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HYDROLOGIC MODEL STUDIES OF THE MT. OLYMPUS COVE AREA OF SALT LAKE COUNTY

by

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ABSTRACT

Urban development on any natural drainage basin causes marked changes in the runoff characteristics of the basin. Urbanization alters natural drainage channels and reduces average infiltration rates. Thus, flood conditions are enhanced both within the urbanizing area itself and at downstream locations, where existing channels might not be able to cope with the increased rates of water flow.

The Olympus Cove area in Salt Lake County is undergoing rapid urban development, and potential flood hazards within the area and at downstream locations are thereby increasing. Recognizing this situation, officials of the Salt Lake County took the initiative in organizing an 'ad hoc' interagency technical team to study and evaluate the problem. The particular responsibilities which were undertaken by the representatives of the Utah Water Research Laboratory on this study team were to synthesize all existing information, and that which might be developed during the study period, and on this basis to formulate computer models to represent the hydrology of the area.

The report describes the model development process and discusses the application of the models to the three source areas being considered, namely: (1) the Neff's Canyon drainage; (2) the northern slopes of Mt. Olympus; and (3) the urbanizing area of Olympus Cove. Runoff from short-term, high-intensity, convective storms is emphasized. Hydrologic response was found to be particularly *sensitive to the magnitude of the runoff producing event* and *to the soil moisture conditions immediately preceding the storm event (antecedent).* Graphical methods are presented for estimating peak runoff rates and flood damages as a function of storm recurrence interval, antecedent soil moisture, and degree of urbanization. Finally, recommendations are included for the management of the area under conditions of continuing urban development.

ACKNOWLEDGMENTS

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Many people assisted with the acquisition of needed data, and provided constructive comments and suggestions throughout the course of this study. Special thanks are extended to the staffs of the Salt Lake County Contract and Intergovernmental Relations Offices, Salt Lake County Planning Commission, the Salt Lake offices of the U.S. Soil Conservation Service, and the U.S. Army Corps of Engineers. Particular mention is made of the help provided throughout the project by Mr. Bruce N. Kaliser of the Utah Geological and Mineral Survey. Gratitude also is expressed to Dr. Richard H. Hawkins, Dr. Trevor C. Hughes, and Dr. Norman E. Stauffer for their careful and constructive review of the manuscript. Their comments contributed much to the content of the report.

The authors would be negligent if they failed to recognize the degree to which the Utah Water Resources Center and the Office of Water Resources Research in Washington, D.C. contributed to the success of this project. Over the years these offices have provided a large portion of the funding support which contributed to the development of the computer modeling techniques andprocedures which were applied in this study. In a very basic sense, the project represents the application of research results to the solution of practical problems of the real world.

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Vernon J. Rogers
George B. Shih

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

CHAPTER I

INTRODUCTION

Urban development throughout the United States has been occurring rapidly during the past quarter century, and the Salt Lake City area is no exception. The rate of urbanization within Salt Lake County has been particularly high along the foothills of the Wasatch Mountains to the east of the City. In fact, at some locations on the so-called 'east bench,' subdivisions for permanent home construction are now being extended up the lower slopes of the mountains themselves and into the canyon drainage channels.

Urban development on any natural drainage area causes changes in the runoff characteristics. Chow (1964) outlines some of the hydrologic effects of urbanization as follows:

> Decreased infiltration, resulting in increased flood flows and lowered groundwater levels. Occasional flooding at channel constrictions (culverts) on remaining small streams. Occasional overlapping or undermining of banks of artificial channels on small streams.

Under urban development, ground surfaces which were formerly covered by native vegetation and rocks are occupied by roofs, streets, parking lots, and lawns. Thus, average soil infiltration rates often are lowered, drainage channels are altered (sometimes completely blocked), and slopes, stripped of native vegetation and disturbed by construction methods, frequently are made less stable. Quoting from the recent publication of the U.S. Geological Survey (Schneider et al., 1973), "The concentration of people in urban areas modifies the natural landscape, bringing about water problems that strongly affect their daily lives."

Because of the changes which it imposes on the watershed, and therefore on the hydrologic system, urbanization frequently tends to increase both volumes and intensities of surface runoff. Thus, flood conditions are enhanced, not only within the urbanizing area itself, but also at downstream locations where existing channels might not be able to cope with the increased flows of water (and often sediment). A further problem for the developing areas of the east bench in Salt Lake County are the large flood flows which frequently originate at upper levels on the adjacent mountains from both high intensity storms and rapid snowmelt.

One of the areas within the county which is undergoing rapid urban development and which is particularly subject to flooding is situated near the mouth of Mill Creek Canyon on the lower slopes of Mt. Olympus, and is known as the Mt. Olympus Cove area, or simply as the Olympus Cove area. Under normal conditions surface runoff from the higher slopes of Mt. Olympus flows down Neff's Canyon and through the cove in a series of natural channels. Under predevelopment conditions surface runoff from much of the Olympus Cove area itself followed this general drainage pattern to Mill Creek. In many cases, roads and buildings now intersect these natural channels and often deflect surface runoff waters on courses which do not convey the drainage to points of natural outflow. The resulting movement of surface waters down slopes which are not provided with either natural or man-made drainage channels frequently causes flooding and erosion problems. Urbanization has increased surface runoff rates from storms and snowmelt which occur within the Olympus Cove area itself, but the problem is further aggravated because flows which enter the area from higher levels on the mountain now have less opportunity to infiltrate. Already some flood damages have been experienced within the cove and in subdivisions farther down the slope which have received flood flows from the developing area.

Recognizing the possibility that potential flood hazards were being produced by the rapid urban development of the Olympus Cove area, officials of Salt Lake County moved to evaluate the magnitude of the problem and to develop a set of recommendations for its solution (Poletto, 1973). Through the initiative of the County Planning Commission an 'ad hoc' study team was formed in January 1973. This team consisted of representatives of the County Planning Commission, the U.S. Soil Conservation Service, the U.S. Forest Service, the U.S. Army Corps of Engineers, the Utah Geological and Mineral Survey, and the Utah Water Research Laboratory at Utah State University. This team was asked to assess the flood problem of the Olympus Cove area and to make specific recommendations regarding ways in which the potential flood hazards might be minimized. Each agency or group accepted a particular task, and the responsibility which was assigned to the Utah Water Research Laboratory (UWRL) was to synthesize all existing information and that which might be developed during the study period, and on this basis to formulate computer models to represent the hydrology of the area. It was recognized that the model development procedure not only would produce an improved understanding of the mechanics of the runoff processes within the area, but also would provide a technique for making realistic predictions of changes in the runoff characteristics as a result of further urbanization. This report summarizes the steps which were followed in the general development of the hydrologic model, and discusses the results of its specific application to the Olympus Cove area. The report also demonstrates the practical utility of this approach as a planning and management technique for the Olympus Cove area and for other similar urbanizing areas within Salt Lake County.

CHAPTER II

THE STUDY AREA

Location

The location of the Olympus Cove area with respect to the general drainage pattern within the easterly part of Salt Lake County is shown by Figure 1. The cove itself is shown in greater detail by Figure 2. As indicated by this figure, Olympus Cove is a crescent-shaped area which is bounded on the north by that portion of Mill Creek which extends between the canyon mouth and Wasatch Boulevard. Between Wasatch Boulevard on the west and the Wasatch National Forest on the east, the area skirts the base of the steeply sloping Wasatch mountains to a vaguely defined boundary approximately two miles to the south.

Drainage Patterns

Three primary sources of surface runoff are involved in this study, and these areas are identified as follows: (1) the cove area itself; (2) Neff's Canyon; and (3) the northerly slopes of Mount Olympus. The cove area is situated largely on an alluvial fan formed by drainage flows from Neff's Canyon and from the north slopes of Mt. Olympus. The major drainage pattern through the area consists of a series of small channels formed by outflows from Neff's Canyon which traverse the alluvial fan and eventually join Mill Creek at several locations. In addition, several other poorly defined channels carry intermittent flows to the cove from the steep slopes of Mt. Olympus. It is these intermittent flows, including those from Neff's Canyon, which are causing much of the concern about flooding in the area.

Topography

The general topography of the cove is shown by Figure 2, which indicates that the area slopes generally in a northwesterly direction. Surface slopes are mostly flat at the north end of the area, ranging between 3 and 8 percent. In the southerly portions of the cove slopes increase sharply and in some cases exceed 45 percent (Van Horn, 1972; Kaliser, 1973).

Geology

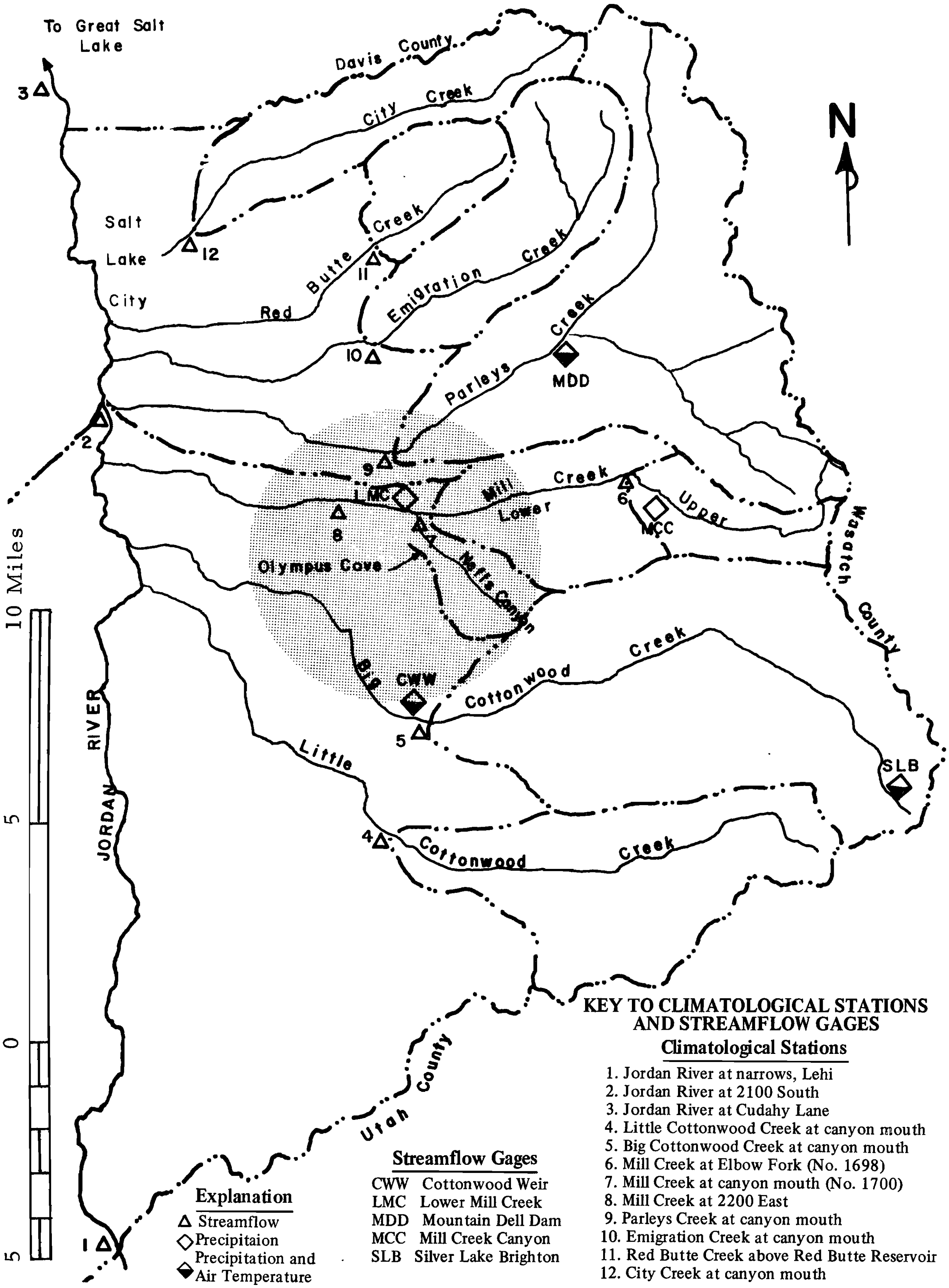
Quoting from a recent report by Kaliser (1973):

> The (Olympus) Cove area itself is largely an alluvial fan. In the northeast the alluvium of the fan abuts against bedrock with a more or less clear break in slope at the contact, but in the southeast the break in slope is not well defined. The alluvium in the fan consists of interrelated muds, sands, and gravels of great thickness. A complex interfingering exists at depth, with better sorted and stratified silts, sands, and gravels that were deposited in Lake Bonneville through the course of multiple regressions and incursions of its shoreline.

Van Horn (1972) ranks the slopes throughout the vast majority of the cove as being 'most stable' (class 1). Only at the upper elevations in the southerly portion of the area do slopes occur which are rated as 'generally stable' (class 2) and 'moderately stable' (class 3). Thus, it would be expected that foundation conditions throughout the cove are generally well drained and stable. Only under conditions of high runoff rates on exposed slopes have problems been experienced from the movement of surface material (Poletto, 1973).

Vegetation

Watershed vegetation can profoundly influence runoff characteristics. The above-ground portions of plants and their associated litter deposits protect the soil surface, and thus enhance infiltration and reduce erosion. The plant roots help to anchor the soil and stabilize slopes. In addition, the roots extract moisture from the soil, which then has a capacity to store subsequent recharges which occur through infiltration and the downslope movement of soil moisture. The effects of the vegetative cover are to a large degree dependent upon the density and depth of the rooting system. Thus, trees with their generally massive and deep rooting systems tend to provide greater slope stability than do grasses. Under urban development, areas of native trees and shrubs are replaced by com-



KEY TO CLIMATOLOGICAL STATIONS AND STREAMFLOW GAGES

Climatological Stations

1. Jordan River at narrows, Lehi
2. Jordan River at 2100 South
3. Jordan River at Cudahy Lane
4. Little Cottonwood Creek at canyon mouth
5. Big Cottonwood Creek at canyon mouth
6. Mill Creek at Elbow Fork (No. 1698)
7. Mill Creek at canyon mouth (No. 1700)
8. Mill Creek at 2200 East
9. Parleys Creek at canyon mouth
10. Emigration Creek at canyon mouth
11. Red Butte Creek above Red Butte Reservoir
12. City Creek at canyon mouth

Streamflow Gages

CWW	Cottonwood Weir
LMC	Lower Mill Creek
MDD	Mountain Dell Dam
MCC	Mill Creek Canyon
SLB	Silver Lake Brighton

Figure 1. Map showing watershed boundaries, streamflow gages, and location of climatologic stations used in the study.

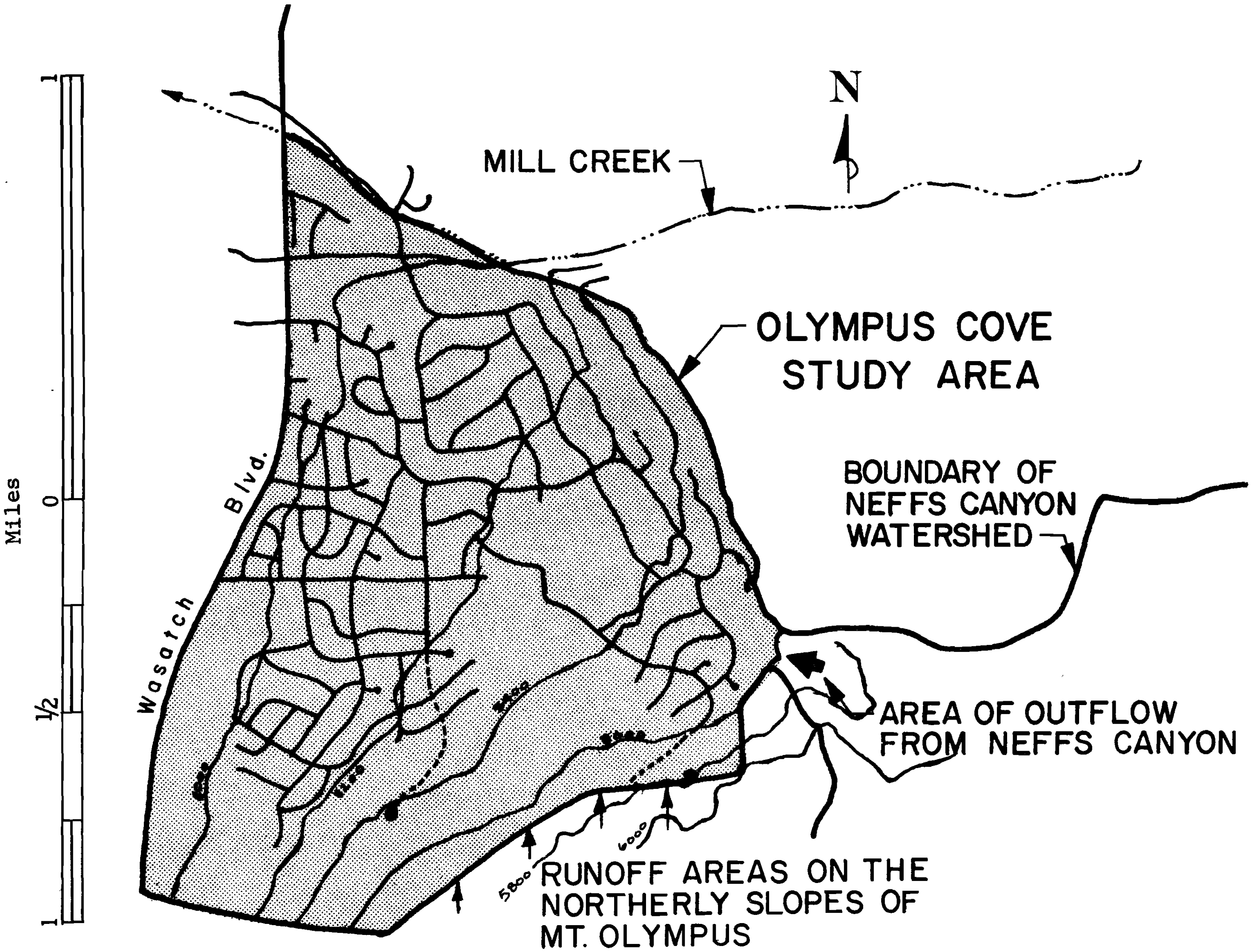


Figure 2. Map showing relation of Mill Creek, Neff's Canyon, and Olympus Cove.

pacted lawns, for which rooting depths are shallow and infiltration rates are *relatively low.*

The dominant native vegetation of the Olympus Cove area consists of scrub oak and brush-type vegetation, with some grass, and minor amounts of timber in the north-facing canyons (U.S. Forest Service, 1973). These shrubs have strong root systems which provide surface stability to the steep slopes, and at the same time foster good infiltration characteristics. At the higher elevations above the subdivisions, particularly on the north face of Mt. Olympus, large areas of steeply sloping rock occur with no soil mantle or vegetative cover.

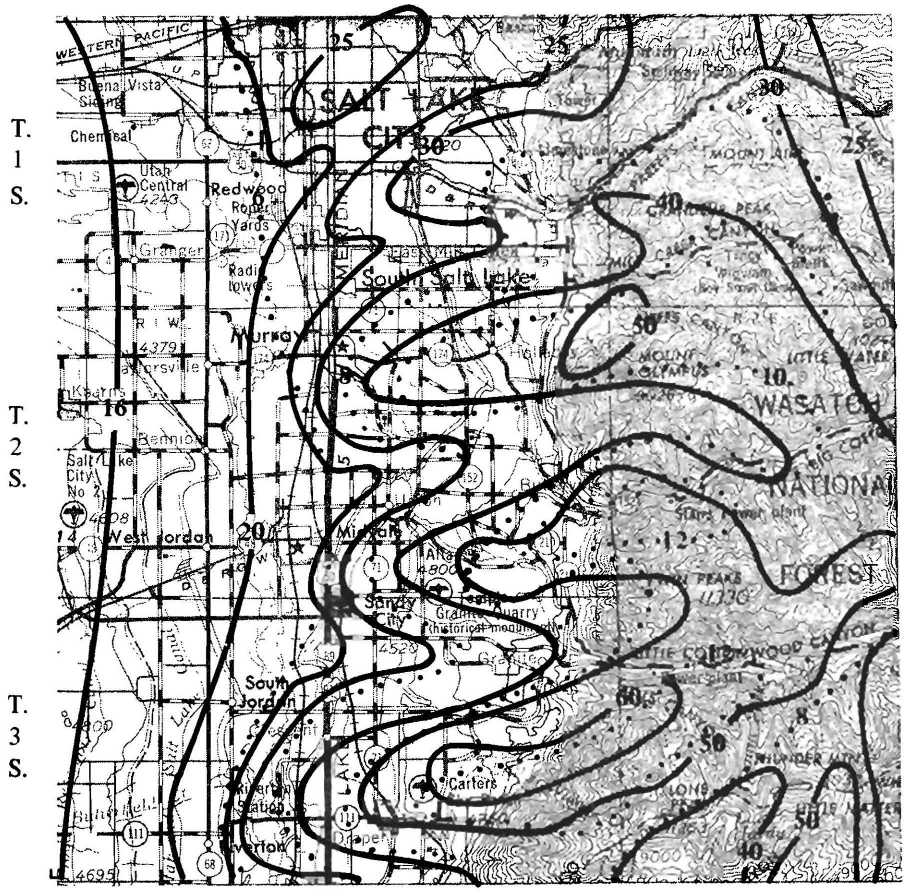
Climate

Precipitation

All runoff from a watershed area originates as some form of precipitation, and precipitation patterns, frequently modified by snow storage, to a very large degree affect flooding conditions. The influence of the Wasatch Mountain Range on the general precipitation pattern throughout the easterly portion of Salt Lake County is shown by Figure 3 (U.S. Weather Bureau, 1962; Kaliser, 1973). As suggested by this figure, more than two-thirds of the total average annual precipitation along the Wasatch Front occurs

NORMAL ANNUAL AND MAY–SEPTEMBER PRECIPITATION

1931-1960



LEGEND

— 20 — Isolines of Normal Annual Precipitation in Inches

• • • 10 • • • Isolines of Normal May–September Precipitation in Inches

(Note isoline interval changes)

Source: 1:500,000 map, State of Utah, by U.S. Weather Bureau, Salt Lake City, Utah, 1962.

Base Map: 1:250,000 Army Map Service, Salt Lake City Sheet, 1963 limited revision

Figure 3. Isolines of annual and summer precipitation on the east bench area of Salt Lake County (after Kaliser, 1973).

during the winter months, mostly in the form of snow. Winter storms are mostly orographic in nature in that the cooling process which induces precipitation is caused by the lifting of the air currents as they pass from west to east over the mountain front. In summer moist air reaches Salt Lake City from both the Gulf of Mexico and the Pacific Ocean. At this time of year the uneven heating of the ground surface is a common cause of vertical lifting, leading to high intensity convective storms of short durations and of small aerial extent. Because the thunder or 'cloudburst' type of storm is common in the mountains during the summer months, the Wasatch Range has a less significant influence on the precipitation patterns of the summer than that of the winter.

Temperatures

The warming temperatures of spring induce new leaf and vegetative growth. The warm summer temperatures cause high potential rates of water use by plants, so that water supplies which are stored in the soil from the snowmelt period or from a summer rain are rapidly depleted. The cooling autumn temperatures again produce significant changes in the hydrologic environment. Changes in the general patterns of mass air movement alters precipitation characteristics, leaves fall, and evapotranspiration rates on a watershed decrease markedly. Thus, air temperatures and the changing seasons have a significant influence on the performance characteristics of a hydrologic system.

Surface air temperatures in the Salt Lake area are subject to a wide range of seasonal fluctuation, which may vary from an average January temperature of 28°F to a July average of 77°F. The normal growing season is the seven month period of April through October. Like precipitation, air temperatures are strongly influenced by topography, with temperatures generally decreasing with altitude in the Wasatch Range.

Flood Characteristics

In the past, runoff from the mountain slopes has caused only minor flooding problems during the snowmelt period in the Olympus Cove area. Although melting snows usually produce large runoff volumes, in most seasons the melting is gradual and disasterous peak flows do not occur. The type of flood caused by convective storms or cloudburst rainfall is the main concern of this study. This kind of storm event usually lasts less than three hours, but occurs in a small area with a high intensity.

According to analyses by the Corps of Engineers (1969), 'rapid melting of the mountain snowpack produces a large volume of water over a long period of time, but with smaller peak flows than cloudburst floods.' However, because total runoff volumes generated by convective storms in general are relatively low, peak flows of flood proportions usually occur near areas of the incidence of the rainfall. As cited by Caldwell, Richards and Sorensen, Inc. (1966), one of the factors which controlthe rate of runoff at any point is the total tributary area to that point. Thus, high runoff rates from thunderstorms usually are associated with small runoff producing areas. As these flows move downstream in larger watersheds, peak flows are reduced by storage effects, so that for a stream such as Mill Creek all of the major flows have been the result of snowmelt conditions. Sufficient records on small watersheds along the Wasatch Front in Salt Lake County are not available to permit a quantitative analysis of the comparative effects of thunderstorm and snowmelt runoff for small source areas. On the basis of hydrologic experience from other areas where similar runoff producing conditions exist, a runoff versus frequency curve of the kind illustrated by Figure 4 might be expected for the drainage areas above Olympus Cove. The curve suggests that for small watersheds, flows of high frequency (return periods of 10 years or less, for example) snowmelt usually is the source of the water. However, for flows of lower frequencies, thunderstorms tend to predominate as the source of the runoff.

Because of the high intensity and short duration characteristics of convective storms, it is normal for only a relatively small portion of the total rainfall to enter the ground surface at the point of incidence. Thus, surface runoff rates usually are high and flooding conditions are common at the storm site and at downstream locations. Because it tends to decrease both infiltration rates and resistance to surface flows, urbanization usually increases surface runoff potential. These effects on the hydrologic system, coupled with the greatly increased damage opportunities, make the flood protection of urban areas in mountainous regions (particularly those which are subject to thunderstorm activity) a matter of prime concern for municipal planners and engineers.

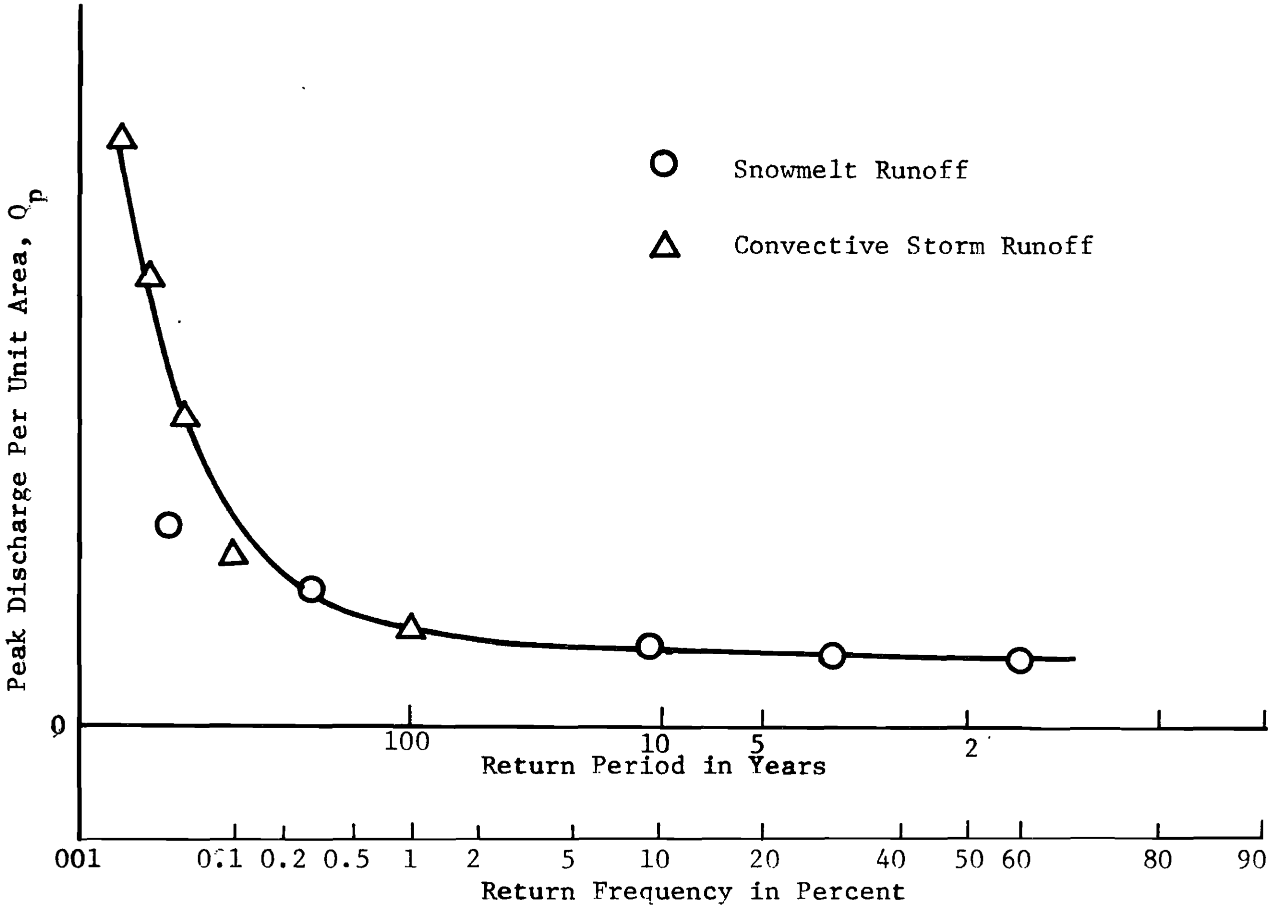


Figure 4. A typical distribution of runoff from snowmelt and convective storms for small watersheds.

CHAPTER III

A HYDROLOGIC MODEL OF THE OLYMPUS COVE AREA

The problems of managing a hydrologic system, such as an urbanizing watershed, require an understanding of the fundamental processes and coupling relationships involved in the system. With this understanding a manager is then able to predict realistically the consequences of possible changes which might be imposed upon the system. For example, in the case of an urbanizing watershed, it might be desirable to be able to predict for design purposes changes in peak runoff rates resulting from projected levels of urban development corresponding to particular frequencies of occurrence. In recent years, the advent of electronic computers has stimulated the use of simulation analysis for planning and management of large and complex systems. In essence, the computer model is intended to reproduce the behavior of the important system variables of the prototype under study.

Mathematical simulation is achieved by using arithmetic relationships to represent the various processes and functions of the prototype system, and by linking these equations into a systems model. Thus, computer simulation is basically a technique of analysis whereby a model is developed for investigating the behavior or performance of a dynamic prototype system subject to particular constraints and input functions. The model behaves like the prototype system with regard to certain selected variables, and can be used to predict probable responses when some of the system parameters or input functions are altered. Computer simulation, therefore, has the following important advantages:

1. A model provides a basis for coordinating information and the efforts of personnel across a broad spectrum of scientific disciplines.

2. A model approach requires a clear identification of problems and objectives associated with the system being examined.

3. Insight into the system being studied is increased. In particular, the relative importance of various system processes and input functions is suggested.

4. Priorities are indicated in terms of planning objectives and data acquisition.

5. A model is capable of indicating in quantitative terms progress toward system definition and conceptual understanding.

6. Proposed modifications of existing systems can be non-destructively tested.

7. Many planning and management alternatives and proposals can be studied within a short time period.

8. Hypothetical system designs can be tested for feasibility or comparison with alternate systems.

As already suggested, a computer model (like any model) is an abstraction from reality, and in this sense is a simplification of the real world which forms the basis of the model. The degree of simplification is a function of both intent or planning and knowledge about the real world. Forrester (1961) pointed out that verbal information and conceptualization may be translated into mathematical form for eventual use in a computer. Therefore, the model development process should proceed essentially from the verbal symbols which exist in both theoretical and empirical studies to the mathematical symbols which will compose the model.

The development of a working mathematical model requires two major steps. The first step is the creation of a conceptual model which represents to some degree the various elements of the system and their interrelationships. In general, the conceptualizations and hypotheses of the real world of a particular study area are formulated in terms of the available data. Efforts are made to use the most pertinent and accurate data available in creating the conceptual model. As additional information is obtained, the conceptual model is improved and revised to more closely approximate reality.

The second major step in the development of a working mathematical computer model is between the conceptual model and the computer or working model itself. During this step an attempt is made to express in both mathematical and verbal forms the various processes and relationships identified by the conceptual model. Thus, the strategy involves a conversion of concepts concerning the real world into terms which can be programmed on a computer. This step usually requires further simplification, and the resulting working model may be a rather gross representation of real life.

In earlier discussions, Dr. Ven T. Chow has compared the loss of information, first between the real world and the conceptual model, and second, between the conceptual model and computer implementation, to a filtering process, as depicted by Figure 5 (Riley, 1972). The real world is 'viewed' through various kinds of data about the system which are gathered. Additional data usually produce an improved conceptual model in terms of time and space resolutions. The improved conceptual model then provides a basis for improvements in the working model. Output from the working model can, of course, be compared with corresponding output functions from the real world, and if discrepancies exist between the two, adjustments are indicated in both the conceptual model and the working model.

The important steps involved in the process of model development are depicted by the diagram of Figure 6 (Riley 1970), and these steps were followed in the formulation of hydrologic models of the Olympus Cove area, including the Neff's Canyon drainage and the urbanizing area of the cove. A brief description of this procedure is given by the remainder of this section of the report.

Identification of Objectives

Clearly, the starting point in the formulation of a model is a precise definition of the purpose or function of the model. The overall or general objective of this study was to develop a computer model of the hydrologic system of the Olympus Cove area, and to use this model to formulate recommendations concerning further urbanization of the area. Thus, the specific objectives of the study are stated as follows:

1. To develop a computer model of the hydrologic system of the Olympus Cove area, including the Neff's Canyon drainage and the urbanizing area of the cove.

2. To use this model to study the influence of urbanization within the cove on surface runoff characteristics from the area, considering (a) inflows to various parts of the area from higher elevations, and (b) runoff generated within the area itself.

3. To define, if possible, those processes or system parameters to which the system seems most sensitive.

4. To develop specific recommendations concerning further urbanization of the Olympus Cove area, including recommendations for additional information needs and studies.

System Identification

The basis of system identification is the conceptual model of the real world developed through various kinds of data which are gathered about the system. In a sense, points at which the system is monitored may be regarded as being 'windows' through which the dynamic operation of the prototype system is observed at a particular point in space and perhaps in time.

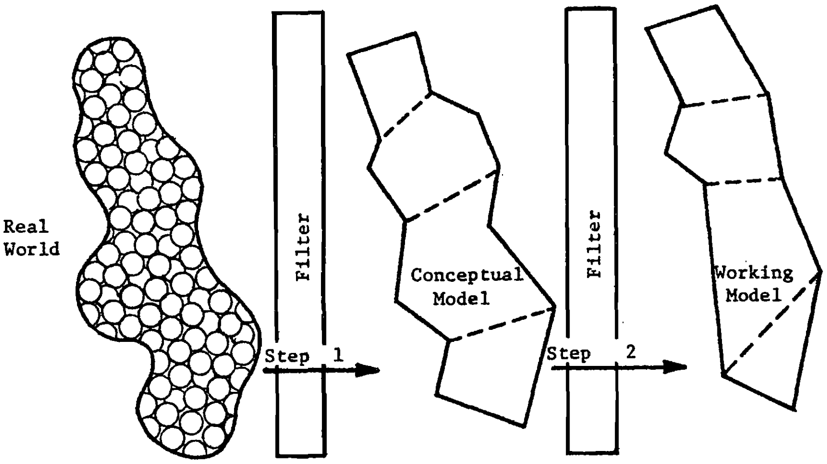


Figure 5. Steps in the development of a model of a real world system.

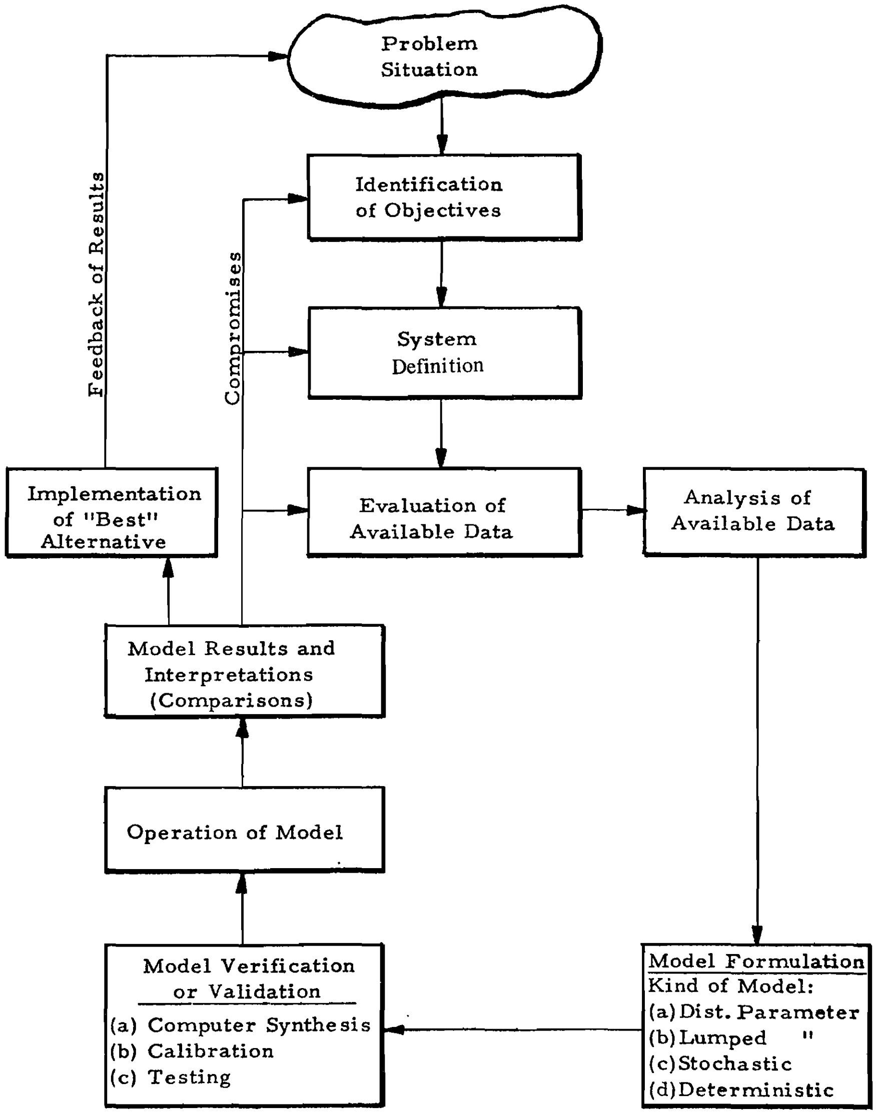


Figure 6. Steps in the development and application of a simulation model.

The spacings of these observations in the time and space dimensions largely determine the refinement of the conceptual model in terms of the actual conditions. In the case of the Olympus Cove study two models involving different time increments were used. One of these (Figure 7) was based on a time increment of one day, and was used to represent the relatively long-term processes which occur on a watershed, such as changes in soil moisture content with time as a result of infiltration, evapotranspiration, and percolation processes. The second model (Figure 8) used an hourly time increment and represented short-term processes and events, such as peak runoff rates from cloudburst storms. It is noted that Figure 8 does not represent a general hydrologic model in that certain processes, such as snowmelt, are omitted. Thus, the model is, in a sense, a planned simplification of the actual situation, but it is a simplification which is consistent with the objectives of the study.

Evaluation and Analysis of Available Data

This is one of the most important and time-consuming steps in the simulation of water resource systems. As already indicated, the data provide an understanding of the real world, and thereby establish a basis for evaluating model performance. The accuracy of predictions from a particular model are governed to a large degree by the reliability of the information on which the model is based and the accuracy of the data which are input to the model to provide the predicted output functions.

In general, the availability of hydrologic data for the Olympus Cove area was found to be limited, and resort was made to various techniques for extending available data in both the space and time dimensions. For example, no streamflow data were available for any channels within the area of the cove. However, as shown by Figure 1, runoff records are available for Mill Creek, and the models, therefore, were calibrated for the two subwatersheds which terminate at gaging stations 1698 and 1700, respectively. Model parameters from these two areas then were used, with appropriate modifications, in the application of the same models to the Neff's Canyon drainage areas. In turn, parameters and some output information from these Neff's Canyon models, such as soil moisture values, were used in the hourly time increment model which was then applied to various subareas within the cove.

In the paragraphs which follow, available data and information relating to the hydrologic models which were applied on the Mill Creek and Olympus Cove drainages are discussed briefly by reference to the various system storage locations and processes depicted by Figures 7 and 8. All gaging stations referred to in this discussion for temperature, precipitation, and streamflow are shown by Figure 1.

Precipitation

Upper Mill Creek subwatershed. Precipitation records are available for the storage gage at Mill Creek Canyon (MCC) during the years selected for the study (1964 to 1968). This gage, located near the center of the Mill Creek Mountain watershed, was read at monthly intervals. Precipitation records for stations at Mountain Dell Dam (MDD) and Silver Lake Brighton (SLB) also are available for the study period. These two stations are operated on a daily basis.

A regression analysis was made to relate the precipitation recorded at Mill Creek Canyon (P_{MCC}) with the precipitation falling at both Mountain Dell Dam (P_{MDD}) and Silver Lake Brighton (P_{SLB}) over the same period. This relation is of the form:

$$P_{MCC} = 0.1250 + 0.7465 \cdot P_{MCC} + 0.4231 \cdot P_{SLB} \ldots (1)$$

A value of 0.95 was found for the coefficient of correlation in the regression analysis. Since Equation (1) was derived from monthly (approximately) precipitation totals, the corresponding equation relating precipitation on a daily basis is:

$$P_{MCC} = 0.1250/30 + 0.7465 \cdot P_{MDD} + 0.4231 \cdot P_{SLB} \ldots (2)$$

Equation (2) was used to generate point precipitation values on a daily basis at the Mill Creek Canyon site, based on the corresponding daily precipitation observations at Mountain Dell Dam and Silver Lake Brighton.

Lower Mill Creek subwatershed. A similar procedure as that described above was used to relate the precipitation at the storage gage at Lower Mill Creek (LMC) to that recorded at Mountain Dell Dam. In this case a regression equation for estimating point daily precipitation at the Lower Mill Creek site was determined as:

$$P_{LMC} = 0.4193/30 \text{ '' } 0.7608\, P_{MDD} \quad \ldots\ldots (3)$$

The daily precipitation values calculated from the regression Equations (2) and (3) were multiplied by a

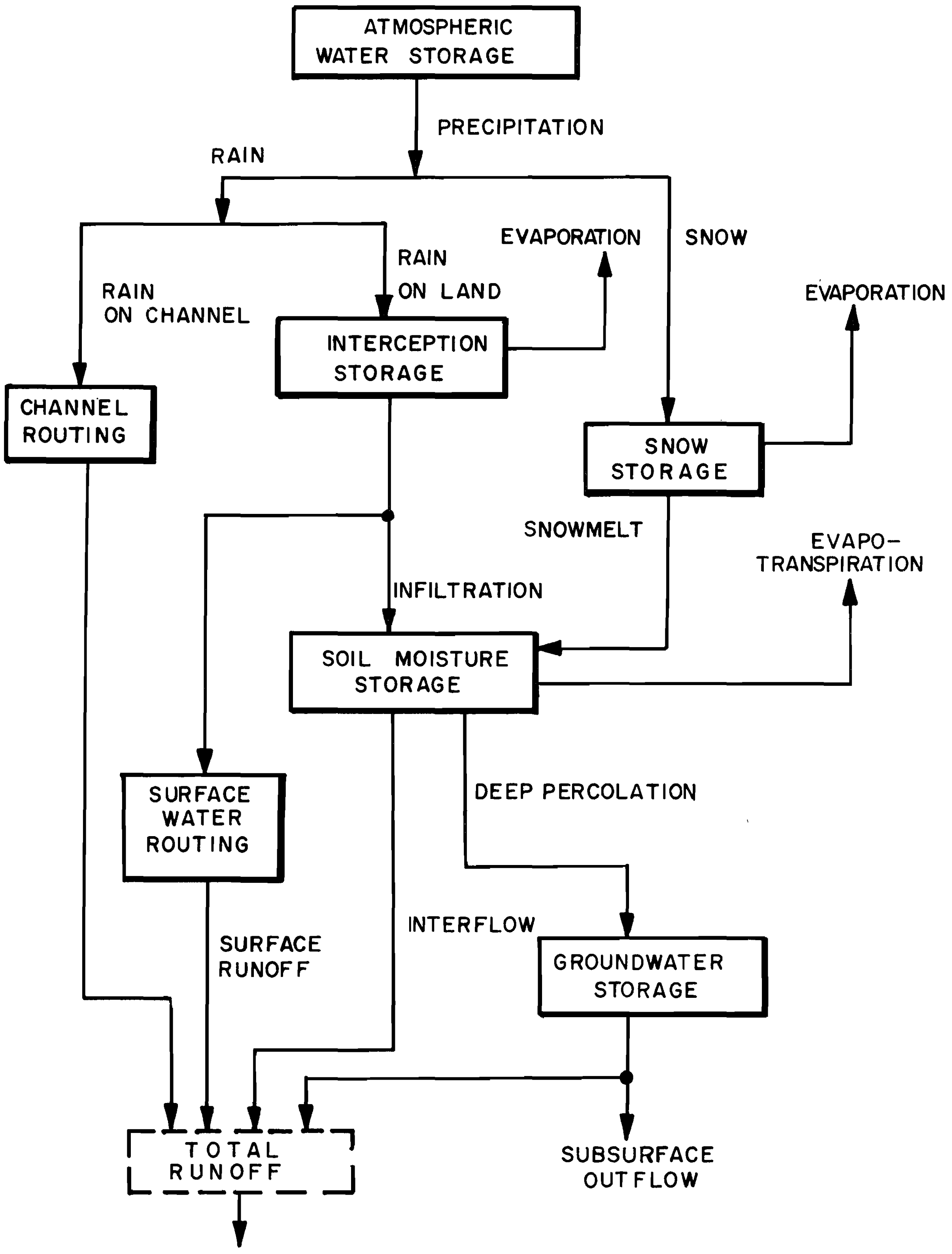


Figure 7. Flow chart showing the various hydrologic processes represented within the daily time increment model.

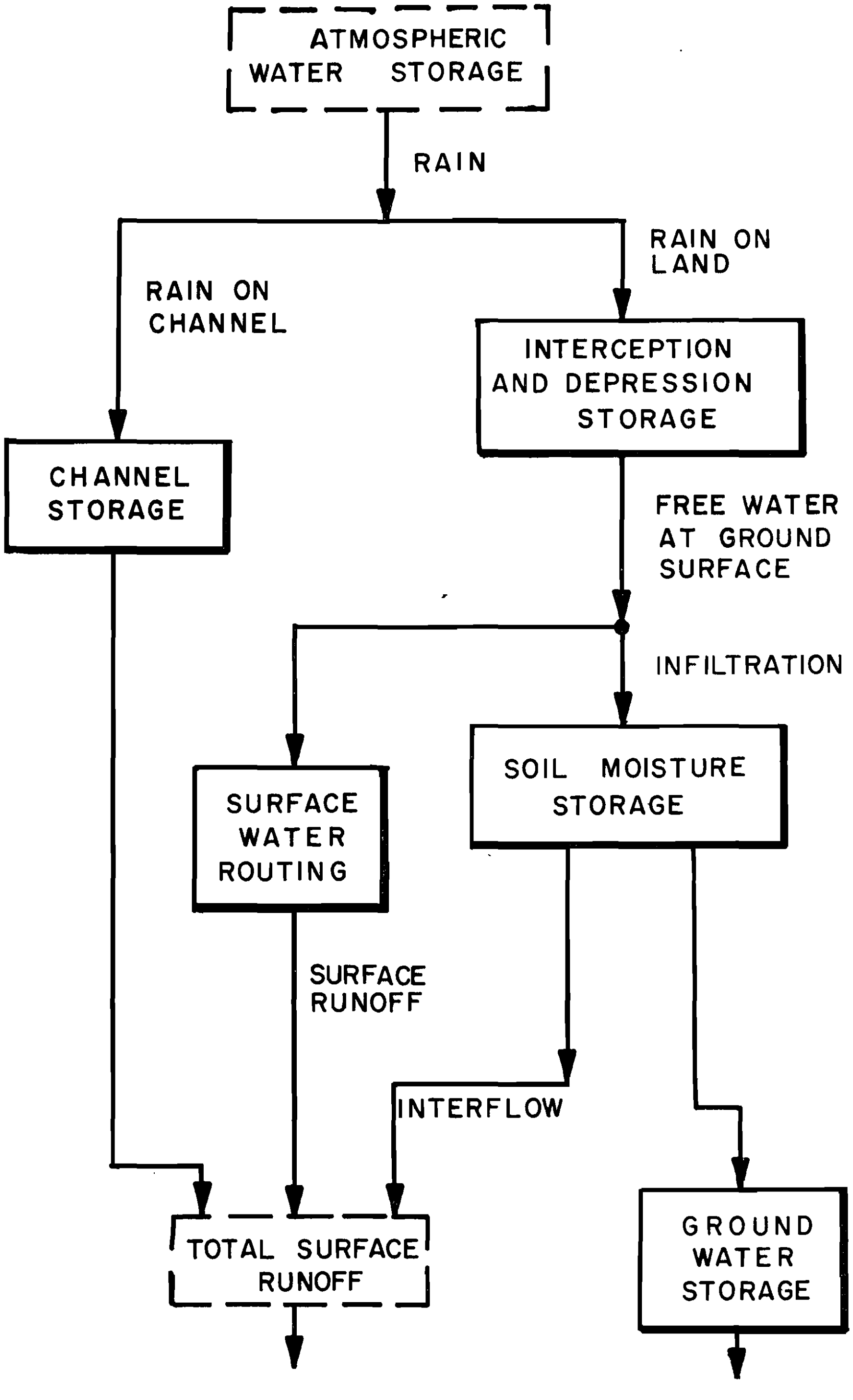


Figure 8. Flow chart showing the various hydrologic processes represented in the hourly time increment model.

correlation factor to ensure that the monthly totals of the calculated precipitation equalled the corresponding storage gage totals actually observed.

Areal integration of precipitation. A map showing the normal annual isohyetal lines for the study area is given by Hely et al. (1971). By reference to this map, weighting factors were derived to relate the mean precipitation over the upper and lower subwatersheds of Mill Creek Canyon to the point precipitation values at Mill Creek Canyon and Lower Mill Creek stations, respectively. The relations found in this manner are as follows:

$$P_{Upper} = 1.05\, P_{MCC} \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

$$P_{Lower} = 0.51\, P_{MCC} + 0.49\, P_{LMC} \quad \ldots\ldots \quad (5)$$

The relationship developed for the mean precipitation over the Neff's Canyon drainage area ($P_{Neff's}$) is:

$$P_{Neffs} = 0.68\, P_{MCC} + 0.32\, P'_{MC} \quad \ldots\ldots \quad (6)$$

in which values for P_{MCC} and P_{LMC} are given by Equations (2) and (3), respectively.

Short duration storms - Olympus Cove. Point precipitation values for storms of 1-hour and 3-hour durations in the Salt Lake City area were obtained for various recurrence intervals (Figure 9) (Corps of Engineers, 1970). The storm recurrence intervals used in the Olympus Cove study were 10, 25, 50, and 100 years. The intensities of these point precipitation values were reduced from a relationship between point precipitation and mean precipitation over an area (Corps of Engineers, 1969). For a drainage area such as Neff's Canyon (3.5 square miles), the relationship indicates that the mean areal precipitation is 89 percent of the point value.

The mean distribution of rainfall intensity as a function of time during a storm was estimated by inspecting specific rainfall hyetographs available from recording stations. Because of the availability of frequency information on 3-hour storms in the Salt Lake area from studies by the Corps of Engineers (1970), storms of this duration were selected for the study. The total rainfall was assumed to be distributed throughout the storm on the following basis: first hour - 33 percent; second hour - 44 percent; and third hour - 23 percent.

Temperature

Surface air temperature is used in the daily time increment model (Figure 7) as an index of the available energy for the evapotranspiration and snowmelt processes, and as a criterion for establishing the form of precipitation as either rain or snow. Daily air temperature recordings are available at Mountain Dell Dam (T_{MDD}) and at Silver Lake Brighton (T_{SLB}) (Figure 1). These temperatures were transposed to the mean elevations of the drainage areas of the study by applying a correction to account for the influence of altitude changes on air temperature. Altitude weighting factors were derived and used to give the following relationships between mean daily air temperature at the measurement point locations and estimated values at the mean elevations of the drainage areas being modeled on Mill Creek and Neff's Canyon. Thus,

$$T_{Upper} = 0.2\, T_{MDD} + 0.8\, T_{SLB} \quad \ldots\ldots \quad (7)$$

$$T_{Lower} = 0.5\, T_{MDD} + 0.5\, T_{SLB} \quad \ldots\ldots \quad (8)$$

$$T_{Neff's} = 0.3\, T_{MDD} + 0.7\, T_{SLB} \quad \ldots\ldots \quad (9)$$

Solar radiation

At a particular location on the earth's surface the direction and degree of slope strongly influence the amount of direct solar radiation which is received on that slope. Thus, for a north-facing slope evapotranspiration and snowmelt rates tend to be lower than is the case for a south slope. For this reason, in the watershed hydrology models which are used an attempt is made to account for the average degree of slope and direction (aspect) of the area under study. The parameter which is applied is termed the solar radiation index (Lee, 1963; and Riley et al., 1966). This index is a relative measure of the amount of direct solar radiation received by a given slope at a particular location and time to that received by a horizontal surface at the same location and time. Because the effects of atmospheric conditions are assumed to be the same for both surfaces in the same location, atmospheric effects are assumed to be removed. Monthly radiation index values for each watershed were determined as a function of aspect, percent slope, and time of year. Latitude was assumed to be the same for each of the three watersheds. These values are shown by Table 1.

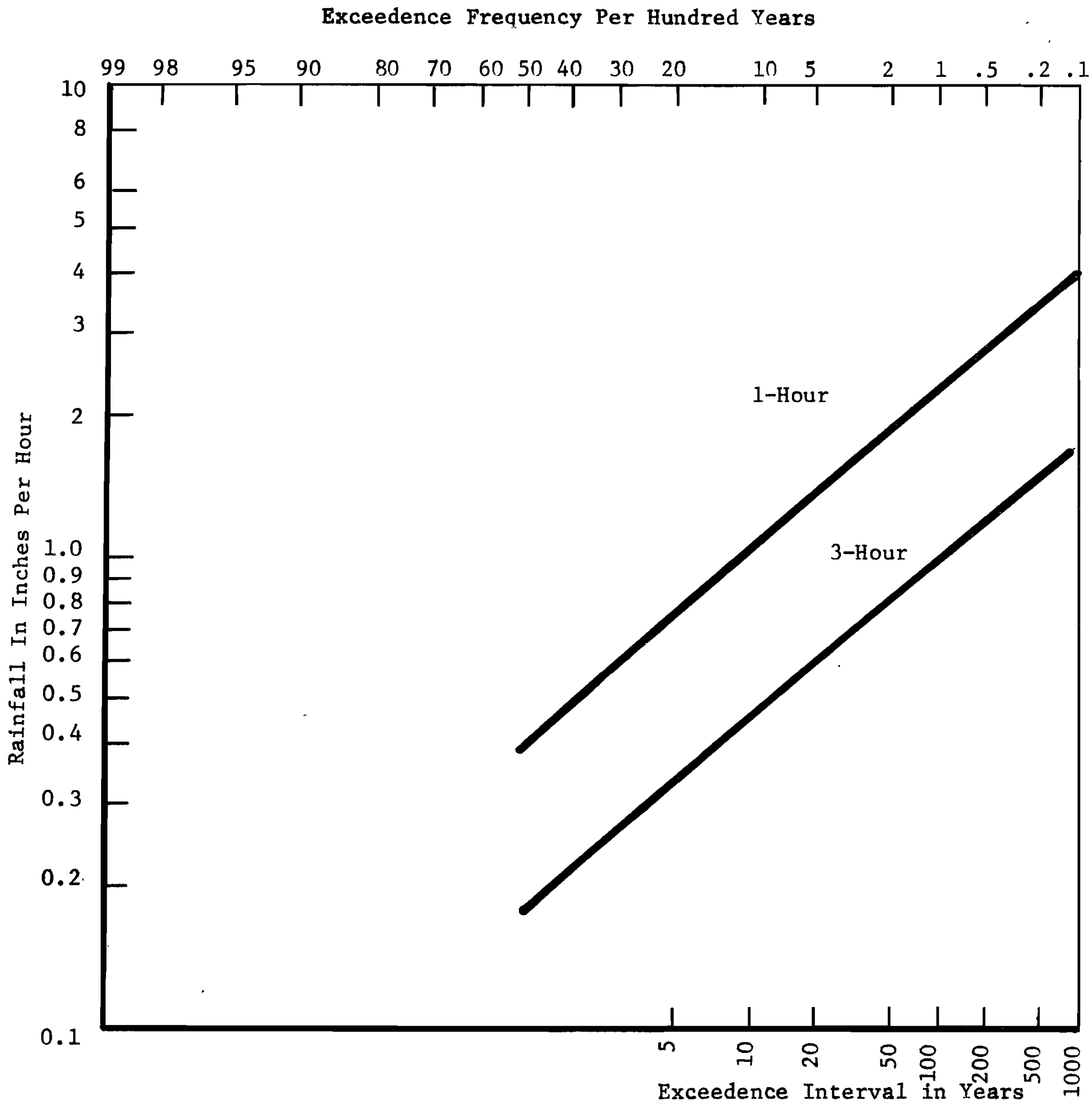


Figure 9. Cloudburst point rainfall frequency at Salt Lake City (after Corps of Engineers, 1969).

Table 1. Average monthly values of the solar radiation index for the Mill Creek subwatersheds and Neff's Canyon drainage.

Watershed	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.
Mill Creek (Upper)	40	31	27	29	37	46	54	58	60	59	56	49
Mill Creek (Lower)	42	34	31	33	38	48	55	58	59	58	56	51
Neff's Canyon	32	22	18	19	27	39	49	55	58	57	52	43

Evaporation

The evaporation of water from lake and stream surfaces and from intercepted storage on vegetative surfaces is represented in the daily time increment model (Figure 7). Values of average monthly pan evaporation rates in the Jordan Valley (elevation 4,600 feet) and at Silver Lake Brighton (elevation 8,700 feet) are given by Hely et al. (1971). A linear relationship between pan evaporation and elevation was suggested by the data. By applying this relationship between the locations of the point evaporation measurements and the mean elevations of the watershed areas under study, evaporation values were predicted for each watershed. On the basis of this information, ratios were developed between mean monthly pan evaporation and mean monthly temperature. These ratios (Table 2) then were used for predicting evaporation rates (monthly quantities by depth) on each watershed area as a function of surface air temperature. Evaporation and plant transpiration are neglected by the hourly model.

Streamflow

Daily streamflow records are available in published form (Hely, Mower, and Horr, 1964-1968). Flow records at all streamflow gaging stations shown by Figure 1 are contained in these publications. Runoff data for the upper and lower Mill Creek subwatersheds were recorded at stations 1698 and 1700, respectively. As indicated earlier, no runoff data are available for outflows from Neff's Canyon, or for any of the other intermittent streams within the Olympus Cove area.

Physiographic characteristics of the study areas

Because they describe the physical nature of the particular hydrologic system under study, a knowledge of the physiographic characteristics is important for the application of a general hydrologic model to a given drainage area. Topographical parameters for the Mill Creek and Neff's Canyon watersheds are shown by Table 3. In addition, the available physiographic information for the Neff's Canyon and Olympus Cove drainage area is discussed briefly by Chapter II of this report. Because they were not directly involved in this study, further physiographic features of the Mill Creek subwatersheds are not included here. The modeling of these two particular hydrologic units is described in some detail by a report which is now under preparation in connection with a separate, though associated study (Andrews et al., forthcoming). Suffice it to say that, as is common in hydrologic modeling, data in addition to those which were available would have facilitated the work. For example, information on infiltration rates and on soil moisture holding characteristics was not established by independent measurements in the field. In all cases these parameters were estimated by the model calibration procedure.

With reference to infiltration rates, the single most important effect of urban development on a watershed is its possible negative influence on average soil infiltration characteristics. As urbanization proceeds, much of the watershed becomes covered with various kinds of impervious surfaces, such as roofs, roadways, and streets. In addition, landscaped and grass covered areas, while still providing opportunities

Table 2. Average monthly values of the ratio between evaporation and temperature for the Mill Creek subwatersheds and the Neff's Canyon drainage[a].

Watershed	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Mill Creek (Upper)	8.21	4.43	2.70	2.74	4.12	8.00	11.46	13.38	14.48	15.73	14.60	11.49
Mill Creek (Lower)	8.33	4.27	2.66	2.85	4.36	8.29	12.54	13.06	14.38	15.60	14.31	11.32
Neff's Canyon	8.26	4.35	2.68	2.89	4.24	8.14	11.90	13.20	14.42	15.65	14.40	11.40

[a] All values are in units of inches per $^{\circ}F \times 10^{-2}$.

Table 3. Topographical parameters of the watersheds involved in the study.

	Mill Creek		
	Upper Sub Watershed	Lower Sub Watershed	Neff's Canyon
drainage area (sq. mi.)	7.7	14.0	3.5
channel length (mi.)	4.8	5.2	3
channel slope (ft./mi.)	530	320	1,100
mean watershed elevation (ft.-msl.)	8,200	7,000	7,800
headwater elevation (ft.-msl.)	9,200	-	8,600
aspect	WNW	W	NW

for infiltration, possess capacity rates which frequently are significantly less than those which existed under natural conditions. Because of drainage from impervious surfaces, the effective impervious area produced by urbanization usually is somewhat less than the actual impervious area (often expressed in percent of the total drainage area). A relationship between these two parameters was postulated by Crawford and Linsley (1966), and is presented here as Figure 10. On the basis of this plot, a relationship was developed which expresses the effective capacity infiltration rate as a function of the degree of urbanization. Thus,

$$F_{ce}(t) = F_{cm}(t)(1 - U^{1.5}) \quad \ldots\ldots\ldots (10)$$

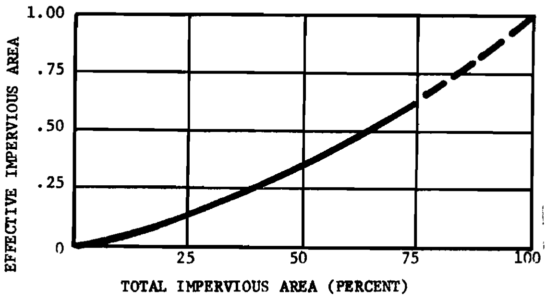


Figure 10. Relation between effective impervious area and total impervious area.

in which

F_{ce} = the effective capacity infiltration rate at any time, t

F_{cn} = the capacity infiltration rate at any time, t, under natural conditions

U = the degree of urbanization expressed as a ratio of the area under impervious cover to the total drainage area

Equation (10) was used in the hourly runoff model.

Model Formulation

Model formulation is the step between the conceptual model and the working model indicated by Figure 5. The form of the model which is used is dependent entirely upon the requirements of the problem (the objectives, funds, facilities, and data which are available for the study). Some insight into this process is given by comparing Figures 7 and 8. In the case of Figure 7 (daily time increment) all of the basic hydrologic processes which occur on a watershed are included. On the other hand, to provide estimations of peak surface runoff rates from cloudburst storms, some processes, such as snowmelt and soil moisture movement, are not needed, but a high degree of resolution in the time dimension is necessary. For this reason, the hourly time increment model (Figure 8) contains fewer processes than the daily model, but the remaining processes are, of necessity, represented with a high degree of time resolution. Thus, the requirements of the problem always are a prime consideration in model formulation and design, including the selection of appropriate time and space increments. In the case of the Olympus Cove area, it was necessary to represent hydrologic inflows and outflows at several different locations within the area. For this reason, the Cove area was modeled as a number of subunits, or small space increments, with each subunit representing an upstream (or upslope) source area.

No attempt will be made in this report to describe the mathematical relationships used to represent the various hydrologic processes shown by Figures 7 and 8. The model structures and mathematical representations are well documented in earlier publications, including those of Narayana, et al. (1969); Evelyn et al. (1970); Eggleston et al. (1971); Shih (1971); Shih et al. (1972); and Chambers (1973). In addition, in a separate study hydrologic models are being applied to much of the urban and rural areas of east Salt Lake County, and the structures of these models will be fully described and documented in a new publication which is now in preparation (Andrews et al., forthcoming). Computer program listings, documentation and sample output for the daily time increment model (Figure 7) and the hourly time increment model (Figure 8) are given by Appendixes A and B, respectively.

Model Verification

Computer synthesis

A computer model of a hydrologic system is produced by programming on a computer the mathematical relationships and logic functions of the hydrologic model. The model does not directly simulate the real physical system, but is analogous to the prototype because both systems are described by the same mathematical relationships. A mathematical function which describes a basic process, such as evapotranspiration, is applicable to many different hydrologic systems. The simulation program developed for the computer incorporates general equations of the various basic processes which occur within the system. The computer model, therefore, is free of the geometric restrictions which are encountered in simulation by means of network analyzers and physical models. The model is applied to a particular prototype system by establishing, through a verification procedure (sometimes called validation or parameter identification), appropriate values for the 'constants' of the equations required by the system.

Model calibration

A general hydrologic model is applied to a particular basin through a verification procedure whereby the values of certain model parameters are established for a particular prototype system. Verification of a simulation model is performed in two steps, namely calibration, or parameter identification, and testing of the model. Data from the prototype system are required in both phases of the verification process. Model calibration involves adjustment of the model parameters until a close fit is achieved between observed and computed output functions. It therefore follows that the accuracy of the model cannot exceed that provided by the historical data from the prototype system. Evaluation of the model parameters can follow any desired pattern, whether it be random or specified. In this study tern, whether it be random or specified. In this study a computerized pattern search procedure described by Hill et al. (1972) was used.

Daily time increment model. Because no surface runoff records were available for the Neff's Canyon and other Olympus Cove drainage areas, the model was calibrated first for the two subwatersheds of Mill Creek (Figure 1). The parameter values for each of the two watersheds as established by this procedure are shown by Table 4. The parameters are listed in order of decreasing sensitivity, or relative importance to system response characteristics. In other words, the model suggested that the system parameter which has the most influence on the outflow hydrograph is the moisture storage capacity of the soil on the watersheds. This observation leads to the conclusion that for a particular average soil moisture storage capacity, antecedent soil moisture conditions (or the soil moisture levels at the beginning of a runoff producing event) have a considerable influence on the characteristics of the ensuing runoff hydrograph.

Table 4 also indicates the values of the watershed parameters which were applied in the model of Neff's Canyon. These values were determined on the basis of experience and information gained in the calibration of the two nearby Mill Creek subwatersheds. The rationale used to justify this procedure are stated briefly as follows:

1. Topography, elevation, and aspect are similar for the three drainage areas.

2. Soil types and vegetation are similar for the three watersheds.

3. Mill Creek and Neff's Canyon are adjacent to one another, and in general are subject to the same climatological patterns. For example, the same values of the normal isohyetal lines occur at much the same elevations for both drainage basins (U.S. Weather Bureau, 1962).

The transfer of parameter values from one watershed to another is not an ideal procedure. In this case the transfer of parameter values from Mill Creek to Neff's Canyon was made necessary by the lack of any suitable runoff records from the latter. Factors which suggest the procedure might give useful results in this case are listed above. There are, however, differences in the geology of the Mill Creek and Neff's Canyon watersheds. Neff's Canyon, for example, has a higher proportion of cavernous limestone in the geological makeup than is the case for the Mill Creek drainage. Some information on these differences and their influence on runoff characteristics was obtained from notes taken by Calvin G. Clyde in a geology class some years ago.at the University of Utah, and this information is summarized in the following paragraph.

In 1948 some measurements were made by Salt Lake County of water flow rates and quality of discharge from Neff's Canyon. A geologic survey of the canyon at that time also indicated the presence of glacial moraine and two faults in the Canyon. The Mt. Olympus Spring Company had submitted an application to direct water from Neff's Canyon, and County officials were concerned that perhaps these waters supplied the Spring Creek, Castro, and Dry Creek Springs which are situated on the lower slopes of Mt. Olympus above the urbanizing area of the cove. In 1950 three students from the University of Utah discovered a cave in Neff's Canyon. It was found that the limestone cavern extended a distance of 1,170 feet from the portel to a point where water blocked the way. It was speculated that this water leaves the stream bed at the fault lines and flows through the cavernous limestone to the three springs mentioned above. To confirm this specu-

Table 4. Optimized parameter values[a] for the Upper and Lower subwatersheds of Mill Creek.

Parameter	Description	Value		
		Mill Creek		
		Upper Sub-watershed	Lower Sub-watershed	Neffs Canyon
SFC	Field capacity of soil (inches)	6.00	4.5	5.0
TBF	Base flow decay constant (day - 1)	.004	.006	.005
GLL	Groundwater storage level above which sub-surface outflow occurs (inches)	4.8	5.0	5.0
TGW	Interflow decay constant (day - 1)	.04	.025	.03
QK	The fraction of outflow from soil mositure that becomes interflow	.15	.26	.20
SMR	Snow melt rate (inches/day - F)	.11	.07	.07
ETF	Evapotranspiration factor	.59	.45	.50
TAUSW	Surface runoff decay constant (day - 1)	.30	.50	.50
SI	Upper limit of interception storage (inches)	.40	.60	.40
FC	Minimum value of infiltration (inches/day)	2.0	1.0	1.0
DKT	Infiltration decay constant	2.0	1.5	1.5
SS	Saturated soil level (inches)	12.8	13.5	13.0
WILT	Wilting point of the soil (inches)	1.0	1.5	1.0
ROS	Factor related to snow melt by rain	.01	.01	01
TRAIN	Temperature above which all precipitation falls as rain	35.0	35.0	35.0
CPF	Channel precipitation factor	.003	.003	.003
FNGM	Factor related to ground melt in snow pack	.02	.023	.02
TFWSN	Temperature of free water in snow pack	.10	.18	.15
Mean value of the objective function (inches per unit area		1.53	3.24	NA
Mean annual stream flow (inches per unit area)		6.97	10.15	NA
Ratio of mean objective function to mean annual streamflow		.22	.32	NA

[a] Parameters are shown in decreasing order of sensitivity.

lation, dye was placed in the waters of Neff's Canyon at a point upstream from the fault lines. This dye appeared at the springs 27 hours later and persisted for 4 days. During the spring runoff period of 1948 the total surface discharge from the Neff's Canyon drainage was measured at 330 acre-feet per square mile. It was estimated that if the flows from the three springs during this same period were added to this figure, the total runoff from the watershed would be 1,800 acre-feet per square mile. This figure is consistent with precipitation on the watershed during the winter of 1948 as estimated from snow survey data.

On the basis of the geologic differences between the Mill Creek and Neff's Canyon watersheds the unit surface runoff might be expected to be less from Neff's Canyon than that from Mill Creek, all other factors being equal. For this reason, the Neff's Canyon model, parameters for which were established from the Mill Creek model, might, therefore, overestimate the surface runoff from the watershed, even though allowances were made for these geological differences in fixing the Neff's Canyon parameters.

Having made this point of difference between the two watersheds, however, it should be mentioned that the results from the Neff's Canyon model are comparable with those obtained from an independent analysis of the same watershed made by the Corps of Engineers (1969). The Corps study predicts the peak flow at the mouth of Neff's Canyon resulting from a '100-year' storm to be 1500 cfs. The corresponding peak flow rate predicted by the model is 1490 cfs, at an antecedent soil moisture level of 11 inches.

Hourly time increment model. As was the case for the daily model, it was necessary to calibrate the hourly model on Mill Creek, and to transfer the resulting parameter values, with appropriate adjustments, to the drainage areas of Neff's Canyon and the remainder of Olympus Cove. The lower Mill Creek subwatershed was selected for this calibration process.

Some parameter values for the hourly time increment model were found by reference to those values obtained for the corresponding parameters in the daily time increment model. For example, the value of the soil field capacity remains unchanged for both time increments. Other parameters, such as the interflow time delay constant, are a function of the model time increment. Those parameter values which could not be established in this way were optimized during the simulation of the lower Mill Creek subwatershed on an hourly basis. The same calibration or optimization procedure was used for both the daily and hourly models.

The size of the Mill Creek watershed, taken together with the existing data network, does not lend itself to simulation on an hourly basis. This is partly due to the areal extent of the simulated thunderstorm-type events, which may cover 5 square miles or less. In other words, given the existing data network for hourly precipitation it is difficult to say what proportion of the watershed is covered by the storm, and is therefore contributing to the gaged watershed outflow.

In transferring parameter values from Mill Creek watershed to Neff's Canyon, and the urbanizing area of Olympus Cove, the differences in areas were taken into account, where necessary. Parameter values, such as the time delay constant in the surface water routing equation, were adjusted for the decrease in size of the watershed. The finalized parameter values used for the hourly time increment simulation of Neff's Canyon and the urbanizing area of Olympus Cove are shown in Table 5.

Model testing

As indicated in the previous section, model calibration involves the two steps of calibration and testing. Model calibration is achieved by a fitting process which establishes the model parameters for a particular set of data from a given hydrologic unit. Model testing involves using a second and independent set of data from the same hydrologic unit, and again operating the model in order to determine the level of agreement between the observed and predicted (or computed) output functions. Thus, model testing is simply an independent test of results achieved under the calibration phase.

Daily time increment model. Following the calibration of this model for the two subwatersheds of Mill Creek, the optimum parameter values as given by Table 4 were fixed in the model, and the runoff patterns were simulated for the 5 years of record at each of the two stations. Sample output showing the degree of agreement which was achieved between observed and computed streamflow hydrographs is shown by Figures 11 and 12 for the upper and lower subwatersheds, respectively. At the bottom of Table 4, the mean value (over the 5 years of simulation) of the objective function is given for the two Mill Creek subwa-

Table 5. Parameter values used in the study area of Olympus Cove hydrologic systems of Neff's Canyon and the urbanizing area of Olympus Cove.

Parameter	Description	Value
SS	Saturated soil level (inches)	13.0
SFC	Field capacity of soil (inches)	6.0
FO	Maximum infiltration capacity rate (inches/hr)	1.0
FC	Minimum infiltration capacity rate (inches/hr.)	.20
DKT	Decay constant in infiltration equation ($\text{hr}^{-\text{hr}}$)	2.0
TAUSW	Decay constant in surface water routing ($\text{hr}^{-\text{hr}}$) equation	.50
TGW	Decay constant in interflow routing ($\text{hr}^{-\text{hr}}$) equation	.01
QK	The fraction of outflow from soil moisture storage that becomes interflow	.30
SI	Upper limit of interception and depression storage (inches)	.20

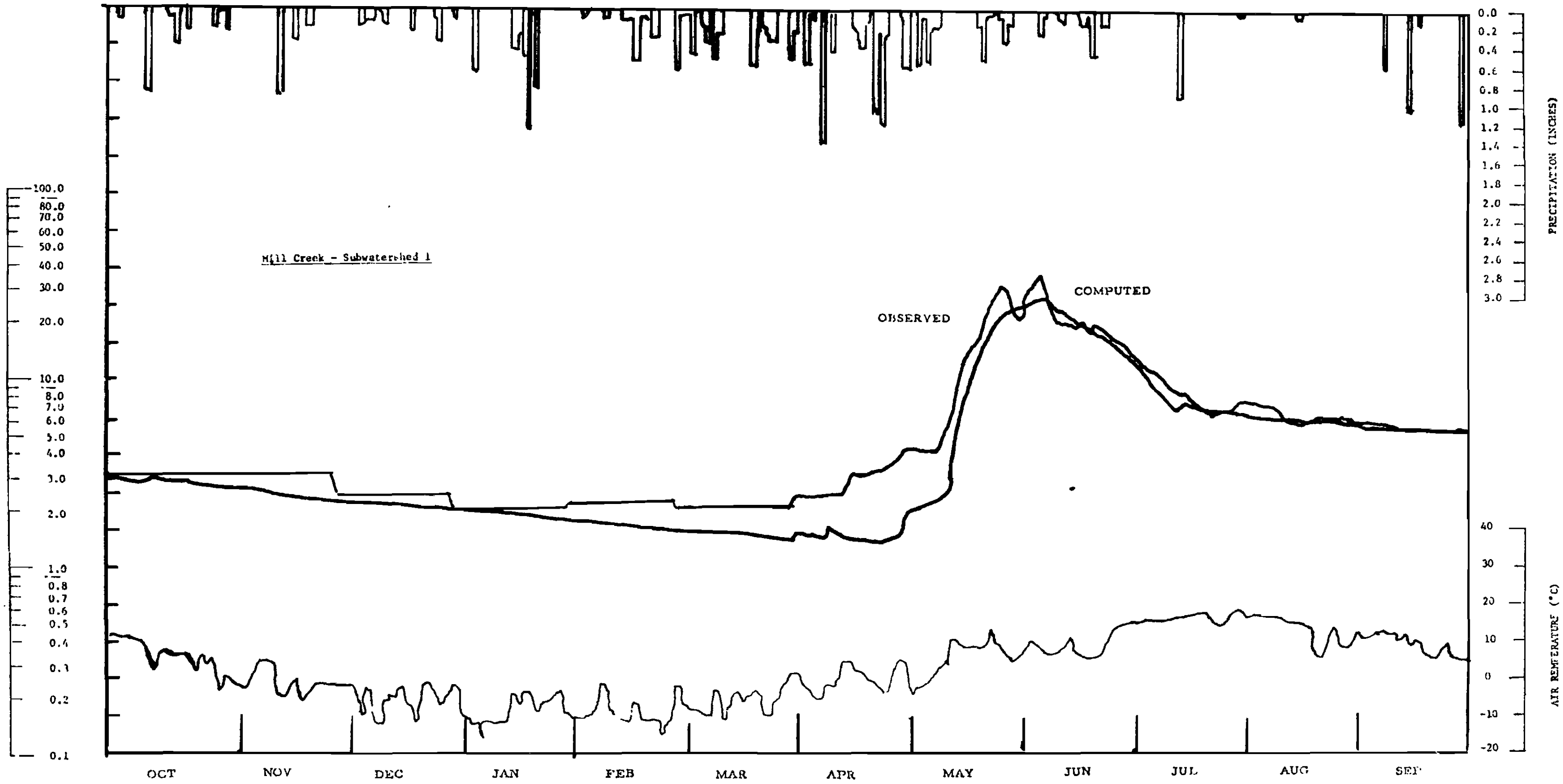


Figure 11. Hydrographs of observed and computed streamflow at Gaging Station No. 1698 on Mill Creek for the water year 1964.

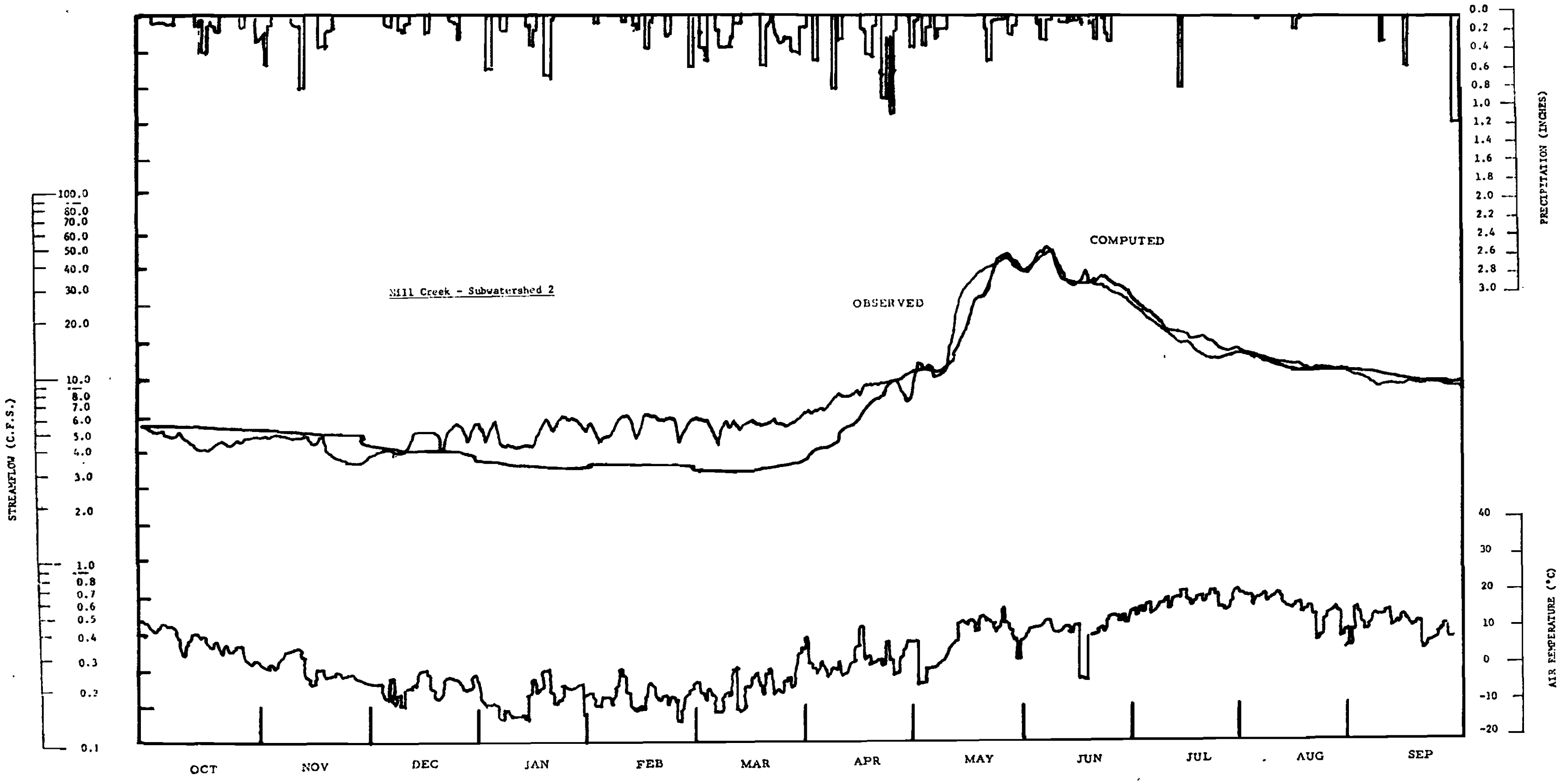


Figure 12. Hydrographs of observed and computed streamflow at Gaging Station No. 1700 on Mill Creek for the water year 1964.

tersheds. The table also includes the ratio of the mean yearly objective function to mean yearly streamflow, a quantity which is termed the relative objective function.

As already indicated, because of the lack of runoff data it was not possible to test the calibration of the model for the Neff's Canyon drainage. However, the runoff predictions were comparable with those of the lower Mill Creek subwatershed, and a sample is shown by Figure 13. Runoff is computed at the points of discharge indicated on Figure 2.

Hourly time increment model. This model was tested by generating runoff hydrographs associated with several short duration, high intensity rainfall events on the lower Mill Creek subwatershed. The computed and observed hydrographs for two of these events are shown by Figure 14.

Model Operation

The model is, of course, operated during the verification procedure, and at this time comparisons are made to test the ability of the model to represent the system of the real world. It is very possible that these tests indicate that some adjustments are necessary, either in the data on which the model is based, or in the structure of the model itself. The various options associated with this looping, or 'feedback,' procedure are indicated by the flow path labeled 'compromises' on the diagram of Figure 6. When suitable model verification has been achieved, the model is ready for use as a technique for investigating the response of the hydrologic system to various input conditions and management alternatives which might be imposed upon the watershed. In the case of the Olympus Cove area (including Neff's Canyon) the models were used to perform several investigations, and the results of these are discussed in the following chapter.

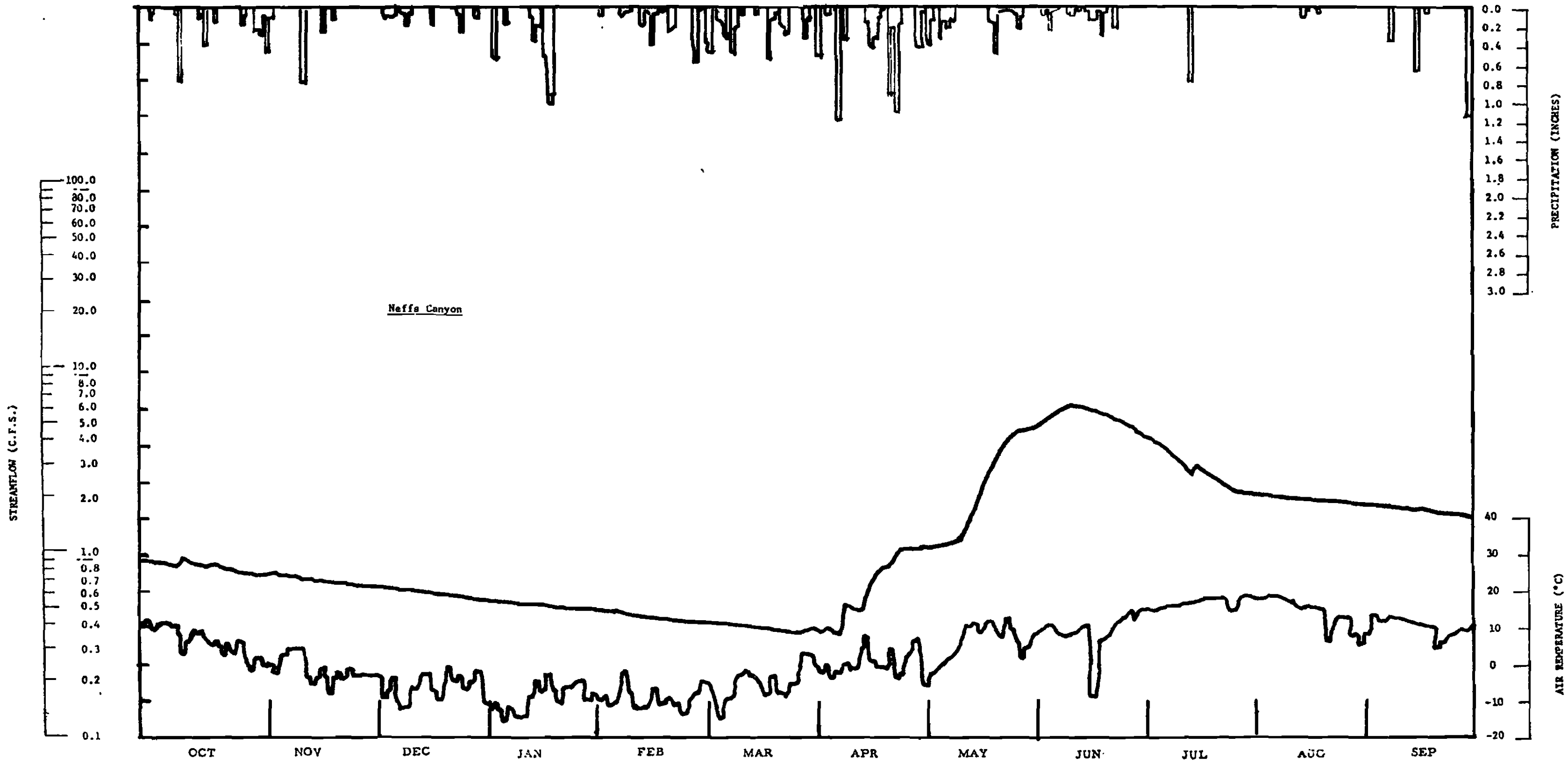


Figure 13. Hydrograph of computed runoff from Neff's Canyon for the water year 1964.

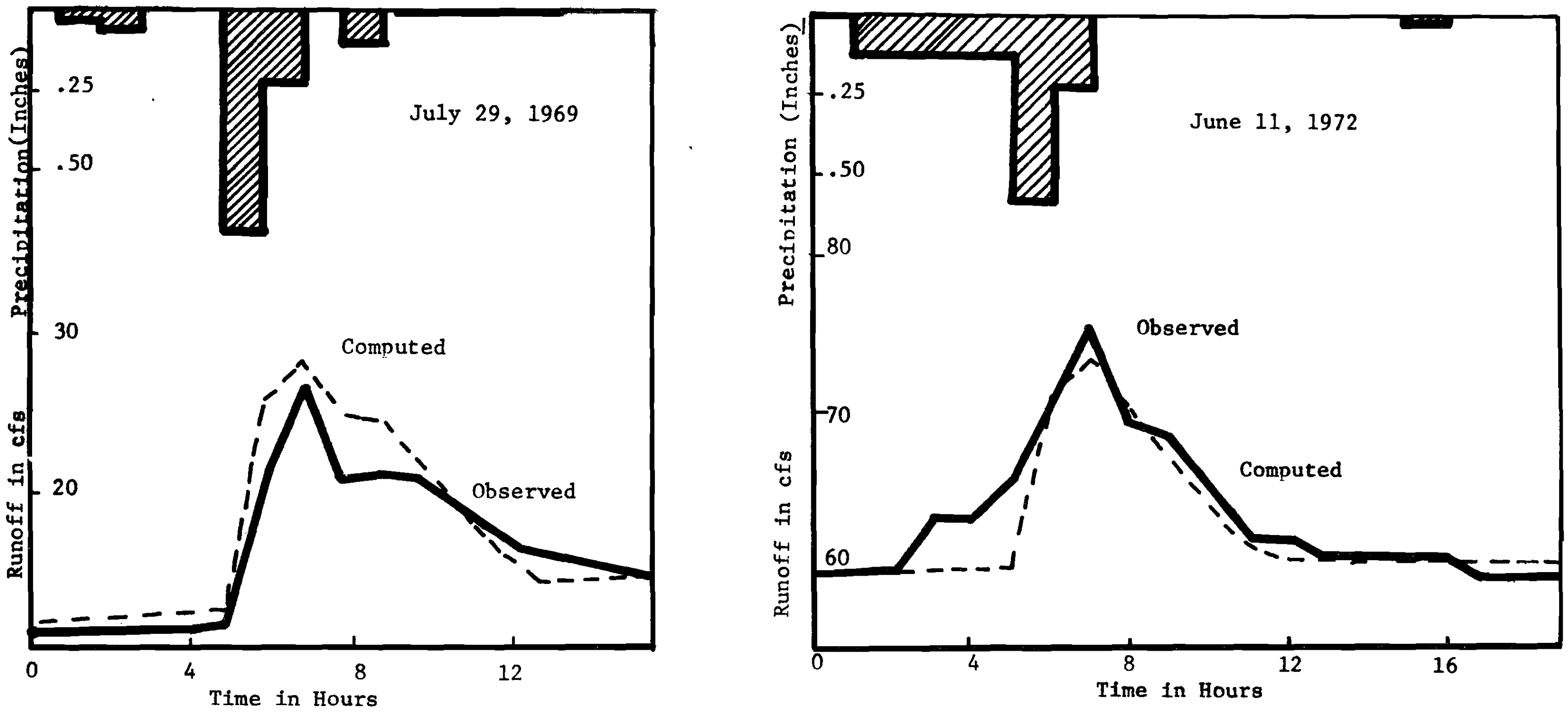


Figure 14. Hydrographs of observed and computed streamflow at Gaging Station No. 1700 on Mill Creek for two storms.

CHAPTER IV

MODEL RESULTS

Both the daily and hourly time increment models were used to predict and examine various runoff characteristics within the study area. As indicated by Figure 2, storm water flows within the cove originate from three primary sources, namely (1) the Neff's Canyon drainage; (2) source areas on the steep slopes of Mt. Olympus immediately above the subdivisions; and (3) the urbanizing area of the cove. For each of these three primary supply areas estimates of flow rates were made of runoff generated within each. In all cases, the primary variables included in the runoff estimates were frequency of the precipitation event and antecedent soil moisture content. For the urbanizing area a third variable, the degree of urbanization, was added.

Because of the sensitivity of the hydrologic response to antecedent soil moisture levels (see Table 4) the daily time increment model of the Neff's Canyon drainage was used to examine soil moisture changes with time during the year. This study was conducted for the 5-year period from 1964 to 1968, and the results are shown by Figure 15. It is noted that average soil moisture levels on the watershed generally peaked between May and June at the time of maximum snowmelt. The deviation of the soil moisture for 1966 from the usual pattern is explained by the fact that 1965 was an exceptionally dry year. It was assumed that the soil moisture curves of Figure 15 reflect the variation in mean values which might have been experienced in the Olympus Cove area before development.

Neff's Canyon

The hourly time increment model of the Neff's Canyon watershed (total drainage area of 3.5 square miles) was generated for various storm recurrence intervals and for several assumed antecedent soil moisture levels. Typical simulated runoff hydrographs at an assumed antecedent soil moisture level of 8.5 inches and storm recurrence intervals of 10, 25, 50 and 100 years are shown by Figure 16. Similar curves for an antecedent soil moisture level of 11 inches are given by Figure 17. The marked influence of antecedent soil moisture on peak runoff rates is seen by comparing, for example, the two ~~hydrographs~~ corresponding to a 25-year storm event. At an antecedent moisture level of 8.5 inches the peak runoff rate is estimated at about 500 cfs, whereas at the 11-inch antecedent level the peak is shown at nearly 700 cfs.

Figure 18 summarizes the peak runoff rates to be expected from the Neff's Canyon drainage for various storm recurrence intervals and for the three levels of antecedent soil moisture used. The plots were developed from the kind of model output information depicted by Figures 16 and 17.

Olympus Cove

As in the case of Neff's Canyon, precipitation data for storms of the same four recurrence intervals (10, 25, 50, and 100 years) were input to the hourly hydrologic model of the Olympus Cove urbanizing area. In this case, a runoff producing area of 0.61 square miles was used. This is approximately the total area of potential urban development within the cove. Typical simulated runoff hydrographs resulting from these storms at an antecedent soil moisture level of 8.5 inches are shown by Figure 19. In simulating these hydrographs natural, or non-urban, conditions on the drainage area were assumed. Figure 20 summarizes the peak runoff rates to be expected from the area under non-urban conditions for various storm recurrence intervals and for the same three levels of antecedent soil moisture. Once again, these plots were developed from simulated computer output information of the kind shown by Figure 19.

The effects of urbanization on runoff hydrographs is illustrated by the similated curves of Figure 21, in which runoff from the Olympus Cove urbanizing area is plotted for a 25-year storm at various degrees of urbanization on the watershed. In this case an antecedent soil moisture level of 4.0 inches is assumed.

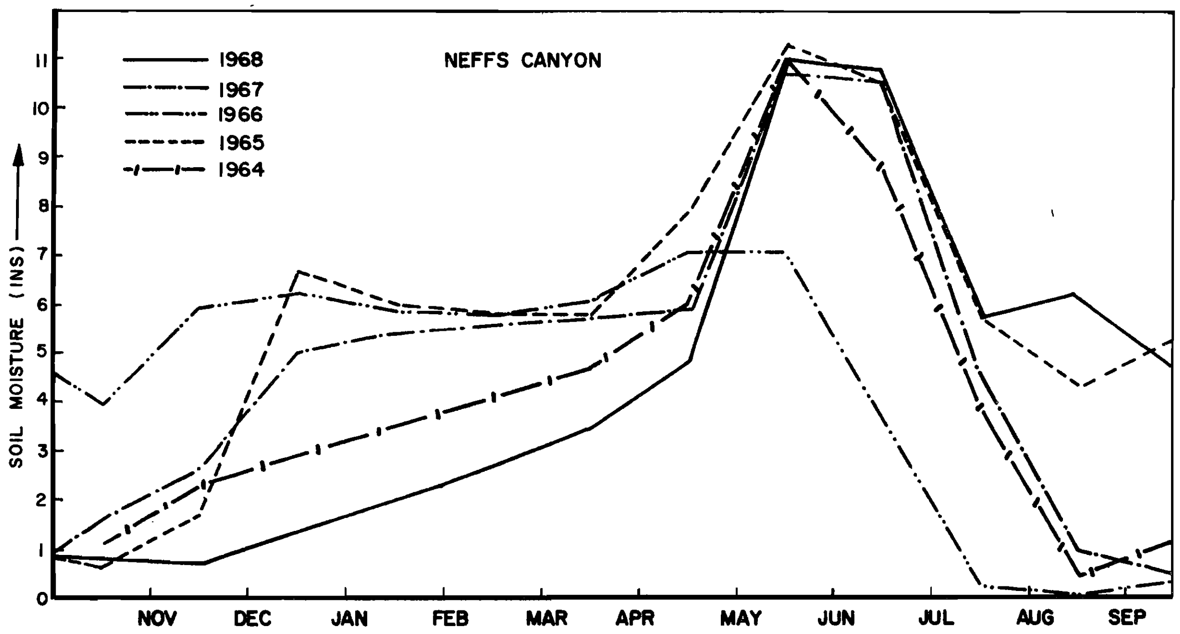


Figure 15. Graph showing simulated variation of average soil moisture throughout the water year for the Neff's Canyon watershed.

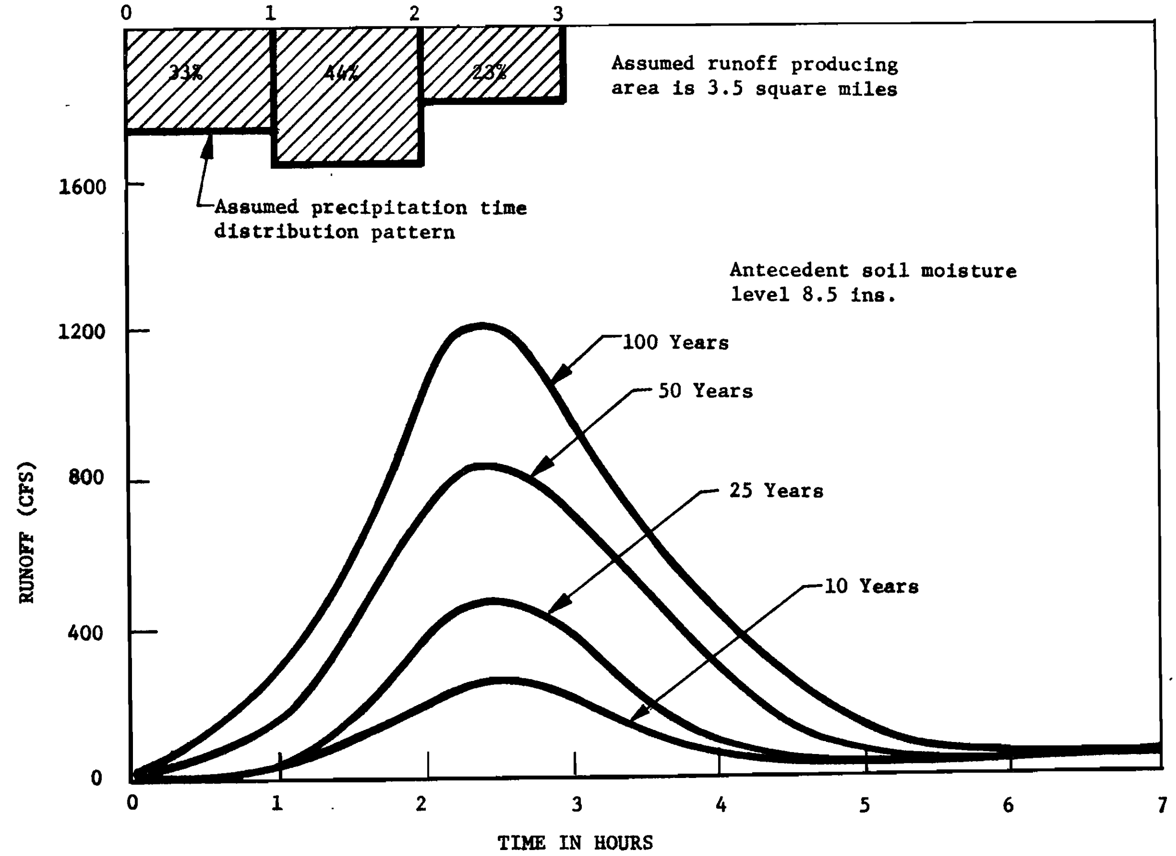


Figure 16. Simulated hydrographs of runoff from Neff's Canyon from storms of various recurrence intervals.

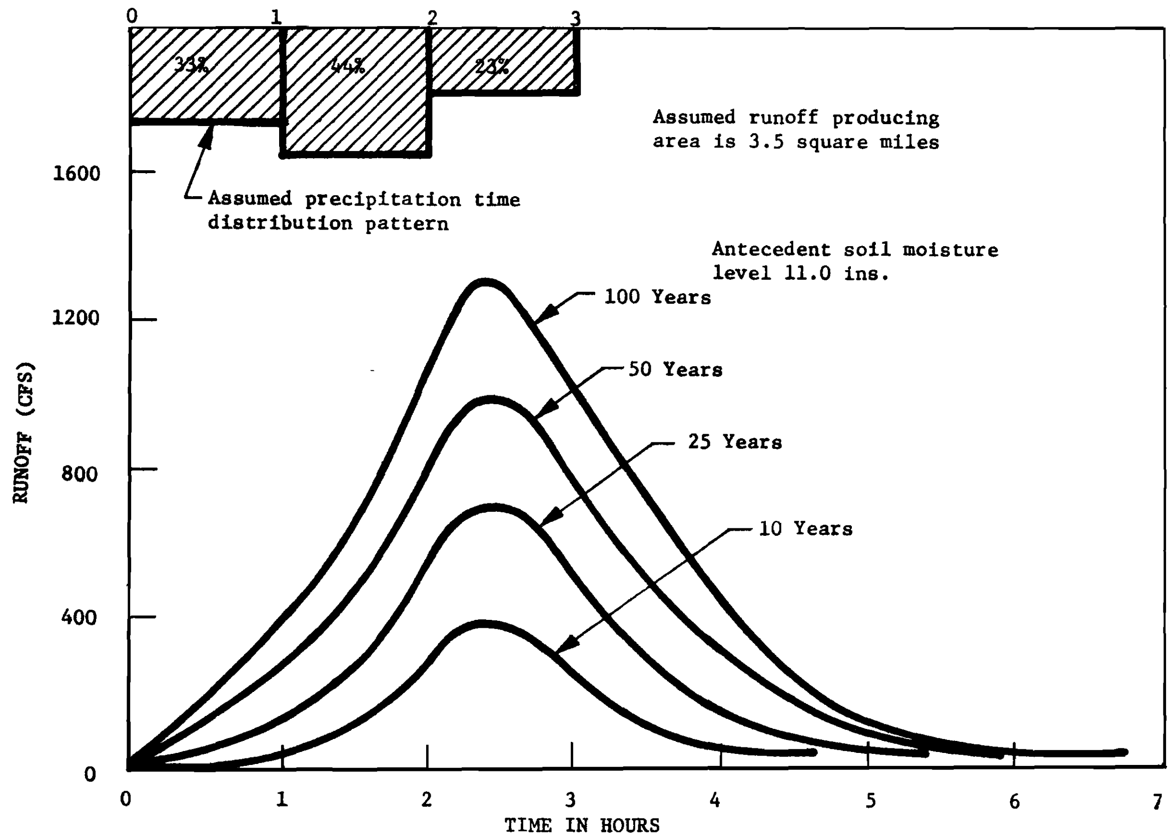


Figure 17. Simulated hydrographs of runoff from Neff's Canyon from storms of various recurrence intervals.

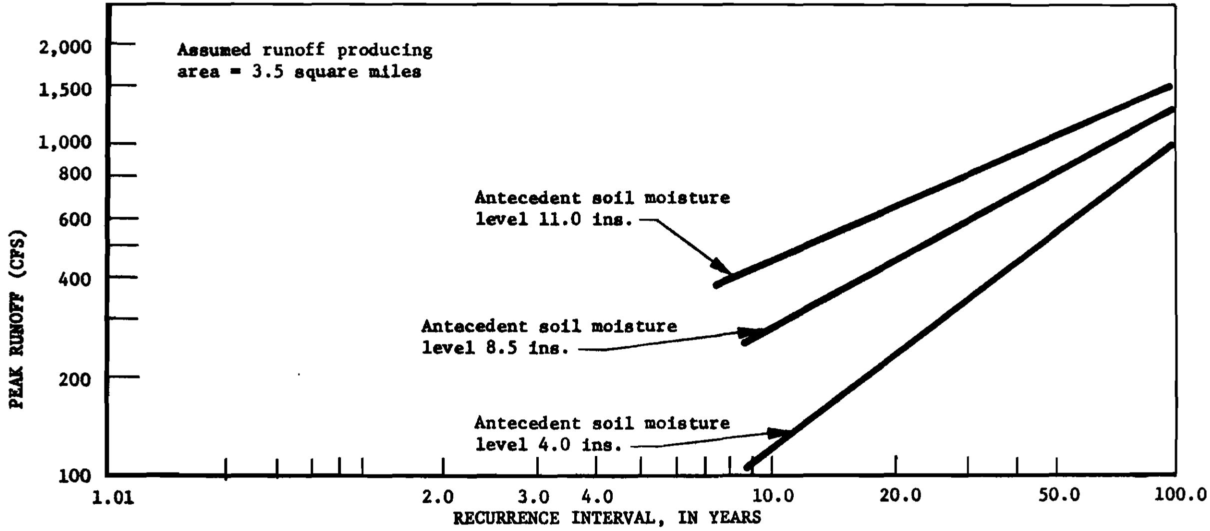


Figure 18. Graph of peak runoff against the causative storm recurrence interval for Neff's Canyon watershed.

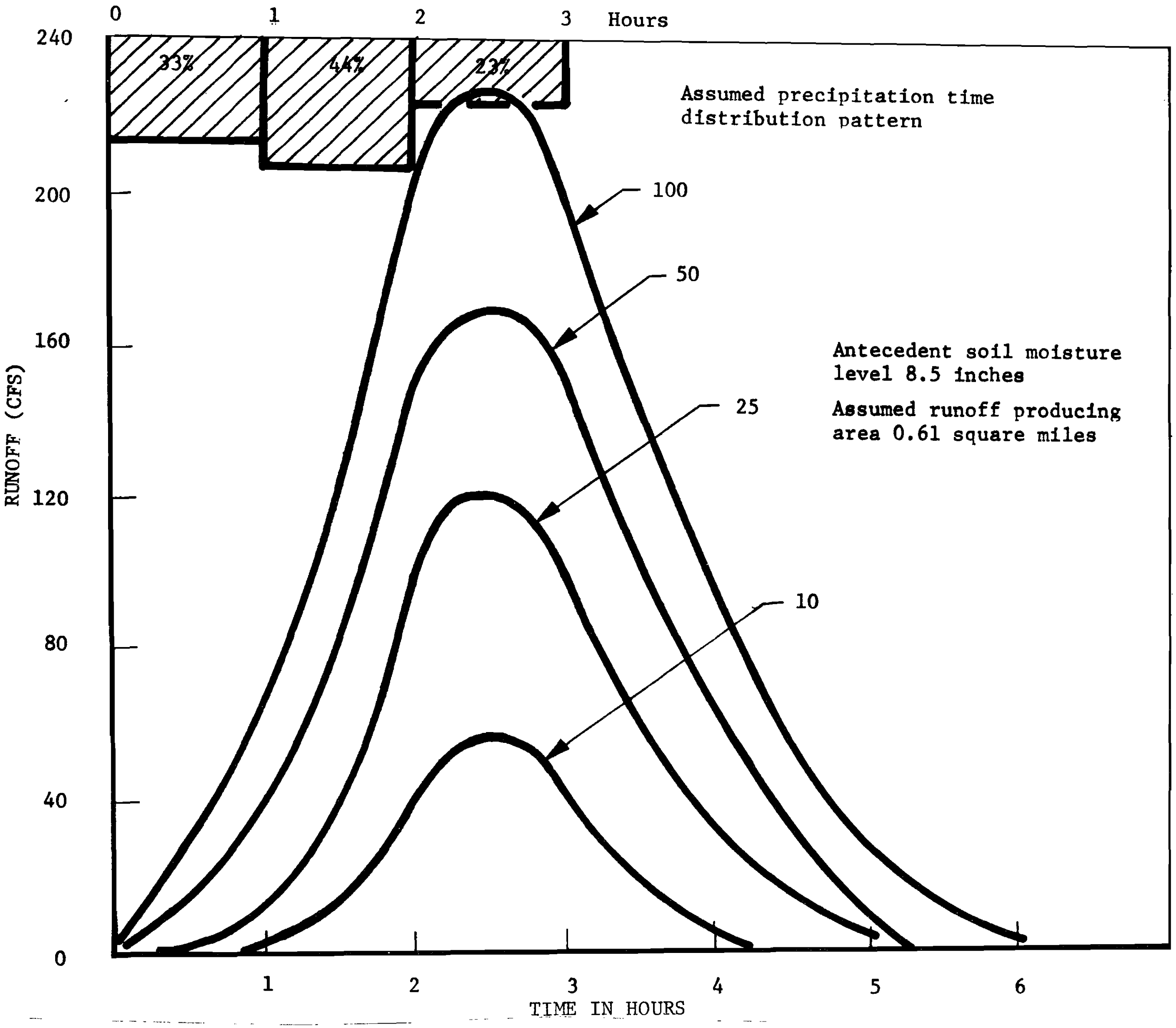


Figure 19. Simulated hydrographs of runoff from the study area of Olympus Cove for storms of various recurrence intervals (non-urban conditions).

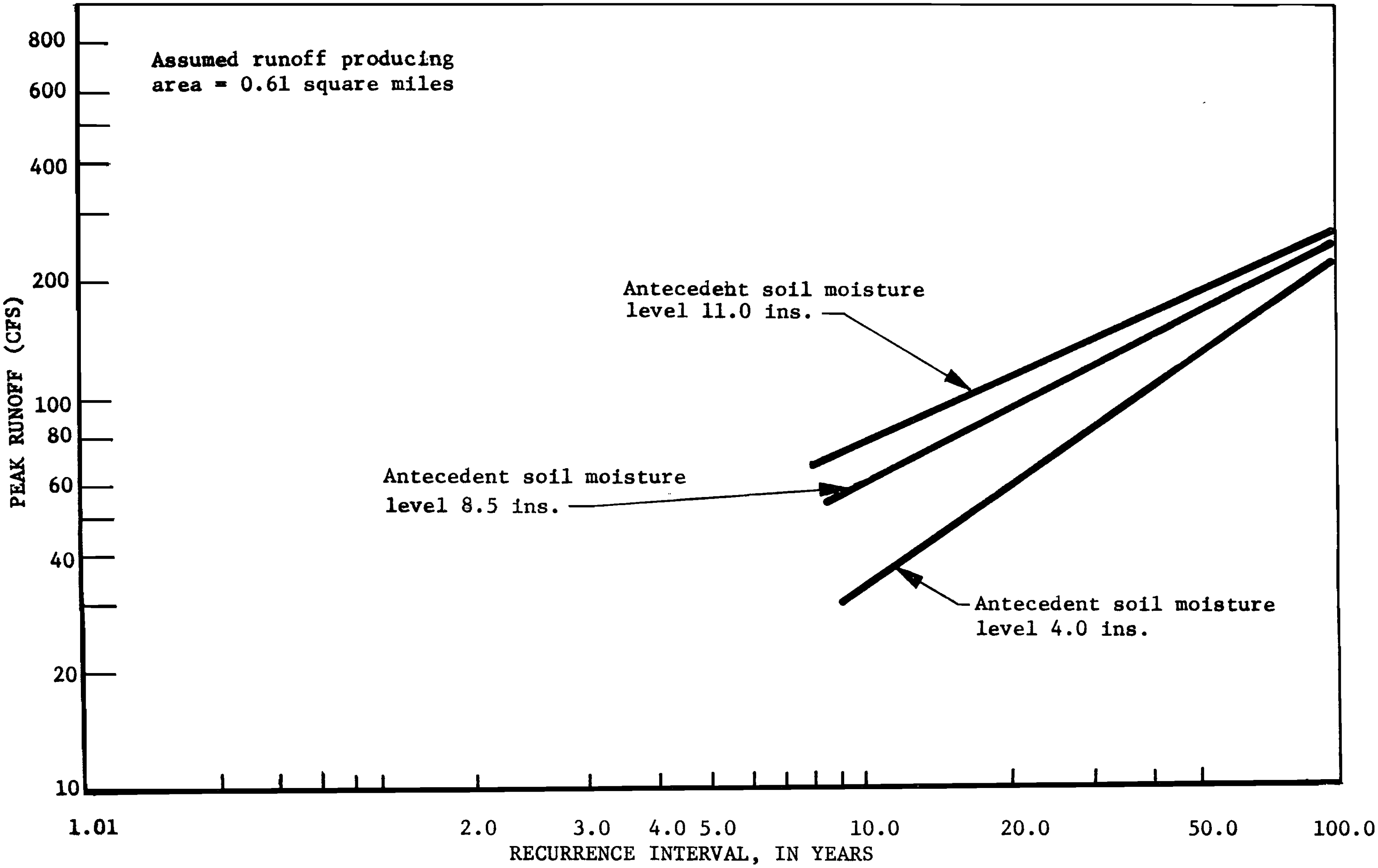


Figure 20. Graph of predicted peak runoff against the causative storm recurrence interval for the study area of Olympus Cove under natural (non-urban) conditions.

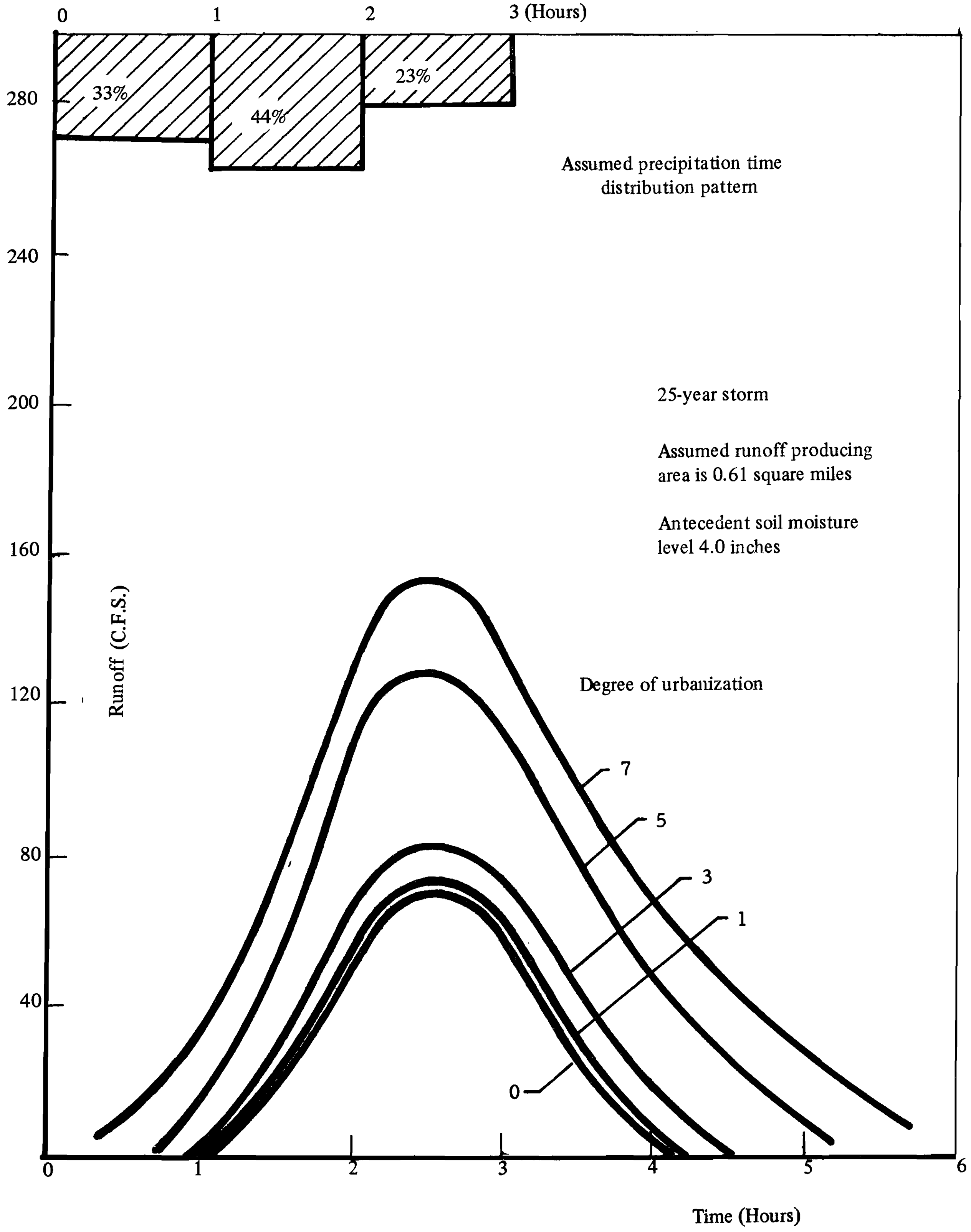


Figure 21. Simulated hydrographs of runoff from the study area of Olympus Cove for various degrees of urbanization.

During the period from 1847 to 1969, 44 percent of the reported cloudburst floods along the Wasatch Front occurred in August (Butler and Marsell, 1972). According to this same reference, a total of 408 cloudburst floods occurred in this area during the 123 year reporting period. Figure 15 indicates a mean soil moisture level for this period of approximately 4 inches. Thus, Figure 21 illustrates the effects of urbanization on the runoff hydrograph from the Olympus Cove area at the antecedent soil moisture level most likely to occur during the period of maximum cloudburst storm activity.

Simulated hydrographs similar to those of Figure 21 also were generated for storm recurrence intervals corresponding to 10 and 50 years. On the basis of these three sets of simulated hydrographs Figure 22 was developed. This figure gives the relative rate of increase in peak runoff rate with increasing degree of urbanization for each of the three selected storm recurrence intervals (10, 25, and 50 years). By using Figure 22 in conjunction with Figure 20, peak runoff rates can be estimated as a function of storm recurrence interval, antecedent soil moisture, and degree of urbanization.

Figure 22 also provides some insight into the relative sensitivity of the hydrologic system to the effects of urban development as a function of the magnitude of the runoff producing storm event. For example, for a storm corresponding to a recurrence interval of 10 years, an increase in urbanization of from 0 to 40 percent more than doubles the peak rate of surface runoff. On the other hand, for a 50-year storm event the corresponding increment is only 2 or 3 percent. This situation is explained on the basis that large runoff producing events, such as a 50-year storm, cause high runoff rates whether under natural or urban conditions, so that in this case the effects of urbanization are relatively less important. Thus, for major or low frequency storm events (those with recurrence intervals of more than 25 years, for example), the impacts of urban development on peak rates of runoff generated within the urbanizing area itself tend to be relatively small.

Mt. Olympus Source Areas

The Mt. Olympus source areas occur on the steeply rising slopes of Mt. Olympus which lie mainly to the south of the urbanizing area of the cove. A total of seven separate drainage areas were identified, and these are indicated by Figure 23. It is conceivable, of course, that a runoff producing event could occur on any one of these drainage areas, and the resulting flows could cause flooding both within the cove and at locations even farther downstream. The probability of the occurrence of flood flows in more than one channel at any one time is a matter of conjecture, but this situation apparently has not been noted in the rather brief history of observations. Because no well-defined

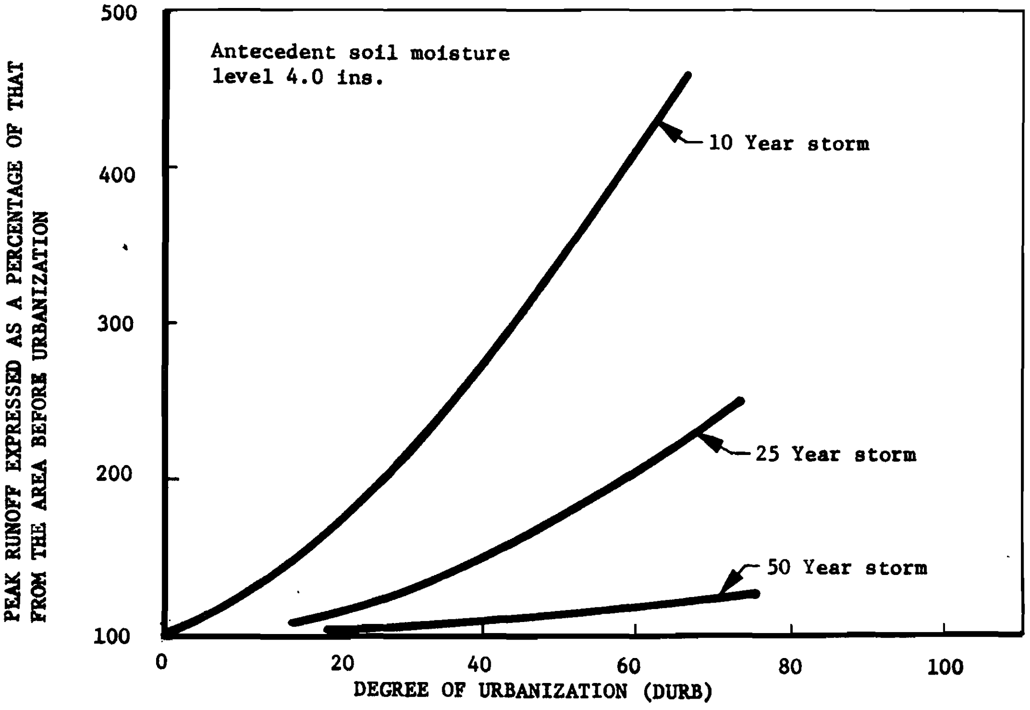


Figure 22. Graph relating peak runoff to degree of urbanization for the study area of Olympus Cove.

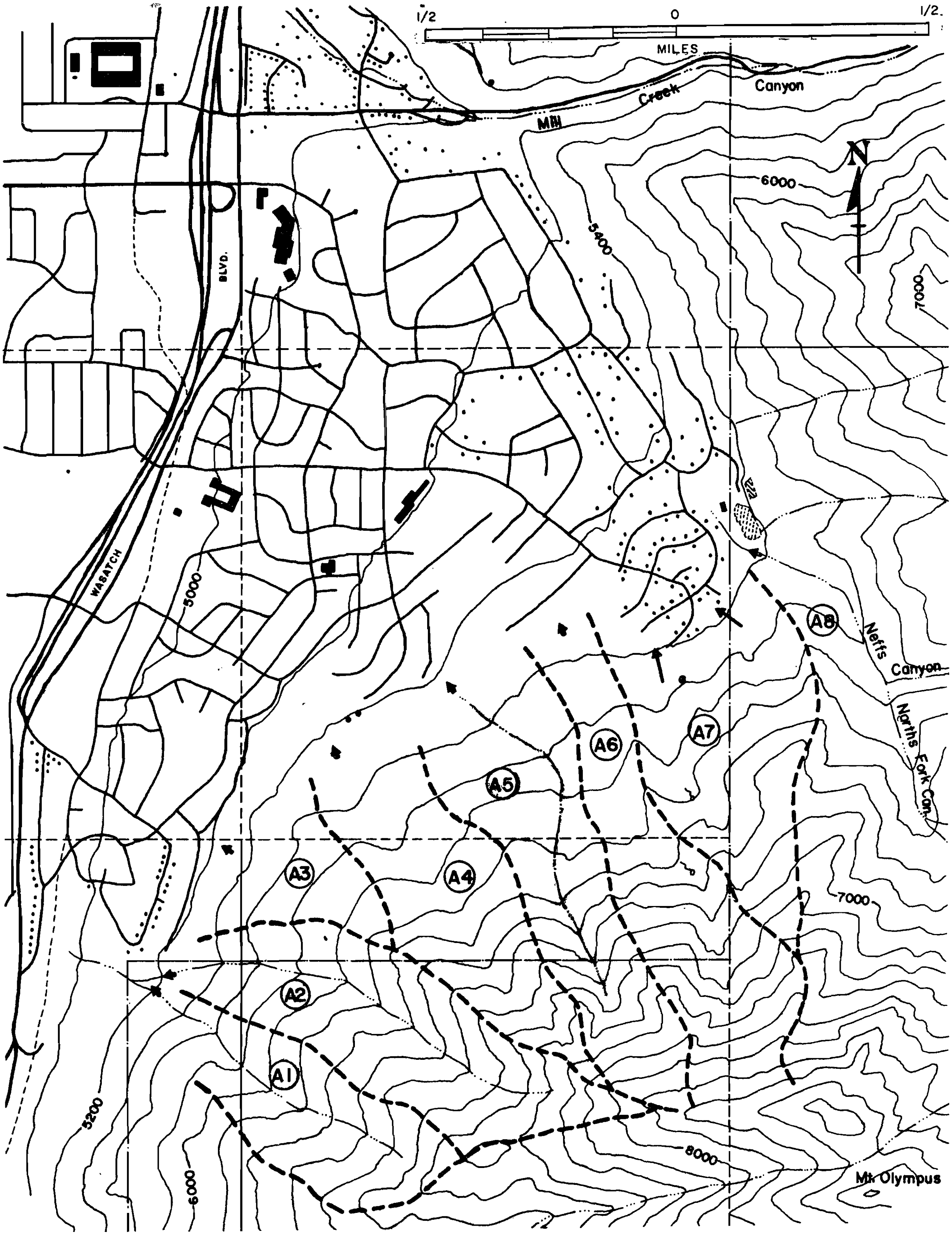


Figure 23. Designated Mt. Olympus source areas.

channels exist in the urbanizing area below the seven sources which are identified by Figure 23, flood runoff is assumed to occur as sheet flow, and a method proposed by Chow (1964) was adopted for calculating the width, depth, and velocity of the flood wave. This procedure considers the frequency of the storm event, the drainage area, the antecedent soil moisture, the slope of the ground surface, and the resistance to flow from vegetation and other surface roughness features. The procedure, including an example of its application, is described by Appendix C. For areas A4, A5, and A6, for example, it is estimated that the flood wave resulting from a 25-year storm event will be about 0.3 feet deep and have an average velocity of 4 feet per second. The same storm on either of areas A1 or A2 would produce corresponding values for the flood wave of 0.13 feet and 5 feet per second. Peak runoff rates were computed for each area for storm frequencies of 10, 25, 50, and 100 years, and these results are summarized by Table 6. In each case, the runoff producing event was considered to be centered directly over the source area in question, and an antecedent soil moisture content of 8.5 inches was assumed. For comparative purposes, corresponding flows from Neff's Canyon as estimated by the hourly computer model also are included in Table 6. It is noted that the runoff rates per square mile used in the calculations for each of the seven source areas are a function of storm frequency and antecedent soil moisture (see the table on Figure C-1). These unit rates were obtained from output information generated by the hourly model of Neff's Canyon (Figure 18).

Combined Flood Flows

In this section an example is presented to illustrate the manner in which predicted peak flows from various sources might be combined to produce estimates of total peak runoff rates. Figure 24 depicts points of outflow from Neff's Canyon and an adjacent Mt. Olympus source area (A7). Included within the dashed line on Figure 24 is the area of the urban watershed (0.27 square miles) from which surface runoff follows the same general drainage pattern as outflows from Neff's Canyon. Assume that a cloudburst storm event corresponding to a 25-year return frequency occurs simultaneously over the Neff's Canyon, source area, A7, and the portion of the Olympus Cove within the dashed lines of Figure 24. The present level of urbanization within this area is less than 20 percent. Assume further that antecedent soil moisture conditions of 8.5 inches exist in all areas. From Figure 18 and from Table 6, the peak outflow rate from Neff's Canyon is equal to 500 cfs. The estimated peak flow from source area A7 is 200 cfs (Table 6). The corresponding peak flow generated within the urbanizing area of the cove is found from Figures 20 and 22 to be about 115 cfs. This estimate, however, refers to a runoff producing area of 0.61 square miles, whereas the area within the dashed lines of Figure 24 is only 0.27 square miles. If the peak rate of outflow is reduced in direct proportion to area, the adjusted estimate is approximately 50 cfs.

Table 6. Estimated peak runoff rates corresponding to storm events of various frequencies for designated source areas above Olympus Cove. [a]

Return Period of Storm Event (Year)	Estimated Peak Rates of Outflow from Designated Source Areas (cfs) (see Figure C-1)							
	A-1	A-2	A-3	A-4	A-5	A-6	A-6	Neff's Canyon
10	115	180	55	145	180	165	175	270
25	134	210	65	170	210	193	200	500
50	153	242	75	195	242	220	230	800
100	172	272	80	219	272	247	265	1240

[a] Assumed antecedent soil moisture level = 8.5 inches.

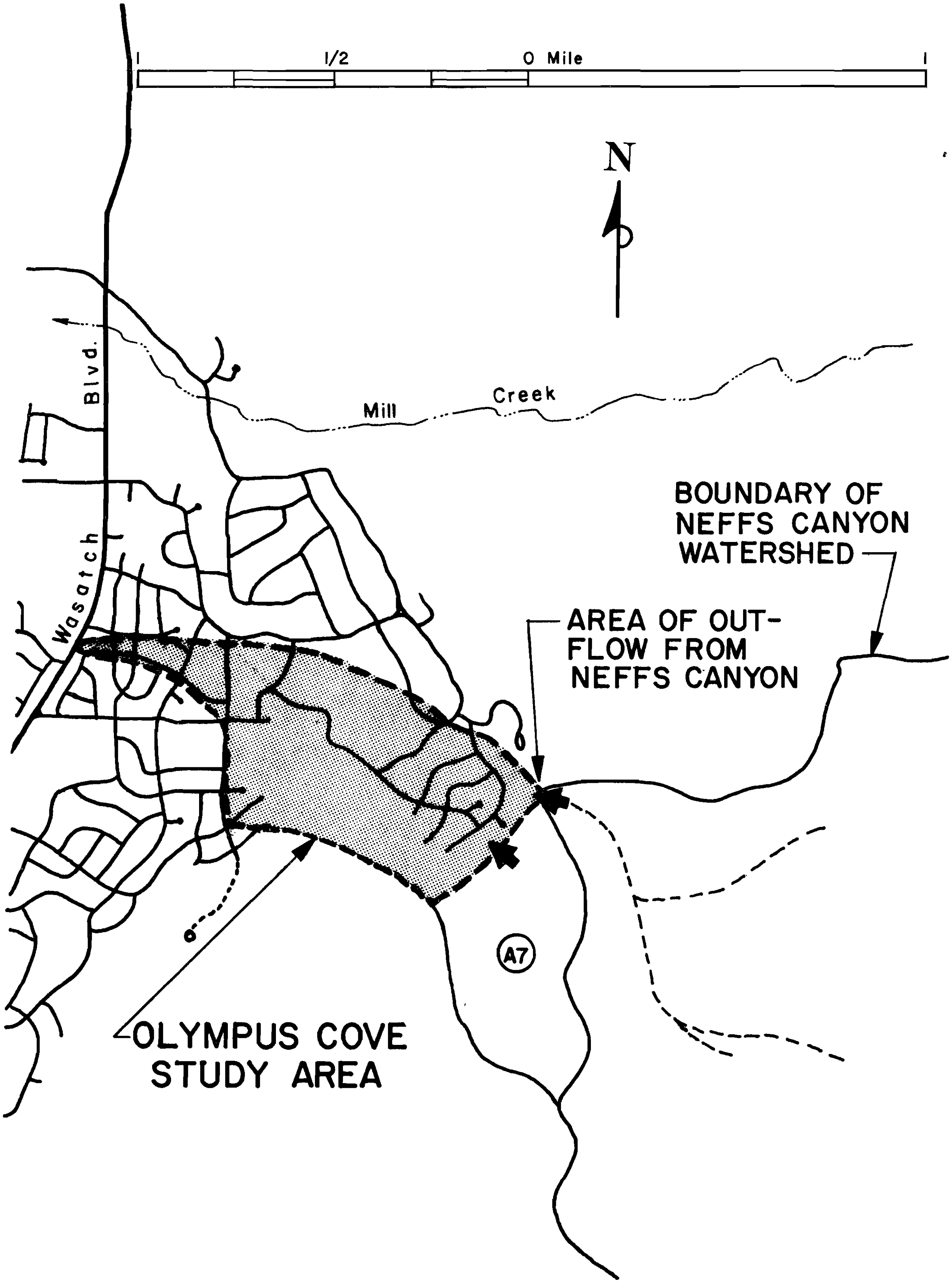


Figure 24. Map showing relation of Mill Creek, Neff's Canyon, and Olympus Cove.

The problem now is to combine these various flow predictions so as to produce a reasonable estimate of the peak flow which might be expected at the Wasatch Boulevard under the assumed conditions. Outflow from the source area A7 has no well defined channel through the urban area. However, at the present level of urban development this situation probably does not represent as great a flood hazard potential as does the Neff's Canyon watershed. Runoff from the A7 drainage might reasonably be expected to spread out from the point of entry to the urban area, and most of the water likely would infiltrate into the ground. On the other hand, if urban development continued to increase in this area, the resulting reduced infiltration opportunities would increase surface runoff both from that generated within the urban area itself and from those waters which entered from the upstream source area. If it were assumed that urbanization were increased to 40 percent, and that accompanying this increase conveyance works were developed to carry runoff from upstream sources through the urban area, peak flows at Wasatch Boulevard would be significantly increased. It is conceivable that the peak flows at Wasatch Boulevard under these two situations might be represented as follows (Table 7).

Table 7 suggests that the urbanization process produced only a rather modest increase in surface runoff rate from within the urbanizing area itself. The major increase in total surface runoff in this case resulted from the loss of a zone of infiltration within the upper portions of the urbanizing area and the corresponding need to find an alternate disposal procedure for the surface inflows from the higher slopes of Mt. Olympus. If these waters are conveyed through the Olympus Cove area, flows might be expected to be increased at Wasatch Boulevard by orders of magnitude suggested by Tables 6 and 7.

Flood Damage Estimates

An important criterion in the analysis of any flood problem is the extent of the damage caused by flows of various magnitudes, and the degree to which this damage might be reduced or prevented by appropriate flood protection measures. Almost always the level of damage is directly related to the magnitude of the flood, with events of lower frequency, and thus of a greater magnitude, causing more damage than the higher frequency events. Recently, the U.S. Soil Conservation Service developed some preliminary flood damage estimates for the Olympus Cove and for the downstream area below (west of) Wasatch Boulevard (1974). The results of this study are shown by Figure 25, which demonstrates the usual trend of increasing damage costs with lower frequency events. Four damage-frequency curves are shown by Figure 25, with each curve depicting a particular stage of development in the Olympus Cove and downstream areas. The level of urban development is, of course, known for Curve I (1972), but the remaining three curves are based on assumed development trends.

As urbanization increases, the damage potential at a particular flood frequency also increases, and this trend is reflected, for example, by the higher ordinates of Curve IV at a given flood frequency than those of Curve I. Putting this statement in another way, the frequency of a particular level of flood damage increases with urbanization. Frequency, incidentally, is interpreted as being the inverse of flood recurrence interval, and usually is expressed as a percentage. Thus, a frequency of 5 percent corresponds to a recurrence interval of 20 years.

Perhaps a word of explanation is needed in connection with the damages shown by the curves of Figure 25 at flood frequencies of as much as 30 percent.

Table 7. A sample of possible changes in peak surface runoff rates from a portion of the Olympus Cove area as a result of urbanization.

Level of Urban Development (percent)	Estimated Peak Runoff Rates (cfs) [a]			
	Neff's Canyon (Model Output)	Source Area A-7 (Figure 22)	Olympus Cove Urban (Figure 23) Area (Model Output)	Total at Wasatch Blvd.
20% Present	500	Infiltration abstraction	50	550
40% Future	500	200	60	760

[a] Notes:
1) 25-year runoff producing storm event
2) Antecedent soil moisture = 8.5 inches
3) Urbanizing area = 0.27 square miles

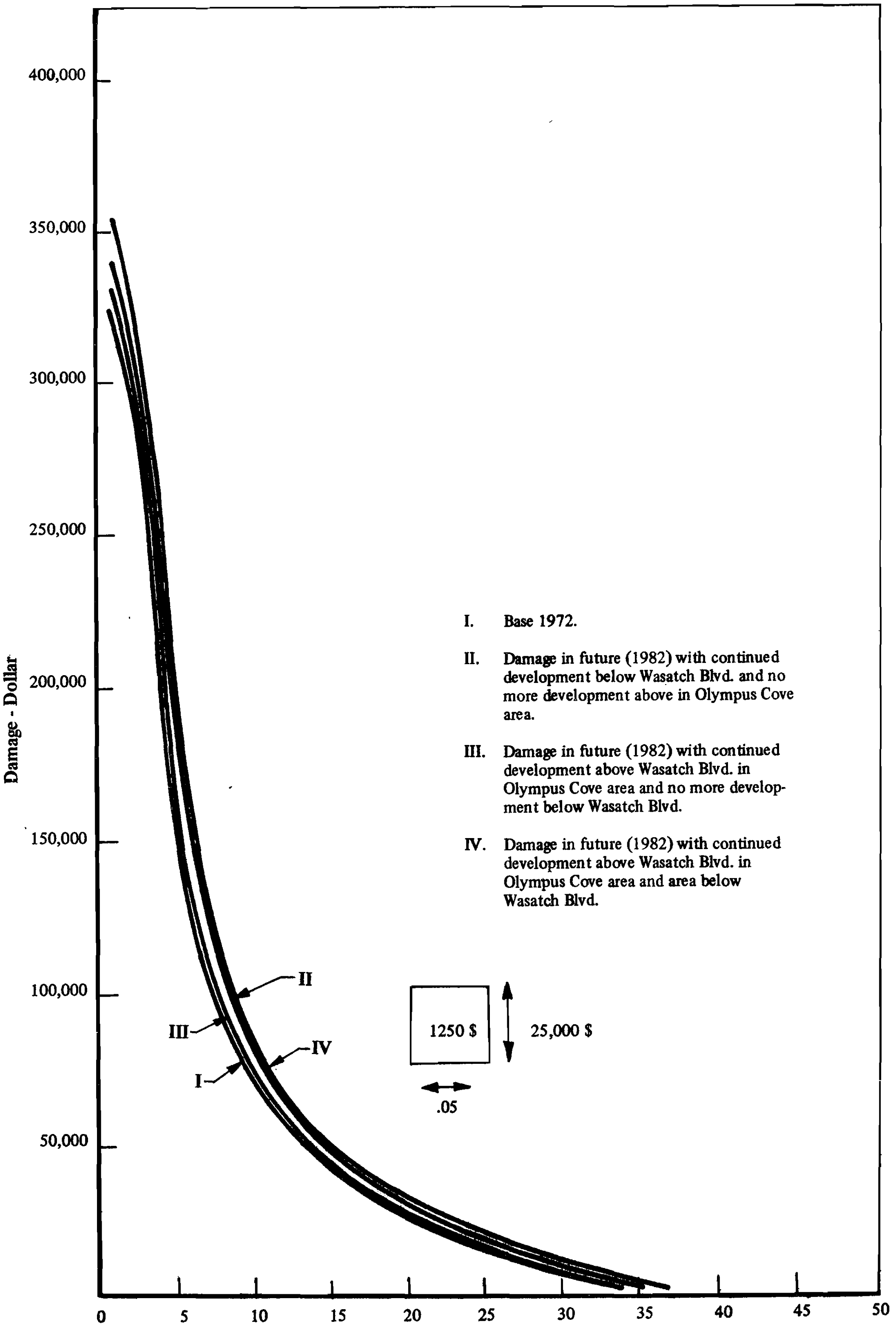


Figure 25. Damage frequency curves for the Olympus Cove and downstream area (after Soil Conservation Service, 1974).

In areas of relatively steep topography, such as the Olympus Cove, flood damage usually is not incurred by inundation, but rather by erosion and by the deposition of water borne sediments and other debris. Erosion can weaken and destroy structural foundations. Damage caused by sediment deposition is reflected in maintenance costs associated with the removal of deposits from waterways, ditches, pipelines, and land surfaces. This kind of damage begins with very high frequency storms long before the carrying capacities of runoff channels and storm sewer lines in the area normally are exceeded.

Figure 26 attempts to summarize in a single chart much of the information which is presented by this chapter of the report. For example, from this chart it is possible to predict peak rates of runoff from either Neff's Canyon or the Olympus Cove urbanizing area as functions of storm recurrence interval, antecedent soil moisture, and degree of urbanization. For all estimates involving Neff's Canyon no urban development is assumed. Of the eight 'upstream' source areas which are potential contributors to Olympus Cove (Figure 23), Neff's Canyon was selected for inclusion on Figure 26 because it is capable of generating the highest peak flows, and thus of causing the greatest damage levels, particularly at the current level of urban development within the cove. As indicated by Figure 23, at the present time there is considerable opportunity for flows which discharge from source areas A1 through A7 to infiltrate into the ground, so that damage is minimal and usually is confined to the cove area.

The damage curve shown in the lower portion of Figure 26 is based on information obtained from Curves I and IV of Figure 25, and is 'keyed' to the predicted rates of peak runoff generated within the urbanizing area of Olympus Cove. Thus, for predicting the damages associated with a 25-year storm event at the present level of urban development (approximately 20 percent), it is necessary to begin on Figure 26 at the line corresponding to a rainfall return period of 25 years. The next step is to move up this line to its point of intersection with one of the solid lines representing three possible antecedent soil moisture conditions. If, for illustrative purposes, an antecedent condition of 4 inches is assumed, a horizontal line is traced from the point of intersection to the curve which represents, in this case, an urban development level of 0.20 (20 percent). Reading vertically downward from this point, the chart provides estimates of a peak discharge rate from the urbanizing source area of 80 cfs and a total flood damage of $220,000. It is noted that this damage estimate corresponds to that obtained from Curve I of Figure 25 for a flood frequency of 4 percent (25-year return period). In locating the cost curve in Figure 26 it was assumed that the damage-frequency relationships of Figure 25 are based on an average antecedent soil moisture level of 4 inches. The basis of this assumption is that, as explained earlier, 4 inches seems to be the soil moisture level most likely to prevail in the area during the month of August, which is the period of greatest thunderstorm activity. For this reason, damage estimates from Figure 26 at an assumed antecedent soil moisture level of 4 inches agree closely with corresponding estimates from Figure 25. Damage estimates based on assumed higher levels of antecedent soil moisture are greater. However, this trend is reasonable because corresponding runoff rates also are higher. Thus, if in the previous example, an antecedent soil moisture level of 8.5 inches is assumed, the estimates of the peak runoff rate from the Olympus Cove source area and the flood damage are 115 cfs and $280,000, respectively.

The question might be raised as to the validity of the above damage estimates from flows of approximately 100 cfs generated within the Olympus Cove. Doubtless most of these damages are caused by runoff from source areas above the Olympus Cove, such as Neff's Canyon. In order to present on Figure 26 the relative magnitude of these potential inflows, a procedure for predicting discharge rates from Neff's Canyon is included. For example, the chart indicates that a 25-year storm event will produce a peak runoff rate from Neff's Canyon of 270 cfs at an antecedent soil moisture level of 4 inches (see also Figure 18).

If urban development on the Olympus Cove were to increase to 40 percent, the peak runoff rate from this area corresponding to a storm recurrence interval of 25 years and an antecedent moisture level of 4 inches would be about 100 cfs. For the same conditions the peak runoff rate from the non-urbanized Neff's Canyon drainage would remain unchanged at 270 cfs. Now, however, because development is assumed to have continued both in the Olympus Cove and in the downstream area below Wasatch Boulevard, the damage estimate has increased from $220,000 to $270,000. This increase resulting from development is also shown by the difference between the ordinates of Curves I and IV of Figure 25 at the 4 percent frequency level. Table 8 summarizes the discussion of the preceding paragraphs, and presents some numbers which further illustrate the use of Figure 26.

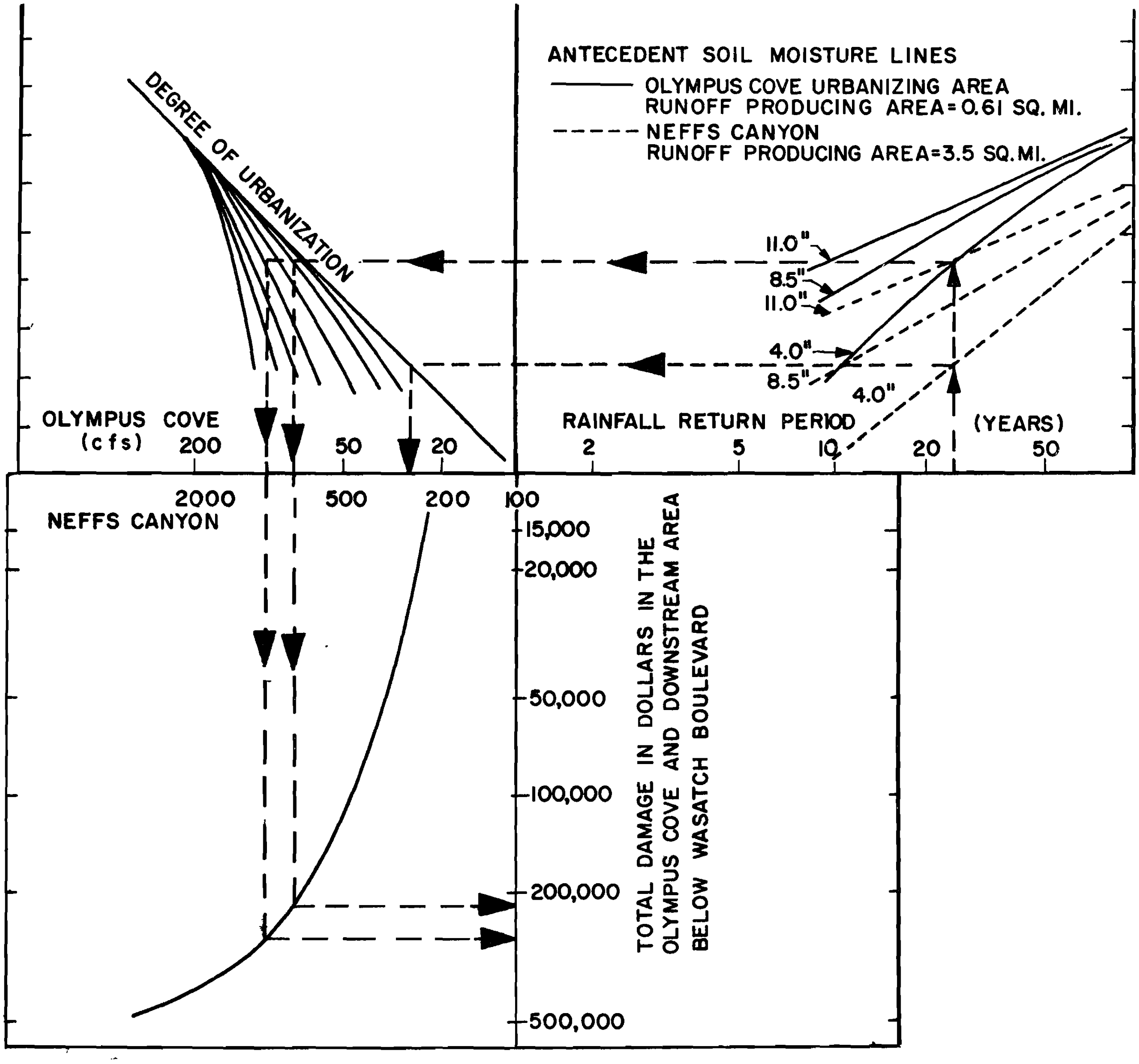


Figure 26. Concurrency chart for predicting peak runoff rates and flood damages for the Olympus Cove and downstream areas.

Table 8. Estimates from Figure 25 of peak runoff rates and associated flood damages for the Olympus Cove and downstream areas resulting from a 25-year storm event.

Antecedent Soil Moisture Level (inches)	Level of Urban Development	Peak Runoff Rate Generated Within Indicated Area (cfs)		Total Peak Runoff Rate (cfs)	Total Damage Estimate $
		Olympus Cove	Neff's Canyon		
4	Present 20% in Olympus Cove area	80	270	350	220,000
	Future 40 % in Olympus Cove area	100	270	370	270,000
8.5	Present 20 % in Olympus Cove area	115	500	615	280,000
	Future 40 % in Olympus Cove area	140	500	640	340,000

CHAPTER V

RECOMMENDATIONS AND SUMMARY

Recommendations for Further Urban Development in Olympus Cove

A number of recommendations are presented in the Kaliser report (1973, pp. 36 and 38), and many of these recommendations are supported by the results of the model studies. The following recommendations for the future development and management of the area are derived largely from the results of the model study. Where appropriate, references are made to the recommendations of the Kaliser (1973) report.

1. A large portion of the flood waters which enter the Olympus Cove and downstream areas originates on the slopes situated above the urbanizing subdivisions of the cove. The problem then is to dispose of these waters in a manner which minimizes flood damages in the area as a whole. Several flood protection possibilities might be considered:

a. *Detention basins.* No suitable sites are available in the Olympus Cove area. Some basins already have been constructed at other locations on the 'east bench,' but the cost is high for collecting the stream waters of Olympus Cove and conveying these to points several miles distant. For this reason, detention basins are not considered to be a very practical solution. However, the computer model could be employed to examine the regulating effects of flood detention basins.

b. *Flood proofing.* This form of protection involves the improvement of drainage channels and the exclusion of dwellings and other permanent structures from flood prone areas. However, because of the present stage of development in the Olympus Cove and downstream areas, this procedure also does not seem practical, but should be examined.

c. *Channel improvements.* Under this method of flood protection street layout and water channels in the Olympus Cove and downstream areas would be designed to convey the waters as quickly as possible through the area. However, this procedure would introduce two other major problems, namely (i) aesthetic considerations, and (ii) the transfer of the flood problem to areas further downstream.

d. *Infiltration zones.* Under present conditions, large portions of the flows which enter Olympus Cove from the mountain drainages enter the ground through infiltration in the southerly, and as yet largely undeveloped, part of the urbanizing area. The possible impact of these infiltration losses on the flood flows is demonstrated by Tables 7 and 8. The maintenance, and even possible enhancement, of the infiltration characteristics of this zone seems to be the most practical flood protection alternative available for the area. Recommendations (6), (7), (14), and (15) of the Kaliser (1973) report refer particularly to this alternative. Kaliser indicates that effective infiltration rates could be enhanced by introducing flood waters into the subsurface soils through wells and recommends this procedure as a practical solution to the floow problem (recommendation 14). As an alternative to injection wells (and possibly in conjunction with them), flow control structures might be considered which would distribute runoff as it entered the upper reaches of the cove from Mt. Olympus. Structures of this nature might not only enhance infiltration of the flood waters, but also reduce surface runoff rates and thus lower erosion potentials.

2. Natural channels within drainage areas above Olympus Cove are well defined and stable. However, because of the steep slopes which prevail, flow velocities from these drainages at points of discharge to the Olympus Cove area (Figure 23) tend to be high, and are estimated at from 3 to 5 feet per second. For this reason, the potential for erosion damage is significant in the urbanizing area of Olympus Cove, and the following protective measures (in addition to infiltration protection and enhancement as discussed above) therefore are suggested:

a. That urban development be prevented on steep slopes. Kaliser (1973) in his first recommendation suggests an upper slope limit for development of 60 percent.

b. That limitations or controls be imposed on the removal of existing native vegetation from slopes and natural drainage courses; and further, that where possible the re-establishment of vegetation on slopes exposed by development be promoted (see recommendations (2), (4), and (5) of Kaliser (1973)).

c. That existing natural drainage courses be maintained carefully, and that all artificial systems be designed and maintained so as to consider potential flood hazards both within the Olympus Cove area itself and at downstream locations which might be affected (see recommendations (3), (8), and (9) of Kaliser (1973)). Natural channels where they exist should not be intercepted or altered by the urbanization process. The design and layout of storm sewers and streets should consider the problem of flood water disposal. If large volumes of surface runoff are collected by paved streets, particularly by those which are steeply sloping, serious erosion problems can result. Streets should be designed to convey waters which they do collect to points of safe disposal. Street designs might include such features as the avoidance of long streets which are normal to the slope direction, adequate gutters, provisions to enable accumulated surface flows to leave the street at frequent points of discharge to either storm sewers or infiltration areas, breaks in the street grade or slope, and 'inverted crowns' (formed by sloping the street surfaces toward the middle) for cases where some channelization of street flows might be desired. Under very high velocity or 'shooting' flow situations there is a tendency for water to leave channels at points of change in the horizontal direction, such as at the corners of steeply sloping streets.

d. That artificial fills and structural foundations be designed to minimize the hazards of potential erosion damage. The design of these structures should recognize that a potential does exist in the area for erosion from surface water flows (see recommendations (10) and (11) of Kaliser (1973)).

3. As a part of the protective measured discussed under both Items (1) and (2) of these recommendations, it is considered that some restrictions should be imposed to limit the future disturbance of natural surface conditions through the urbanization process. Natural conditions are disturbed and altered through the construction of streets,buildings,and landscaped areas. The resulting degree of urbanization usually is expressed as a function of the impervious area covered. As already discussed, however, landscaping and lawn cultivation practices also can materially change infiltration characteristics. For example, in the Olympus Cove area, capacity infiltration rates for the compacted soils of lawns are doubtless less than those which exist under natural conditions. In addition, available soil moisture levels under lawns and other landscaped areas are usually high because of watering practices. Thus, at any given time, soil moisture storage capacities beneath these areas are likely to be low, and the effects of antecedent soil moisture on surface runoff rates within the Olympus Cove are clearly illustrated by Figure 26 and other figures presented by this report. A possible procedure for implementing the restriction suggested by this recommendation would be to impose for future subdivisions a maximum ratio of developed area within each lot (including landscaped area) to total lot size. As indicated by the chart of Figure 26, at an urban development within Olympus Cove of 20 percent or less (expressed in terms of impervious cover) the effects on the runoff characteristics tend to be rather minimal. If it is assumed for illustrative purposes that the effects of landscaping are approximately half those of impervious cover, and that impervious cover would occupy about 10 percent of the total area of a lot, a total development ratio of 30 percent could be adopted while still remaining within the normal definition of 20 percent for degree or urbanization. To ensure adequate spatial distribution of the disturbed areas, it is suggested that a development ratio of this nature normally should be applied on a lot rather than a subdivision or zone basis. In making this recommendation, however, it is recognized that appropriate landscaping, such as sunken lawns, can increase surface storage and infiltration volumes, and thus reduce surface runoff rates and volumes.

4. As indicated by Tables 6 and 7, Neff's Canyon is potentially a major contributor to runoff rates below (or downstream from) the Olympus Cove area. For this reason, it is possible that any downstream effects of urbanization within the cove might be offset by both structural and non-structural measures within the drainage area of Neff's Canyon. Non-structural measures could be cultural practices and land treatment, including contour trenching and bench construction. This possibility would require further investigation, however.

Summary

The results and recommendations of this study are based on the interpretation of very limited data concerning the hydrologic system and runoff characteristics. For example, the application of the hydrologic computer models to the Neff's Canyon drainage on the basis of modeling results obtained from Mill Creek could be subject to much question. The physical characteristics of the two drainage areas are significantly different, and in applying the models an attempt was made to adjust for these differences. However, no gaged flow records were available for Neff's Canyon, and so no checks of the model predictions for this drainage were possible. The results of the study, therefore, will need to be interpreted in the light of these kinds of limitations which were imposed because of the lack of time and funds to obtain additional data from the field.

With reference to the previous paragraph, modeling is a continuous process for which it is difficult to establish a specific end-point. Modifications and improvements are always possible, and the models of this study are no exception. However, it is felt that the fundamental objectives of the study have been reached. Available data have been used to calibrate hydrologic models of Olympus Cove and the 'upstream' source areas on the slopes of Mt. Olympus. These models are able to provide estimates of surface runoff rates under various known and/or assumed hydrologic conditions. Some of these conditions are subject to management changes, others are not. Urbanization is always accompanied by change, and within the scope of this change the hydrologic system must be considered and accommodated. In some cases, this accommodation might involve a basic change in the hydrologic system, such as the construction of lined drainage channels to convey storm runoff quickly and safely from the area being considered. In other cases, the urban development process itself might be adjusted so as to minimize its impacts upon the hydrologic system. Often a combination of these two approaches is used with success.

In this report model output information is presented for three main sources of surface runoff within the Olympus Cove area, namely (1) the Neff's Canyon drainage; (2) seven identifiable source areas above the Olympus Cove on the northern slopes of Mt. Olympus and (3) the urbanizing area of the cove itself. On the basis of information provided by the models, charts and tables were developed which provide estimates of peak surface runoff rates under cloudburst storm events of various frequencies for several conditions of antecedent soil moisture and, where applicable, degrees of urbanization. Damage estimates associated with various peak rates of runoff also are presented, and an attempt is made to summarize much of this information in the form of a single chart (Figure 26).

Some specific items which might be mentioned in summary are as follows:

1. Surface runoff characteristics were found to be most sensitive to (or most influenced by) the magnitude of the runoff producing event as represented by the recurrence interval of the storm, the degree or extent of urbanization on the watershed, and the level of soil moisture (antecedent soil moisture) prevailing on the drainage area at the time of the storm event.

2. The relative influence of antecedent soil moisture on the peak runoff rate from an urban area is inversely proportional to the degree of urbanization. In other words, as the extent of impervious cover increases, soil moisture effects on the runoff characteristics decrease. This trend is indicated by the increasingly steep slopes of the curves associated with degree of urbanization in the upper left portion of Figure 26. Thus, for a particular storm frequency the relative increase in peak runoff rate between an antecedent soil moisture content of, for example, 4 inches and 11 inches, is much more pronounced at a degree of urbanization of 10 percent than is the case at an urbanization level of 70 percent.

3. As indicated by Figure 22, the degree of sensitivity of the hydrologic system to urbanization is inversely proportional to the magnitude of the runoff producing event. Thus, for low frequency events of recurrence interval greater than 25 years, for example, urbanization has relatively little influence on peak runoff rates.

4. From the results of the Neff's Canyon model study (Figure 18), unit surface runoff rates associated with various storm frequencies and antecedent soil moisture levels were developed (see Appendix C, Figure C-1). These unit rates, in turn, were used to predict surface runoff rates from the source areas on the slopes of Mt. Olympus above the urbanizing area of the cove (see Table 6).

5. Although urbanization within the cove influences surface runoff rates of flows generated within this area (Figure 22), because the contributing area is small, the total magnitudes of these flows also tend to be rather small (see Tables 7 and 8, and Figure 26). Thus, much of the flood hazard within the Olympus Cove and areas further downstream lying west of Wasatch Boulevard is associated with potential runoff from the source areas above the cove, including the Neff's Canyon drainage. This situation is illustrated by Table 7 and the discussion which accompanies this table. For this reason, any action within the Olympus Cove urbanizing area which would tend to reduce soil infiltration rates, particularly in the zone adjacent to the points of outflow from the mountain drainages, would increase downstream flood hazards both within the cove and in the area lying west of Wasatch Boulevard. The results of the model calibration indicated that the average maximum infiltration capacity rate for the urbanizing area of Olympus Cove is approximately 1.0 inch per hour (Table 5). Although this average rate is not high, it is likely that the rate is considerably more in the still undeveloped areas lying adjacent to and immediately beneath the mountain drainages. Thus, modifications which would tend to reduce the effectiveness of this infiltration zone might considerably increase normal surface runoff rates at points farther downstream. In this connection, Tables 7 and 8 suggest that the maximum surface runoff rates from

Olympus Cove and adjacent areas might be expected to be approximately 500 to 600 cfs for a 25-year storm event at an antecedent soil moisture level of 8.5 inches. According to the Salt Lake County Flood Control Commission, the capacity of the storm drain beneath Wasatch Boulevard at Mill Creek is about 550 cfs. This capacity is probably adequate to provide drainage of the area for 25-year storm events under fully urbanized conditions in the cove. For storms of lower frequency, more drainage capacity would be needed (Figure 26).

6. Estimated velocities of sheet flows emanating from the source areas above Olympus Cove are significant, and range between 3 and 5 feet per second. At these velocities water flows are capable of causing serious erosion problems.

7. The computer model of the Olympus Cove area is fully operational and is capable of answering many other questions which might not have been discussed by this report. As far as possible, results are presented in graphical form to enable their ready interpretation and extension to a variety of conditions which might be assumed. However, if other information is required, further computer studies are possible. In any case, as demonstrated by this study, the basic structures of the models used are general in nature, so that they are readily applicable to other drainage basins for which similar kinds of information might be required.

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APPENDICES

Appendix A

The Daily Time Increment Model

Program output

The results of a water balance analysis are shown below. These results are described as follows.

Monthly water balance. The identifiers used in the monthly water balance are given below. All units are in inches over the watershed.

Identifier	
PPT	Total monthly precipitation
STM	Total monthly streamflow
TEM	Average monthly temperature
LOSS	Difference between PPT and STM
RN	Precipitation falling as rain
SN	Precipitation falling as snow

Yearly water balance. The identifiers are as used in the monthly water balance. The yearly water balance is obtained by using the monthly values within the water year.

Watershed characteristic data. The monthly values of CP and RAD are given on the output.

Identifier	
CP	Values of the ratio mean monthly evaporation to mean monthly temperature
RAD	Values of the monthly radiation index

The initial parameter values and model output are given on page 52 .

Parameter values. The various parameter values used in the model are given at the top of the printout. The meaning of each identifier is given in Table 4.

Hydrologic data-model output. The identifiers used in the monthly output are given below. All units are in inches over the watershed.

Identifier	
SI	Surface interception
SN	Snow storage
SM	Soil moisture storage
GW	Groundwater storage
PE	Potential evapotranspiration
AV	Actual evapotranspiration
SO	Subsurface outflow
SR	Surface runoff
IF	Interflow
BF	Base flow
RF	Surface runoff
ER	Error function
AE	Absolute error (objective function)
VR	Variance

```
MONTHLY WATER BALANCE
  10 PPT 2.42 STM   .26 TEM 45.19 LOSS  2.15 RN  2.34 SN   .07
  11 PPT 3.00 STM   .25 TEM 30.26 LOSS  2.74 RN   .71 SN  2.28
  12 PPT 1.43 STM   .20 TEM 21.19 LOSS  1.22 RN   .00 SN  1.43
   1 PPT 5.07 STM   .17 TEM 15.83 LOSS  4.89 RN   .00 SN  5.07
   2 PPT 2.35 STM   .17 TEM 14.31 LOSS  2.17 RN   .00 SN  2.34
   3 PPT 5.38 STM   .17 TEM 19.48 LOSS  5.20 RN   .00 SN  5.38
   4 PPT 7.53 STM   .23 TEM 32.86 LOSS  7.29 RN  3.02 SN  4.50
   5 PPT 4.55 STM  1.20 TEM 41.93 LOSS  3.34 RN  2.86 SN  1.68
   6 PPT 2.02 STM  1.82 TEM 46.76 LOSS   .19 RN  1.99 SN   .03
   7 PPT 1.29 STM   .75 TEM 61.61 LOSS   .53 RN  1.29 SN   .00
   8 PPT  .25 STM   .56 TEM 56.93 LOSS  -.31 RN   .25 SN   .00
   9 PPT 3.55 STM   .46 TEM 49.90 LOSS  3.08 RN  3.55 SN   .00
YEARLY WATER BALANCE
1964 PPT38.83 STM  6.29 TEM 36.35 LOSS 32.54 RN 16.03 SN 22.80
WATERSHED CHARACTERISTIC DATA
    1.00      .00
 CP .08211.04430.02702.02744.04120.08002.11458.13376.14483.15726.14600.114
 RAD   .40  .31  .27  .29  .37  .46  .54  .58  .60  .59  .56  .49
```

```
 SIO= .00 SNIC=  .00 SMOIC= .71 GWIC= 2.00 SFW=  .00 TAUSW=  .30 NYR= 5
 ETF= .450 SI= .35 ROS= .010 SMR= .080 FO=2.00 FC=2.00 KNTR=0 KTRL=3
 CPF= .00 PMV= .00 GLL=4.80 GUL=  .0 GMM= .00SNGM= .02000 TFWSN= .1000
 SS=12.80 SFC= 6.020 WILT= 1.00 QK= .20 TGW=  .03 TBF=  .00 TRAIN=34.0
HYDROLOGIC DATA--MODEL OUTPUT
10
SI  1.43  SN    .03  SM  1.40  GW  1.76  EP  1.66  AV  1.48            .00
SR   .00  IF    .00  BF   .23  RF   .23  ER   .02  AE   .02  VR         .00
11
SI   .41  SN   1.21  SM  2.80  GW  1.56  EP   .60  AV   .60             .00
SR   .00  IF    .00  BF   .19  RF   .20  ER   .05  AE   .05  VR         .00
12
SI   .00  SN   1.77  SM  3.42  GW  1.38  EP   .25  AV   .25             .00
SR   .00  IF    .00  BF   .18  RF   .18  ER   .02  AE   .02  VR         .00
 1-1964
SI   .02  SN   6.02  SM  4.04  GW  1.22  EP   .19  AV   .19             .00
SR   .00  IF    .00  BF   .16  RF   .16  ER   .01  AE   .01  VR         .00
 2
SI   .00  SN   7.53  SM  4.62  GW  1.08  EP   .26  AV   .26             .00
SR   .00  IF    .00  BF   .13  RF   .13  ER   .04  AE   .04  VR         .00
 3
SI   .00  SN  11.59  SM  5.24  GW   .96  EP   .70  AV   .70             .00
SR   .00  IF    .00  BF   .12  RF   .12  ER   .04  AE   .04  VR         .00
 4
SI  1.56  SN  15.55  SM  6.76  GW  1.04  EP  1.69  AV  1.69            .00
SR   .00  IF    .04  BF   .11  RF   .17  ER   .06  AE   .06  VR         .00
 5
SI  2.06  SN   7.99  SM 13.11  GW  3.31  EP  2.52  AV  2.52            .00
SR   .00  IF    .62  BF   .21  RF   .84  ER   .35  AE   .35  VR         .01
 6
SI  1.76  SN    .00  SM 12.61  GW  4.80  EP  3.04  AV  3.04  SO       4.08
SR   .00  IF   1.53  BF   .57  RF  2.11  ER  -.28  AE   .60  VR         .01
 7
SI   .69  SN    .00  SM  6.59  GW  4.79  EP  4.36  AV  4.36  SO       1.75
SR   .00  IF    .58  BF   .60  RF  1.19  ER  -.43  AE   .43  VR         .01
 8
SI   .24  SN    .00  SM  3.07  GW  4.25  EP  3.74  AV  3.74            .00
SR   .00  IF    .01  BF   .56  RF   .56  ER  -.01  AE   .02  VR         .00
 9
SI  1.71  SN    .00  SM  3.83  GW  3.77  EP  2.57  AV  2.57            .00
SR   .00  IF    .00  BF   .48  RF   .48  ER  -.02  AE   .02  VR         .00
ANNUAL RF  6.43  ER  -.13  AE  1.71  VR       .02  PE 21.64  SI 10.03
     SUBSURFACE OUT.   5.84                        AV 21.46
```

```
          PAR          PH          PL          DF          NL


           1          .120        .020        .100         5
           2         7.000       4.500       2.500         5
           3          .300        .050        .250         3
           4          .020        .006        .013         1
           5          .005        .003        .002         3
           6        36.000      32.001       3.999         4
           7          .060        .010        .050         5
           8          .500        .200        .300         1
           9         6.000       4.000       2.000         4
          10          .650        .350        .299         3
          11          .500        .200        .300         3
          12          .180        .055        .124         1
```

Output from subroutine OPTVER

The identifiers used on the first page of output from OPTVER (above) are described below.

Identifier	
PAR	The parameter number
PH	The highest value assigned to the parameter
PL	The lowest value assigned to the parameter
DF	The difference between PH and PL
NL	The number of levels

```
                    PHASE  1  PMIN=      1.7117
 .080  6.000   .200   .010   .004 34.000   .030   .300  4.800   .450
 .350   .100
```

```
IP  LV    PAR          OBJ
 1   1       .020     3.7220
 1   2       .040     2.7875
 1   3       .060     2.1343
 1   4       .080     1.7117
 1   5       .100     1.3067
 1   6       .120     1.0772
 2   1      4.500     1.2876
 2   2      5.000     1.2076
 2   3      5.500     1.1419
 2   4      6.000     1.0772
 2   5      6.500     1.0430
 2   6      7.300     1.0859
 3   1       .050     1.9771
 3   2       .133     1.0084
 3   3       .216     1.1592
 3   4       .300     2.1541
 5   1       .003     1.5212
 5   2       .003     1.0464
 5   3       .004     1.0650
 5   4       .305     1.3981
 6   1     32.001     1.0426
 6   2     33.000     1.0036
 6   3     34.000     1.0552
 6   4     35.000     1.2076
 6   5     36.000     1.3352
 7   1       .010     2.2726
 7   2       .020     1.3721
 7   3       .030     1.0036
 7   4       .040      .9281
 7   5       .050     1.0649
 7   6       .060     1.2481
 9   1      4.000     1.2371
 9   2      4.500     1.0304
 9   3      5.000      .8875
 9   4      5.500      .8826
 9   5      6.000      .9779
10   1       .350      .9728
10   2       .450      .8828
10   3       .550      .9884
10   4       .650     1.1614
11   1       .200      .9557
11   2       .300      .9026
11   3       .400      .8666
11   4       .500      .8508
```

Printout of Phase 2. The printout of Phase 2 of the optimization process is given on page 54. The parameter values that gave the minimum objective function (PMIN) in the first phase are shown at the top of the printout. The identifiers used in the tabulation are as follows.

Identifier	
IP	The parameter number
LV	The level within the parameter optimization range
PAR	The parameter value at each level
OBJ	The value of the objective function corresponding to each level

As an illustration, the optimum value of parameter 2 (SFC) is 6.5 ins, that is at level 5 within the optimization range; the value of the objective function at this level is 0.8508.

```
                  PHASE  2  PMIN=      .8508
  .120  6.500   .133   .010   .003 33.000   .040   .300  5.500   .450
  .500   .100


IP  LV    PAR            OBJ
 1   1        .020       3.3808
 1   2        .040       2.5308
 1   3        .060       1.8393
 1   4        .080       1.3769
 1   5        .100        .9786
 1   6        .120        .8508
 2   1       4.500       1.0147
 2   2       5.000        .9692
 2   3       5.500        .9186
 2   4       6.000        .8713
 2   5       6.500        .8508
 2   6       7.000        .8681
 3   1        .050       1.8221
 3   2        .133        .8508
 3   3        .216       1.4593
 3   4        .300       2.6668
 5   1        .003       1.2034
 5   2        .003        .8508
 5   3        .004       1.0188
 5   4        .005       1.4391
 6   1      32.001        .9483
 6   2      33.000        .8508
 6   3      34.000        .9677
 6   4      35.000       1.1637
 6   5      36.000       1.3299
 7   1        .010       2.5310
 7   2        .020       1.5829
 7   3        .030       1.0655
 7   4        .040        .8508
 7   5        .050        .8613
 7   6        .060        .9862
 9   1       4.000       1.1674
 9   2       4.500        .9706
 9   3       5.000        .8381
 9   4       5.500        .8508
 9   5       6.000        .9643
10   1        .350        .8748
10   2        .450        .8381
10   3        .550       1.0436
10   4        .650       1.3087
11   1        .200        .9791
11   2        .300        .9128
11   3        .400        .8651
11   4        .500        .8381
```

Output following the optimization process

The optimum parameter values for each phase are shown at the top of page 56. Beneath this the model output at monthly intervals is given, this time using parameter values established in the optimization process.

After optimum values of the parameters had been derived for each year on record, the final parameter values were arrived at. These values are given at the top of the table below. The model output at monthly intervals using these finalized parameter values is also shown by this table.

Daily output in CFS. Final output from the model is given on a daily basis; a listing for the water year 1964 is shown beginning on pages 57 and 58. The identifiers used are given below.

Identifier	
TCPQ	The daily precipitation, expressed in cubic feet per second over the watershed
OBSR	The daily observed streamflow
COMP	The daily computed streamflow

Sample hydrographs

Mill Creek. Sample hydrographs of observed and computed streamflow for Subwatersheds 1 and 2 (upper and lower, respectively) of Mill Creek are given on pages 59 through 62.

Neff's Canyon. Sample computed hydrographs for Neff's Canyon are given on pages 63 and 64.

```
 SIO= .00 SNIC=  .00 SMOIC= .71 GWIC= 2.00 SFW=  .00 TAUSW=  .30 NYR= 5
 ETF= .590 SI= .40 ROS= .010 SMR= .110 FO=2.00 FC=2.00 KNTR=2 KTRL=2
 CPF= .00 PMV= .00 GLL=4.80 GUL=  .0 GMM= .00SNGM= .02000 TFWSN= .1000
 SS=12.80 SFC= 6.000 WILT= 1.00 QK= .15 TGW=  .04 TBF= 0.004TRAIN=35.0
HYDROLOGIC DATA--MODEL OUTPUT
10
SI  1.61   SN    .03   SM   1.09   GW   1.76   EP   2.18   AV   1.88             .00
SR   .00   IF    .00   BF    .23   RF    .23   ER    .02   AE    .02   VR        .00
11
SI   .58   SN   1.11   SM   2.32   GW   1.56   EP    .79   AV    .79             .00
SR   .00   IF    .00   BF    .19   RF    .20   ER    .05   AE    .05   VR        .00
12
SI   .00   SN   1.58   SM   2.94   GW   1.38   EP    .33   AV    .33             .00
SR   .00   IF    .00   BF    .18   RF    .18   ER    .02   AE    .02   VR        .00
 1-1964
SI   .00   SN   5.76   SM   3.56   GW   1.22   EP    .25   AV    .25             .00
SR   .00   IF    .00   BF    .16   RF    .16   ER    .01   AE    .01   VR        .00
 2
SI   .00   SN   7.20   SM   4.14   GW   1.08   EP    .34   AV    .34             .00
SR   .00   IF    .00   BF    .13   RF    .13   ER    .04   AE    .04   VR        .00
 3
SI   .00   SN  11.04   SM   4.76   GW    .96   EP    .91   AV    .91             .00
SR   .00   IF    .00   BF    .12   RF    .12   ER    .04   AE    .04   VR        .00
 4
SI  2.05   SN  14.95   SM   6.08   GW    .86   EP   2.22   AV   2.22             .00
SR   .00   IF    .00   BF    .10   RF    .11   ER    .11   AE    .11   VR        .00
 5
SI  2.36   SN   4.27   SM  13.66   GW   4.25   EP   3.30   AV   3.30             .00
SR   .00   IF    .63   BF    .21   RF    .86   ER    .33   AE    .35   VR        .01
 6
SI  1.89   SN    .00   SM   8.67   GW   4.80   EP   3.99   AV   3.99   SO       5.16
SR   .00   IF   1.11   BF    .59   RF   1.71   ER    .10   AE    .22   VR        .00
 7
SI   .74   SN    .00   SM   3.64   GW   4.43   EP   5.71   AV   5.71   SO        .28
SR   .00   IF    .09   BF    .58   RF    .67   ER    .08   AE    .08   VR        .00
 8
SI   .24   SN    .00   SM    .11   GW   3.92   EP   4.90   AV   3.77             .00
SR   .00   IF    .00   BF    .51   RF    .51   ER    .04   AE    .04   VR        .00
 9
SI  1.86   SN    .00   SM   1.21   GW   3.47   EP   3.38   AV   2.24             .00
SR   .00   IF    .00   BF    .44   RF    .45   ER    .01   AE    .01   VR        .00
ANNUAL RF   5.39  ER   .90  AE   1.04  VR        .01   PE  28.37   SI  11.39
      SUBSURFACE OUT.   5.45                           AV  25.80
```

```
                                  INITIAL VECTORS

                 PHASE        1          2          3          4          5

                  OBJ      1.7117      .8508      .8381
                  PAR

                   1         .080       .120       .120
                   2        6.000      6.500      6.500
                   3         .200       .133       .133
                   4         .010       .010       .010
                   5         .004       .003       .003
                   6       34.000     33.000     33.000
                   7         .030       .040       .040
                   8         .300       .300       .300
                   9        4.800      5.500      5.000
                  10         .450       .450       .450
                  11         .350       .500       .500
                  12         .100       .100       .100
10
SI   1.58   SN    .03   SM  1.25   GW  1.77   EP  1.67   AV  1.48               .00
SR    .00   IF    .00   BF   .22   RF   .23   ER   .03   AE   .03   VR          .00
11
SI    .44   SN   1.18   SM  2.65   GW  1.58   EP   .60   AV   .60               .00
SR    .00   IF    .00   BF   .19   RF   .19   ER   .05   AE   .05   VR          .00
12
SI    .00   SN   1.92   SM  3.27   GW  1.40   EP   .25   AV   .25               .00
SR    .00   IF    .00   BF   .17   RF   .17   ER   .02   AE   .02   VR          .00
 1-1964
SI    .04   SN   6.17   SM  3.89   GW  1.24   EP   .19   AV   .19               .00
SR    .00   IF    .00   BF   .15   RF   .15   ER   .01   AE   .01   VR          .00
 2
SI    .00   SN   7.68   SM  4.47   GW  1.11   EP   .26   AV   .26               .00
SR    .00   IF    .00   BF   .13   RF   .13   ER   .04   AE   .04   VR          .00
 3
SI    .00   SN  11.73   SM  5.09   GW   .99   EP   .70   AV   .70               .00
SR    .00   IF    .00   BF   .12   RF   .12   ER   .04   AE   .04   VR          .00
 4
SI   1.94   SN  14.15   SM  7.74   GW  1.31   EP  1.69   AV  1.69               .00
SR    .00   IF    .06   BF   .11   RF   .19   ER   .04   AE   .06   VR          .00
 5
SI   2.26   SN   2.06   SM 15.84   GW  5.00   EP  2.52   AV  2.52              1.07
SR    .00   IF    .78   BF   .33   RF  1.12   ER   .07   AE   .17   VR          .00
 6
SI   1.91   SN    .00   SM  9.56   GW  5.00   EP  3.05   AV  3.05              6.05
SR    .00   IF   1.02   BF   .59   RF  1.63   ER   .19   AE   .26   VR          .00
 7
SI    .84   SN    .00   SM  5.43   GW  4.79   EP  4.36   AV  4.36               .51
SR    .00   IF    .14   BF   .59   RF   .73   ER   .02   AE   .05   VR          .00
 8
SI    .24   SN    .00   SM  1.94   GW  4.26   EP  3.74   AV  3.74               .00
SR    .00   IF    .00   BF   .53   RF   .53   ER   .02   AE   .03   VR          .00
 9
SI   2.16   SN    .00   SM  2.54   GW  3.79   EP  2.58   AV  2.58               .00
SR    .00   IF    .00   BF   .46   RF   .47   ER  -.01   AE   .01   VR          .00
ANNUAL RF  5.72  ER   .57  AE   .83  VR       .01  PE 21.65  SI 11.46
     SUBSURFACE OUT.   7.65                        AV 21.47
```

```
DAILY OUTPUT IN CFS

10
TPCQ          .0    .0    .0    .0  60.2  30.1    .0    .0    .0    .0    .0
OBSR       3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200
COMP       3.005 2.993 2.981 2.969 3.004 3.003 2.977 2.954 2.934 2.916 2.900
TPCQ        45.1 342.5    .0    .0    .0    .0  41.4  18.8 150.5  22.5    .0
OBSR       3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200
COMP       2.920 3.163 3.074 3.005 2.952 2.909 2.906 2.884 2.967 2.926 2.876
TPCQ        90.3   3.7    .0    .0    .0    .0    .0  94.1  11.2
OBSR       3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200
COMP       2.906 2.857 2.816 2.783 2.755 2.732 2.712 2.756 2.724
11
TPCQ          .0   7.5  94.1 109.1  48.9 173.1  75.2    .0   3.7    .0    .0
OBSR       3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200
COMP       2.698 2.681 2.710 2.679 2.673 2.737 2.691 2.655 2.629 2.603 2.582
TPCQ          .0    .0    .0  56.4 357.6   3.7    .0    .0    .0 131.7    .0
OBSR       3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200
COMP       2.564 2.547 2.533 2.563 2.539 2.519 2.502 2.486 2.472 2.459 2.447
TPCQ          .0  67.7    .0    .0    .0    .0    .0    .0
OBSR       3.200 3.200 3.200 3.200 3.200 3.200 3.200 3.200
COMP       2.436 2.425 2.414 2.404 2.394 2.384 2.374 2.364
12
TPCQ          .0    .0    .0    .0   3.7   3.7    .0  67.7  41.4  33.8  11.2
OBSR       2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500
COMP       2.355 2.345 2.336 2.326 2.317 2.308 2.298 2.289 2.280 2.271 2.262
TPCQ         7.5  26.3  60.2  22.5    .0    .0    .0    .0  15.0  71.5   3.7
OBSR       2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500
COMP       2.253 2.244 2.235 2.226 2.217 2.208 2.199 2.191 2.182 2.173 2.164
TPCQ          .0    .0    .0    .0   7.5  30.1 131.7    .0    .0
OBSR       2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500
COMP       2.155 2.147 2.139 2.130 2.122 2.113 2.105 2.096 2.088
 1
TPCQ          .0  48.9   3.7   3.7   7.5  26.3 259.7   3.7    .0  82.8   7.5
OBSR       2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100
COMP       2.080 2.071 2.063 2.055 2.047 2.038 2.030 2.022 2.014 2.006 1.998
TPCQ          .0    .0    .0    .0    .0  37.6 158.1 105.4   3.7 188.2 530.7
OBSR       2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100
COMP       1.990 1.982 1.974 1.966 1.958 1.951 1.943 1.935 1.927 1.920 1.912
TPCQ       376.4  26.3   7.5    .0    .0    .0    .0  30.1    .0
OBSR       2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100
COMP       1.904 1.897 1.889 1.882 1.874 1.867 1.859 1.852 1.844
 2
TPCQ         3.7   7.5    .0   3.7  45.1  18.8   3.7   3.7   3.7   3.7  37.6
OBSR       2.300 2.300 2.300 2.300 2.300 2.300 2.300 2.300 2.300 2.300 2.300
COMP       1.837 1.830 1.822 1.815 1.808 1.801 1.793 1.786 1.779 1.773 1.765
TPCQ        33.8  33.8  11.2   3.7  82.8  30.1  11.2 207.0  45.1  11.2  30.1
OBSR       2.300 2.300 2.300 2.300 2.300 2.300 2.300 2.300 2.300 2.300 2.300
COMP       1.758 1.751 1.744 1.737 1.730 1.723 1.716 1.709 1.703 1.696 1.689
TPCQ        11.2 116.6 109.1   3.7   3.7   3.7   3.7
OBSR       2.300 2.300 2.300 2.300 2.300 2.300 2.300
COMP       1.682 1.676 1.669 1.662 1.656 1.649 1.642
 3
TPCQ        18.8 248.4  26.3  18.8 176.9 207.0    .0    .0  67.7 139.2    .0
OBSR       2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100
COMP       1.636 1.629 1.623 1.616 1.610 1.603 1.597 1.591 1.584 1.578 1.572
TPCQ       222.1 105.4   3.7  48.9    .0    .0  18.8  45.1    .0    .0 233.3
OBSR       2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100
COMP       1.565 1.559 1.553 1.547 1.541 1.534 1.528 1.522 1.516 1.510 1.504
TPCQ        75.2  41.4  82.8 112.9 131.7    .0    .0    .0    .0
OBSR       2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100 2.100
COMP       1.498 1.492 1.486 1.480 1.474 1.468 1.462 1.457 1.451
```

```
 4
TPCQ      195.7  86.5   7.5    .0 225.8  11.2  37.6    .0    .0 534.5    .0
OBSR      2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500 2.500
COMP      1.597 1.563 1.525 1.496 1.560 1.519 1.487 1.461 1.441 1.702 1.616
TPCQ      173.1    .0    .0    .0    .0    .0  71.5 203.2 150.5  52.7  26.3
OBSR      2.500 2.500 2.500 2.500 3.300 3.200 3.200 3.200 3.200 3.200 3.200
COMP      1.552 1.502 1.464 1.435 1.412 1.393 1.433 1.459 1.483 1.454 1.417
TPCQ         .0 395.2  82.8 466.7 105.4    .0   3.7   3.7
OBSR      3.300 3.500 3.500 3.500 3.600 3.800 4.200 4.500
COMP      1.389 1.469 1.425 1.418 1.504 1.510 1.526 1.547
 5
TPCQ       30.1 248.4  41.4   3.7 225.8  79.0  22.5 199.5  60.2  94.1  63.9
OBSR      4.600 4.600 4.500 4.300 4.300 4.200 4.100 4.200 4.100 4.300 4.800
COMP      2.028 2.040 2.055 2.074 2.182 2.182 2.191 2.305 2.323 2.386 2.415
TPCQ        3.7   7.5   3.7  22.5   3.7   3.7   3.7   3.7   3.7   3.7  60.2
OBSR      5.400 7.000 8.90010.00012.00014.00016.00016.00016.00018.00021.000
COMP      2.727 3.702 4.941 6.273 7.696 9.10410.30711.65313.20214.79616.214
TPCQ      210.8  22.5  18.8  11.2  37.6  26.3 127.9  56.4  11.2
OBSR     25.00028.00032.00032.00034.00032.00030.00025.00022.000
COMP     17.94419.07520.65722.18423.43824.25024.13324.09724.267
 6
TPCQ         .0  11.2   3.7    .0  26.3   7.5  97.8  22.5  11.2    .0  11.2
OBSR     22.00023.00030.00034.00034.00038.00040.00032.00026.00022.00021.000
COMP     24.74925.53626.40827.02127.74728.57628.42927.59126.69825.61324.664
TPCQ       22.5  45.1   3.7  15.0    .0  11.2  60.2  60.2  15.0 184.4  26.3
OBSR     21.00021.00021.00020.00020.00022.00021.00020.00018.00021.00020.000
COMP     23.81823.17022.23721.38820.75620.21919.74919.28918.78618.65718.184
TPCQ        3.7  46.9  67.7   3.7    .0    .0    .0    .0
OBSR     19.00019.00018.00018.00018.00017.00016.00015.000
COMP     17.71817.31516.94216.37815.61214.92214.21913.553
 7
TPCQ        3.7   3.7   3.7   3.7   3.7   3.7   3.7   3.7   7.5   3.7   3.7
OBSR     14.00014.00013.00013.00012.00012.00011.00011.00010.00010.000 9.800
COMP     12.92912.33111.75811.18010.66710.173 9.659 9.172 8.696 8.274 7.828
TPCQ        3.7   3.7   3.7 353.8   3.7   3.7   3.7   3.7   7.5   3.7   3.7
OBSR      9.100 8.600 8.600 9.100 8.200 8.200 7.800 7.000 7.000 7.000 7.000
COMP      7.391 7.179 7.150 7.981 7.871 7.478 7.177 7.121 7.074 7.030 6.989
TPCQ        3.7   3.7   3.7   3.7   3.7   3.7   3.7    .0  18.8
OBSR      7.000 7.000 7.000 7.400 7.400 7.800 8.200 8.200 7.800
COMP      6.953 6.918 6.886 6.855 6.825 6.796 6.767 6.736 6.721
 8
TPCQ         .0    .0    .0   3.7   3.7    .0    .0    .0    .0    .0    .0
OBSR      7.800 7.800 7.800 7.800 7.800 7.800 7.800 7.400 7.000 6.400 6.400
COMP      6.688 6.657 6.627 6.601 6.575 6.546 6.518 6.491 6.464 6.437 6.411
TPCQ         .0    .0    .0  15.0  33.8    .0    .0  11.2    .0    .0    .0
OBSR      6.400 6.100 6.100 6.400 6.400 6.400 6.400 6.700 6.700 6.700 6.700
COMP      6.385 6.359 6.333 6.320 6.318 6.284 6.252 6.231 6.200 6.171 6.143
TPCQ         .0    .0    .0    .0    .0  11.2    .0   7.5   7.5
OBSR      6.700 6.700 6.400 6.400 6.700 6.700 6.400 6.400 6.400
COMP      6.116 6.090 6.064 6.039 6.014 5.998 5.972 5.952 5.931
 9
TPCQ        7.5   7.5   7.5   7.5   7.5   7.5   7.5 229.6   7.5   7.5   7.5
OBSR      6.400 6.400 6.400 6.400 6.400 6.100 6.100 6.100 6.100 5.800 5.800
COMP      5.909 5.887 5.865 5.843 5.820 5.797 5.775 5.925 5.857 5.801 5.754
TPCQ        7.5   7.5   7.5 406.5   7.5   7.5  52.7   7.5   7.5   7.5   7.5
OBSR      5.800 5.800 5.800 5.600 5.600 5.600 5.600 5.600 5.600 5.600 5.600
COMP      5.714 5.678 5.645 5.926 5.818 5.732 5.698 5.632 5.577 5.531 5.492
TPCQ        7.5   7.5   7.5   7.5   7.5   7.5 447.9  11.2
OBSR      5.600 5.600 5.600 5.600 5.600 5.600 5.600 5.600
COMP      5.457 5.426 5.397 5.370 5.345 5.321 5.640 5.531
```

```
      GWR=(1.-QK)*OSW
      OSW=OSW*QK
      GWIC=GWIC+GWR
      SUMNR=SUMNR+OSW
C
   83 CONTINUE
   85 RUNOFF=(SRO+OSW+CHPF)
      SUM=SUM+RUNOFF
      COMP(I)=RUNOFF*XXCF

      WRITE(6,40)PPT,SIA,FT,SMOIC,SRO,OSW,BF,RUNOFF,I
  120 CONTINUE

C
   40 FORMAT(1H0,2HPT,F4.2,2X,2HSI,F3.2,2X,2HFT,F4.2,2X,2HSM,F6.2,2X,2HS
     1R,F4.2,2X,2HIF,F4.3,2X,2HBF,F5.2,2X,2HRF,F4.2,6X,I2)
  106 WRITE(KW,102)SUMPT,SUMSI,SMOIC,SUMSRO,SUMNR,SUM,ERSUM,ABE,I
  102 FORMAT(////1X,3HTPT,F5.2,2X,2HSI,F4.2,2X,2HSM,F6.2,2X,2HSR,F5.2,2X
     1,2HIF,F5.2,2X,2HRF,F6.2,2X,2HER,F6.4,2X,2HAE,F6.4,2X,I2)
      WRITE(6,42)GWIC
   42 FORMAT(1H0,32HINFLOW INTO GROUNDWATER STORAGE ,F4.2)
      IF(KNTR.EQ.1)GO TO 199
      CALL OUT
   43 CONTINUE
      OBJ=ABE
  199 RETURN
      END
```

```
PAGE  1      C
      SUBROUTINE GRAPH
C
      COMMON/BLK1/CP(12),PRCP(48),BFA(48)
     1/BLK2/STRM(48),NPPT,NSTRM,INDEX
     2/BLK3/COMP(48),XXCF,DURB,P,ENIC,SMIC
     3/BLK4/KTRL,KNTR,OBJ,NYR,MYR
     4/BLK5/SIO,SMOIC,GWIC,SFW,TAUSW,SI,FO,SS,SFC,TGW,QK,FC,KK,KR,KW,CPF
      DATA JJ,XSCALE,YSCALE,XREF,YREF,XP,YN,XVAL,XN,YVAL,YP/0,1.,1.,0.,0
     1.,19.,0.,0.,0., 0.0,10./
      DATA ISP,ISLSH/1H ,1H//
      CALL PLTSET(XSCALE,YSCALE,XREF,YREF,XVAL,YVAL,XP,YP,XN,YN)
      CALL SBYSET
      PAUSE 10100
C     COMPUTED STREAMFLOW PLOTTING
  241 JJ=0
      CALL PENDN
      YY=COMP(1)
      Y=YY*0.03
      X=0.0
      CALL PLOT(X,Y)
      DO 245 I=1,NSTRM
      JJ=JJ+1
      X=FLOAT(JJ)*(.25)
      YY=COMP(I)
      Y=YY*0.03
      CALL PLOT(X,Y)
  245 CONTINUE
      CALL PENUP
  250 CONTINUE
      X=0.
      Y=10.
      CALL INPLOT (X,Y)
      JJ=0
      YP=0.
      YVAL=0.
      YN=-10.
      CALL PLTSET(XSCALE,YSCALE,XREF,YREF,XVAL,YVAL,XP,YP,XN,YN)
      CALL SBYSET
   10 CONTINUE
      PAUSE 1100
C     PRECIP PLOTTING
      CALL PENDN
      DO 225 I=1,NPPT
      JJ=JJ+1
      X=FLOAT(JJ)*(.25)
      YY=PRCP(I)
      Y=-YY*2.0
      X=X-.25
      CALL INPLOT(X,Y)
      X=X+.25
      CALL INPLOT(X,Y)
  225 CONTINUE
      CALL PENUP
      X=0.
      Y=-10.
      CALL INPLOT(X,Y)
      JJ=0
      YVAL=00.0
      YP=10.
      YN=0.
      RETURN
      END
```

Appendix C

Calculation of Depth and Velocity of Flood Flows from Neff's Canyon

Procedure

The depth and velocity of flood flows from areas above Olympus Cove may be calculated as described below. Graphed solutions of Manning's equation (Chow, 1964, p. 21-54) are utilized.

1. Determine the area (A) in square miles of the watershed contributing to the flood runoff.
2. From the table given in Figure C-1 (derived from Figure 18) determine the peak runoff from an area of one square mile (q_u) for the appropriate antecedent soil moisture level and storm recurrence interval.
3. Calculate the actual peak runoff rate (Q):

   $$Q = q_u \cdot A \quad \ldots\ldots\ldots \quad \text{(C-1)}$$

4. From Chow (1964, Figure 21-17) derive the value of V·r is equal to V d for sheet flow).

   The degree of vegetal retardance and the value of Manning's n for the "brush" hillsides above Olympus Cove are taken as C and 0.080 respectively.

5. If d is the depth of the flood wave, W the width of the wave front, and V the mean velocity (Figure C-1) then:

   $$Q = L\cdot(V\cdot d) \quad \ldots\ldots\ldots\ldots \quad \text{(C-2)}$$

   $$\text{and} \quad L = Q/(V\cdot d) \quad \ldots\ldots\ldots\ldots \quad \text{(C-3)}$$

6. Using the curve for solution of Manning's equation for a C degree of retardance (Chow, 1964, Figure 21-20), read off the value of mean velocity V and depth of flow d (equal to r on the curve when sheet flow occurs).

Example

What is the depth and mean velocity of sheet flow from Neffs Canyon resulting from a "100-year storm" with an antecedent soil moisture level of 8.5 inches and a contributing area of 3.5 square miles?

Figures C-2 shows the likely extent of flooding from this storm. Suppose the depth and velocity of flow are required along line AA, where the ground slope is 20%.

1. From the table in Figure C-1, $q_u = 354$ cfs
2. Then from Equation C-1:

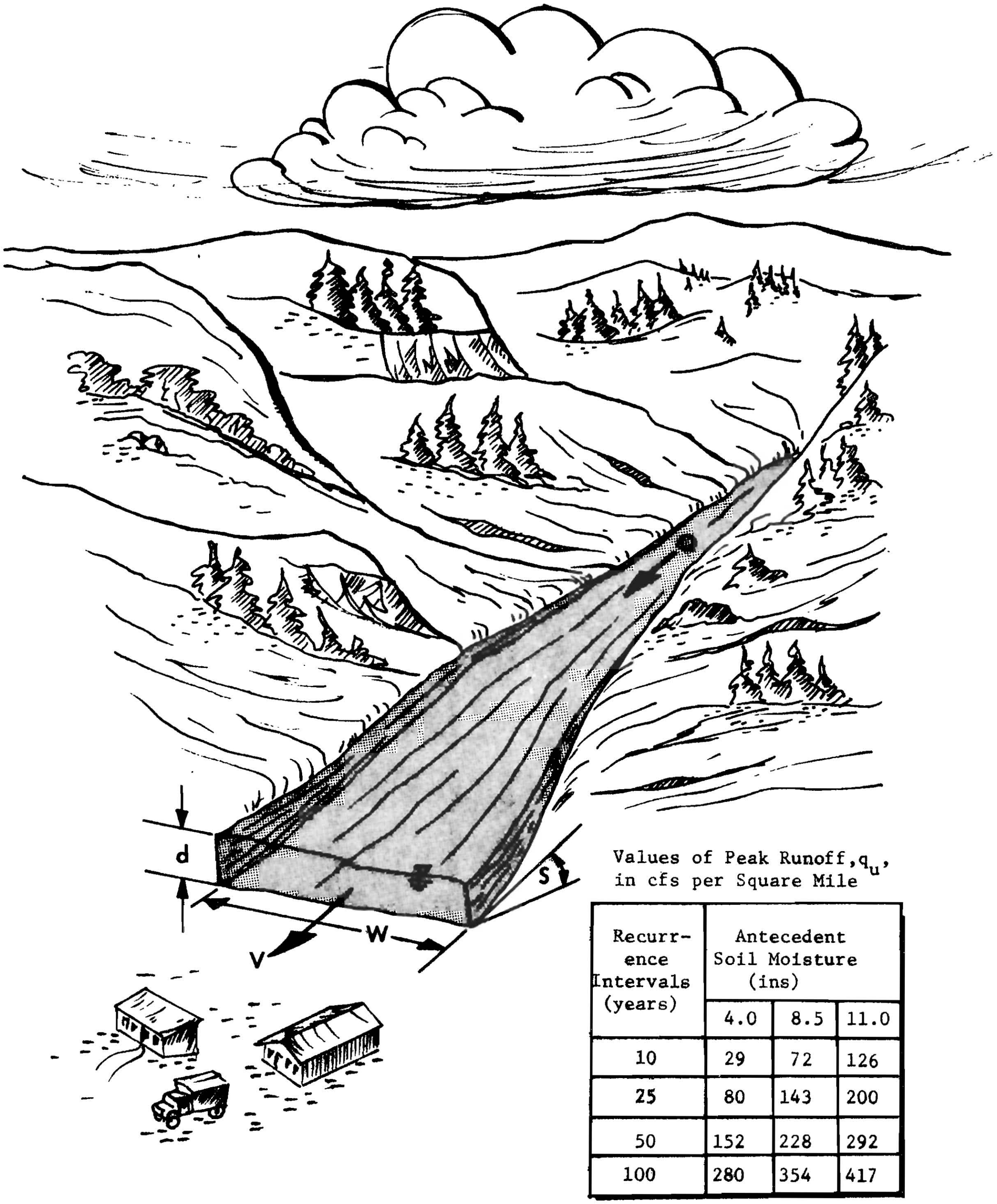
   $$Q = 354\ (3.5) = 1{,}240 \text{ cfs}$$

3. From Chow (1964, Figure 21-17) the value of $V \cdot d$ is 1.2
4. Then from Equation C-3, the width of the flood wave

   $$W = 1240/1.2 = 1030 \text{ feet}$$

5. From Chow (1964, Figure 21-20) with retardance C, and n = 0.080, and a 20 percent slope, the depth and mean velocity of flow are, respectively:

   $$V = 4.0 \text{ fps, and } d = 0.3 \text{ ft}$$



Values of Peak Runoff, q_u, in cfs per Square Mile

Recurrence Intervals (years)	Antecedent Soil Moisture (ins)		
	4.0	8.5	11.0
10	29	72	126
25	80	143	200
50	152	228	292
100	280	354	417

Figure C-1. Parameters used in the calculation of depth and velocity of flood flows.

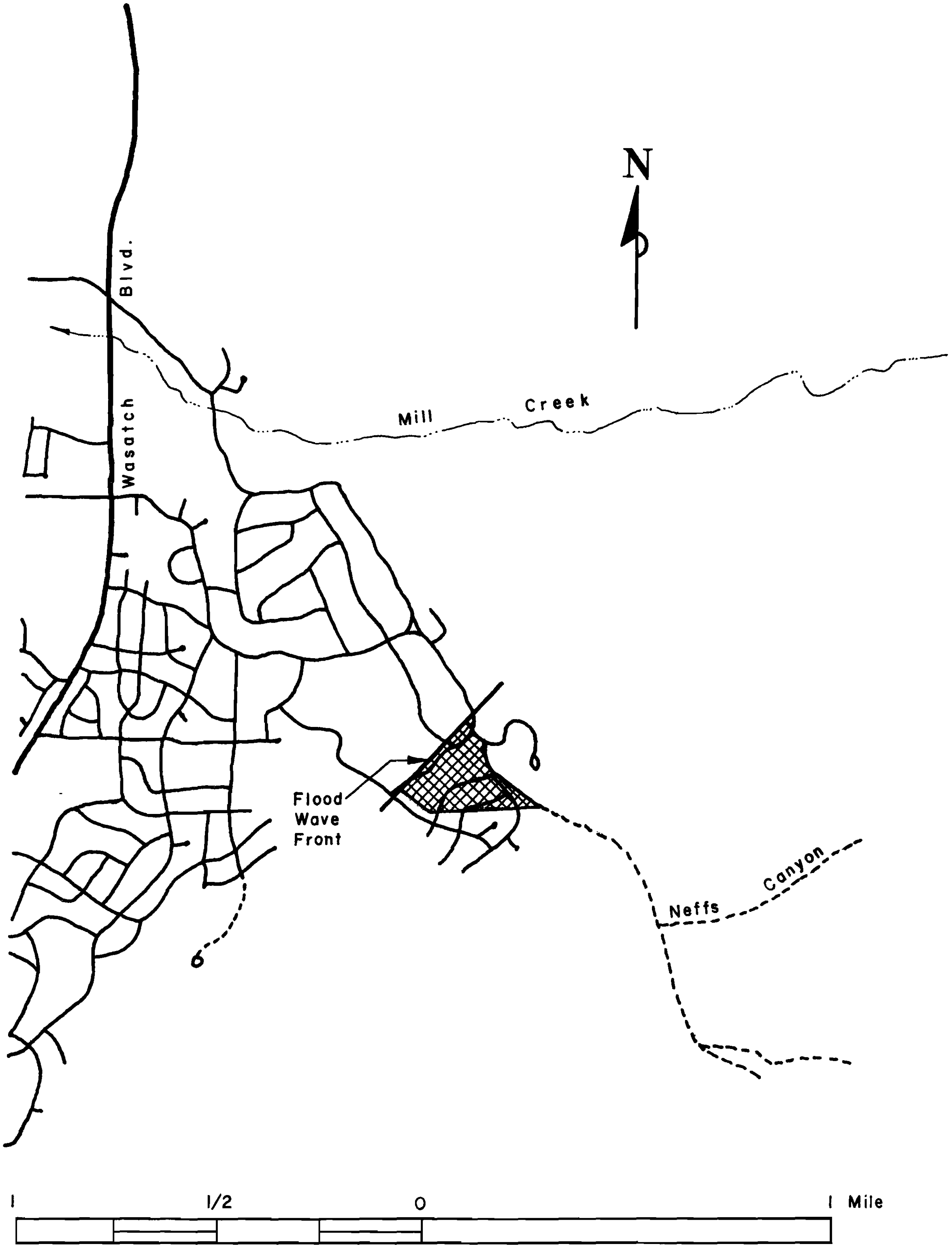


Figure C-2. Map showing location of the wave front used in the sample calculation.