
SW 1 .34* .0204P .36*.0277* .70* .3500P .01*.0050P  7.* .4285P  5.* .0000P


SW* 1       LAG* 0        Q*  40.0       **40
 SUBZONE   CFS  ACC TOTAL CFS  1000 ACRE FT.     STORED  CFS   1000 ACRE FT
           .00         11.63             .02               4.63           .00
           .00         15.45             .09               4.43           .00
           .00         18.22             .38               4.50           .00
           .00         19.85             .38               4.79           .00
           .00         20.79             .00               4.80           .00
           .00         21.02             .00               4.94           .00
           .30         21.02             .38               5.03           .00
           .23         21.55             .01               9.03           .00
          4.30         28.20             .01              12.03           .00
         12.38         35.74             .01              13.50           .00
         28.49         50.69             .01              14.50           .00
         39.77         61.90             .01              15.40           .00
         34.33         56.29             .01              16.70           .00
         38.90         60.03             .01              17.20           .00
         38.77         61.00             .01              17.60           .00
         39.47         41.00             .02              18.10           .00
         39.71         62.83             .02              18.40           .00
         40.41         62.83             .02              19.03           .00
         41.34         63.77             .02              20.04           .00
         42.04         64.78             .03              19.04           .00
         19.38         41.34             .03              17.08           .00
         19.15         41.34             .03              16.00           .00
           .00         22.10             .33              14.40           .00
           .00         21.49             .03              14.00           .00
           .00         21.72             .03              13.50           .00
           .00         21.49             .03              16.00           .00
           .00         21.49             .03              18.59           .00
           .00         21.72             .04              17.03           .00
           .00         21.49             .04              16.16           .00
           .00         21.49             .04              14.53           .00
           .00         21.95             .04              12.90           .00
           .00         21.95             .04              12.58           .00
           .00         21.49             .04              12.03           .00
           .00         21.25             .04              14.03           .00
           .00         21.95             .04              15.40           .00
           .00         21.49             .04              17.50           .00
           .00         21.25             .04              19.37           .00
           .00         21.49             .04              19.22           .00
           .00         21.49             .04              19.10           .00
           .00         21.49             .05              19.00           .00
           .00         21.49             .05              19.09           .00
           .00         21.49             .05              18.50           .00
           .00         21.49             .05              18.00           .00
           .00         21.49             .05              18.00           .00
           .00         21.00             .05              18.70           .00
           .00         21.72             .05              18.65           .00
           .00         21.49             .05              18.03           .00
           .00         21.49             .05              18.30           .00
           .00         21.25             .05              18.39           .00
```

Table 5.3

```
COTTONWOOD WEIR (W-9) IS THE RECORDING  COTTONWOOD WEIR (W-9) IS THE RECORDING


WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA       1968
     BI(IN)        SD(IN)       FO(IN/HR)    FC(IN/HR)        TR(MIN)      TL(MIN)
      P-10          P-15          P-12        P-11,,13          P-16          P-19
SW 2 .53* .0100P .53*.0100F .74* .3700P .01*.0050P  7.* .4285P  5.* .0000P


SW* 2       LAG* 0        Q*  84.7       **40
 SUBZONE   CFS  ACC TOTAL CFS  1000 ACRE FT.     STORED  CFS   1000 ACRE FT
           .00          7.47             .02                .00           .00
           .00         11.91             .03                .00           .00
           .00         14.09             .00                .00           .00
           .00         17.75             .00                .00           .00
           .00         19.62             .00                .00           .00
           .00         20.55             .00                .00           .00
           .00         21.49             .00                .00           .00
           .00         22.47             .00                .00           .00
           .00         23.22             .01                .00           .00
           .00         39.63             .01                .00           .00
          5.13         46.01             .01                .00           .00
         11.40         63.77             .01                .00           .00
          9.01         64.00             .01                .00           .00
         13.00         70.79             .01                .00           .00
         18.41         77.78             .01                .00           .00
         23.95         81.99             .02                .00           .00
         23.50         87.13             .02                .00           .00
         20.39         90.87             .02                .00           .00
         19.20         94.00             .03                .00           .00
         11.30         96.47             .03                .00           .00
         14.71         71.24             .03                .00           .00
         14.71         80.37             .04                .00           .00
           .00         38.31             .04                .00           .00
           .00         30.02             .04                .00           .00
           .00         27.50             .04                .00           .00
           .00         25.52             .04                .00           .00
           .00         24.29             .04                .00           .00
           .00         23.59             .04                .00           .00
           .00         23.30             .05                .00           .00
           .00         23.50             .05                .00           .00
           .00         23.12             .05                .00           .00
           .00         23.30             .05                .00           .00
           .00         23.12             .05                .00           .00
           .00         22.90             .05                .00           .00
           .00         23.30             .05                .00           .00
           .00         23.12             .05                .00           .00
           .00         23.12             .05                .00           .00
           .00         22.47             .05                .00           .00
           .00         22.96             .05                .00           .00
           .00         23.12             .05                .00           .00
           .00         23.12             .06                .00           .00
           .00         22.89             .06                .00           .00
           .00         22.65             .06                .02           .00
           .00         22.42             .06                .02           .00
           .00         22.65             .06                .00           .00
           .00         23.20             .06                .00           .00
           .00         22.65             .06                .00           .00
           .00         22.76             .06                .00           .00
           .00         22.42             .06                .00           .00
```

Table 5.4

```
COTTONWOOD WEIR (W-9) IS THE RECORDING  COTTONWOOD WEIR (W-9) IS THE RECORDING


WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA       1968
     BI(IN)        SD(IN)       FO(IN/HR)    FC(IN/HR)        TR(MIN)      TL(MIN)
      P-10          P-15          P-12        P-11,,13          P-16          P-19
SW 3 .71* .0140P .70*.0142P .50* .2500P .01*.0050P  6.* .5000P  5.* .0000P


SW* 3       LAG* 0        Q*  98.4       **40
 SUBZONE   CFS  ACC TOTAL CFS  1000 ACRE FT.     STORED  CFS   1000 ACRE FT
           .00          6.07             .03                .03           .00
           .00          9.11             .00                .00           .00
           .00         12.20             .00                .00           .00
           .00         15.41             .02                .03           .00
           .00         17.90             .02                .00           .00
           .00         19.62             .00                .00           .00
           .00         21.05             .00                .00           .00
           .00         22.19             .00                .00           .00
           .00         24.29             .01                .00           .00
           .00         27.50             .01                .00           .00
           .00         37.14             .01                .00           .00
          3.07         53.72             .01                .00           .00
          1.16         58.40             .01                .00           .00
          3.73         57.97             .01                .00           .00
          6.30         77.76             .01                .00           .00
          8.34         88.19             .02                .00           .00
         11.91         94.80             .02                .00           .00
         14.40        102.98             .02                .00           .00
         17.20        108.02             .03                .00           .00
         19.05        114.23             .03                .00           .00
         11.44         98.71             .04                .00           .00
         12.14         89.03             .04                .00           .00
           .00         80.50             .04                .00           .00
           .00         47.65             .04                .00           .03
           .00         36.24             .05                .00           .00
           .00         33.03             .05                .00           .03
           .00         29.80             .05                .00           .00
           .00         27.70             .05                .00           .00
           .00         26.10             .05                .00           .00
           .00         25.60             .05                .00           .00
           .00         25.40             .05                .00           .00
           .00         24.90             .05                .00           .00
           .00         24.99             .06                .00           .00
           .00         24.29             .06                .00           .00
           .00         24.76             .06                .00           .00
           .00         24.76             .06                .00           .00
           .00         24.99             .06                .00           .00
           .00         24.29             .06                .00           .00
           .00         24.52             .06                .00           .00
           .00         24.29             .06                .00           .00
           .00         24.75             .06                .00           .00
           .00         24.52             .06                .00           .00
           .00         24.52             .06                .00           .00
           .00         24.05             .07                .00           .00
           .00         23.82             .07                .00           .00
           .00         24.06             .07                .00           .00
           .00         24.29             .07                .00           .00
           .00         24.29             .07                .00           .00
           .00         23.36             .07                .00           .00
```

Table 5.5

```
COTTONWOOD WEIR (W-9) IS THE RECORDING  COTTONWOOD WEIR (W-9) IS THE RECORDING

WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA      1965
      SI(IN)       SD(IN)      FO(IN/HR)   FC(IN/HR)       TR(MIN)      TL(MIN)
       P-18         P-15         P-12        P-11,.13        P-16          P-19
SW 4 ,50* .020PP ,60*,0100P3,10* .5000P .01*,0000P 20,* .1071P 20,* .1000P

SWN 4      LAG* 1       2*  20,0        H*49
 SUBZONE   CFS  ACC TOTAL CFS  1000 ACRE FT.     STORED  CFS   1000 ACRE FT
           .02           .08              .00              .00            .00
           .00          3.27              .00              .60            .00
           .28          4.50              .00              .00            .00
           .02          6.54              .00              .00            .00
           .00          8.17              .02              .00            .00
           .00         10.27              .00              .00            .20
           .00         11.58              .02             1.25            .00
           .00         13.08              .00             2.19            .00
           .00         14.40              .00             4.29            .00
           .00         15.65              .00             7.36            .00
           .06         16.58              .00            17.14            .00
           .03         18.45              .00            33.72            .00
           .78         18.22              .00            38.40            .00
          3.03         21.72              .01            47.97            .00
          6.30         25.40              .01            57.70            .00
         10.84         30.13              .01            66.10            .00
         13.70         33.87              .01            74.00            .00
         17.28         38.00              .01            82.00            .00
         20.55         41.34              .01            90.02            .00
         23.92         44.15              .01            94.83            .00
         17.98         39.47              .01            76.71            .00
         10.11         37.80              .01            69.93            .00
           .80         26.39              .01            40.50            .00
           .08         22.85              .01            27.65            .00
           .08         21.40              .01            19.24            .00
           .07         20.70              .02            13.63            .00
           .00         21.02              .02             9.66            .00
           .00         21.02              .02             7.79            .00
           .00         21.02              .02             6.18            .00
           .07         21.23              .02             5.40            .00
           .08         21.02              .02             5.46            .00
           .00         21.49              .02             4.99            .00
           .03         21.49              .02             4.09            .00
           .07         21.25              .02             4.29            .00
           .08         21.25              .02             4.70            .00
           .02         21.40              .02             4.76            .00
           .00         21.40              .02             4.29            .00
           .00         21.40              .02             4.00            .00
           .07         21.05              .03             4.32            .00
           .04         21.42              .03             4.20            .00
           .07         21.25              .03             4.76            .00
           .08         21.42              .03             4.92            .00
           .02         21.49              .03             4.02            .00
           .03         21.07              .03             4.09            .00
           .00         21.47              .03             3.02            .00
           .00         21.72              .03             4.06            .00
           .00         21.43              .03             4.20            .00
           .00         21.05              .03             4.20            .00
           .05         21.72              .03             3.50            .00
```

Table 5.6

```
COTTONWOOD WEIR (W-9) IS THE RECORDING  COTTONWOOD WEIR (W-9) IS THE RECORDING

WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA      1965
      SI(IN)       SD(IN)      FO(IN/HR)   FC(IN/HR)       TR(MIN)      TL(MIN)
       P-18         P-15         P-12        P-11,.13        P-16          P-19
SW 5 ,70* .020PP ,50*,022NP .5** ,252** ,51*,000dP 18.* ,30EPP 8.* .375dP

SWN 5      LAG* 0       0*  44.1        H*49
 SUBZONE   CFS  ACC TOTAL CFS  1000 ACRE FT.     STORED  CFS   1000 ACRE FT
           .00          1.88              .00              .07            .00
           .00          2.89              .00              .00            .00
           .00          4.43              .30              .30            .00
           .00          5.13              .00              .02            .00
           .00          6.77              .07              .00            .30
           .00          8.40              .30              .00            .00
           .00          9.37              .02              .02            .00
           .00         11.44              .20              .20            .02
           .00         12.64              .03              .70            .00
           .00         14.81              .03              .04            .00
           .00         15.41              .00              .00            .00
           .00         16.81              .30              .00            .32
           .00         17.88              .02              .52            .00
           .00         20.32              .00              .00            .00
          2.06         24.76              .01              .00            .20
          5.13         30.36              .01              .03            .00
          8.17         36.67              .01              .00            .30
         10.27         43.21              .01              .00            .30
         13.31         48.82              .01              .00            .02
         14.71         54.42              .01              .04            .00
          8.07         48.82              .01              .00            .00
          8.07         48.88              .01              .00            .00
           .00         36.20              .01              .00            .00
           .00         32.47              .02              .00            .00
           .00         28.90              .02              .00            .20
           .00         26.86              .02              .44            .00
           .00         25.46              .02              .08            .06
           .00         24.29              .02              .00            .00
           .00         23.82              .02              .90            .00
           .00         23.89              .22              .00            .00
           .00         23.36              .02              .42            .00
           .20         23.59              .02              .20            .00
           .00         23.12              .02              .30            .00
           .00         22.59              .02              .03            .02
           .20         23.12              .03              .08            .00
           .00         23.12              .03              .04            .00
           .00         22.42              .03              .00            .00
           .00         23.12              .03              .70            .00
           .00         23.12              .03              .00            .00
           .00         22.89              .03              .00            .00
           .00         22.89              .03              .04            .00
           .00         22.65              .03              .30            .00
           .00         22.42              .03              .30            .00
           .00         22.42              .03              .00            .00
           .00         22.89              .03              .00            .00
           .00         22.89              .04              .03            .00
           .50         23.12              .04              .04            .00
           .00         22.80              .04              .07            .00
           .00         22.89              .04              .30            .00
```

Table 5.7

```
COTTONWOOD WEIR (W-9) IS THE RECORDING  COTTONWOOD WEIR (W-9) IS THE RECORDING

WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA      1965
      SI(IN)       SD(IN)      FO(IN/HR)   FC(IN/HR)       TR(MIN)      TL(MIN)
       P-18         P-15         P-12        P-11,.13        P-16          P-19
SW 6 .02* .0105P .52*.0200P .40* .2400P .01*.0050P 7.* .4200P 5.* .0000P

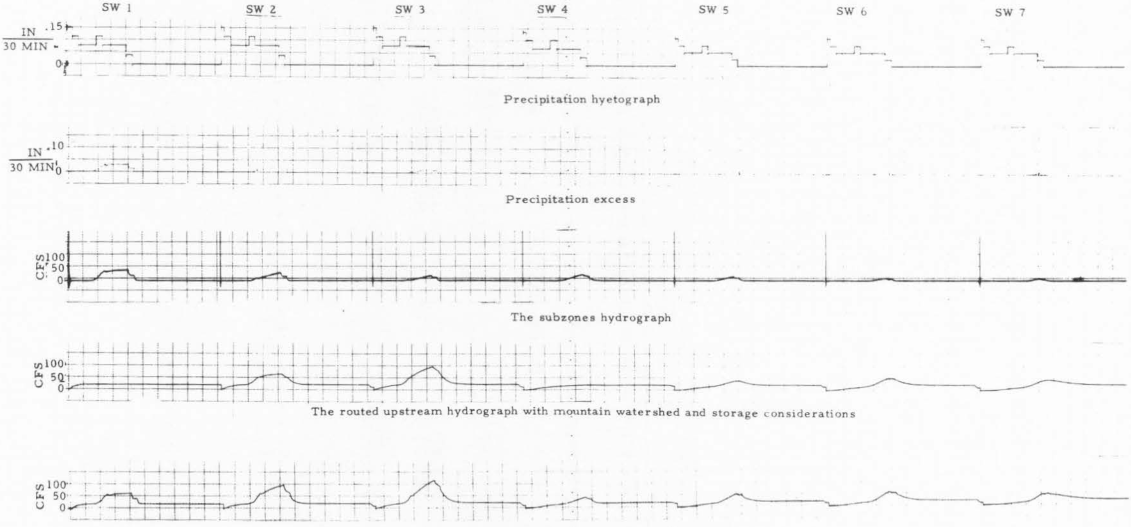
SWN 6      LAG* 0       0*  54.4        H*49
 SUBZONE   CFS  ACC TOTAL CFS  1000 ACRE FT.     STORED  CFS   1000 ACRE FT
           .00          3.03              .00              .00            .00
           .00          3.50              .00              .00            .00
           .00          4.07              .00              .00            .00
           .00          5.94              .00              .00            .00
           .00          6.54              .20              .00            .00
           .06          7.94              .00              .03            .00
           .00          9.57              .00              .00            .00
           .00         10.07              .00              .00            .00
           .00         12.04              .30              .00            .00
           .00         14.01              .00              .00            .00
           .00         15.41              .00              .03            .00
           .02         16.58              .02              .03            .00
           .00         17.75              .00              .00            .00
           .02         19.30              .00              .00            .00
           .23         23.42              .01              .03            .00
          1.03         28.20              .01              .00            .00
          3.50         35.07              .01              .03            .00
          5.84         44.15              .01              .00            .00
          7.94         51.02              .01              .00            .00
          9.81         60.03              .01              .00            .00
          4.90         55.39              .01              .00            .00
          5.37         50.29              .01              .00            .00
           .06         44.01              .02              .04            .00
           .00         39.71              .02              .00            .00
           .00         35.07              .02              .00            .00
           .00         32.23              .02              .00            .00
           .02         29.05              .02              .00            .00
           .00         28.03              .02              .00            .00
           .02         26.40              .02              .00            .00
           .00         25.09              .02              .30            .00
           .00         25.22              .02              .00            .00
           .00         25.22              .03              .00            .00
           .00         24.03              .03              .00            .00
           .00         24.29              .03              .00            .00
           .00         24.78              .03              .00            .00
           .00         24.52              .03              .00            .00
           .00         24.29              .03              .02            .00
           .01         24.76              .03              .00            .00
           .01         24.22              .03              .00            .00
           .01         24.20              .03              .00            .00
           .01         24.20              .03              .00            .30
           .02         24.20              .04              .20            .00
           .00         23.02              .04              .90            .00
           .00         23.02              .04              .00            .00
           .00         24.52              .04              .30            .00
           .00         24.29              .04              .03            .30
           .00         24.52              .04              .00            .00
           .00         24.26              .04              .00            .30
           .06         24.10              .04              .00            .00
```

Table 5.8

```
COTTONWOOD WEIR (W-9) IS THE RECORDING  COTTONWOOD WEIR (W-9) IS THE RECORDING

WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA      1965
      SI(IN)       SD(IN)      FO(IN/HR)   FC(IN/HR)       TR(MIN)      TL(MIN)
       P-16         P-15         P-12        P-11,.13        P-16          P-19
SW 7 .70* .0140P .50*.0200P .90* .4700P .01*.0050P 17.* .1764P 14.* .2142P

SWN 7      LAG* 0       0*  50.0        H*49
 SUBZONE   CFS  ACC TOTAL CFS  1000 ACRE FT.     STORED  CFS   1000 ACRE FT
           .00          3.27              .01              .03            .02
           .00          3.97              .00              .03            .00
           .00          4.20              .00              .00            .30
           .00          4.87              .00              .00            .00
           .00          5.13              .02              .00            .00
           .00          6.07              .20              .00            .00
           .00          7.00              .00              .00            .00
           .00          7.44              .03              .30            .33
           .00          9.34              .00              .00            .30
           .00         10.51              .00              .00            .00
           .00         11.68              .00              .00            .00
           .00         12.61              .00              .00            .00
           .00         14.21              .00              .00            .00
           .00         15.65              .00              .00            .00
           .00         17.28              .00              .00            .00
           .00         20.00              .01              .00            .00
           .93         25.48              .01              .00            .00
          3.27         32.80              .01              .00            .00
          5.84         38.77              .01              .02            .00
          8.17         47.18              .01              .00            .00
          4.20         48.95              .01              .00            .00
          4.90         49.75              .01              .00            .00
           .00         48.25              .01              .01            .00
           .00         44.38              .01              .02            .00
           .00         42.74              .01              .03            .00
           .00         41.11              .02              .00            .00
           .00         39.24              .02              .03            .30
           .00         37.37              .02              .00            .00
           .00         35.50              .02              .00            .00
           .00         33.83              .02              .00            .00
           .00         32.78              .02              .00            .00
           .00         31.53              .02              .00            .00
           .00         30.38              .03              .00            .20
           .00         28.98              .03              .00            .06
           .00         29.28              .03              .00            .00
           .06         28.03              .03              .00            .02
           .00         28.03              .03              .00            .00
           .02         27.56              .03              .00            .00
           .00         27.09              .03              .03            .00
           .00         27.09              .03              .23            .00
           .00         26.96              .03              .00            .20
           .00         26.83              .04              .20            .30
           .00         27.18              .04              .00            .30
           .00         25.92              .04              .00            .90
           .04         26.16              .04              .00            .30
           .06         25.40              .04              .00            .46
           .00         25.42              .04              .00            .00
           .04         25.80              .04              .00            .00
           .00         25.69              .04              .00            .00
```



Precipitation hyetograph

Precipitation excess

The subzones hydrograph

The routed upstream hydrograph with mountain watershed and storage considerations

The hydrograph at the outflow point of the subzones

TIME SCALE: 1 UNIT = 30 MINUTES

Figure 5.1. Graphical results for the combined subzones of Mill Creek for the event of May 22-23, 1968.

storage of runoff within various subzones, are given in the previously mentioned tables. At the upper end of subzone 1, it was assumed a storage area could be available and retain the runoff above a selected 20 cfs. The 20 cfs would be the capacity of the downstream channel, and flows above 20 cfs could conceivably cause flood damage. Presently, there is no reservoir, and the storage consideration is only hypothetical. Another location for temporary watershed storage was selected at the upper end of subzone 4. The same assumptions were applied here as were applied at the subzone 1 location.

Storage consideration due to channel storage alone, alluded to as Plan A, was considered by the rise time parameter since storage was a function of this parameter. Subzones that were assumed not to have temporary storage were modeled with only channel storage. The affect of this channel storage is shown to be negligible in obtaining the hydrograph at the subzones outflow point after the addition of the subzone contribution and the routed upstream discharge. The graphical results present an illustration of this minimal channel storage for the value of t_R used in the initial modeling process. The sensitivity analyses for the rise time parameter also shows the attenuation effect for various values tried.

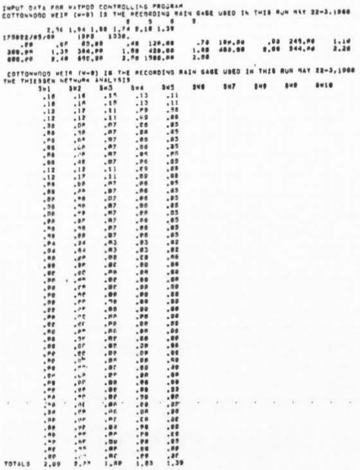
Big Cottonwood Creek

Urban parameters were calculated for use with the regression equations for each of the five subzones of the Big Cottonwood Creek watershed. The urban parameters were summarized earlier in Table 3.2. The watershed coefficients calculated were given in Table 3.3. The same problem with the watershed coefficients as derived from the regression equations occurred as occurred with the Mill Creek watershed. The same assumptions were applied to this watershed to obtain an initial estimate for the watershed coefficients to yield a hydrograph.

The Thiessen network analyses for the event of May 22-23, 1968, are presented as Table 5.9. It should be noted that for this particular storm, the more abundant precipitation occurred on the Big Cottonwood Creek watershed and nearer to the mountains. Mill Creek also had more precipitation near the mountains, with the precipitation decreasing in the lower and flatter areas downstream. It is this type of precipitation distribution that necessitates design of flood control works to protect the downstream inhabitants and their property. With the mountain watersheds contributing to the urban flow, natural channels are overtaxed and flooding occurs.

Temporary storage to store flows greater than 100 cfs was assumed at the upper end of subzone 1 for this watershed. It was assumed that the downstream channel can carry the 100 cfs, and the temporary storage could store all additional flow. Another temporary storage location was assumed to be at the upper end of subzone 4, with a channel capacity limited to 50 cfs because of obstructions. The results for the event of May 22-23, 1968, via digital computer printout are presented as Tables 5.10 through 5.14. The graphical results via analog output are presented as Figure 5.2.

Table 5.9

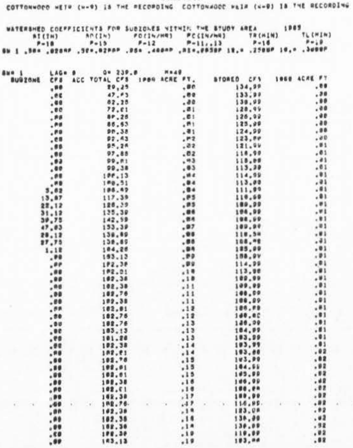


```
INPUT DATA FOR WATMOD CONTROLLING PROGRAM
COTTONWOOD WEIR (W-9) IS THE RECORDING RAIN GAGE USED IN THIS RUN MAY 22-3,1968

COTTONWOOD WEIR (W-9) IS THE RECORDING RAIN GAGE USED IN THIS RUN MAY 22-3,1968
THE THIESSEN NETWORK ANALYSIS
       SW1    SW2    SW3    SW4    SW5    SW6    SW7    SW8    SW9    SW10

TOTALS  2.09   2.??   1.8?   1.83   1.39
```

Table 5.10

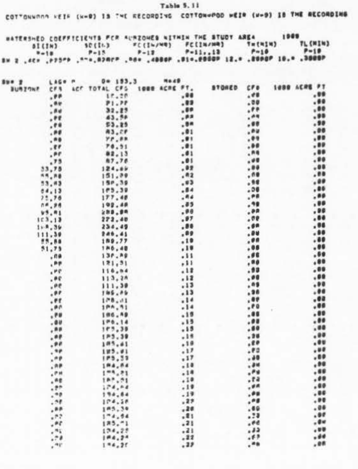


```
COTTONWOOD WEIR (W-9) IS THE RECORDING  COTTONWOOD WEIR (W-9) IS THE RECORDING

WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA      1969
     SI(IN)       SD(IN)      FO(IN/HR)    FC(IN/HR)      TR(MIN)      TL(MIN)
      P-18         P-15         P-12        P-11,.13        P-16         P-19

SW# 1         LAG= 0        Q= 239.0        M=49
 SUBZONE   CFS  ACC TOTAL CFS  1000 ACRE FT.      STORED  CFS   1000 ACRE FT
```

Table 5.11

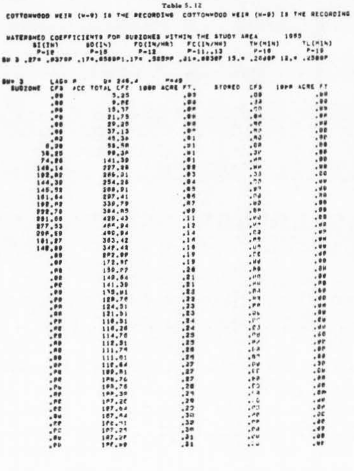


```
COTTONWOOD WEIR (W-9) IS THE RECORDING  COTTONWOOD WEIR (W-9) IS THE RECORDING

WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA      1969
     SI(IN)       SD(IN)      FC(IN/HR)    FC(IN/HR)      TW(MIN)      TL(MIN)
      P-18         P-15         P-12        P-11,.13        P-18         P-19

SW# 2         LAG= 0        Q= 193.3        M=49
 SUBZONE   CFS  ACC TOTAL CFS  1000 ACRE FT.      STORED  CFS   1000 ACRE FT
```

Table 5.12



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COTTONWOOD WEIR (W-9) IS THE RECORDING  COTTONWOOD WEIR (W-9) IS THE RECORDING

WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA      1969
     SI(IN)       SD(IN)      FO(IN/HR)    FC(IN/HR)      TW(MIN)      TL(MIN)
      P-18         P-15         P-12        P-11,.13        P-18         P-19

SW# 3         LAG= 0        Q= 246.4        M=49
 SUBZONE   CFS  ACC TOTAL CFS  1000 ACRE FT.      STORED  CFS   1000 ACRE FT
```

Table 5.13

```
COTTONWOOD WEIR (W=9) IS THE RECORDING  COTTONWOOD WEIR (W=9) IS THE RECORDING

WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA       1965
      SI(IN)       SD(IN)      FC(IN/HR)   FC(IN/HR)      TP(MIN)      TL(MIN)
       P=10         P=15        P=12       P=11,.13        P=16         P=19
SW 4 .17= .0588P .33=.1111P1.11= .5550P .21=.0030P 13.= .2307P 11.  .2727P

SW= 4        LAG= 0      Q=  58.0       M=49
  SUBZONE  CFS  ACC TOTAL CFS  1000 ACRE FT.     STORED  CFS   1000 ACRE FT
            .00          5.52            .00             .00           .00
            .00          6.75            .00             .00           .00
            .00          9.37            .00             .00           .00
            .00         12.75            .00             .00           .00
            .00         17.62            .00             .00           .00
            .00         22.53            .00             .00           .00
            .00         29.62            .00             .00           .00
          13.87         49.86            .00            8.50           .00
          29.12         69.38            .01           49.38           .00
          34.88         78.38            .01           91.39           .00
          61.88        106.69            .01          177.28           .00
          67.76        135.39            .01          239.91           .00
          76.88        124.63            .02          204.28           .00
          87.38        136.89            .02          218.91           .00
          92.53        144.39            .03          247.41           .01
          98.81        145.89            .04          289.79           .01
          95.91        147.39            .04          334.05           .01
          97.88        150.39            .05          379.43           .01
         103.13        154.89            .05          416.94           .01
         114.39        156.29            .06          449.94           .01
          46.25        111.39            .07          313.42           .01
          47.38        111.39            .07          292.42           .01
            .00         57.38            .07          152.90           .01
            .00         52.88            .08          122.89           .01
            .00         52.50            .08          109.02           .01
            .00         52.50            .08           99.64           .01
            .00         52.13            .08           91.39           .01
            .00         52.50            .08           85.61           .01
            .00         52.13            .09           79.76           .01
            .00         52.13            .09           74.51           .01
            .00         52.88            .09           71.51           .01
            .00         51.75            .09           68.51           .01
            .00         52.13            .09           66.26           .01
            .00         52.50            .12           64.76           .01
            .00         52.13            .12           62.51           .02
            .00         52.50            .12           61.76           .02
            .00         52.50            .12           61.01           .02
            .00         52.50            .12           60.54           .02
            .00         52.88            .11           59.51           .02
            .00         53.25            .11           58.76           .02
            .00         53.25            .11           58.76           .02
            .00         52.50            .11           58.39           .02
            .00         52.13            .11           57.26           .02
            .00         52.56            .12           57.04           .02
            .00         52.40            .12           57.64           .02
            .00         52.50            .12           58.01           .02
            .00         52.13            .12           57.26           .02
            .00         51.63            .12           57.26           .02
            .00         52.50            .13           56.65           .02
```

Table 5.14

```
COTTONWOOD WEIR (W=9) IS THE RECORDING  COTTONWOOD WEIR (W=9) IS THE RECORDING

WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE STUDY AREA       1965
      SI(IN)       SD(IN)      FD(IN/HR)   FC(IN/HR)      TP(MIN)      TL(MIN)
       P=10         P=15        P=12       P=11,.13        P=16         P=19
SW 5 .50= .0200P .50=.0200P .30= .1500P .01=.0050P  9.= .3333P  7.= .4285P

SW= 5        LAG= 0      Q= 168.8       M=49
  SUBZONE  CFS  ACC TOTAL CFS  1000 ACRE FT.     STORED  CFS   1000 ACRE FT
            .00          5.25            .00             .00           .00
            .00          6.37            .00             .00           .00
            .00          9.00            .00             .00           .00
            .00         11.25            .00             .00           .00
            .00         14.62            .00             .00           .00
            .00         16.37            .00             .00           .00
            .00         22.87            .00             .00           .00
            .00         34.08            .00             .00           .00
            .00         46.68            .01             .00           .00
            .00         58.88            .01             .00           .00
            .00         76.86            .01             .00           .00
            .00         99.38            .01             .00           .00
            .00        108.89            .01             .00           .00
            .37        122.39            .02             .00           .00
           1.50        130.89            .02             .00           .00
           3.37        139.89            .03             .00           .00
           4.12        147.39            .03             .00           .00
           6.00        151.89            .04             .00           .00
           7.50        157.89            .05             .00           .00
           8.62        166.09            .05             .00           .00
           4.87        147.39            .06             .00           .00
           4.12        136.89            .06             .00           .00
            .00        105.39            .07             .00           .00
            .00         90.38            .07             .00           .00
            .00         76.01            .08             .00           .00
            .00         69.38            .08             .00           .00
            .00         64.50            .08             .00           .00
            .00         61.13            .08             .00           .00
            .00         57.38            .09             .00           .00
            .00         57.75            .09             .00           .00
            .00         58.25            .09             .00           .00
            .00         55.50            .09             .00           .00
            .00         54.38            .10             .00           .00
            .00         57.36            .10             .00           .00
            .00         56.25            .10             .00           .00
            .00         55.50            .10             .00           .00
            .00         54.38            .10             .00           .00
            .00         55.50            .11             .00           .00
            .00         55.13            .11             .00           .00
            .00         55.13            .11             .00           .00
            .00         54.38            .11             .00           .00
            .00         57.38            .12             .00           .00
            .00         55.88            .12             .00           .00
            .00         54.75            .12             .00           .00
            .00         55.50            .12             .00           .00
            .00         55.13            .12             .00           .00
            .00         54.36            .13             .00           .00
            .00         57.38            .13             .00           .00
            .00         55.50            .13             .00           .00
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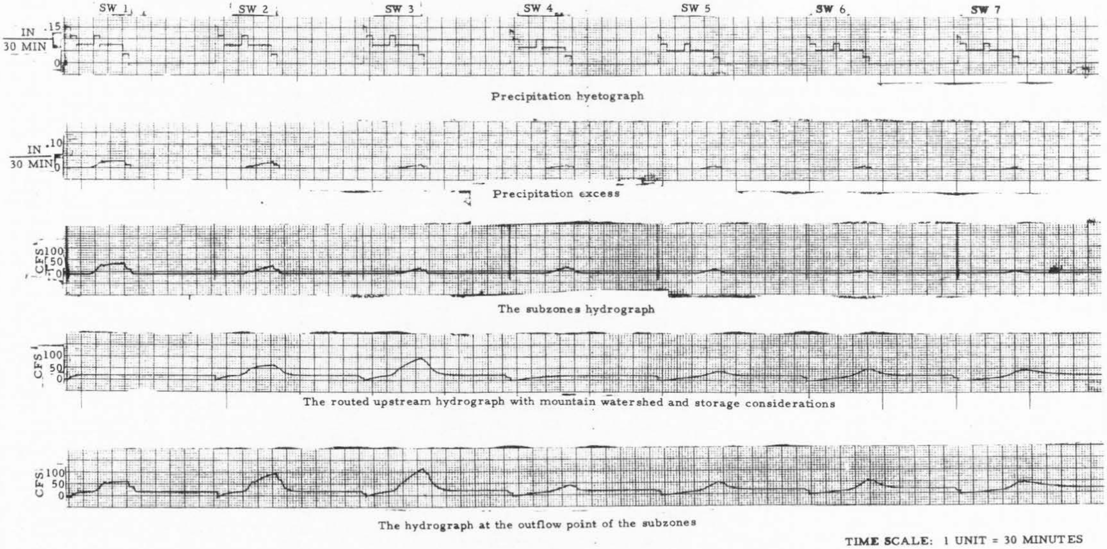

Figure 5.2. Graphical results for the combined subzones of Big Cottonwood Creek for the event of May 22-23, 1968.

The Mill Creek and the Big Cottonwood Creek hydrographs were summed to yield the combined hydrograph of the two watersheds at the Jordan River (Figure 5.3).

The development of a model of this type necessitates that the model be verified. The verification would normally occur at this point in the study. A similar combined hydrograph without temporary storage considerations was compared to the gaged flow of the Jordan River, and it became apparent that from the existing watershed gaging station pattern that the urban watershed of Little Cottonwood Creek must be included in the model study. The addition of Little Cottonwood Creek to the model would be necessary since neither Mill Creek nor Big Cottonwood Creek had a gaging station at the Jordan River. The existing gaging station upstream and the gages downstream at the Jordan River and the surplus canal were to be used in the verification procedure. At this point in the verification procedure, the ungaged flow from Little Cottonwood was greater than first expected, and therefore its contribution to the Jordan River should be considered in the study. In lieu of verification of the model, due to time limitations, a sensitivity analysis for various parameters was undertaken. In the sensitivity analyses, one parameter was varied while the other watershed coefficients were held constant. The sensitivity analyses was undertaken for subzone 1 of Mill Creek. No surface inflow was considered and no temporary subzone storage was assumed in this analysis. The initial estimation of S_I, S_d, and F_c from the regression equations

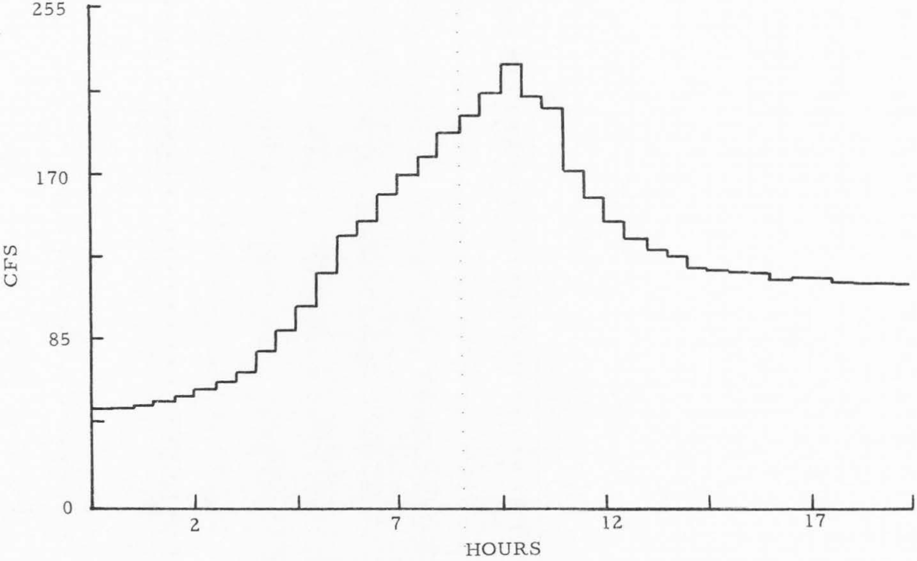

Figure 5.3. The combined hydrograph for Mill Creek and Big Cottonwood Creek for the event of May 22-23, 1968.

abstracted too much precipitation for the existing conditions. Therefore, an analysis of the sensitivity of the model to these parameters was undertaken since model verification was deleted. Two of these coefficients are part of an exponential function for the abstraction of precipitation and have their greatest impact in the earlier periods of precipitation. These earlier periods of the storms usually had the highest precipitation within the equal time increments. The parameter for minimum infiltration, F_c, abstracts constantly throughout the subzone modeling period and has the greatest effect on the abstraction process after the exponential decay function losses are abstracted. The parameter, F_c, was probably the most crucial parameter in the model study since it was a constant abstraction and had an affect on the peak flow. The peak flow is used in the determination of the lag parameter, T_L, and this in turn effects the recession side of the hydrograph. The peak discharge is also used in the computing storage. Figure 5.4 presents the sensitivity analyses for S_I, Figure 5.5 for S_d, Figure 5.6 for F_c, and Figure 5.7 for t_R. Note that the assumed watershed coefficients used previously serve as a reference for sensitivity . This reference point has a discharge of 49 cfs. The input precipitation was doubled for the sensitivity analysis since it would allow greater separation of the graphs and would show the reference point.

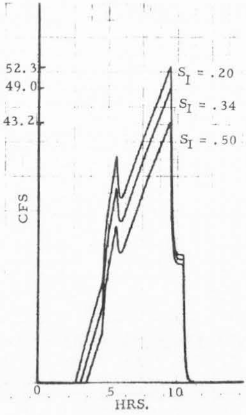

Figure 5.4. Sensitivity analyses for S_I.

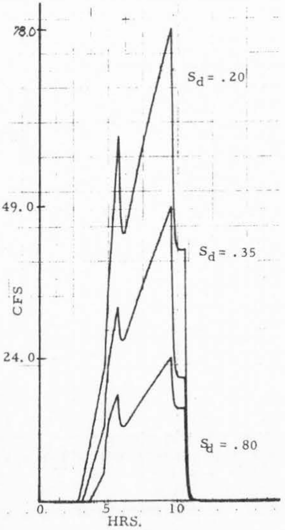

Figure 5.5. Sensitivity analyses for S_d.

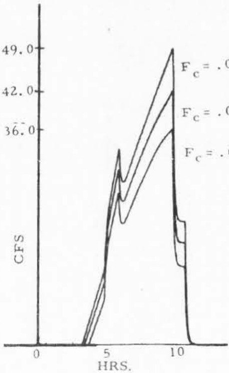

Figure 5.6. Sensitivity analyses for F_c.

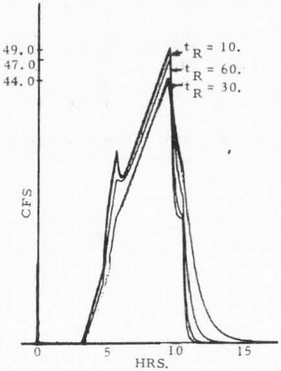

Figure 5.7. Sensitivity analyses for t_R.

CHAPTER VI

SUMMARY AND RECOMMENDATIONS

Summary

The computer simulation of urban runoff characteristics within Salt Lake County of the two urban watersheds of Mill and Big Cottonwood Creeks made use of the watershed model developed by Narayana et al. (1969) and improved by Evelyn et al. (1970). This study combined their separate digital computer programs and the analog program into a hybrid system. The resulting hybrid system will allow general flexibility and a greater variety of conditions to be simulated with little or no changes made to the hybrid model. The one possible program change for a watershed outside of the indicated urban watersheds within Salt Lake County would be the Thiessen network analysis as this network changes with a given situation and the precipitation instrumentation location and number.

In the development of a systems model, utilizing the urban hydrology simulation model developed at the Utah Water Research Laboratory, due consideration was given to the watershed under study. The availability of large scale aerial photographs, precipitation records, and stream gaging stations were considered. The objectives of this study are listed below.

1. To develop a systems model utilizing the urban hydrology simulation model developed at the Utah Water Research Laboratory.

2. To calculate the urban watershed parameters, C_f and L_f, needed by the regression equations in the simulation model.

3. To include storage considerations for the temporary storage of portions of the watershed subzone discharge.

4. To synthesize urban outflow hydrographs with the calculated input parameters.

5. To set the watershed systems model up in a manner that an economic analysis for hydraulic design can be achieved.

The present study utilized the previous work of Narayana et al. (1969) and Evelyn et al. (1970) for the development of the systems model. This systems model consists of the digital program WATMOD and the accompanying analog computer program. The combination of the analog computer and the digital computer has been termed a hybrid system.

The calculations for the urban watershed parameters, C_f and L_f, are done by the URBPAR digital program. These urban watershed parameters are used in the WATMOD program for the calculations of the watershed coefficients. The URBPAR and WATMOD programs are given in Appendix A and Appendix B, respectively, along with sample input and output data.

The systems model was applied and results obtained. The model was not verified because of ungaged flows originating outside of the two urban watersheds studied. This ungaged inflow was from the urban watershed of Little Cottonwood Creek and caused significant variation in the total flow of the Jordan River. The watershed systems model, in hybrid form, is in a form that allows future additions to the system for economic and other considerations.

The urban watershed systems model as applied to the two urban watersheds of Mill Creek and Big Cottonwood Creek, within Salt Lake County, Utah, and with the results obtained suggested the following conclusions.

1. The systems model applied to the two urban watersheds could adequately verify the outflow hydrograph at the outflow point if the gaged outflow data for each watershed were available.

2. The urban watershed of Little Cottonwood Creek should have been included in this model study due to the location of the available stream gaging stations. If Little Cottonwood Creek had been included, then verification may have been possible since the contributions of this creek could have been included in the total watershed runoff.

3. The regression equations developed by Narayana et al. (1969) for the Waller Creek experimental watershed, near Austin, Texas, and used in the present study, lack the accuracy needed to predict the watershed coefficients. The regression equations as applied in this study gave a good initial approximation of the watershed coefficients but were not completely satisfactory.

Recommendations

The results of this study lead to the following recommendations for additional research.

1. The Little Cottonwood urban watershed should be incorporated into the model for verification purposes, or a correlation study made to include the Little Cottonwood watershed outflow in the Jordan River flow. This problem could have been alleviated if there were stream gaging stations at the mouths of Mill Creek and Big Cottonwood Creek.

2. More precipitation and streamflow instruments should be locationed within the watershed and data accumulated for shorter time intervals. This would enhance a more accurate model.

3. The urban watershed model should be applied in planning, design, and economic studies to demonstrate the usefulness of the system model.

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APPENDICES

APPENDIX A

DIGITAL COMPUTER PROGRAM "URBPAR" FOR CALCULATING THE PERCENT IMPERVIOUS AREA, C_f, AND THE CHARACTERISTIC IMPERVIOUS LENGTH FACTOR, L_f. SAMPLE OUTPUT FOR THE MILL CREEK AND THE BIG COTTONWOOD URBAN WATERSHEDS WITHIN SALT LAKE COUNTY, UTAH, IS ALSO GIVEN.

```
PAGE  1     C        URBPAR   PROGRAM     UTAH STATE UNIVERSITY   1971  RNP

C     PROGRAM WRITTEN FOR THE  EAI 640 DIGITAL COMPUTING SYSTEM
C     PROGRAM FOR IMPERVIOUS AREA,CF, AND LENGTH FACTOR,LF, FOR WATHOD
C     NS=SUBAREA NUMBER
C     A =SUBAREA AREA IN MILLIONS FT.SQ.
C     R =ROADS        IN THOUSAND FT.SQ.
C     H =HOMES        IN THOUSAND FT.SQ.
C     S =SIDEWALKS    IN THOUSAND FT.SQ.
C     P =PARKING LOTS IN THOUSAND FT.SQ.
C     B =BUILDINGS    IN THOUSAND FT.SQ.
C     TIA=TOTAL IMP.  IN THOUSAND FT.SQ.
C     XLI=FLOW LENGTH
C     XLM=WEIGHTED AVERAGE
C     XLF= CHACTERISTIC IMPERVIOUS LENGTH FACTOR
C     XL= WATERSHED SUBAREA LENGTH
C     N =NUMBER OF SUBAREAS IN WATERSHED
      REAL IAP
      DIMENSION NS(20),A(20),R(20),H(20),S(20),P(20),B(20),XLI(20),TIA(2
     10),RP(20),HP(20),SP(20),PP(20),BP(20),Q(20),T(20),AP(20)
    1 READ (8,2) N, XL,(Q(I), I=1,17)
    2 FORMAT ( I2, F7.1, 3X,17A4)
      IF ( N .EQ. 0) GO TO 500
      DO 10 I=1,N
      READ (8,5)  NS(I),A(I),R(I),H(I),S(I),P(I),B(I),XLI(I)
    5 FORMAT(5X, I5, 7F5.1)
   10 CONTINUE
      TIAS=0.0
      ET=0.0
C     ADDING THE IMPERVIOUS AREAS-TOTAL IMPERVIOUS AREA
      DO 20 I=1,N
      TIA(I)= R(I) + H(I) + S(I) + P(I) + B(I)
      TIAS = TIAS + TIA(I)
      T(I) = XLI(I) *TIA(I)
      ET= T(I) + ET
   20 CONTINUE
      XLM=ET/TIAS
      XLF= XLM/XL
      DO 30 J=1,N
      RP(J)=R(J)/A(J) *.1
      HP(J)=H(J)/A(J) *.1
      SP(J)=S(J)/A(J) *.1
      PP(J)=P(J)/A(J) *.1
      BP(J)=B(J)/A(J) *.1
   30 CONTINUE
      AT=0.0
      DO 40 I=1,N
      AT= A(I) + AT
   40 CONTINUE
      DO 45 I=1,N
      AP(I) = A(I) / AT *100.
   45 CONTINUE
      IAP = TIAS/(AT) * .001
      WRITE (6,100)
  100 FORMAT ( 1H1)
      WRITE (6,47)    (Q(I),I=1,17)
   47 FORMAT ( 4X, 17A4//)
      WRITE (6,50)
```

```
PAGE  2     C        URBPAR   PROGRAM     UTAH STATE UNIVERSITY   1971  RNP

   50 FORMAT (77H  A     AREA   ROADS   HOMES  SIDEWALK PARKLOT  BUILD
     1IMPAREA  LENGTH  SUMS )
      WRITE ( 6,55 )
   55 FORMAT  (71H          MSF     KSF     KSF     KSF     KSF     KSF
     1     KSF      KF )
      DO 200 I=1,N
      WRITE(6,60)  NS(I),A(I),R(I),H(I),S(I),P(I),B(I),TIA(I),XLI(I),
     1 T(I)
   60 FORMAT (2X,I2,6F8.1,3X,3F8.1)
      WRITE(6,70)     AP(I), RP(I), HP(I), SP(I), PP(I), BP(I)
   70 FORMAT ( 4X,6F8.1 )
  200 CONTINUE
      WRITE (6,80)     AT,ET
   80 FORMAT ( 4X,F8.1,60X,F8.1 )
      WRITE (6,85) IAP, XLF
   85 FORMAT (25H PERCENT IMPERVIOUS AREA=, F9.4, 5X,27H IMPERVIOUS  LEN
     1GTH FACTOR=, F7.4)
      GO TO 1
  500 WRITE ( 6,90)
   90 FORMAT (33H THIS COMPLETS THE WORK REQUESTED)
      STOP
      END
```

```
    BIG COTTONWOOD WATERSHED  SW-1

 A     AREA   ROADS   HOMES  SIDEWALK PARKLOT  BUILD  IMPAREA  LENGTH  SUMS
        MSF     KSF     KSF     KSF     KSF     KSF      KSF     KF
  1    11.7   855.0   352.8    18.6    34.5    44.0   1987.0    10.2 19785.2
        8.1     7.5     3.2      .1      .2      .3
  2     5.8   534.0   598.2      .8   480.0   140.0   1778.0    15.2 27025.0
        2.8    10.5    13.9      .0     8.0     2.9
  3     8.1   821.7   744.0    36.0   216.0   212.5   1829.5    12.6 23051.0
        4.7     7.5     9.1      .4     2.6     2.6
  4    10.7   954.8  1452.0     9.6      .0      .0   2415.8    13.0 31402.7
        5.5     8.0    13.5      .1      .0      .0
  5    10.4  1023.4  1341.5     4.0   125.5    78.0   2572.8    14.0 36076.0
        5.4     9.8    12.9      .2     1.2      .7
  6     8.9   788.0   540.2    14.4    38.0    22.0   1314.3     9.0 11829.5
        4.6     7.9     6.3      .1      .3      .2
  7     5.8   536.0   384.0    45.0      .0      .0   1262.0     7.4  7056.7
        3.5     9.2     3.6      .7      .0      .0
  8     7.4   676.2   494.4    14.4    27.0   125.0   1336.7    10.0 14101.2
        3.8     6.1     6.6      .1      .3     1.6
  9    17.7   762.2   592.5    28.8    38.0    50.0   1480.5     3.8  5584.4
        3.3     7.5     5.9      .2      .3      .5
 10     9.1   592.4   456.0     5.2      .0      .0   1153.5     3.0  3836.0
        4.7     7.6     5.0      .1      .0      .0
 11     5.6   312.0   254.4      .0      .0      .0    566.4     3.2  1812.4
        1.8     6.8     7.0      .0      .0      .0
 12     7.5   989.0   824.0    12.0   297.5      .0   1921.5     4.0  6066.0
        3.7     7.0     8.3      .1     3.9      .0
 13    41.2  1338.4  1512.0    21.0   110.0    42.4   3023.3    16.0 50146.4
       21.5     3.2     3.6      .1      .2      .1
 14    51.9  1121.0   940.6      .2      .0    58.0   1420.5    11.0 15626.5
       27.4     2.1      .4      .0      .0      .1
      141.4                                                         255751.0
PERCENT IMPERVIOUS AREA=    .1178     IMPERVIOUS  LENGTH FACTOR=  .8230
```

```
         MILL CREEK SW-1

 A     AREA   ROADS   HOMES  SIDEWALK PARKLOT  BUILD  IMPAREA  LENGTH  SUMS
        MSF     KSF     KSF     KSF     KSF     KSF      KSF     KF
  1     1.2   744.0   465.0      .0      .4      .0   1209.5     7.4  8951.0
        1.9    62.7    38.8      .0      .0      .0
  2     6.7   432.0   762.0    14.4   262.5   634.5   2135.3     5.0 10770.0
       10.8     6.4    11.8      .2     4.2     9.4
  3     3.5   432.0   326.0     7.2    91.5    73.0    933.3     3.5  3266.5
        5.8    12.3     9.3      .2     2.6     2.1
  4     3.8   162.0   112.4     6.0    34.0    31.0    388.3     1.0   385.4
        4.8     5.4     3.7      .2     1.1     1.7
  5     9.2   770.0  1017.6    13.5   263.0   102.5   2154.5     1.5  3461.4
       14.9     8.3    11.0      .1     3.0     1.0
  6     3.7   460.2   549.9      .0      .0      .0   1010.0     7.4  7533.1
        6.0    12.6    14.8      .0      .0      .0
  7     7.2   666.0   732.9     9.4    20.0   232.0   1620.3     7.5 12152.9
       11.7     8.3    10.1      .1      .3     3.5
  8     4.0   932.3   542.4     3.6    87.3    49.0   1614.9    14.0 22469.0
        7.0    19.0    11.8      .1     1.7      .8
  9     2.2   224.0     7.2      .0      .0     3.0    234.2     7.2  1686.2
        3.5    10.1      .3      .0      .0      .1
 10     2.5   334.0   256.0      .3      .0      .0    590.8    10.0  5867.9
        4.0    13.8    10.2      .0      .0      .0
 11     4.1   440.9   547.4      .0   266.0    58.0   1364.3     7.3 10015.1
        6.6    16.0    13.2      .0     6.0     2.1
 12     5.4   962.9   364.8     4.0   262.0   144.0   1492.7     5.2  6498.7
        9.5     6.9    10.7      .1     8.2     4.1
 13     2.6   432.0   554.4      .2   131.5    23.5   1130.3     5.3  6036.3
        4.0    15.3    10.6      .0     4.5      .0
 14     7.1   210.4   369.6     6.0      .2      .0    593.6     8.0  4748.7
       11.5     3.0     5.2      .1      .0      .0
       81.5                                                         107520.4
PERCENT IMPERVIOUS AREA=    .2616     IMPERVIOUS  LENGTH FACTOR=  .4772
```

APPENDIX B

DIGITAL COMPUTER PROGRAM "WATMOD" WITH SUBROUTINE "ANALOG" FOR CALCULATING THE EQUAL INTERVAL PRECIPITATION DATA, THE WATERSHED COEFFICIENTS, AND CONTROLLING THE ANALOG COMPUTER. SUBROUTINE "PRINT" IS INCLUDED. SAMPLE INPUT DATA ARE GIVEN.

```
PAGE 1      C      WATMOD   PROGRAM      UTAH STATE UNIVERSITY   1971  RWP

C      WRITTEN FOR THE EAI 8400 DIGITAL AND 580 ANALOG/HYBRID SYSTEMS
C      URBAN HYDROLOGY HYBRID PROGRAM SALT LAKE COUNTY,UTAH  RWP 1971
C      COMPUTING PRECIPITATION IN EQUAL TIME INTERVALS
C      T= INTERVAL TIME FOR PRECIPATION      P=PRECIPATION DATA
C      GF=GAGE FACTOR     GT = GAGE TOTAL
C      DELT   =  TIME INCREMENT   K= NO. OF OBSERVATIONS
C      NGA = GAGE NUMBER        Q= HEADER CARD INFORMATION
C      DT1DT2= DATE,MONTH AND YEAR   NTO= TIME OF COMMENCEMENT OF STORM
C      IC IS THE GAGE PROGRAM NUMBER FOR THE THIESSEN NETWORK
       COMMON/BK1/SW(50,7 ),PI(50,7 ),ASP(50,7 ), QT(50,7 )
       COMMON/BLK/ SSW(10),GT(10),Q(20),T(50),P(50),GF(10),
      1IN(10),NAT(50),J,ID,LL,M,I,NYEAR,N
       COMMON/BK2/ CN(10),B(10),                 VOLQ(10),TLV(10),QX(10),
      1CFSX(10),CF(10),XLF(10),SI(10),FO(10),FC(10),SD(10),TR(10),SIV(10)
      2,FCV(10),SCV(10),TRV(10),CL(10),S(10),          FOV(10),APOT(10),
      3      VAL(10),A(10),TL(10),               HH(50,2),DELT,QMAX,AREA,SCALE
C    START OF DATA INPUT
     7 WRITE (6,21)
    21 FORMAT (42H1INPUT DATA FOR WATMOD CONTROLLING PROGRAM)
       READ (5,103) (Q(I),I=1,20)
       WRITE (6,103)  (Q(I), I = 1,20)
   103 FORMAT ( 20A4)
       READ (5,30)ID, NWS,NRG,LO
       WRITE (6,30)  ID, NWS, NRG,LO
    30 FORMAT (25X,4I5)
       READ(5,80)     (GT(IC),IC=1,NRG)
       WRITE (6,80)  (GT(IC),  IC = 1,NRG)
    80 FORMAT (10X, 10F5.2)
       READ(5,102) NGA,DT1,DT2,NTO,K,DELT
   102 FORMAT(I5,2A4,I5,I5,F3.0)
       WRITE (6,102)  NGA ,DT1,DT2,NTO,K,DELT
C      FIRST VALUE OF PRECIP SHOULD EQUAL ZERO FOR BEST RESULTS
       READ (5,104) ( T(J),P(J), J=1,K)
   104 FORMAT ( 10X, 14F5.2)
       WRITE (6,105)  (T(J),P(J), J=1,K)
   105 FORMAT ( 10F8.2)
       MC = 1
       CR=1.0
       AP=P(1)
       AT=DELT
       I=0
       J=1
       ASPR = 0.
     3 I=I +1
       IF(AT-T(J+1)) 5,7,8
     5 DT=DELT
       API=AP
       GO TO 10
     8 J=J+1
       IF((J+1)-K) 6,6,14
     6 IF(AT-T(J+1)) 9,7,8
     7 TAP=P(J+1)
       GO TO 11
     9 DT=AT-T(J)
       API=P(J)
       GO TO 10
```

```
PAGE 2      C      WATMOD   PROGRAM      UTAH STATE UNIVERSITY   1971  RWP

    14 TAP=P(K)
       GO TO  11
    10 TAP=DT*(P(J+1)-P(J))/(T(J+1)-T(J))+API
    11 PI(I,MC) = TAP -AP
       IF( I .EQ. 1 ) GO TO 40
    60 ASP(I,MC) = ASP(I-1,MC) + PI(I,MC)
       GO TO 61
    40 ASP(I,MC) = ASPR+ PI(I,MC)
    61 NAT(I) = AT
       IF(AT- T(K)) 12,15,15
    12 CR=CR+1.0
       AT=CR*DELT
       AP=TAP
       GO TO 3
    15 CONTINUE
       J = I
       SUM = P(K)
       DO 16 IC = 1,NRG
       GF(IC) = GT(IC) /SUM
       DO 16 I=1,J
       PI(I,IC) = PI(I,MC) * GF(IC)
       ASP(I,IC) = ASP(I,MC) * GF(IC)
    16 CONTINUE
       IF ( LO  .EQ. 2) GO TO 44
       WRITE(6,100) (Q(I),I=1,20)
   100 FORMAT(1H0, 20A4)
       WRITE(6,101) DT1,DT2,NTO
   101 FORMAT (1H ,15X,4HDATE,2A4,8X,9HTIME ZERO,I6)
       WRITE (6,300) DELT
   300 FORMAT(1H ,20HTIME INCREMENT(MIN)=,F4.0)
       DO 115 IC=1,NRG
       WRITE (6,110) NGA
   110 FORMAT (1H ,7HGAGE NO,I9,3X,13HACC TIME(MIN),4X,19HINTERVAL PRECIP
      1(IN),3X,20HACC STORM PRECIP(IN))
       WRITE (6,106)  (NAT(I),    PI(I,IC),ASP(I,IC), I=1,J)
   106 FORMAT ( 1H , 23X, I5. 2F22.2)
       WRITE (6,107)
   107 FORMAT ( ///, 53H FOLLOWING PRECIP IS PROPORTIONAL TO RECORDING
      1GAGE)
       NGA =NGA + 10
   115 CONTINUE
C      PROGRAM UTILIZES THE THIESSEN METHOD FOR WEIGHTED AVERAGES
C      NRG= NUMBER OF RAIN GAGES EFFECTING THE THIESSEN METHOD
C      NWS = NUMBER OF WATERSHED SUBZONES
C      GIP= GAGE EQUAL INTERVAL PRECIPATION
C      SW =SUBWATERSHED
    44 IF ( ID.EQ. 2) GO TO 54
C      THIESSEN NETWORK ANALYSIS FOR MILL CREEK      ID = 1
C      GAGES USED 1=W-8,2=W-37,3=W-15,4=W-36,5=W-34,6=W-38
    45 DO 50  I=1,J
       SW(I,1) = .11*  PI(I,2) + .89* PI(I,3)
       SW(I,2) = .26*  PI(I,2) + .74 *  PI(I,3)
       SW(I,3) = .03 *  PI(I,2) + .47 *  PI(I,3)
       SW(I,4) = .26 *  PI(I,2) + .32 *  PI(I,3) + .42 *  PI(I,8)
       SW(I,5) = 1.0 *  PI(I,8)
       SW(I,6) = 1.0 *  PI(I,6)
    50 SW(I,7) = 1.0 *  PI(I,6)
       GO TO 73
```

```
PAGE 3      C      WATMOD   PROGRAM      UTAH STATE UNIVERSITY   1971  RWP

C      THIESSEN NETWORK ANALYSIS FOR BIG COTTONWOOD CREEK   ID = 2
    54 DO 70  I=1,J
       SW(I,1) = .29 *  PI(I,1) + .10 *  PI(I,5) + .11 *  PI(I,4) + .41
      1 * PI(I,3)
       SW(I,2) = .07 *  PI(I,1) + .39 *  PI(I,5) + .23* PI(I,4) + .31 *
      1  PI(I,3)
       SW(I,3)= .34* PI(I,5) + .59* PI(I,4) + .05* PI(I,3) + .02 * PI(I,6
      1 )
       SW(I,4) = .70* PI(I,4) + .30* PI(I,6)
    70 SW(I,5) = .91 *  PI(I,4) + .09 *  PI(I,6)
    73 DO 59 L=1,NWS
       SSW( L ) = 0.0
    59 CONTINUE
       DO 72 L=1,NWS
       DO 72 I=1,J
       SSW( L ) = SSW( L ) + SW(I, L )
    72 CONTINUE
       WRITE (6,100) (Q(I), I=1,20)
       WRITE (6,108)
   108 FORMAT ( 30H THE THIESSEN NETWORK ANALYSIS)
       WRITE (6,109)
   109 FORMAT (70H           SW1     SW2     SW3     SW4     SW5     SW6     SW7
      1    SW8    SW9     SW10)
       DO 205 I=1,J
       WRITE (6,200) (SW(I,L), L=1,NWS)
   200 FORMAT ( 6X,10F7.2)
   205 CONTINUE
       WRITE (6,210) (SSW(L) , L=1,NWS)
   210 FORMAT (7H TOTALS, 10F7.2)
    71 IF (LO .NE. 0) GO TO 212
   400 DO 75 I=1,J
       SUMMY = 0.0
       XN = NWS
       DO 74 II =1,NWS
    74 SUMMY=SUMMY + SW(I,II )
    75 SW(I,1) = SUMMY / XN
       WRITE (6,404) ( SW(I,1), I=1,J)
   404 FORMAT (///, 17H SINGLE WATERSHED, / (F10.2))
C      TO CALCULATE OTHER PRECIP DATA AND NOT CALL SUBROUTINE ANALOG LO=1
   212 IF ( LO .EQ. 1) GO TO 7
       CALL ANALOG
       GO TO 7
       END
```

```
INPUT DATA FOR WATMOD CONTROLLING PROGRAM
COTTONWOOD [illegible] IS THE RECORDING RAIN GAGE USED IN THIS RUN MAY 22-3,1968
                                    [illegible]    7    4    2
            [illegible] 1.64 1.58 1.74 2.10 1.[illegible]
175072/[illegible]       [illegible]      1332.
   .00       [illegible]     [illegible]       .42  12[illegible]       .78  18[illegible]       .44  240.[illegible]     1.10
 300.[illegible]      [illegible]     [illegible]      1.[illegible]  420.[illegible]      1.08  450.10      1.63  34[illegible]     2.20
 [illegible]      [illegible]     [illegible]      [illegible]  [illegible]      2.[illegible]
```

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       SUBROUTINE ANALOG
C      SI= INTERCEPTION STORAGE
C      SD= DEPRESSION STORAGE
C      FO= MAXIMUM INFILTRATION RATE
C      FC= MINIMUM INFILTRATION RATE
C      TR= RISE TIME              TL= LAG TIME
C      SW= SUBWATERSHED
C      CL= CHANNEL LENGTH
C      CF= COEF. OF IMPERV. COVER   XLF=CHNR. LENGTH   N= NO. OF SUB WAT
C      S= SLOPE
C      SCALE= SCAILING FACTOR FOR ANALOG COMPUTER PROGRAMMING
C      TOL= TOLERANCE FOR FINAL OUTFLOW HYDROGRAPH  0.0001 USED
C      CN=MANNINGS COEF.  B=CHANNEL WIDTH  A=AREA IN SQ. MILES
C      RSG=1.0 FOR ROUTING   MOUNTAIN  HYDROGRAPHS  ARSG= THAT AREA IN MI
       COMMON/BK1/SW(50,7 ),  QC(50,7 ),RSLT(50,7 ),QT(50,7 )
       COMMON/BLK/WTY(10),GT(10),Q(20),T(50),PS(50), GF(10),
      1 IN(10),NAT(50),J,IC,LL,M,I,NYEAR,N
       COMMON/BK2/ CN(10),B(10),                 VOLQ(10),TLV(10),CFS(10),
      1CFSX(10),CF(10),XLF(10),SI(10),FO(10),FC(10),SD(10),TR(10),SIV(10)
      2,FCV(10),SDV(10),TRV(10),CL(10),S(10),          FOV(10),APOT(10),
      3      VAL(10),A(10),TL(10),               HH(50,2),DELT,QMAX,AREA,SCALE
       DATA PO10,PO11,PO12,PO13/4HP010,4HP011,4HP012,4HP013/
       DATA PO14,PO15,PO16,PO17/4HP014,4HP015,4HP016,4HP017/
       DATA PO18,PO19,PO20,PO21/4HP018,4HP019,4HP020,4HP021/
       CALL OSHVIN (IERR, 500)
       CALL OSC    ( 1, IERR)
       WRITE (6,4)
     4 FORMAT (1H1, 33H INPUT DATA FOR SUBROUTINE ANALOG)
       READ(5,5) N,NYEAR,KOUNT,SCALE,TOL,RSG,ARSG,CFSF,QTP
       WRITE (6,5) N, NYEAR, KOUNT,SCALE,TOL,RSG,ARSG,CFSF,QTP
     5 FORMAT (3I5,6F5.1)
       READ(5,1)(IN(I), CL(I),S(I),CF(I),XLF(I),CN(I),B(I),A(I),CFS(I),I=
      11,N)
       WRITE(6,1)(IN(I), CL(I),S(I),CF(I),XLF(I),CN(I),B(I),A(I),CFS(I),
      1I = 1,N)
     1 FORMAT (3X,I2,5X, 6F10.4, 2F5.1)
C      READING OF UPSTREAM NON URBAN WATERSHED HYDROGRAPHS  MOUNTAIN
       IF ( RSG .NE. 1.) GO TO 10
       READ (5,11)(RSLT(M,1), M=1,50)
       WRITE (6,11)(RSLT(M,1), M=1,50)
    11 FORMAT ( 10F8.1)
       QMAX = 0.0
    10 AREA = 0.0
       L = J + 1
       DO 15  I=1,N
       AREA = AREA + A(I)
       SW(L,I) = 0.0
    15 CONTINUE
       DO 18  I=1,N
       APOT (I) = A(I)/AREA
    18 CONTINUE
       DIGTA = DELT /  ( SCALE * 3871.0 * AREA )
C      MAXIMUM DISCHARGE FROM MOUNTAIN WATERSHEDS FOR LAG TIME VALUES
       QMAX = 0.0
       DO 17 M = 1,5[illegible]
       IF ( RSG .EQ. 1.0) [illegible]
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      SUBROUTINE PRINT
      COMMON/BK1/SW(50,7 ),  QC(50,7 ),RSLT(50,7 ),QT(50,7 )
      COMMON/BLK/QTV(10),GT(10),Q(20),T(50),QS(50), GF(10),
     1 IW(10),NAT(50),J,ID,LL,M,I,NYEAR,N
      COMMON/BK2/ CN(10),B(10),                  VOLQ(10),TLV(10),CFS(10),
     1CFSX(10),CF(10),XLF(10),SI(10),FO(10),FC(10),SD(10),TR(10),SIV(10)
     2,FCV(10),SDV(10),TRV(10),CL(10),S(10),           FOV(10),APOT(10),
     3     VAL(10),A(10),TL(10),               HH(50,2),DELT,QMAX,AREA,SCALE
      WRITE (6,71)    (Q(L) , L=1,20)
   71 FORMAT ( 1H1, 20A4)
      WRITE (6,2) NYEAR
    2 FORMAT (1H  // 61H  WATERSHED COEFFICIENTS FOR SUBZONES WITHIN THE
     1 STUDY AREA      4X, I4,)
      WRITE (6,7)
    7 FORMAT (79H             SI(IN)        SD(IN)       FO(IN/HR)   FC(IN/HR)
     1  TR(MIN)      TL(MIN)      ,/, 77H               P-10            P-15           P-1
     22       P-11,.13        P-16         P-19    )
      WRITE (6,3) I,SI(I),SIV(I),SD(I),SDV(I),FO(I),FOV(I),FC(I),FCV(I),
     1TR(I),TRV(I),TL(I),TLV(I)
    3 FORMAT ( 3H SW,I2,F4.2,1H=,F6.4,1HP,F4.2,1H=,F5.4,1HP,F4.2,1H=,
     1F6.4,1HP,F4.2,1H=,F5.4,1HP,F4.0,1H=,F6.4,1HP,F4.0,1H=,F6.4,1HP,//)
      WRITE (6,75) IW(I),LL,QMAX,M
   75 FORMAT ( 4H SW=,I2,5X,5H LAG=,I2,5X,3H Q=,F6.1,5X,3H M=,I2)
      WRITE (6.76)
   76 FORMAT (75H   SUBZONE  CFS  ACC TOTAL CFS  1000 ACRE FT.     STORED
     1  CFS   1000 ACRE FT)
   80 WRITE (6,81) ( RSLT(K,I), QC(K,I) , QT(K,I),QS(K),T(K), K=1,M)
   81 FORMAT ( 5F15.2)
      IF ( I .EQ. N) GO TO 83
      QMAX = 0.0
      DO 83 K=1,M
      QS(K) = 9.0
      IF (QC(K,I) .LT. CFS(I+1)) GO TO 96
      QS(K) = QC(K,I) - CFS(I+1)
      QC(K,I) = CFS(I+1)
C     FINDING MAXIMUM DISCHARGE
   96 IF ( QC( K,I) .GE. QMAX)  QMAX=QC( K,I)
C     CONVERTING CFS DISCHARGE VALUES BACK INTO ANALOG UNITS
      IF (QC(K,I) .EQ. .0) GO TO 82
      QC(K,I) = QC(K,I) * DELT / (SCALE * 3871.2 * AREA)
   82 IF(QS(K) .EQ. 0.0) GO TO 83
      QS(K) = QS(K) * DELT / ( SCALE * 3871.2 * AREA)
      IF (QMAX .EQ. 0.) QMAX = 1.0
   83 CONTINUE
      RETURN
      END
```

VITA

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Master of Science

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