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A PEAK RUNOFF PREDICTION METHOD FOR SMALL RURAL WATERSHEDS IN COLORADO

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16. Abstract

In this study, a peak runoff regression model was derived using dimensional analysis. The model was calibrated by 63 rainfall/runoff events observed from 30 small rural basins in the State of Colorado. It has been found that basin area, slope, shape factor, precipitation, vegetation, and soil type are important factors. In the developed model, vegetation and soil type are merged into a single coefficient. Although for some combinations of soil type and vegetation, sample data were not enough to adequately calibrate the model, the general trend agrees with common understanding of catchment behavior.

Implementation

A three to five page manual is being developed as an aide to the hydraulic engineers in utilizing this model.

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CHAPTER I

INTRODUCTION AND REVIEW

Much progress has been made in recent years in the development of the methodologies for watershed rainfall-runoff prediction, including digital and analog computer techniques for simulating the runoff accumulation mechanism, stochastic and statistic approaches to generate synthetic series of hydrological events, and regression analyses on the collected hydrologic, meteorological, physiographic, and geological data (Bock, et al., 1972). Chow (1962) published a comprehensive summary of various methods used in the hydraulic determination of drainage waterways for the design of small drainage structures. He classified the existing methods into nine categories:

(1) judgment,
(2) classification and diagnosis,
(3) empirical rules,
(4) formula,
(5) tables and curves,
(6) direct observation,
(7) rational methods,
(8) correlation analyses, and
(9) hydrograph synthesis.

In general, peak runoff prediction methods should meet the following criteria: (a) requiring input data that can be readily obtained, (b) using parameters and functional relationships that are physically reasonable, (c) presenting the information desired in a readily usable form, and (d) having few restrictions in applications.

The following methods are generally applied in the state of Colorado for peak runoff predictions:

A) Flood Frequency Analysis
B) Hydrograph Synthesis
C) Regression Analysis Method

They are further discussed in the following sections.

A. Flood Frequency Analysis

Hydrologic events are so random in magnitudes that they generally can be interpreted and predicted in a probabilistic sense. Flood frequency analysis assumes that the laws of probability for outcomes of a hydrologic event apply. It implies that hydrological variables can be treated as a continuous random process with a steady distribution such as normal distribution, log normal distribution, gamma (or Pearson Type III) distribution and Gumbel distribution. These distributions are used to fit hydrological data. Statistical analysis may be used to predict trends, cycles, and variations of a hydrologic event. Confidence intervals can further be used to assess the reliability of the predicted values (Guo, 1986). Frequency analysis may be applied to an annual exceedence series, and an extreme value series such as maximum and minimum value series (Viessman et al, 1972).

Short records of data may reduce the accuracy of prediction, and the extrapolation of the fitted frequency curves may become very sensitive when estimating an event with occurrence probability close to zero. For those selected gage stations on small watersheds in the state of Colorado, the average length of records is about 10 years. Although a 10-year record is the minimum requirement suggested by the American Water Resources Council (1981), inadequacy of data, in turn, restricts the reliability of frequency analyses for predicting the runoff from small rural watersheds in Colorado. In addition, variations of basin hydrologic conditions, such as constructions of reservoirs and highways, change the outcome probability of flood flow from the drainage basin. When a drainage basin fails to remain hydrologically stationary, frequency analysis may not present valid prediction.

B. Hydrograph Synthesis

A runoff hydrograph is a plot of runoff discharge versus time. When there is enough rainfall/runoff data, the unit hydrograph method can be derived and then applied to generate a storm runoff hydrograph for a given excess rainfall with the same duration as the unit hydrograph. When there is not enough data, a regional synthetic unit hydrograph method can be utilized to predict runoff.

The unit hydrograph has a volume of one unit depth of runoff from the drainage basin and is identified by its rainfall duration. The primary assumptions in the unit hydrograph approach include: (1) the runoff rate is linearly proportional to the amount of excess rainfall which is uniformly distributed over its duration, and (2) the base time of hydrograph is constant and independent of rainfall duration.

To develop a unit hydrograph for a basin, one needs enough rainfall and streamflow records. The chosen storm must be representative of the temporal and spatial distributions of rainfall, and the resulting hydrographs can only be applied to storms having similar patterns to those used to develop the unit hydrograph. Rainfall intensity hyetograph is seldom uniform during its duration. This fact may result in difficulty in the data analysis. In addition, storm movement and basin storage are other factors affecting the peak flow. Generally storms that move down towards the basin outlet will result in higher peak flows than those storms that move up the basin. Any significant storage in the basin should be evaluated using a flood routing method between storage and outflow rate.

The synthetic hydrograph method is used to develop the relationship between rainfall and runoff for gaged sites and then to transfer this relationship to the project site in the same hydrologic region. Based on judgment and empirical evidence, the synthetic hydrograph method provides a method to calculate the time to peak flow and peak discharge on the unit hydrograph according to the basin hydrologic characteristics. Snyder's synthetic method is one of the pioneering works which relates the geographical properties of the basin to the runoff hydrograph (Viessman, et al., 1977).

The Soil Conservation Service (SCS) (Wilkes 1980) has indicated that the SCS 24-hour Type IIa rainfall distribution and triangular unit hydrographs are suitable for flood predictions for the rural watersheds in the state of Colorado. Although the suggested 24-hour Type IIa storm distribution has not been adequately validated by the observed rainfall patterns in the Rocky Mountain area, the SCS method has been adopted by several cities and counties for hydrology design.

The SCS hydrograph was developed based on an analysis of a large number of agricultural unit hydrographs from a wide range of rural basins less than 2000 acres. SCS proposed several design storm distributions such as Type I, Type II, and Type IIa for a rainfall duration of 24 hours. Rainfall excess is determined by the soil type and the curve number which represents different types of land uses.

To determine the direct runoff (excess rainfall) from a given rainfall depth and the curve number, SCS has developed several empirical relationships and provides graphs, tables and charts for easy application of this method. The limitations of the SCS method are closely associated with the nature of the original data used to develop the method. To expand the applicability of the SCS method, computer model, TR-20, was developed for coping with complicated drainage network simulations. Although SCS has improved this method for large urbanized areas using Technical Release 55 procedures, (Wilkes 1980), it has been observed that this method tends to give lower predictions for large watersheds. However, many states such as the state of Maryland, has adopted the SCS runoff/rainfall method as a valid method for the prediction of runoff (McCuen, 1982).

In addition to the SCS Technical Release 55, the Colorado Urban Unit Hydrograph Procedure (CUHP) was also developed by the Denver Urban Drainage and Flood Control District, using synthetic unit hydrograph method calibrated by the data collected in the Denver Metropolitan areas. The related hydrograph coefficients calculated in the CUHP are supposed to be valid for the regions nearby Denver. The data used to develop this method were collected from catchments less than 5 square miles with basin slopes between 0.005 ft/ft and 0.037 ft/ft. This procedure is applicable to basin sizes from 90 acres to 3000 acres. For basins larger than 3000 acres, it is suggested to perform flood hydrograph routing through the drainage network. For less than 90 acres, the Rational Method provided by the CUHP should be used for the entire storm hydrograph prediction.

C. Regression Analysis Method

The U.S. Geological Survey has conducted extensive studies for many states to develop techniques for estimating the magnitude and frequency of floods. Most of these studies are regional regression analyses, and U.S.G.S. relates the drainage physiographic and regional climatic factors to runoff flow characteristics.

The relationships for estimating peak flow are usually developed using a statistical regression technique with a large amount of hydrologic data processed by digital computers. Stepwise regression is often used to evaluate the predictive capability of predictor variables in a stepwise manner until the solution point is reached where the addition of another predictor does not meet a selected significance level. Regression equations developed for different states and for different regions within a state are different. For instance, in New Mexico's San Juan basin, the most important variables are found to be drainage area, active channel width, main channel slope, basin slope and silt-clay content in active channel banks (Thomas and Gold, 1982). In Florida, the significant variables are found to be drainage area, lake area, slopes and precipitation (Bridges, 1982). To improve flood frequency estimates, USGS separates regions into various hydrologic zones according to the homogeneity of watershed and drainage characteristics.

In Colorado, USGS (1976) recommended three methods to predict flood flows at sites on natural flow streams. They are:

(1) at gaged sites; we use frequency analysis.

(2) near gaged sites on the same stream; translate the gaged site calculation proportionally to the unaged site by an area ratio.

(3) at unaged sites; use the regression equations derived from data analysis. According to Technical Manual Number 1 (TM-1) (McCain and Jarrett, 1976), Colorado is divided into four different hydrologic

zones shown in Fig. 1 and flood prediction equations for each of the regions are listed in Tables 1 through 4.

The USGS methods are tailored for various hydrologic zones. TM-1 was derived for basins with an area greater than 15 square miles. Applying it to smaller watersheds tends to overestimate runoff.

In 1981, USGS completed a regional small watershed study for the Arkansas River basin in Colorado (Jarrett, 1981). It was found that peak runoff is primarily determined by the effective drainage area, A_E, and return period. Regression analysis was separately performed for two sets of basins: one set is for basin sizes between 0.5 and 3.0 square miles and the other set is for basin sizes between 3.0 and 15.0 square miles. Results are presented in Table 5. In this study, derivation of a synthetic hydrograph was attempted. Although it was found that the peak runoff on a synthetic hydrograph is related to its runoff volume, V, in acre-feet, the developed procedures were not comprehensive enough to provide a complete storm hydrograph.

In summary, there is an urgent need to develop a legitimate method for predicting the peak runoff from the small rural watersheds in the state of Colorado. In addition, when facing a ponding storage or a complicated drainage network, just knowing peak flow is inadequate. Therefore, it is also imperative to

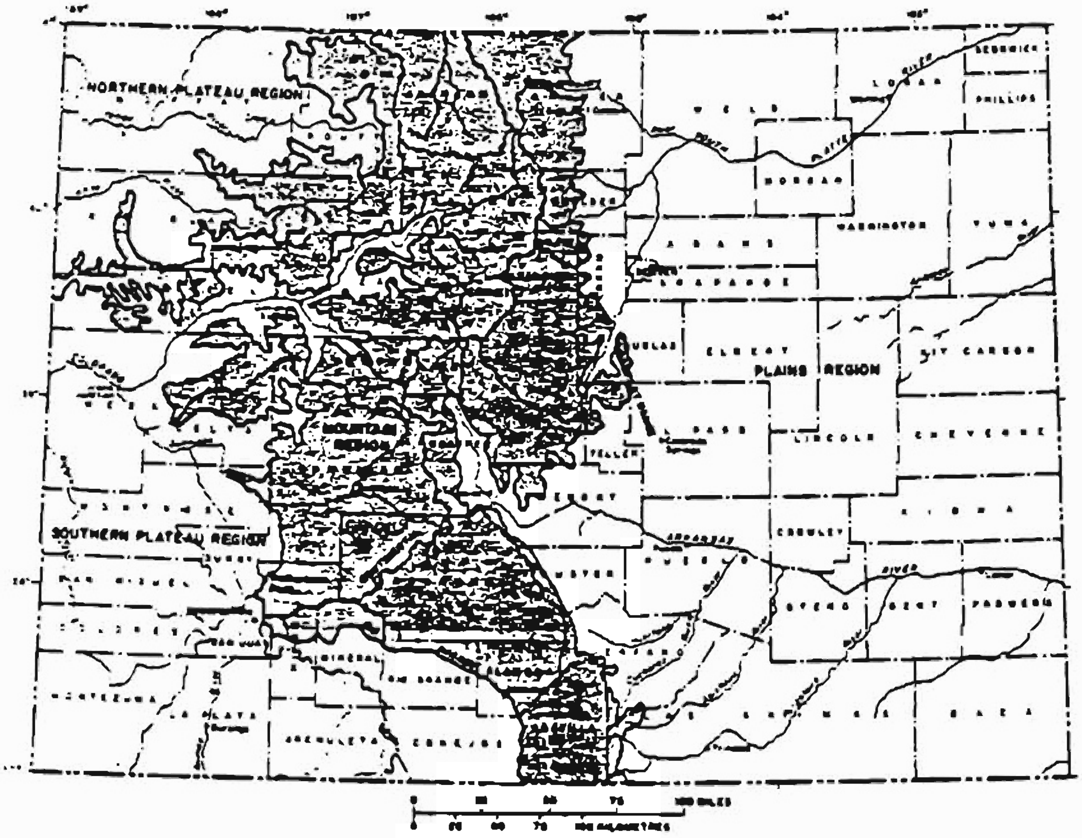

Figure 1 Hydrologic Regions in the State of Colorado.

Table 1 Peak Flow Prediction for Plain Region by USGS TM-1.

Equation	Standard error of estimate, in percent	
	Average	Range
$Q_{10} = 144A^{0.528}S_B^{0.336}$	31	+36 to -26
$Q_{50} = 891A^{0.482}S_B^{0.154}$	24	+27 to -21
$Q_{100} = 1770A^{0.463}S_B^{0.086}$	28	+32 to -24
$Q_{500} = 5770A^{0.432}$	45	+55 to -35
$D_{10} = 35.5S_S^{-0.462}$	28	+32 to -24
$D_{50} = 52.1S_S^{-0.500}$	23	+26 to -20
$D_{100} = 59.3S_S^{-0.517}$	21	+23 to -19
$D_{500} = 77.3S_S^{-0.553}$	26	+29 to -23

Table 2 Peak Flow Prediction for Mountain Region by USGS TM-1.

Equation	Standard error of estimate, in percent	
	Average	Range
$Q_{10} = 0.12A^{0.815}p^{1.592}$	39	+46 to -32
$Q_{50} = 0.91A^{0.795}p^{1.110}$	37	+44 to -30
$Q_{100} = 1.88A^{0.787}p^{0.932}$	38	+45 to -31
$Q_{500} = 8.70A^{0.766}p^{0.560}$	45	+55 to -35
$D_{10} = 0.44A^{0.196}p^{0.347}$	27	+31 to -23
$D_{50} = 1.05A^{0.192}p^{0.133}$	28	+32 to -24
$D_{100} = 1.44A^{0.187}p^{0.059}$	28	+32 to -24
$D_{500} = 1.94A^{0.184}$	31	+36 to -26

Table 3 Peak Flow Prediction for Northern Plateau by USGS TM-1

Equation	Standard error of estimate, in percent	
	Average	Range
$Q_{10} = 11.0A^{0.552}p^{0.706}$	28	+32 to -24
$Q_{50} = 70.5A^{0.509}p^{0.289}$	29	+33 to -25
$Q_{100} = 135A^{0.494}\ p^{0.143}$	30	+34 to -26
$Q_{500} = 293A^{0.469}$	34	+40 to -28
$D_{10} = 13.9S_S^{-0.288}$	24	+27 to -21
$D_{50} = 16.6S_S^{-0.311}$	22	+24 to -20
$D_{100} = 17.2S_S^{-0.310}$	22	+24 to -20
$D_{500} = 19.0S_S^{-0.321}$	21	+23 to -19

Table 4 Peak Flow Prediction for Southern Plateau by USGS TM-1

Equation	Standard error of estimate, in percent	
	Average	Range
$Q_{10} = 59.7A^{0.709}$	47	+58 to -36
$Q_{50} = 89.1A^{0.709}$	50	+62 to -38
$Q_{100} = 103A^{0.710}$	53	+66 to -40
$Q_{500} = 137A^{0.713}$	65	+84 to -46
$D_{10} = 1.25A^{0.261}$	25	+28 to -22
$D_{50} = 1.54A^{0.254}$	34	+40 to -28
$D_{100} = 1.64A^{0.254}$	36	+42 to -30
$D_{500} = 1.98A^{0.239}$	44	+53 to -35

Table 5 Peak Flow Prediction for the Arkansas River Basin.

Peak discharge (Q_P) in cubic feet per second,

0.5- to 3.0-square-mile basins:

$Q_{10}= 500A_E^{0.89}$ (S_e=41.1)[1]

$Q_{25}= 840A_E^{0.97}$ (S_e=40.1)

$Q_{50}=1,140A_E^{1.01}$ (S_e=40.2)

$Q_{100}=1,550A_E^{1.07}$ (S_e=34.0)

3.0 to 15.0-square-mile basins:

$Q_{10}= 830A_E^{0.41}$ (S_e=48.6)

$Q_{25}=1,560A_E^{0.44}$ (S_e=39.8)

$Q_{50}=2,280A_E^{0.47}$ (S_e=35.4)

$Q_{100}=2,930A_E^{0.50}$ (S_e=29.7)

Flood volume (V), in acre-feet

$V=0.141Q_P^{0.919}$ (S_e=62)

Synthetic hydrograph constants: discharge constant (Q'), in cubic feet per second per discharge unit; time constant (T'), in minutes per time unit.[2]

$Q'=Q_P/60$

$T'=0.748V/Q'$

---

[1] Average standard error of estimate, in percent.

[2] Dimensionless hydrograph time and discharge units, and an example application of the synthetic hydrograph procedure, given in table 5.

derive a synthetic hydrograph method for the rural drainage areas in the state of Colorado.

In this study, a peak runoff regression model that is physically sound and easily to use, was developed. In addition, the availability of rainfall/runoff data sources was also evaluated for the future development of a more sophisticated synthetic hydrograph method for the rural areas in the state of Colorado. Dimensional analysis was employed to formulate the mathematical expressions of the regression model. It was found that basin area, slope, shape, and precipitation are major contributing factors to both peak runoff and its hydrograph.

CHAPTER II

THEORETICAL CONSIDERATIONS

A. General Description

Precipitation is the major factor of surface runoff. Other factors may include soil antecedent moisture condition, infiltration loss, vegetation cover, basin area, shape, slope and drainage network. The relationship between peak flow and these factors may be expressed in the following mathematical function:

$$Q_p = F_1(A, S_b, W, L, i, T_d, T_c, T_r, D_p, P, V, v, g, \text{soil type}, \text{vegetation} \ldots) \qquad (1)$$

where F_1 = functional relationship. Q_p = peak flow discharge, A = drainage area, S_b = basin average slope along the waterway, W = basin width, L = basin waterway (flow) length, i = average rainfall intensity, T_d = rainfall duration, T_c = time of concentration, T_r = recurrence interval, D_p = soil antecedent moisture contents, P = precipitation, V = runoff flow velocity, v = viscosity of the flow, and g = gravitational acceleration.

This function can be formed into a mathematical model which gives the relation among variables and can therefore be used to describe, analyze and predict runoff for given conditions.

In the derivation of a regression model, one always attempts to include as many independent variables as needed in the formulation of mathematical relationships. However, before developing a mathematical relationship, one should weigh the relative importance among the independent variables in predicting the dependent variable. Then one may select the important ones and ignore the less important ones. This procedure facilitates the data analysis and eases the future applications of the developed method.

B. Major Factors Affecting Runoff

As expressed in Eq. 1, the magnitude of peak runoff depends on many factors. These major factors can be classified into three different groups; (1) precipitation, (2) watershed characteristics, and (3) fluid properties. They are further discussed as follows:

1. Precipitation. Water input in the form of precipitation is the major cause of runoff; the amount of precipitation is directly related to the amount of water which runs off. Precipitation can be categorized into three different types depending on the air mass lifting mechanism. The first one is cyclonic precipitation or frontal lifting, where warm air meets with cold air. The second one is orographic precipitation which is caused by the existence of natural barriers such as mountains. Warm air masses are lifted, condensed and then precipitated. The third one is

convective precipitation. When the air mass close to the ground gets warmed, it will expand and rise. When dynamic cooling takes place, it will then be condensed and precipitated. In the state of Colorado, it has been observed that rainstorms often have upslope character where there is an easterly flow of air mass against the mountains. Denver Urban Drainage and Flood Control District observed that out of 73 storms studied, 68 had the most intense precipitation occurring in the first hour (Urbonas, 1979). This fact favors the use of uniform rainfall intensity for basins with the time of concentration less than one hour.

Important factors describing a given rainfall event include, precipitation (P), intensity (i), duration (T_d), and recurrence interval (T_r). In practice, the rainfall type generally is not considered when estimating peak runoff from a small watershed. This is particularly true when using the rainfall statistics, such as those in Technical Paper 40 (TP-40), that only provide depth, recurrence interval, and rainfall duration. Of course, when local rainfall data are adequate, the most representative rainfall distribution might be derived for design purposes. However, in many regression models, the effects of the rainfall hyetograph and type are usually ignored.

2. Watershed Characteristics. Surface runoff phenomenon are closely associated with the watershed drainage characteristics, including basin area, waterway slope, basin

shape, flow length, soil type, vegetation and soil antecedent moisture condition.

Basin Area: Many studies have revealed that the amount of runoff is proportional to the size of the catchment. For a constant rainfall intensity, the larger the basin, the more water runs off. This fact is mathematically expressed in the Rational formula.

Waterway (Flow) Length: Flow length includes overland flow length and stream flow length. The time required for water to travel through a basin is proportional to its waterway length. A longer travel time generally results in a lower peak flow.

Basin Slope: The slope of waterway is an important factor that is directly related to flow velocity. A steeper slope will lead to a shorter travel time than a flatter one; this in turn will increase the peak discharge. For instance, on a steep reach, the soil may not be fully saturated before runoff occurs.

Basin Shape: A long and narrow basin will generally have a longer travel time. This can result in a lower peak discharge than that from a shorter and wider drainage area. Dewiest (1965) and Guo (1988) demonstrated how the runoff hydrograph shape may be changed by watershed configurations.

Soil Type: The infiltration and percolation rates of soils indicate their potential to reduce the amount of direct runoff by absorbing rainfall. The size and shape of soil grains contribute to the surface roughness, which serves as a retarding factor to runoff flow.

Soils are classified into four different hydrologic types by the Soil Conservation Service (McCuen, 1982). They are:

Type A: Soils having high infiltration rates even when thoroughly wetted. These consist chiefly of deep, well drained to excessively drained sands or gravel. These soils have a high rate of water transmission and low runoff potential.

Type B: Soils having moderate infiltration rates when thoroughly wetted. These consist chiefly of moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.

Type C: Soils having slow infiltration rates when thoroughly wetted. These consist chiefly of soils with a layer that impedes downward movement of water or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.

Type D: Soils having very slow infiltration rates when thoroughly wetted. These consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with claypan or clay layer at or near the surface, and shallow soils over nearly impervious materials. These soils have a very slow rate of water transmission and high runoff potential.

Vegetation Cover: The density distribution and type of vegetation can affect runoff volume through its influence on the infiltration rate of soil. Ground litter forms barriers along the flow path on the ground surface. Detention storage and interception reduce the peak and the amount of direct runoff through the increased evapotranspiration and infiltration.

Soil Moisture Condition: The soil moisture conditions of the watershed at the beginning of a storm directly affect the volume of runoff. The lower the moisture content in the soil at the beginning of precipitation, the less precipitation that will become surface runoff. Antecedent moisture conditions (AMC) has also been grouped into three categories by SCS as follows:

AMC I - Low moisture. Soil is dry.

AMC II - Average moisture conditions. Condition normally used for annual flood estimates.

AMC III - High moisture, heavy rainfall over preceding few days.

Horton (1935) suggested using an exponential decay curve to represent the decrease in infiltration capacity. This decay curve is defined by soil initial and final infiltration capacities. The values of these two infiltration capacities depend on soil antecedent moisture condition and soil type. Normally, the second level of soil moisture condition is used in estimating peak runoff for design purposes.

C. Fluid Characteristics

Theoretically, fluid and flow characteristics include flow velocity, fluid density, viscosity, and gravity. Natural stream flow is governed by gravity, which in turn affects the travel velocity. Water temperature governs flow viscosity which affects the flow pattern and velocity distribution. Generally, physical properties of water such as density and viscosity, can be considered as constant.

C. **Model Formulation**

To generate a meaningful mathematical expression for Eq. 1, dimensional analysis is employed in this study. In Eq. 1, some of the independent variables are related to others. For instance, flow velocity is, in fact, governed by basin slope and waterway roughness, and the time of concentration is a function of flow velocity and waterway length. As a result, flow velocity and flow time may be replaced with basin slope, flow length, and waterway roughness. Similarly, design rainfall statistics are a function of recurrence interval, locality, storm distribution and rainfall pattern. After further reductions to exclude the related independent variables, Eq. 1 can be simplified to

$$Q_p = F2\ (A,\ S,\ W,\ L_t,\ i,\ v,\ g,\ V,\ D_p,\ T_d,\ \text{soil},\ \text{vegetation}) \qquad (2)$$

where F2 =functional relationship.

It is necessary to arrange these variables in Eq. 2 into a practical and applicable form. In this study, dimensional analysis is used to further develop Eq. 2.

D. Dimensional Analysis

In the development of hydrological empirical equations, the collection of data is necessary. Moreover, it is a difficult task to derive useful conclusions from analyzing all information and data collected. Dimensional analysis provides a means to screen out the abstract or interfering variables and yields a dimensionless mathematical form for the model developed.

Many examples can reflect this useful practice. Darcy-Weisbach's resistance equation is a typical example which expresses the pressure gradient needed to overcome resistance as a function of dimensionless variables. The drag force and the lift force in the flow around an immersed body are some other examples. They all have the form of dependent nondimensional variables which are expressed as a coefficient multiplied by the independent nondimensional variables to certain powers.

Eq. 2 includes ten physical quantities with two dimensional units: length in feet and time in seconds. The quantities can be arranged into eight dimensionless parameters. Choosing two repeating variables, rainfall intensity, i, and waterway length, L_t, and applying the Buckingham theorem yields the following dimensionless form:

$$F3 \left\{ \frac{Q_p}{iA}, \frac{W}{L_t}, \frac{iL_t}{v}, \frac{i^2}{gL_t} \frac{V}{i}, \frac{D_p}{L_t}, \frac{iT_d}{L_t}, S_b, \text{Soil}, \text{Vegetation} \right\} = 0 \qquad (3)$$

in which F3 is a functional relationship.

Basin width-to-length ratio is an index of basin shape. Considering that the width-to-length ratio should have the same order as the area to length to square ratio, thus we may write

$$\frac{W}{L_t} = \frac{W.\ L_t}{L_t . L_t} \approx \frac{A}{L_t^2} \qquad (4)$$

The antecedent moisture condition, D_p, involves a complicated subsurface flow monitoring and calculation. There is no readily available field data. For design purposes, it is reasonable to take an average condition and therefore, it is justifiable to eliminate the consideration of soil antecedent condition from the model development process. Eq. 4 can be further reduced to:

$$F4 \left\{ \frac{Q_p}{iA}, S_b, \frac{A}{L_t^2}, \frac{P}{L_t}, \frac{iL}{v}, \frac{i^2}{gL_t}, \text{Soil}, \text{Vegetation} \right\} = 0 \qquad (5)$$

in which F4 is a functional relationship.

The fifth and sixth terms are Reyonds number and Froude number. Reynolds number is believed to be related to hydraulic resistance. In a laminar flow, flow resistance is a function of Reynolds number. On the contrary, in a fully turbulent flow, roughness is only a function of surface vegetation and soil type. In the surface runoff, the Reynolds number of flow is high enough to be fully turbulent. Therefore Reynolds number can be ignored from Eq. 5. Froude number indicates flow regime and water surface profile conditions as super-critical flow, critical flow, or sub-critical flow. In the surface runoff modeling, backwater effects are quite insignificant, so it is believed that Froude number is negligible in the determination of the peak runoff.

After further reduction, the above equation can be simplified to

$$\frac{Q_p}{iA} = F5 \{ S_b, \frac{A}{L_t^2}, \frac{P}{L_t}, \text{Soil, Vegetation} \} \qquad (6)$$

where F5 is a functional relationship.

Mathematically, Eq. 6 may further be expressed into the following form:

$$\frac{Q_p}{iA} = b_1 * \left(\frac{A}{L_t^2}\right)^{b_2} * (S_b)^{b_3} * \left(\frac{P}{L_t}\right)^{b_4} \qquad (7)$$

where Q_p/iA is equal to the basin average runoff coefficient used in the Rational formula. It has been widely recognized that the value of runoff coefficient is a function of basin slope, land uses and return period. This fact is reflected in Eq. 7 with an additional term, A/L_t^2, which represents the basin shape. The ratio, P/L_t represents the precipitation considerations which include site locality effect, and the return period of the storm. The coefficient b_1 is primarily a function of vegetation, and soil type. The value of b_1 generated from a large amount of data, should represent the mean value of the roughness in terms of vegetation and soil type. Of course, we many divide the data base into groups based on the combinations of vegetation and soil type, and then further compute the average value of b1 for each combination.

To determine the coefficients, b_1, b_2, b_3 and b_4, the regression analysis using the least square method is employed. The required rainfall/runoff data sources and data reduction procedures are further discussed in the next chapter.

CHAPTER III

DATA SOURCES AND ANALYSIS

A. Rainfall/Runoff Data Sources

Colorado is near the center of the United States, with a total area of 104,247 square miles, of which about 450 square miles are water area. It is the 8th largest state and has an average altitude of 6800 ft. The average annual precipitation in the state of Colorado is about 90 million acre-feet (16.2"), of which 16 million acre-feet (2.90") becomes surface runoff (Livingston, 1970).

The U.S. Geological Survey has made an effort to systematically record the stream flow data in Colorado since 1960. The purpose of this effort was to provide adequate streamflow information on the major streams. Up to 1981, about 460 pertinent gage stations, 22 lakes and many miscellaneous sites had been recorded and published in the Water Resources Data for Colorado annually. Most of these gaged watersheds are larger than ten square miles. For small watershed studies, USGS data do not seem helpful.

From 1968 to 1980, USGS (1982), in cooperation with the Colorado Department of Highways and U. S. Department of Transportation and Federal Highway Administration were engaged in a statewide monitoring program for the rainfall and runoff data collection from small rural catchments. The gaged watersheds were generally less than ten square miles. A network of stations was selected to provide continuous records of rainfall and runoff data on the major streams. This monitoring program ended in 1980 and three volumes of rainfall-runoff data with five-minute intervals have been published (USGS Open File 79-1261).

A total of 43 small rural basins in Colorado were gaged for both rainfall and runoff records during the period from 1969 to 1980. No winter flow nor snowmelt was recorded. Distribution of these selected gaging stations are shown in Fig. 2. A list of the gaging stations and site locations are shown in Appendix I.

B. Basin Physiographic Characteristics

Basin geographic characteristics, such as drainage size, basin shape, basin slope, and flow length, can be established directly from USGS topographic maps. The drainage area, waterway length including overland flow length and channel length can be determined from these maps. From the contour lines one can calculate the elevation drop along the waterway, which provides the information to calculate the average slopes.

The U.S. Soil Conservation Service has published soil maps and land usage maps which provide the necessary information for soil type and vegetation cover for each drainage basin in Colorado.

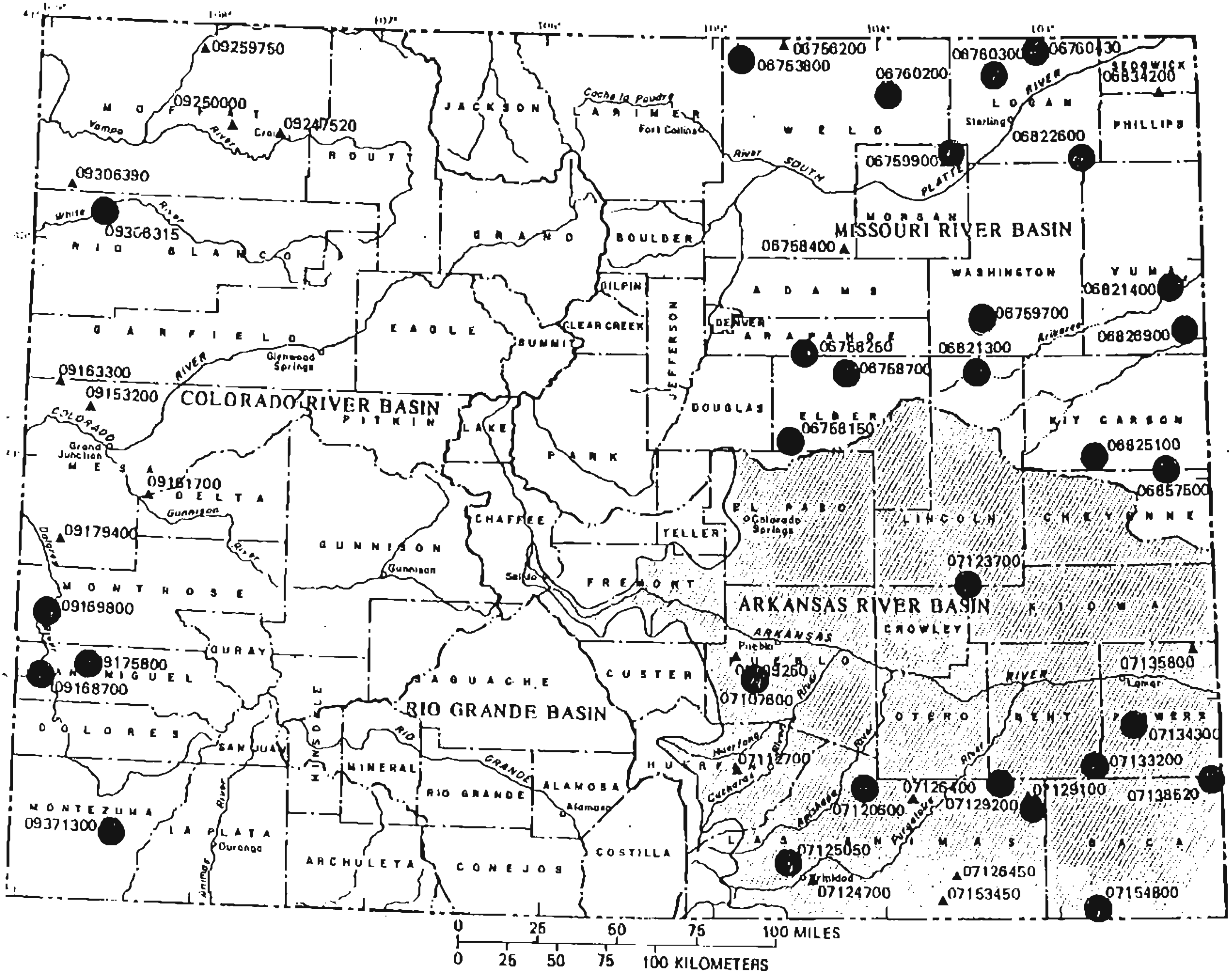

Figure 2 Locations of Gaging Stations.

C. Basin Characteristics and Rainfall/Runoff Data Reduction

The model derived from dimensional analysis, essentially expands the rational formula. Modifications are made to improve the inadequacy of the rational method. One inherent assumption in the rational method is that the critical rainfall duration is the time of concentration of the basin. By definition, the time of concentration is the sum of overland flow time and channel flow time.

McCuen, Wong, and Rawl (1984), in which they reviewed eleven different methods for estimating the time of concentration, concluded that the velocity-based method provides a reasonably accurate estimate for the time of concentration, T_c. In this study, the waterway is divided into two segments: (1) overland flow length from the most upstream basin boundary to the headwater, and (2) channel flow length from the headwater to the basin outlet. The detailed computations of the corresponding flow times are determined as follows:

(C.1) Overland Flow

The SCS upland velocity method, as shown in Fig. 3, is chosen to calculate the travel time for overland flow because it specifies the land uses and ground slopes. Equations for the SCS upland method are as follows:

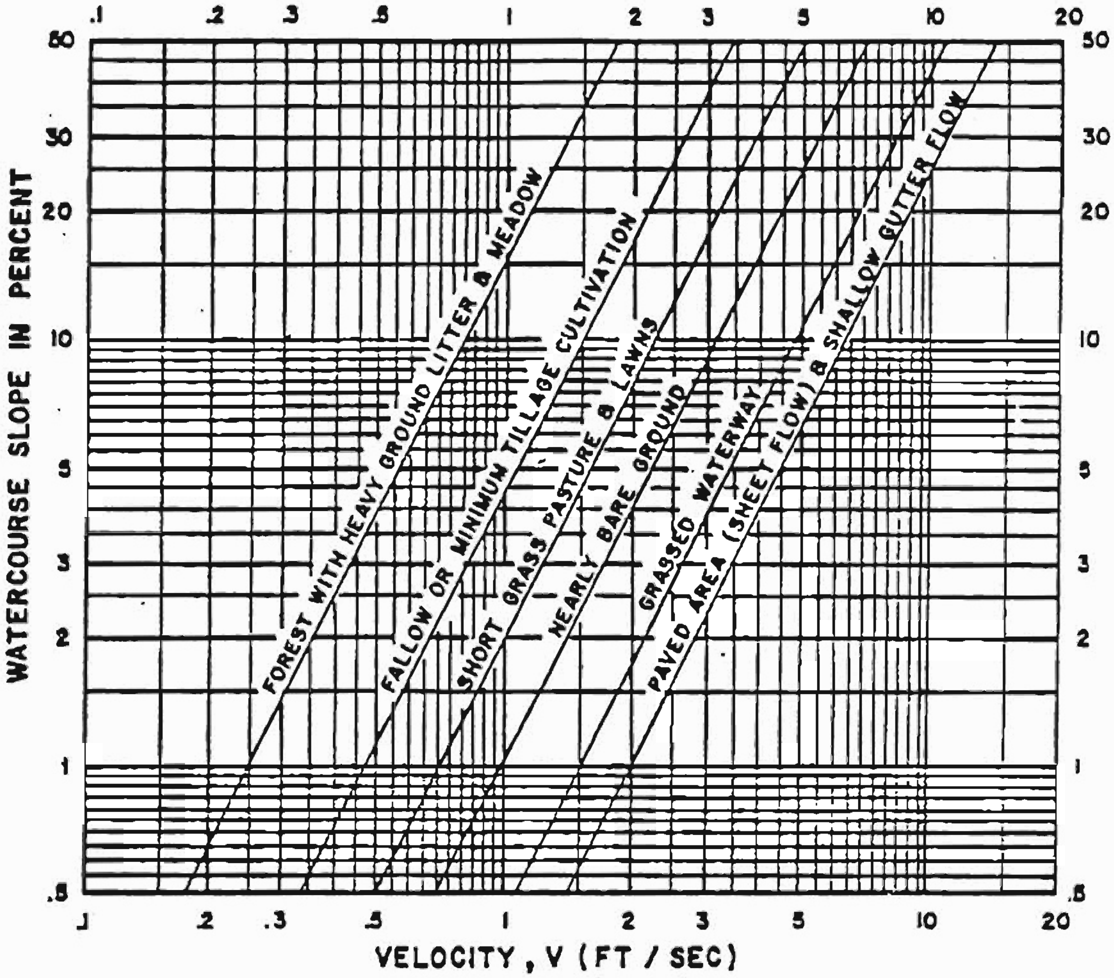

Figure 3 SCS Upland Method.

Forest with heavy ground litter and meadow:

$$V_o = 2.61 * (S_o{}^{.51}) \tag{8}$$

Fallow or minimum tillage cultivation:

$$V_o = 4.57 * (S_o{}^{.50}) \tag{9}$$

Short grass pasture and lawn:

$$V_o = 6.95 * (S_o{}^{.51}) \tag{10}$$

Nearly bare ground.

$$V_o = 15.2 * (S_o{}^{-50}) \tag{11}$$

in which V_o = overland flow velocity in feet/second.

S_o = overland slope in feet/feet.

The required overland flow time is estimated to be

$$T_o = L_o/(V_o * 60) \tag{12}$$

in which T_o = overland flow time in minutes.

L_o = overland flow length in feet.

(C.2) Channel Flow

In general, engineers do not have enough information of channel geometries to predict the peak runoff from small basins. To estimate channel flow time, Kirpich equation was adopted.

$$T_f = \left[11.9 * \frac{(L_f/5280)^3}{H}\right]^{0.385} * 60 \tag{13}$$

in which L_f = channel length in miles.
H = elevation drop along L_f, in feet.
T_f = channel flow time in minutes.

The time of concentration for the basin is

$$T_c = T_f + T_o \tag{14}$$

And the total flow length, L_t, and basin slope, S_b, can be computed as follows:

$$L_t = L_o + L_f \tag{15}$$

$$S_b = H_t/L_t \tag{16}$$

in which H_t = total elevation drop, in feet, from the most upstream boundary to the basin outlet.

According to kinematic wave theory, the rainfall contributing to the runoff at the basin outlet is the rainfall excess that occurs within the period of time required for water to travel from the most remote point of the basin to the outlet. Any rainfall excess occurring prior to or after this period would not contribute to peak flow. This assertion has been confirmed by Guo (1984) and Rossemiller (1982).

Applying this concept to rainfall data analysis, the data reduction is further divided into the following two cases:

Case I: Rainfall duration, Td, is equal to or greater than the time of concentration, Tc.

Data process steps are:

a) identify the peak rain block as the center block.
b) compare rain blocks on both sides of the center block and add the precipitation of the larger one to the center block.
c) repeat the above steps until the time span is equal to the time of concentration.
d) sum the precipitation within this time span.
e) get the average rainfall intensity by the total precipitation divided by the time of concentration.

Fig 4 presents an example to illustrate the detailed computations.

Case II: Rainfall duration is less than the time of concentration.

When the rainfall duration T_d, is shorter than Tc, the average intensity is obtained by the total precipitation divided by its rainfall duration. Under this situation, the peak runoff on the outlet hydrograph did not result from the entire drainage basin because runoff from the far upstream area had not reached the outlet before rain ceased. Considering the time of concentration of the basin represents the flow time through the entire waterway, the ratio of T_d/T_c may be used to approximate the contributing

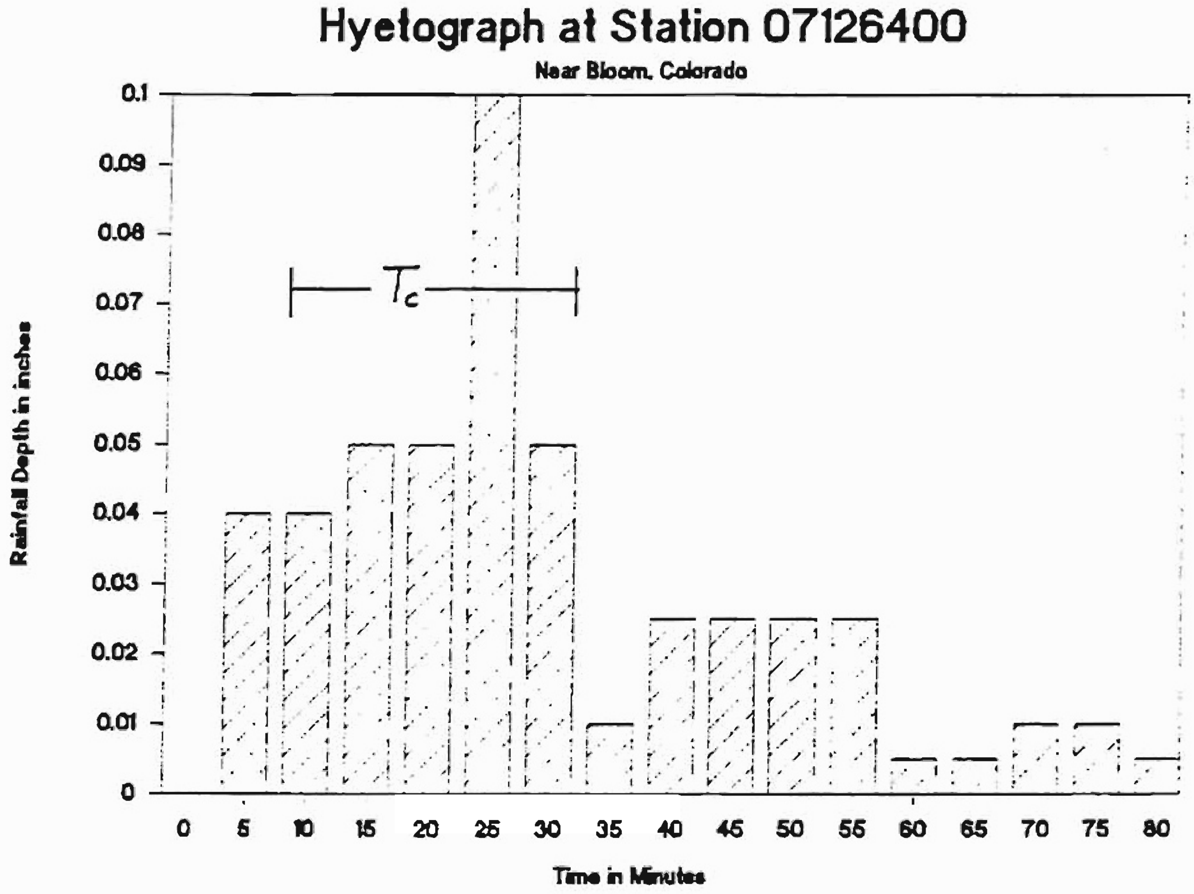

Figure 4 Illustration of Rainfall Data Analysis.

area. Therefore, the effective area was determined by multiplying the ratio T_d/T_c to the basin area.

A computer program was developed for rainfall and basin data reduction. The source code of this program is presented in Appendix IV.

D. Results of Data Reduction

In this study, the data bases considered for regression analysis were selected from the 43 gaging stations. They consisted of 11 years of rainfall and runoff event records from 43 small watersheds. A total of 272 storm events were evaluated through the data reduction process. After checking data consistency based on the basin drainage antecedent conditions and considering data reliability based on the reported functioning conditions of data recording equipments during the storm, there were 63 storms from 30 basins selected for the use in the development of the model parameters. Table 6 presents the measurements of 43 basin parameters from USGS topographic maps. Table 7 is the list of those basins and events selected and used in the regression study.

Among the selected basins and storms, surface vegetation were woods and bare ground, and soil types included types B, C, and D. Detailed data base structure is tabulated in Table 8.

There were five catchments selected from the Colorado

River Basin, 15 catchments selected from Missouri River Basin, and 10 catchments selected from Arkansas River Basin. The range of basin slope is between 0.40% to 6.8% and basin area varies between 0.62 to 14.50 square miles. Detailed basin locations and data distribution can be found in Fig. 2 and Table 7.

WATER -SHED ID#	AREA	OVERLAND FLOW LENGTH	CHANNEL LENGTH	UPPER HEAD ELEV	CHNNL. BNDRY ELEV	OUTLET BNDRY ELEV
9247520	6.26	1200.0	31400.0	7020.0	6906.0	6200.0
9306390	4.36	800.0	24200.0	7730.0	7660.0	6026.0
9306315	13.60	2400.0	63000.0	7560.0	7230.0	5280.0
9163300	1.48	600.0	15600.0	6578.0	5800.0	4658.0
9151700	4.87	2000.0	31400.0	7768.0	7200.0	5175.0
9179400	2.28	1600.0	26000.0	8170.0	7680.0	4915.0
9169800	4.40	4100.0	16200.0	6600.0	5520.0	5218.0
9175800	5.33	1840.0	35190.0	8450.0	8120.0	6470.0
9168700	1.73	3600.0	12800.0	6282.0	5880.0	5610.0
9371300	4.43	1300.0	29600.0	8360.0	7800.0	6300.0
6756200	5.70	8976.0	26928.0	6050.0	5925.0	5500.0
6760430	10.00	7000.0	22000.0	4420.0	4380.0	4300.0
6760300	5.74	2200.0	22800.0	4677.0	4560.0	4150.0
6753800	4.68	2250.0	25170.0	6215.0	6070.0	5625.0
6760200	1.53	2800.0	19000.0	5430.0	5330.0	5020.0
6822600	2.41	5300.0	17100.0	121.0	80.0	0.0
6759900	3.19	13200.0	7000.0	4653.0	4543.0	4466.0
6758400	3.75	300.0	18600.0	5030.0	5015.0	4550.0
6821400	7.84	4080.0	20790.0	3919.0	3900.0	3675.0
6759700	2.35	1100.0	15800.0	5055.0	5040.0	4925.0
6758250	6.41	1100.0	28200.0	6113.0	6047.0	5720.0
6826900	17.80	4200.0	23200.0	3909.0	3886.0	3750.0
6821300	5.72	6800.0	34400.0	5460.0	5405.0	5243.0
6758700	2.27	1120.0	7900.0	6080.0	5995.0	5650.0
6758150	0.62	2400.0	6500.0	7065.0	6974.0	6889.0
6825100	6.47	2000.0	33000.0	4745.0	4720.0	4565.0
6857500	7.84	4100.0	18200.0	4332.0	4265.0	4157.0
7123700	5.73	6820.0	21900.0	5098.0	5053.0	4793.0
7135800	6.28	9800.0	22000.0	4050.0	3940.0	3790.0
7099250	8.35	1600.0	29600.0	6140.0	5983.0	5230.0
7107600	2.87	2300.0	17800.0	5782.0	5660.0	5282.0
7112700	3.10	2450.0	19200.0	6760.0	6680.0	6250.0
7126400	4.14	1600.0	16200.0	5445.0	5260.0	4910.0
7134300	14.50	1400.0	59600.0	4301.0	4272.0	3848.0
7133200	2.34	1400.0	13800.0	4560.0	4520.0	4280.0
7120600	6.56	8600.0	26600.0	6840.0	5725.0	5330.0
7129200	3.56	500.0	19900.0	5060.0	5035.0	4630.0
7129100	7.07	1500.0	23800.0	5120.0	5020.0	4590.0
7138520	12.40	8300.0	37400.0	3936.0	3890.0	3730.0
7125050	6.16	1450.0	28500.0	7492.0	7320.0	6220.0
7124700	8.56	3100.0	37300.0	9625.0	9440.0	6180.0
7153450	4.56	1500.0	24200.0	6822.0	6698.0	5754.0
7154800	3.50	3370.0	21600.0	4663.0	4655.0	4505.0

Table 6 Characteristics of Small Gaged Watersheds in Colorado.

Table 7 Basin Characteristics Used in the Regression Analysis.

WATER -SHED ID#	OBSERVED C	A/L**2	S	P/L	PREDICTED C
9306315	0.11213	0.08864	0.03486	0.34404E-06	0.10897
9169800	0.17671	0.29766	0.06808	0.31609E-05	0.23108
	0.18065	0.29766	0.06808	0.18062E-05	0.19710
9175800	0.19543	0.10837	0.05347	0.12152E-05	0.16604
	0.17080	0.10837	0.05347	0.99019E-06	0.15665
9168700	0.28938	0.17932	0.04098	0.35061E-05	0.21942
9371300	0.17870	0.12935	0.06667	0.99784E-06	0.16245
6760430	0.19386	0.33149	0.00414	0.54023E-05	0.18550
	0.12929	0.33149	0.00414	0.48276E-05	0.17967
	0.06913	0.33149	0.00414	0.40230E-06	0.08866
6760300	0.16275	0.25604	0.02108	0.42667E-05	0.21425
	0.13513	0.25604	0.02108	0.20333E-05	0.17356
	0.17588	0.25604	0.02108	0.90000E-06	0.13767
	0.20578	0.25604	0.02108	0.30333E-05	0.19445
6753800	0.21577	0.17353	0.02152	0.13372E-05	0.15292
	0.31132	0.17353	0.02152	0.42548E-05	0.21249
	0.15144	0.17353	0.02152	0.10637E-05	0.14329
6760200	0.11005	0.08975	0.01881	0.20642E-05	0.16700
6822600	0.10154	0.13390	0.00540	0.29018E-05	0.15733
	0.11341	0.13390	0.00540	0.28274E-05	0.15617
6759900	0.13969	0.21795	0.00926	0.35066E-05	0.18073
6821400	0.31594	0.35337	0.00981	0.70366E-05	0.22485
6759700	0.30224	0.22938	0.00769	0.58185E-05	0.20387
6758250	0.12187	0.20816	0.01341	0.23037E-05	0.16835
	0.16931	0.20816	0.01341	0.34414E-05	0.18869
6826900	0.20498	0.66098	0.00580	0.26764E-05	0.16188
	0.26077	0.66098	0.00580	0.70560E-05	0.21322
	0.18174	0.66098	0.00580	0.17640E-05	0.14379
6821300	0.17978	0.09394	0.00527	0.34183E-05	0.16275
	0.17295	0.09394	0.00527	0.32969E-05	0.16108
	0.10698	0.09394	0.00527	0.14361E-05	0.12719
	0.17263	0.09394	0.00527	0.24474E-05	0.14800
6758700	0.39786	0.77782	0.04767	0.15336E-04	0.35395
	0.35757	0.77782	0.04767	0.11641E-04	0.32728
6758150	0.19480	0.21821	0.01978	0.63670E-05	0.23703
	0.28681	0.21821	0.01978	0.57116E-05	0.22982
	0.22679	0.21821	0.01978	0.50562E-05	0.22200

WATER -SHED ID#	OBSERVED C	A/L**2	S	F/L	PREDICTED C
6825100	0.10818	0.43952	0.00785	0.23169E-05	0.16006
	0.12697	0.43952	0.00785	0.37743E-05	0.18387
	0.16362	0.43952	0.00785	0.37743E-05	0.18387
6857500	0.20083	0.19367	0.01062	0.28726E-05	0.17340
	0.20102	0.19367	0.01062	0.44974E-05	0.19697
7123700	0.16405	0.19804	0.02488	0.12436E-05	0.15327
	0.21460	0.19804	0.02488	0.14925E-05	0.16143
	0.18732	0.19804	0.02488	0.16584E-05	0.16633
	0.17338	0.19804	0.02488	0.55970E-05	0.23503
	0.22947	0.19804	0.02488	0.66750E-05	0.24709
7107600	0.20870	0.18438	0.02356	0.19246E-05	0.17194
7134300	0.20992	0.10864	0.00743	0.34426E-05	0.17140
7133200	0.17309	0.28236	0.01842	0.40022E-05	0.20716
7120600	0.11665	0.14760	0.04290	0.10890E-05	0.15754
	0.11313	0.14760	0.04290	0.75758E-06	0.14210
	0.19892	0.14760	0.04290	0.66288E-06	0.13681
7129200	0.13784	0.23848	0.02108	0.17974E-05	0.16726
7129100	0.19720	0.30793	0.02095	0.25033E-05	0.18486
7138520	0.13604	0.16552	0.00451	0.19329E-05	0.13758
	0.15202	0.16552	0.00451	0.15135E-05	0.12834
	0.16254	0.16552	0.00451	0.12582E-05	0.12177
	0.18190	0.16552	0.00451	0.19876E-05	0.13867
7125050	0.13769	0.19145	0.04247	0.13077E-05	0.16687
	0.11609	0.19145	0.04247	0.63996E-06	0.13619
	0.14444	0.15649	0.00633	0.66747E-06	0.10626
7154800	0.08796	0.15649	0.00633	0.83433E-06	0.11322

```
B(1)=      1.09702
 BB  =    12.50305
B(2)=      0.02624
B(3)=      0.13385
B(4)=      0.28421
```

```
SS=   0.652  SSY=   1.357  RSQR=   0.519  REGV=   0.011  YV=   0.022
```

Soil Type	Vegetation	
	Woods and Bushes	Bare Ground
B	17	29
C	4	3
D	3	7

Note: numeric represents the number of event.

Table 8. Data Base Distribution for Various Combinations of Vegetations and Soil Types.

CHAPTER IV

MODEL REGRESSION ANALYSIS

A. Least-Squared Regression Analysis

The least-squared method is a numerical optimization technique which determines the parameters in a mathematical model by minimizing of the overall deviations between the observed and predicted values. In this study, a linear multiple regression analysis was adopted to determine the relationship between the dependent variable and independent variables. To do so, the equation developed from dimensional analysis, must be transformed into its logarithms of both sides.

$$\log(C) = b_1 + b_2 * \log\left(\frac{A}{L_t^2}\right) + b_3 * \log(S_b) + b_4 * \log\left(\frac{P}{L_t}\right) \qquad (17)$$

in which $C = Q_p/Ai$

Let SS be the summation of squared errors between observed values of Q_p/Ai, Co(i), and predicted values of Q_p/Ai, Cp(i), in which i represents the ith event in the data array. Thus, for a total of n observations, we have

$$SS = \sum_{i=1}^{i=n} \left(\log(C_p(i)) - \log(C_o(i)) \right)^2 \qquad (18)$$

in which SS = summation of squared error, i = ith event, n= total number of events, $C_p(i)$ = observed runoff coefficient, and Co(i) = predicted runoff coefficient.

The least-squares method chooses the best values for b1, b2, b3, and b4 to minimize SS. Mathematically, this is done by taking the first derivative of the summation with respect to the unknown variables and setting the derivatives equal to zero. It can be expected that after logarithmic transformation, a set of four linear equations can be obtained. These mathematic procedures can be written as follows:

$$\frac{d\ SS}{d\ b_1} = 0 \qquad (19)$$

$$\frac{d\ SS}{d\ b_2} = 0 \qquad (20)$$

$$\frac{d\ SS}{d\ b_3} = 0 \qquad (21)$$

$$\frac{d\ SS}{d\ b_4} = 0 \qquad (22)$$

The computer program used to solve this mathematical process is presented in Appendix V.

B. Results of Regression Analysis

Solving Eq's 19 through 22 simultaneously, the following equation was obtained:

$$\frac{Q_p}{Ai} = 12.503 * \left(\frac{A}{L_t^2}\right)^{0.026} * S_b^{0.134} * \left(\frac{P}{L_t}\right)^{0.284} \qquad (23)$$

Fig. 5 presents the comparison between the predicted and observed values. It has a correlation coefficient of 0.72 and a standard deviation of 0.65. The range of the values of Q_p/Ai used to derive this model was between 0.1 and 0.4. This is the same range as suggested by Chow (1964) and Gray (1970) for non-urban areas.

The value of 12.503 is the mean of the variable b_1. As mentioned previously, the value of b_1 should reflect the effects of vegetation and soil. Applying Eq. 23 to each group as shown in Table 8, the values of b1 for various combinations are tabulated in Table 9.

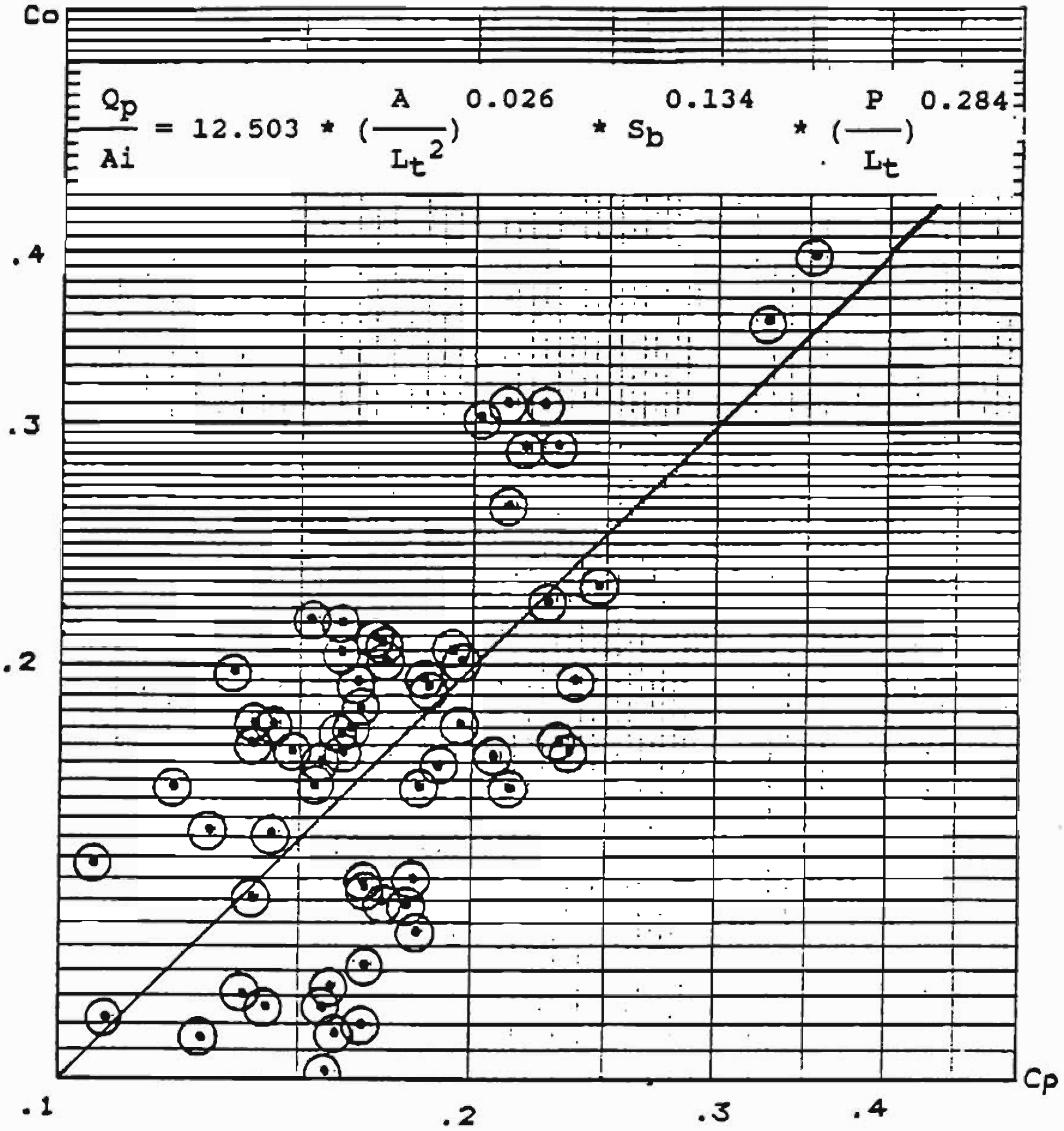

Figure 5 Comparison between Predicted and Observed Runoff

Soil Type	Vegetation	
	Woods and Bushes	Bare Ground
B	12.281	12.946
C	13.683	10.602
D	13.645	12.953

Note: numeric represents the value of b_1 in Eq. 7.

Table 9. Values of b_1 for Various Combinations of Vegetations and Soil Types.

Detailed computations for Table 9 can be found in Appendix II. Table 9 indicates that a bare ground condition will generally produce more runoff than a woods/bushes condition; and a clay type soil generated more runoff than a loamy soil.

The runoff coefficient, Q_p/Ai, in the Rational method is a constant. However, Schaake, Geyer and Knapp (1975), and Guo (1986) indicated that the value of C should increase with respect to the recurrence interval and basin slope. Eq. 23 does agree with this observation. In addition, Eq. 23 indicates that basin shape factor seems less significant than basin slope and precipitations. The slope in Manning's equation has a power of 0.5. In this study, the exponent of the slope was found to be 0.13, which indicates that in surface hydrology, the ground slope may not affect the runoff flow as much as flows in a well-defined channel; but it is sufficiently significant to be counted in predicting the peak discharge. The return period and rainfall intensity, which are represented in precipitation, are important factors contributing to the peak discharge. This agrees with the suggestions on the variation of runoff coefficient to the recurrence interval.

CHAPTER V

MODEL APPLICATION AND COMPARISON

To apply the developed model to a small basin in the state of Colorado, it is required to know the basin area, basin slope, overland flow and channel flow lengths, design precipitation, soil, and vegetation. USGS has published quadrangle topographic maps for the entire United States. Any drainage basin can be located on the USGS topographic map and SCS soil and land usage map by its longitude and latitude. The basin drainage parameters can then be determined.

Based on soil type and vegetation determined from SCS maps, the proper value of b_1 may be determined from Table 9. If Table 9 does not cover the particular combination, the engineer may use the average value of b_1 in Eq 7.

Rainfall statistics are available in several publications from the National Oceanic and Atmospheric Administration (NOAA), such as Technical Paper 40, NOAA Atlas 2 Volume III for the state of Colorado. When assuming that the critical rainfall duration is the time of concentration of the basin, the required design precipitation, P, can be obtained from the Rainfall Atlas Volume III by the basin location and return period, and then the design rainfall intensity, i, can be calculated as follows:

$$i = \frac{P}{T_c} \tag{24}$$

Substituting all design parameters into Eq. 23, Q_p/Ai can be calculated.

For the purposes of comparison, several basins were studied and presented in Appendix III. The gaging stations were randomly selected to cover wide ranges of basin drainage characteristics and precipitations. Peak runoff rates were calculated and compared with the results from the frequency analysis, SCS method, and USGS TM-1 method.

The developed method seems, in general, to give better agreements to the results from the frequency analysis than the SCS method which tends to be lower, and USGS TM1 whose prediction is conservative for small basins. The developed method tends to give lower predictions for less frequent floods such as a 100-year flood and higher preditions for more frequent floods such as a two-year flood, comparing with the results from the frequency analysis.

CHAPTER VI

EVALUATION ON DEVELOPMENT OF HYDROGRAPH SYNTHESIS

Development of a single-equation regression model is to simplify the complicated nonlinear surface hydrology into several key factors and hope that numerical optimization may provide a good description to the data analyzed. A single-equation regression equation is generally easy to use and applicable for simple hydrology and hydraulic structure designs. These equations had been widely used in the past because of their simplicity.

Hydrograph routing is more complicated and time consuming as far as calculation procedures are concerned. However, the advent of high speed computers has revolutionized many hydrology and hydraulic design procedures. For instance, the SCS method has been computerized into TR-20 and TR-55 models and the Colorado Urban Hydrograph Procedure has been coded into CUHP computer software. The synthetic hydrograph approach allows the engineer to consider more basin characteristics than with single equation methods. With the hydrograph routing approach, the engineer can divide a larger basin into smaller, but more hydrologically homogenous ones, and then route hydrographs through drainage network to find the outlet hydrograph at the design point.

(A) Development of Synthetic Hydrograph

To investigate the possibility of deriving synthetic hydrograph procedures for the rural catchments in the state of Colorado, 25 basins were selected from those 30 basins used to develop Eq. 23. For each basin, the most representative unit hydrograph was derived from two to four rainfall/runoff events. All events had a duration of five minutes for the rainfall excess derived from the selected direct runoff hydrographs. Several empirical relationships have been developed as follows:

$$t_p = 15.14 \left(\frac{L_t}{\sqrt{S_b}} \cdot \frac{L_t^2}{A} \right)^{0.18} \qquad (R = 0.84) \qquad (25)$$

$$q_p = 812.83\, A^{1.01} \qquad (R = 0.71) \qquad (26)$$

$$W_{75} = 4073.8 \left(\frac{q_p}{A} \right)^{-0.80} \qquad (R = 0.73) \qquad (27)$$

$$W_{50} = 13803.84 \left(\frac{q_p}{A} \right)^{-0.88} \qquad (R = 0.85) \qquad (28)$$

in which t_p = time to peak on the unit hydrograph in minutes, q_p = peak runoff on the unit hydrograph in cfs, W_{75} = the width in minutes at the flow rate equal to 75% of the peak flow, W_{50} = the width in minutes at the flow rate equal to 50% of the peak flow and R = correlation coefficient which represents the goodness of the regression equation.

Table 10 tabulates the data array used in the synthetic unit hydrograph regression analyses. Fig's 6 through 9 present data scattering and the best fitted lines whose equations and statistics are shown in Tables 11 through 14. In this study, it was found that about one third (33%) of W_{75} and about one quarter (23%) of W_{50} should be allocated to the rising portion, i.e. before the time to peak. Detailed computations are presented in Table 15.

In general, when a basin becomes larger, the observed values deviate farther from the best fitted line. This may be improved by defining an upper limit of basin size based on data sensitivity in the derivation of the best fitted line. In application, any basin larger than the upper limitation of the synthetic hydrograph formulas should be divided into smaller ones.

USGS has attempted to derive a synthetic hydrograph for the Arkansas River Basin (Jarrett, 1981). However, the model used was not comprehensive enough to have applicable conclusion. These set of empirical formulas derived in this study are similar to many other synthetic unitgraph formulas, such as CUHP, except the values of exponents are different. To apply this method to the prediction of a storm hydrograph does not require any more basin information than the one-equation regression model developed in

Table 10 Unitgraph Characteristics from Colorado Small Basins.

Basin ID no.	Overland Flow Length (feet)	Channel Flow Length (feet)	Overland Flow Slope (%)	Channel Flow Slope (%)	Basin Area Sq Mile	Obs'd Peakflow on Unitgraph (cfs)	Obs'd Time to Peak (min)	Basin Slope (%)
6758150	2400.00	6500.00	3.79	1.31	0.62	470.00	35.00	1.9788
6760200	2800.00	19000.00	3.57	1.63	1.53	2350.00	35.60	1.8792
6758700	1120.00	7900.00	7.50	4.38	2.27	2500.00	22.30	4.7674
6825100	2000.00	33000.00	1.25	0.47	6.47	3300.00	50.10	0.5146
7107600	2300.00	17800.00	5.30	2.12	2.87	6350.00	33.60	2.4839
7112700	2450.00	19200.00	3.27	2.24	3.10	3600.00	34.50	2.3566
7129200	500.00	19900.00	5.00	2.04	3.56	3250.00	34.60	2.1125
6753800	2250.00	25170.00	6.44	1.77	4.68	5500.00	39.30	2.1532
9169800	4100.00	16200.00	26.34	1.88	4.40	5300.00	33.50	6.8202
7153450	1500.00	24200.00	8.27	3.90	4.56	2200.00	35.40	4.1551
9175800	1840.00	35190.00	17.93	4.69	5.33	4500.00	40.50	5.3479
6759700	1100.00	15800.00	1.36	0.73	2.35	800.00	35.30	0.7710
7125050	1450.00	28500.00	11.86	3.88	6.16	6900.00	37.80	4.2663
6821300	6800.00	34400.00	0.81	0.47	5.72	8400.00	52.30	0.5261
7099250	1600.00	29600.00	9.81	2.54	8.35	9200.00	40.20	2.9128
7124700	3100.00	37300.00	5.97	8.74	8.56	8800.00	39.10	8.5275
7123700	6820.00	21900.00	0.66	1.19	5.73	9500.00	40.10	1.0641
9306315	2400.00	63000.00	13.75	3.10	13.60	24000.00	53.70	3.4908
7134300	1400.00	59600.00	2.07	0.71	14.50	20500.00	60.90	0.7412
7138520	8300.00	37400.00	0.55	0.43	12.40	3200.00	54.90	0.4518
6826900	4200.00	23200.00	0.55	0.59	17.80	4733.00	43.30	0.5839
6760430	7000.00	22000.00	0.57	0.36	10.00	5100.00	45.50	0.4107

Basin ID no.	Basin Area Sq Mile	Obs'd PeakFlow on UH Cfs	Q/A	Obs'd 75% Width min	Obs'd 0.50 Width min
6759700	2.35	800.00	340.43	35.00	88.00
6758400	3.75	1300.00	346.67	43.50	90.00
7153450	4.56	2200.00	482.46	26.50	63.00
6760430	10.00	5100.00	510.00	32.00	57.00
9371300	4.43	2700.00	609.48	27.00	52.50
6825100	5.41	3300.00	609.98	24.00	45.00
6758150	0.62	470.00	758.06	18.50	43.50
7154800	3.50	2700.00	771.43	23.50	45.00
9175800	5.33	4500.00	844.28	24.00	39.50
7129200	3.56	3250.00	912.92	17.00	45.00
7123700	10.40	9500.00	913.46	20.50	36.00
7124700	8.46	8800.00	1040.19	9.00	19.00
6758700	2.27	2500.00	1101.32	21.00	34.00
7099250	8.35	9200.00	1101.80	11.20	26.10
7125050	6.16	6900.00	1120.13	14.60	28.00
7112700	3.10	3600.00	1161.29	16.50	31.50
9169800	4.40	5300.00	1204.55	10.50	28.50
6821300	6.55	8400.00	1282.44	11.00	18.00
6753800	4.28	5500.00	1285.05	11.00	22.00
7134300	13.90	20500.00	1474.82	16.00	23.00
6760200	1.53	2350.00	1535.95	8.00	21.20
9306315	13.60	24000.00	1764.71	12.00	25.50
7107600	2.87	6350.00	2212.54	12.50	21.00

Basin ID no.	Obs'd Time to Peak (min)	Measured L@3 / (A.S@.5) (shape)	Log10 Tp	Log10 shape	Pred'd Time to Peak (min)
6758700	22.30	10.06	1.35	1.00	23.23
9169800	33.50	49.46	1.53	1.69	31.03
6758150	35.00	54.91	1.54	1.74	31.63
6826900	43.30	102.75	1.64	2.01	35.44
7129200	34.60	111.46	1.54	2.05	35.97
7107600	33.60	121.97	1.53	2.09	36.56
7153450	35.40	124.06	1.55	2.09	36.68
7125050	37.80	143.44	1.58	2.16	37.66
7099250	40.20	144.78	1.60	2.16	37.72
7112700	34.50	144.87	1.54	2.16	37.72
6759700	35.30	158.91	1.55	2.20	38.36
7124700	39.10	179.21	1.59	2.25	39.21
6753800	39.30	203.94	1.59	2.31	40.15
6760430	45.50	258.54	1.66	2.41	41.91
7123700	40.10	272.27	1.60	2.43	42.31
9175800	40.50	279.86	1.61	2.45	42.52
6760200	35.60	335.58	1.55	2.53	43.95
6825100	50.10	627.59	1.70	2.80	49.25
9306315	53.70	747.87	1.73	2.87	50.84
7138520	54.90	777.96	1.74	2.89	51.21
6821300	52.30	1145.12	1.72	3.06	54.94
7134300	60.90	1235.23	1.78	3.09	55.70

```
          Regression Output:
Constant                            1.18
Std Err of Y Est                    0.04
R Squared                           0.84
No. of Observations                22.00
Degrees of Freedom                 20.00

X Coefficient(s)        0.18
Std Err of Coef.        0.02
```

Table 11 Regression Analysis for the Time to Peak on Unitgraph.

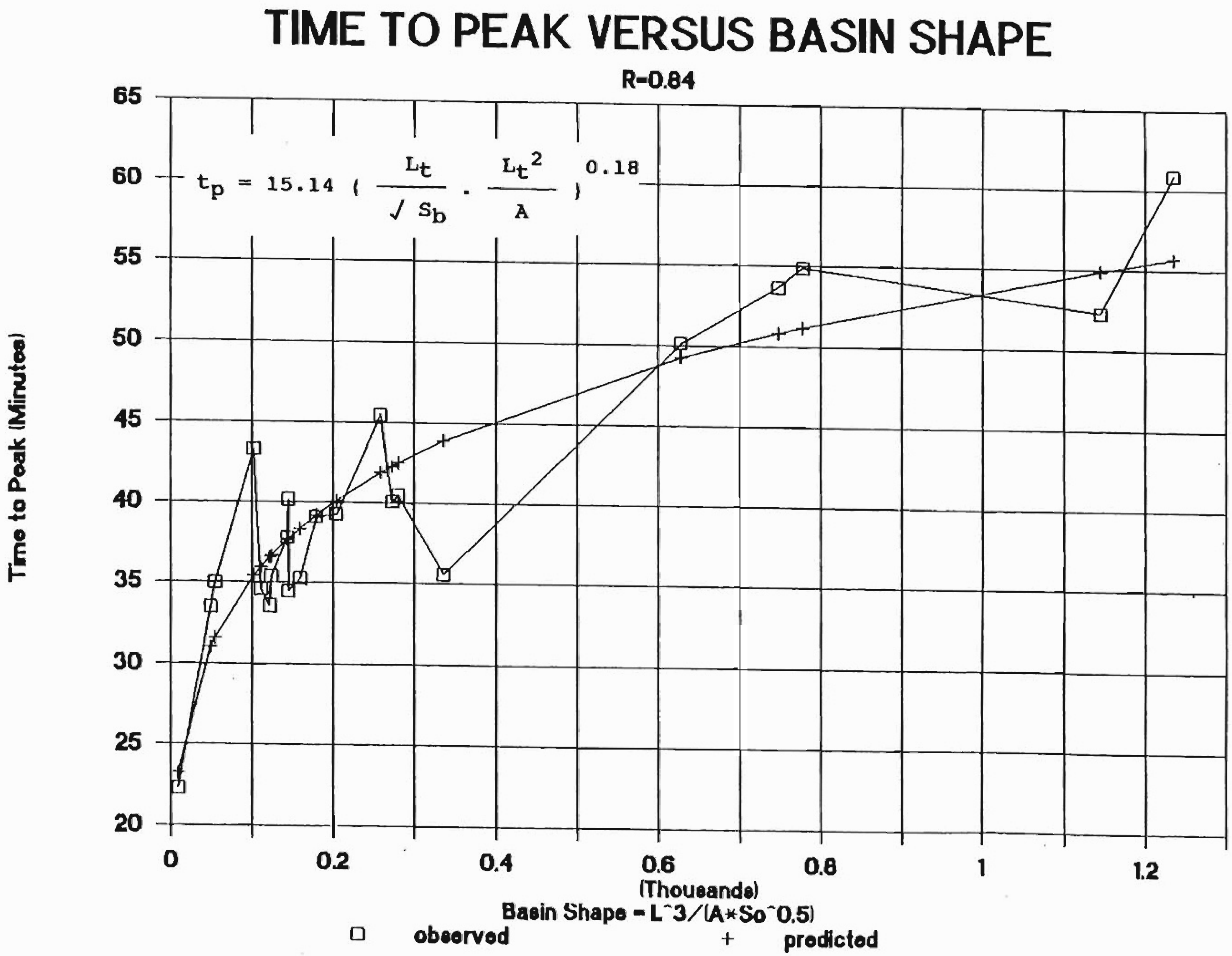

Figure 6 Time to Peak on Unit Hydrograph Versus Basin Shape.

Basin ID no.	Basin Area Sq Mile	Obs'd Peakflow on Unitgraph (cfs)	Log(Area)	Log(Qp)	Pred'd Peakflow on Unitgraph (cfs)
6758150	0.62	470.00	-0.21	2.67	500.77
6760200	1.53	2350.00	0.18	3.37	1249.51
6758700	2.27	2500.00	0.36	3.40	1862.83
6759700	2.35	800.00	0.37	2.90	812.43
7112700	3.10	3600.00	0.49	3.56	2553.68
7154800	3.50	2700.00	0.54	3.43	2887.48
7129200	3.56	3250.00	0.55	3.51	2937.59
6758400	3.75	1300.00	0.57	3.11	3096.35
6753800	4.28	5500.00	0.63	3.74	3539.69
9169800	4.40	5300.00	0.64	3.72	3640.16
9371300	4.43	2700.00	0.65	3.43	3665.29
7153450	4.56	2200.00	0.66	3.34	3774.19
9175800	5.33	4500.00	0.73	3.65	4419.93
6825100	5.41	3300.00	0.73	3.52	4487.09
7125050	6.16	6900.00	0.79	3.84	5117.28
6821300	6.55	8400.00	0.82	3.92	5445.35
7099250	8.35	9200.00	0.92	3.96	6962.46
7124700	8.46	8800.00	0.93	3.94	7055.31
6760430	10.00	5100.00	1.00	3.71	8356.71
7123700	10.40	9500.00	1.02	3.98	8695.16
7138520	12.40	3200.00	1.09	3.51	10389.66
9306315	13.60	24000.00	1.13	4.38	11408.01
7134300	13.90	20500.00	1.14	4.31	11662.77
7107600	2.87	6350.00	0.46	3.80	2361.99

Regression Output:

Constant		2.91
Std Err of Y Est		0.19
R Squared		0.71
No. of Observations		20.00
Degrees of Freedom		18.00
X Coefficient(s)	1.01	
Std Err of Coef.	0.15	

Table 12 Regression Analysis for the Peak Runoff on Unitgraph.

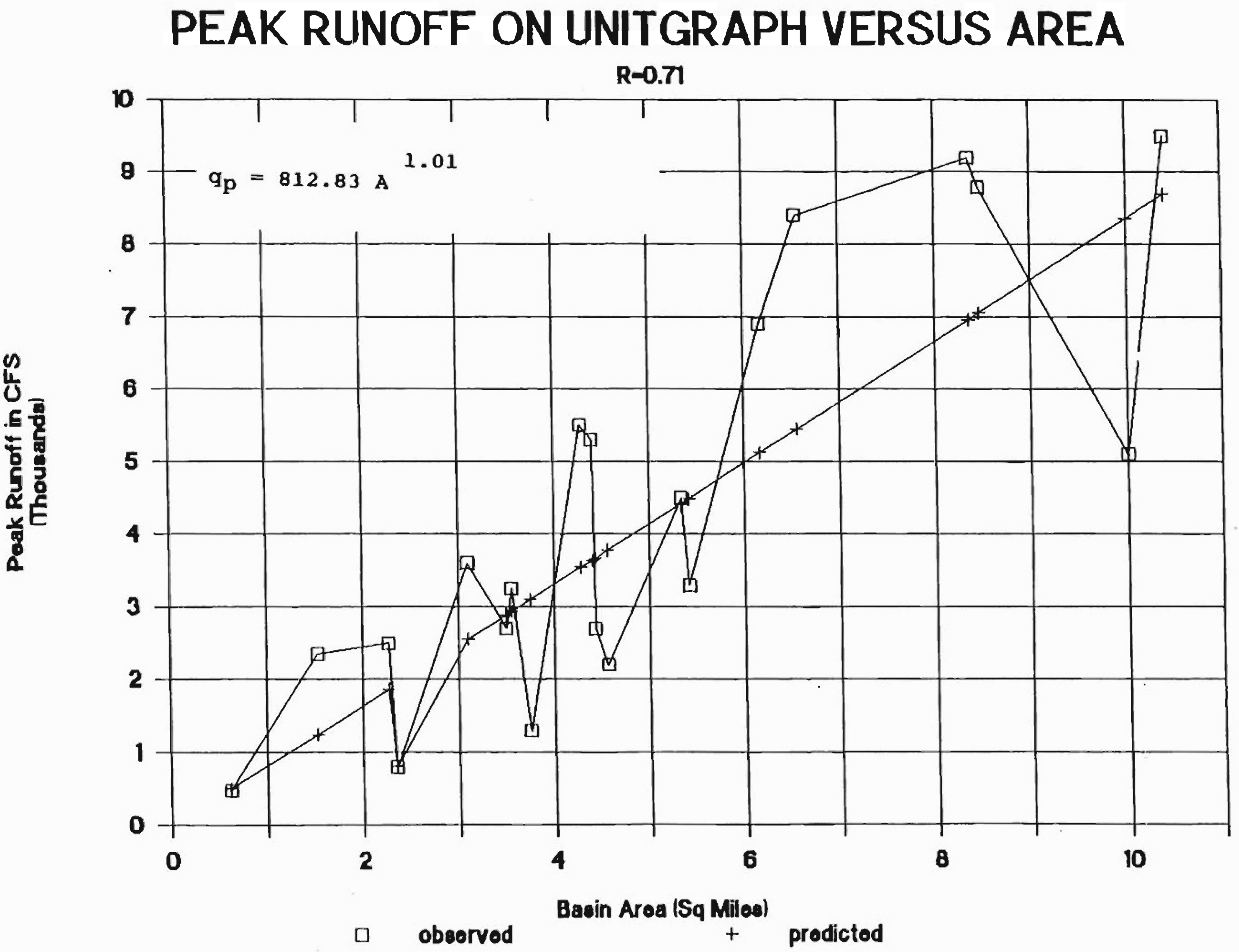

Figure 7 Peak Flow on Unit Hydrograph Versus Basin Area.

Basin ID no.	Q/A	Obs'd Width W75 at 75% Qp (min)	Log10 of Q/A	Log10 of Obs'd W75	Pred'd Width W75 at 75% Qp (min)
6759700	340.43	35.00	2.53	1.54	38.52
6758400	346.67	43.50	2.54	1.64	37.97
7153450	482.46	26.50	2.68	1.42	29.15
6760430	510.00	32.00	2.71	1.51	27.88
9371300	609.48	27.00	2.78	1.43	24.18
6825100	609.98	24.00	2.79	1.38	24.16
6758150	758.06	18.50	2.88	1.27	20.31
7154800	771.43	23.50	2.89	1.37	20.03
9175800	844.28	24.00	2.93	1.38	18.63
7129200	912.92	17.00	2.96	1.23	17.50
7123700	913.46	20.50	2.96	1.31	17.50
7124700	1040.19	9.00	3.02	0.95	15.77
6758700	1101.32	21.00	3.04	1.32	15.07
7099250	1101.80	11.20	3.04	1.05	15.06
7125050	1120.13	14.60	3.05	1.16	14.86
7112700	1161.29	16.50	3.06	1.22	14.44
9169800	1204.55	10.50	3.08	1.02	14.02
6821300	1282.44	11.00	3.11	1.04	13.34
6753800	1285.05	11.00	3.11	1.04	13.32
7134300	1474.82	16.00	3.17	1.20	11.93
6760200	1535.95	8.00	3.19	0.90	11.55
9306315	1764.71	12.00	3.25	1.08	10.33
7107600	2212.54	12.50	3.34	1.10	8.62

```
                 Regression Output:

Constant                                 3.61
Std Err of Y Est                         0.11
R Squared                                0.73
No. of Observations                     23.00
Degrees of Freedom                      21.00

X Coefficient(s)        -0.80
Std Err of Coef.         0.11
```

Table 13 Regression Analysis for 75% Width on Unitgraph.

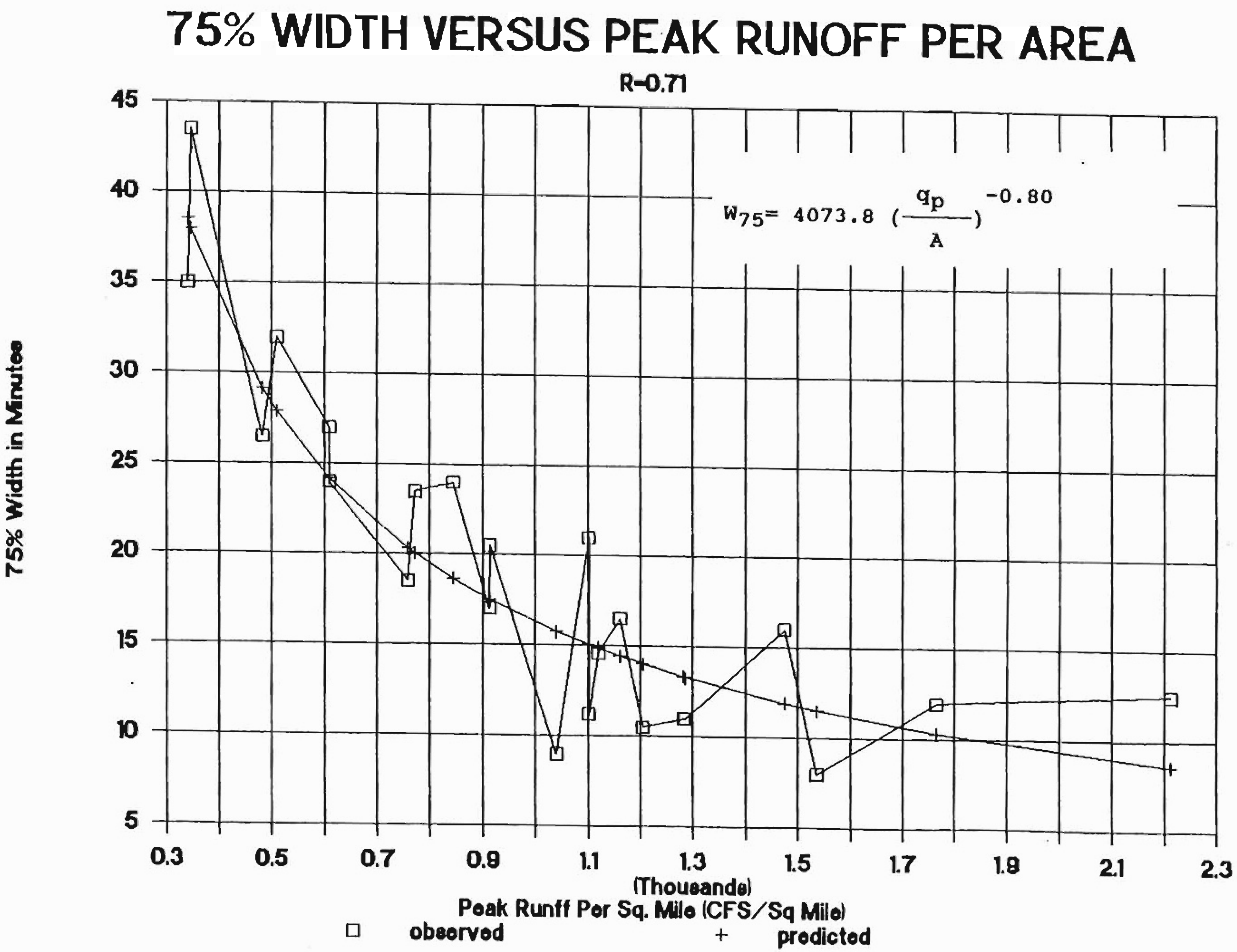

Figure 8 75% Width on Unit Hydrograph Versus Peak Runoff/Area.

Basin ID no.	Q/A	Obs'd 50% Width min	Log10 of Q/A	Log10 of W50	Pred'd 50% Width min
6759700	340.43	88.00	2.53	1.94	83.67
6758400	346.67	90.00	2.54	1.95	82.35
7153450	482.46	63.00	2.68	1.80	61.64
6760430	510.00	57.00	2.71	1.76	58.71
9371300	609.48	52.50	2.78	1.72	50.22
6825100	609.98	45.00	2.79	1.65	50.18
6758150	758.06	43.50	2.88	1.64	41.48
7154800	771.43	45.00	2.89	1.65	40.85
9175800	844.28	39.50	2.93	1.60	37.74
7129200	912.92	45.00	2.96	1.65	35.24
7123700	913.46	36.00	2.96	1.56	35.22
7124700	1040.19	19.00	3.02	1.28	31.43
6758700	1101.32	34.00	3.04	1.53	29.90
7099250	1101.80	26.10	3.04	1.42	29.89
7125050	1120.13	28.00	3.05	1.45	29.46
7112700	1161.29	31.50	3.06	1.50	28.54
9169800	1204.55	28.50	3.08	1.45	27.64
6821300	1282.44	18.00	3.11	1.26	26.16
6753800	1285.05	22.00	3.11	1.34	26.12
7134300	1474.82	23.00	3.17	1.36	23.15
6760200	1535.95	21.20	3.19	1.33	22.34
9306315	1764.71	25.50	3.25	1.41	19.78
7107600	2212.54	21.00	3.34	1.32	16.22

Regression Output:

Constant		4.14
Std Err of Y Est		0.08
R Squared		0.85
No. of Observations		23.00
Degrees of Freedom		21.00
X Coefficient(s)	-0.88	
Std Err of Coef.	0.08	

Table 14 Regression Analysis for 50% Width on Unitgraph.

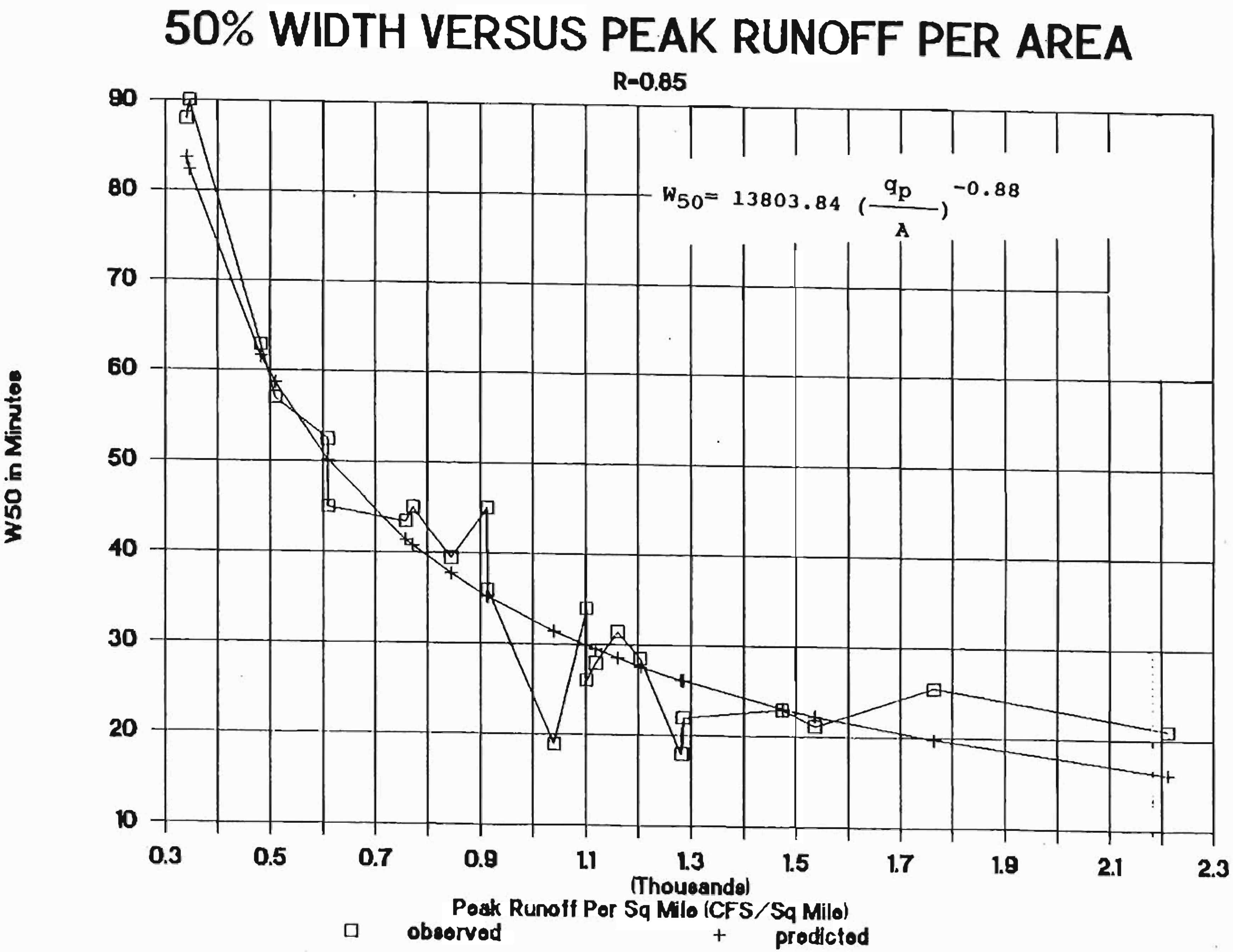

Figure 9 50% Width on Unit Hydrograph Versus Peak Runoff/Area.

Study of Width Distribution, Recession Width/Rising Width

W75	W50
2.60	3.10
2.00	2.80
2.00	2.00
1.20	5.50
2.00	6.50
4.00	1.00
1.00	5.00
3.20	3.20
2.80	4.20
3.00	2.20
2.00	3.00
2.00	2.60
1.80	2.80
2.00	1.30
1.30	6.00
3.50	10.00
3.00	1.70
1.10	2.50
2.10	2.50
3.00	3.60
1.20	2.80
1.10	1.30
1.00	1.40
1.00	1.00
1.60	1.80
4.00	6.00
Average	Average
2.13	3.30
Sd	Sd
0.92	2.07

Table 15 Regression Analysis of Width Skewness on Unitgraph.

this study; but it has much more flexibility and adaptability to simulate a wide variety of hydrologic phenomena.

B. Design Example

The gaging station 071334300 located in the Arkansas River Basin, on Wolf Creek near Carlton, Colorado was randomly selected. Basin hydrologic parameters are:

Basin Area	14.4 square miles (measured from USGS map).
Flow Length	11.55 miles (measure from USGS map).
Basin Slope	0.0074 ft/ft.

Substituting the above basin hydrologic parameters into Eq's 25 through 29 for shaping the basin unit hydrograph yields the time to peak, t_p, equal to 54.5 minutes, q_p, equal to 12105.5 cfs, W_{75}, equal to 18.7 minutes, and W_{50}, equal to 37.1 minutes. Detailed computations of the synthetic unit hydrograph are presented in Table 16 and plotted in Fig. 10.

Using the Horton's infiltration exponential formula, rainfall excess was determined as shown in Table 17. The values for the parameters used in the Horton's infiltration formula were determined based on the soil antecedent moisture condition and estimate of depression losses for a rural basin. As shown in Table 17, although rainfall duration was recorded as long as seventy minutes, only two rain blocks of ten minutes produced rainfall excess for the runoff hydrograph. The corresponding storm hydrograph convolution is computed and presented in Table

18 and then plotted in Fig. 11. It can be seen that the predicted hydrograph with a peak runoff of 455.35 cfs, gives good agreements in both shape and peak runoff, to the observed hydrograph with a peak runoff of 464 cfs.

Total rainfall depth in this event was 1.02 inch for a duration of 70 minutes. The corresponding uniform rainfall intensity is

$$i = 1.02 *60/70 = 0.87 \text{ inch/hr.}$$

Using Eq. 23, we have

$$\frac{Q_p}{iA} = 12.503 \left(\frac{14.5}{11.55 \text{x} 11.55}\right)^{0.026} (0.0074)^{0.134} \left(\frac{1.02/12}{11.55 \text{x} 5280}\right)^{0.284}$$

$$\approx 0.0513$$

So, the peak runoff is

$$Q_p = 0.0513 \text{ x } 14.5 \text{ x } 5280 \text{ x } 5280 \text{ x } 0.87/(12 \text{x} 3600) = 417.6 \text{ cfs}$$

For this example, the predicted runoff peak from Eq. 23 is about ten percent lower than the observed one.

For a hydrologically complicated drainage basin, the advantage of using a storm hydrograph other than just a peak runoff is that we can route hydrographs through drainage network flood routing in a drainage network consisting of pipes, channel, and ponds, is independent of basin hydrology. There are several routing models available such as RUNOFF Block of the EPA SWMM Model, HEC-1 Flood Hydrograph Model of the Corps of Engineering, and UDSWMM routing Model of the Denver Urban Drainage and Flood Control District. As long as the hydrograph prediction procedures have been developed and calibrated against local runoff data, the predicted storm hydrograph can then be transferred into any existing routing computer model for flood routing computations.

COMPUTATION OF SYNTHETIC UNITGRAPH

Gage Number	7134300
River Basin	Arkansas River
Location	Near Carlton, Colorado
Basin Area	14.5 Sq miles
Length	11.55 Miles
Slope	0.0074

Unitgraph Parameters	Tp =	54.53094 Minutes
	Qp =	12105.46 Cfs
	W75 =	18.73738 Minutes
	W50 =	37.06637 Minutes

Time Minutes	Unitgraph Cfs
0	0
5	100
10	250
15	475
20	600
25	900
30	1250
35	2000
40	3750
45	6000
50	10000
55	12100
60	11000
65	9500
70	8400
75	7250
80	6125
85	5500
90	4750
95	4000
100	3750
105	3250
110	2500
115	2150
140	850
145	500
150	250
155	100
160	50

Volume 34020000 cubic ft
Depth 1.009903 inch

Table 16 Computation of Synthetic Unitgraph for Station 7134300

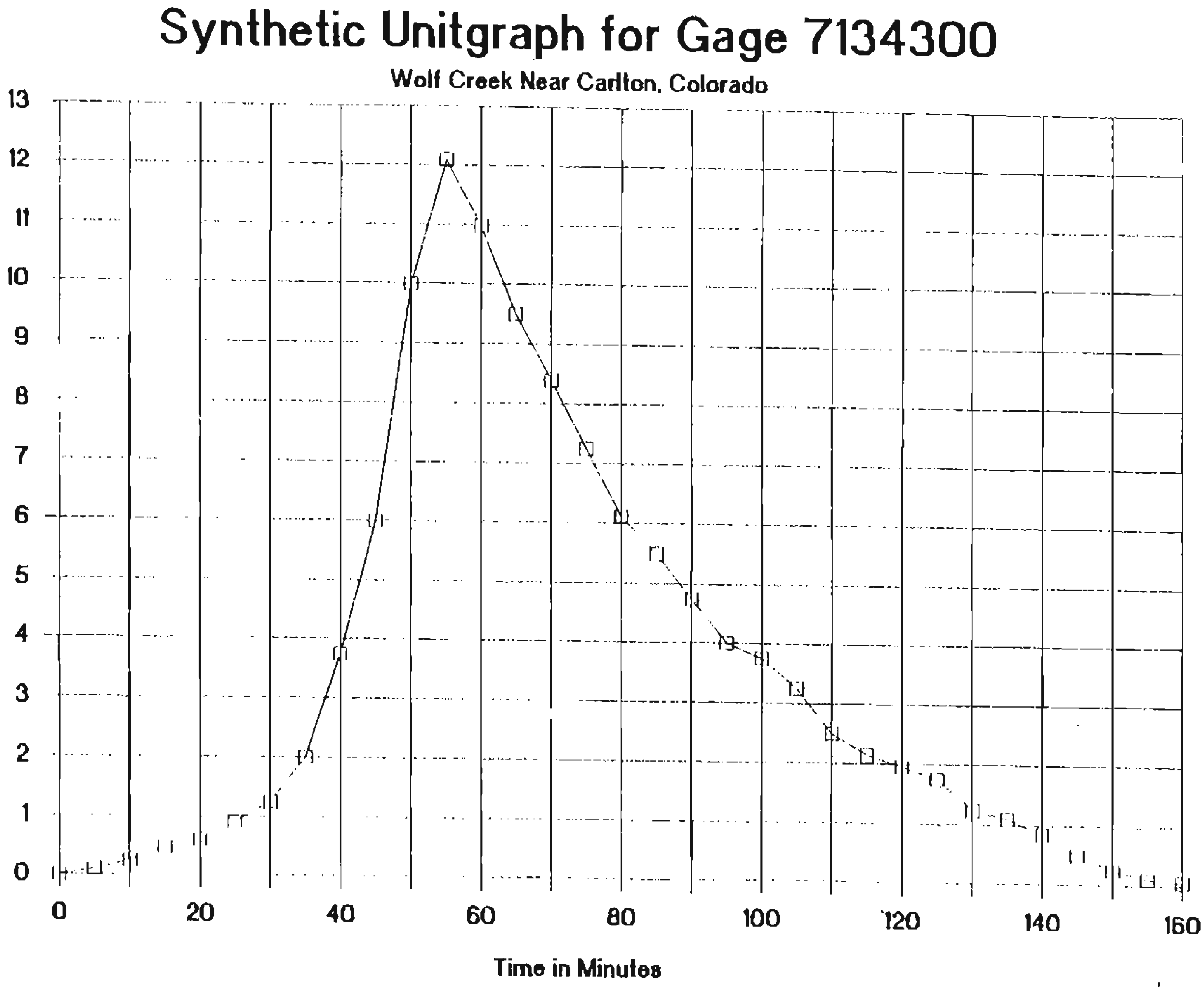

Figure 10 Synthetic Unit Hydrograph for Gaging Station 7134300.

RAINFALL EXCESS COMPUTATION

Gage Number	7134300
River Basin	Arkansas River
Location	Near Carlton, Colo

Horton's Infiltration Loss

Fo = 8.5 inches

Fc = 0.19 Inches

K = -0.0018 1/sec

Date: June 2-5, 1978

Rain started at 23:00 P.M..

Time Minutes	Observed Precip Inch	Soil Loss Inch	Net Precip Inch
0	0	8.5	0
5	0.02	5.032637	0
10	0.01	3.012038	0
15	0.04	1.834538	0
20	0.04	1.148351	0
25	0.05	0.748477	0
30	0.09	0.515451	0
35	0.04	0.379656	0
40	0.15	0.300522	0
45	0.29	0.254406	0.035593
50	0.23	0.227532	0.002467
55	0.04	0.211872	0
60	0.01	0.202745	0
65	0.01	0.197427	0
70	0.005	0.194328	0
75	0.005	0.192522	0
80			
85			

Table 17 Rainfall Excess Computation for Station 7134300

COMPUTATION OF HYDROGRAPH CONVOLUTION

Gage Number	7134300
River Basin	Arkansas River
Location	Near Carlton, Colorado
Basin Area	14.5 Sq miles

Rain started at 23:00 P.M. on June 2, 1978

Time Minutes	Net Precip Inch	Unitgraph Cfs	Hydrograph Convolution		Computed Hydrograph CFS	Observ'd Hydrograph CFS
0	0	0			0	0
5	0	100			0	0
10	0	250			0	0
15	0	475			0	0
20	0	600			0	0
25	0	900			0	0
30	0	1250			0	0
35	0	2000			0	0
40	0	3750			0	0
45	0.035593	6000	0		0	0
50	0.002467	10000	3.56	0.00	3.56	0.00
55	0	12100	8.90	0.25	9.15	0.00
60	0	11000	16.91	0.62	17.52	4.00
65	0	9500	21.36	1.17	22.53	7.00
70	0	8400	32.03	1.48	33.51	9.00
75	0	7250	44.49	2.22	46.71	9.00
80		6125	71.19	3.08	74.27	74.00
85		5500	133.48	4.93	138.41	80.00
90		4750	213.56	9.25	222.81	389.00
95		4000	355.93	14.80	370.74	464.00
100		3750	430.68	24.67	455.35	449.00
105		3250	391.53	29.85	421.38	422.00
110		2500	338.14	27.14	365.28	446.00
115		2150	298.99	23.44	322.42	377.00
120		1950	258.05	20.72	278.78	290.00
125		1750	218.01	17.89	235.90	233.00
130		1250	195.76	15.11	210.88	246.00
135		1100	169.07	13.57	182.64	220.00
140		850	142.37	11.72	154.09	184.00
145		500	133.48	9.87	143.34	192.00
150		250	115.68	9.25	124.93	168.00
155		100	88.98	8.02	97.00	147.00
160		50	76.53	6.17	82.69	132.00
165			69.41	5.30	74.71	123.00
170			62.29	4.81	67.10	117.00
175			44.49	4.32	48.81	102.00
180			39.15	3.08	42.24	93.00
185			30.25	2.71	32.97	84.00
190			17.80	2.10	19.89	74.00
195			8.90	1.23	10.13	65.00
200			3.56	0.62	4.18	0.00

Table 18 Hydrograph Convolution for Station 7134300

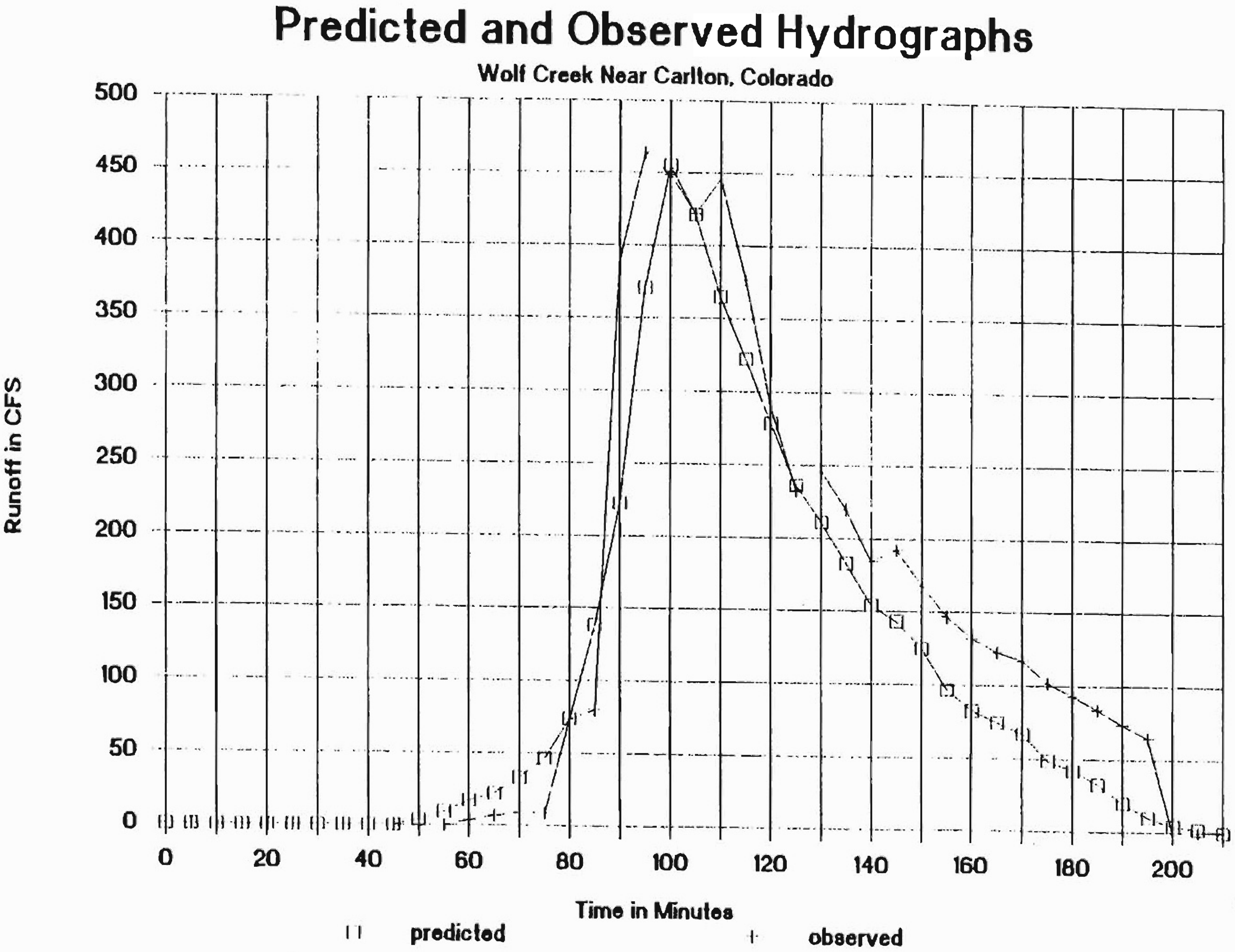

Figure 11 Predicted and Observed Hydrographs at Station 7134300.

CHAPTER VII

CONCLUSIONS AND FUTURE STUDY

In this study, a peak runoff regression model was derived using dimensional analysis. The model was calibrated by 63 rainfall/runoff events observed from 30 small rural basins in the state of Colorado. It has been found that basin area, slope, shape factor, precipitation, vegetation, and soil type are important factors. In the developed model, vegetation and soil type are merged into a single coefficient. Although for some combinations of soil type and vegetation, sample data were not enough to adequately calibrate the model, the general trend agrees to common understanding of catchment behavior.

The assumptions for the developed model are:

(1) the recurrence interval of the peak flow rate is the same as that of the precipitation,

(2) the rainfall is uniformly distributed in space over the drainage,

(3) the rainfall intensity is uniform throughout the time of concentration of the basin, and

(4) for a short rain, the effective, i.e. contributing area,

can be linearly determined by the T_d/T_c ratio

An extensive investigation was also performed on the feasibility of developing a synthetic unit hydrograph method. More than 75 rainfall/runoff events selected from 25 small basins were examined and used in the developments of empirical formulas for shaping the synthetic unit hydrograph, such as the time to peak, peak runoff, 75 percent width, and 50 percent width. Correlation coefficients between 0.71 to 0.85, have been obtained.

CONCLUSIONS

The following summary and conclusions are drawn from this study:

1. The peak runoff prediction regression model developed in this study was formulated by the dimensional analysis. It provides a new methodology to estimate peak discharge from the small rural watersheds in Colorado.

2. A total of 272 events from 43 small gaged basins were used in the data screening process and among these, 63 events were selected and used in the regression analysis, including 56 events from the eastern Colorado and seven from the western Colorado. The basin area ranged from 0.62 square miles to 14.5 square miles and average basin slopes ranged from 0.004 to 0.07. The range of the observed runoff coefficients was between 0.1 and 0.4.

3. The resulting regression model had a correlation coefficient of 0.72. In the model, the shape factor was raised to the 0.026 power, slope to the 0.134 power and rainfall factor to the 0.284 power. This indicates that shape factor was less important variable than the rainfall factor. The basin slope plays an important role in the prediction of peak flow as well as in the determination of the time of concentration.

4. This model improves the rational method by including more basin drainage factors. It presents a more objective and specific way to obtain the appropriate value rather than just guessing a value in a given range.

5. Compared with the results from the frequency analysis using an average record of 10 years, the peak flow predicted by the regression model developed in this study seems a little higher for smaller floods such as a 2-year runoff and a little lower for larger floods such as a 100-year flood.

6. Results from the synthetic unit hydrograph study are encouraging. There were 25 basins used in the regression analysis. The correlation of coefficients for those empirical formulas developed are between 0.71 to 0.85. Agreements between the predicted and observed

hydrographs for a randomly selected event are reasonably good.

FUTURE STUDY

It is obvious that the one-equation approach is too simple to adequately include a wide variety of rural basin hydrology. With the advent of the high speed personal computers, the complicated computations of hydrograph convolution and flood routing can be replaced by a digital simulation. Merits of this approach are not only to improve accuracy of computation but also to allow the engineer to divide the basin into more hydrologically homogenous subbasins.

In the state of Colorado, a ten-year effort has been spent in the collection of the rainfall-runoff data from those selected small drainage basins. It is worthy of extending our efforts to make more use of these costly collected data and further develop a synthetic hydrograph method which takes advantage of new computer technology and provides more reliable runoff predictions.

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Appendix I

Locations
of
Gaging Stations
of
Small Watersheds
in
Colorado.

USGS Station No.	Station name	Location Latitude	Location Longitude
06753800	Owl Creek Tributary Near Rockport, CO.	40°55'07"	104°46'01"
06756200	Geary Creek Tribut. Near Rockport, CO.	40°58'00"	104°33'50"
06758150	Kiowa Creek Tribut. Near Elbert, CO.	39°12'06"	104°30'14"
06758250	Kiowa Creek Tribt.	39°36'47"	104°27'01"
06758400	Goose Creek Near Hoyt, CO.	40°01'10"	104°13'06"
06758700	Middle Bijou Creek Near Dear Tail, CO.	39°20'33"	104°09'46"
06759700	Sand Creek Tribut. Near Lindon, CO.	39°43'54"	103°21'18"
06759900	Antelope Draw Near Union, CO.	40°25'57"	103°36'15"
06760200	Igo Creek Tribut. Near Keota, CO.	40°47'24"	103°57'18"
06760300	Darby Creek Near Buchanan, CO.	40°52'48"	103°19'12"
06760430	Spring Canyon Creek Near Peetz, CO.	40°58'12"	103°00'34"
06821300	N. Fork Arikaree River Near Shan, CO.	39°31'12"	103°26'35"
06821400	N. Fork Black Wolf Creek, Near Vernon, CO	39°54'24"	102°16'08"
06822600	Patent Creek Near St. Peters, CO.	40°29'50"	102°46'30"
06825100	Landsman Crek Tribt. Near Stratton, CO.	39°06'43"	102°40'25"

06826900	Sand Creek Near Hale, CO.	39°41'50"	102°10'37"
06857500	Big Timber Creek Tribt. Near Arapahoe, CO.	38°59'36"	102°17'06"
07099250	Soda Creek Near Livesey, CO.	38°11'46"	104°50'44"
07107600	St. Charles River Tribt. Near Goodpasture, CO.	38°04'05"	104°46'33"
07112700	Butte Creek Near Delcarbon, CO.	37°42'24"	104°51'58"
07120600	Timpas Creek Tribt. Near Thatcher, CO.	37°34'18"	104°06'10"
07123700	Mustang Creek Near Karval, CO.	38°33'54"	103°31'18"
07124700	Gray Creek Near Engleville, CO.	37°09'36"	104°25'38"
07125050	Tingley Canyon Creek Near Ludlow, CO.	37°16'48"	104°32'04"
07126400	Red Rock Canyon Creek Near Bloom, CO.	37°33'24"	103°50'20"
07129100	Rule Creek Near Ninaview, CO.	37°33'57"	103°10'26"
7129200	Muddy Creek Trib. Near Ninaview, CO.	37°35'56"	103°19'48"
7133200	Clay Creek Trib. Near Deora, CO.	37°43'27"	102°44'24"
7134300	Wolf Creek Near Carlton, CO.	37°52'30"	102°28'54"
7135800	Wild Horse Creek Trib. Near Hartman, CO.	38°15'45"	102°09'42"
7138520	Little Bear Creek Tribut. Near Lycan, CO.	37°37'48"	102°07'30"
07153450	Longs Canyon Creek Near Tobe, CO.	37°05'24"	103°41'09"

07154800	Cimarron River Trib. Near Edler, CO.	37°05'10"	102°45'38"
09151700	Deer Creek Trib. Near Dominguez, CO.	38°51'30"	108°18'53"
09163300	East Salt Creek Trib. Near Mack, CO.	39°21'28"	108°48'51"
09168700	Disappointment Creek Trib. Near Slick Rock, CO.	38°01'33"	108°48'51"
09169800	E. Paradox Creek Trib. Near Bedrock, CO.	38°16'53"	108°48'21"
09175800	Dead Horse Creek Near Naturita, CO.	38°02'37"	108°34'38"
09179400	West Creek Tribt. Near Gateway, CO.	38°43'01"	108°55'28"
09247520	Cedar Mountain Gulch At Craig, CO.	40°30'52"	107°34'31"
09306315	Gillam Draw Near Rangely, CO.	40°05'31"	108°44'45"
09306390	West Twin Wash Near Dinosaur, CO.	40°14'34"	108°57'16"
09371300	McElmo Creek Trib. Near Cortez, CO.	37°20'51"	108°28'56"

Appendix II

Regression Analysis
for
the Coefficients
under
Various Vegetation
and
Soil Combinations.

```
                         BARE GROUND AND SOIL B

  Product= (A/L^2)^b2*Sb^b3*(P/L)^b4
    b1=      12.50000
    b2=       0.02624
    b3=       0.13385
    b4=       0.28421

  Total number of events      29.00000
                              Average  12.94614 Sum        375.44
=================================================================================
Obsev'd     A/L^2      Sb       P/L *E-number                           Predicted
Runoff Co  shape     slope     dpt/lgth   number  Product  Coeff       Runoff Cp
=================================================================================
 0.31132  0.17353  0.02152  0.42550  5.00000  0.01700 18.31620  0.22005
 0.28681  0.21821  0.01978  0.57110  5.00000  0.01838 15.60225  0.23798
 0.22679  0.21821  0.01978  0.50560  5.00000  0.01776 12.77182  0.22989
 0.21580  0.17353  0.02152  0.13400  5.00000  0.01224 17.63173  0.15845
 0.19890  0.14760  0.04290  0.13680  5.00000  0.01345 14.79335  0.17406
 0.19480  0.21821  0.01978  0.63670  5.00000  0.01896 10.27450  0.24545
 0.17978  0.09394  0.00527  0.23037  5.00000  0.01164 15.44843  0.15066
 0.17295  0.09394  0.00527  0.34414  5.00000  0.01304 13.25938  0.16886
 0.17263  0.09394  0.00527  0.32969  5.00000  0.01289 13.39718  0.16682
 0.16362  0.43952  0.00785  0.18387  5.00000  0.01199 13.64771  0.15521
 0.16275  0.25600  0.02110  0.42670  5.00000  0.01714  9.49547  0.22189
 0.15144  0.17353  0.02152  0.10637  5.00000  0.01146 13.21254  0.14839
 0.13970  0.21795  0.00926  0.35066  5.00000  0.01446  9.66329  0.18716
 0.12697  0.43952  0.00785  0.18387  5.00000  0.01199 10.59069  0.15521
 0.11665  0.14760  0.04290  0.15754  5.00000  0.01400  8.33476  0.18119
 0.11340  0.13390  0.00540  0.02827  5.00000  0.00649 17.46804  0.08404
 0.11005  0.08975  0.01881  0.02064  5.00000  0.00694 15.85075  0.08988
 0.10820  0.43952  0.00785  0.16006  5.00000  0.01153  9.38789  0.14921
 0.10698  0.09394  0.00527  0.14361  5.00000  0.01017 10.51422  0.13172
 0.10698  0.09394  0.00527  0.34183  5.00000  0.01302  8.21744  0.16854
 0.10154  0.13390  0.00540  0.29020  5.00000  0.01258  8.06912  0.16291
 0.20500  0.66100  0.00580  0.26800  5.00000  0.01295 15.82766  0.15906
 0.26100  0.66100  0.00580  0.70560  5.00000  0.01705 15.30435  0.20944
 0.18170  0.66100  0.00580  0.17640  5.00000  0.01150 15.79940  0.14123
 0.13604  0.16560  0.00451  0.19330  5.00000  0.01101 12.36110  0.13516
 0.15200  0.16560  0.00451  0.15135  5.00000  0.01027 14.80577  0.12608
 0.16254  0.16560  0.00451  0.12582  5.00000  0.00974 16.68594  0.11963
 0.08800  0.15650  0.00630  0.08343  6.00000  0.00470 18.70697  0.05777
=================================================================================
```

WOODS AND SOIL B

```
Product= (A/L^2)^b2*Sb^b3*(P/L)^b4
  b1=     12.50000
  b2=      0.02624
  b3=      0.13385
  b4=      0.28421

Total number of events      12.00000
                            Average  12.28073 sum=       147.37
=========================================================================
Obsev'd    A/L^2      Sb       P/L *E-number                      Predicted
Runoff Co  shape     slope     dpt/lgth    number Product  Coeff  Runoff Cp
=========================================================================
 0.11213  0.08864  0.03486  0.34404  6.00000  0.00872 12.86488  0.10704
 0.17671  0.29766  0.06808  0.31609  5.00000  0.01848  9.56048  0.22699
 0.18065  0.29766  0.06808  0.18062  5.00000  0.01577 11.45862  0.19361
 0.19543  0.10837  0.05347  0.12152  5.00000  0.01328 14.71499  0.16310
 0.17080  0.10837  0.05347  0.99000  6.00000  0.01253 13.63185  0.15387
 0.28940  0.18000  0.04100  0.35100  5.00000  0.01756 16.48152  0.21564
 0.20000  0.19400  0.01060  0.28730  5.00000  0.01387 14.42206  0.17030
 0.20100  0.19400  0.01060  0.44974  5.00000  0.01575 12.76083  0.19344
 0.20580  0.29766  0.06808  0.30330  5.00000  0.01827 11.26581  0.23650
 0.13510  0.29766  0.06808  0.20330  5.00000  0.01630  8.28609  0.21108
 0.17590  0.29766  0.06808  0.90000  6.00000  0.01293 13.60005  0.16744
 0.11310  0.14760  0.04290  0.14210  5.00000  0.01359  8.32152  0.17595
=========================================================================
```

BARE GROUND AND SOIL D

```
Product= (A/L^2)^b2*Sb^b3*(P/L)^b4
  b1=     12.50000
  b2=      0.02624
  b3=      0.13385
  b4=      0.28421

Total number of events      7.00000
                            Average  12.95271 sum=     90.66896
=========================================================================
Obsev'd  A/L^2     Sb           P/L*E-number                     Predicted
  Co     shape    slope     precip      number Product  Coeff    Cp
=========================================================================
 0.16405  0.19804  0.02488  0.12438  5.00000  0.01226 13.38061  0.15057
 0.21460  0.19804  0.02488  0.14925  5.00000  0.01291 16.61997  0.15857
 0.18732  0.19804  0.02488  0.16584  5.00000  0.01330 14.07910  0.16339
 0.17338  0.19804  0.02488  0.55970  5.00000  0.01880  9.22255  0.23087
 0.22947  0.19804  0.02488  0.66750  5.00000  0.01976 11.61013  0.24272
 0.20992  0.10864  0.00743  0.34426  5.00000  0.01371 15.31049  0.16838
 0.17309  0.28236  0.01842  0.40022  5.00000  0.01657 10.44611  0.20349
=========================================================================
```

WOODS AND SOIL D

```
Product= (A/L^2)^b2*Sb^b3*(P/L)^b4
  b1=    12.50000
  b2=     0.02624
  b3=     0.13385
  b4=     0.28421

Total number of events       3.00000
                            Average  13.64467 sum=      40.93400
=========================================================================
Obsev'd    A/L^2      Sb     P/L *E-number                          Predicted
Runoff Co  shape     slope   dpt/lgth    number  Product   Coeff    Runoff Cp
=========================================================================
 0.17870  0.12935  0.06667  0.99784  6.00000  0.01299 13.75231  0.15958
 0.13784  0.23848  0.02108  0.17974  5.00000  0.01338 10.30263  0.16431
 0.12972  0.30793  0.02095  0.25033  6.00000  0.00769 16.87905  0.09438
=========================================================================
```

BARE GROUND AND SOIL C

```
Product= (A/L^2)^b2*Sb^b3*(P/L)^b4
  b1=    12.50000
  b2=     0.02624
  b3=     0.13385
  b4=     0.28421

Total number of events       3.00000
                            Average  10.60242 sum=      31.80725
=========================================================================
Obsev'd    A/L^2      Sb     P/L *E-number                          Predicted
Runoff Co  shape     slope   dpt/lgth    number  Product   Coeff    Runoff Cp
=========================================================================
 0.19386  0.33149  0.00414  0.54023  5.00000  0.01484 13.06440  0.18223
 0.12929  0.33149  0.00414  0.48276  5.00000  0.01437  8.99599  0.17650
 0.06913  0.33149  0.00414  0.40230  6.00000  0.00709  9.74686  0.08710
=========================================================================
```

WOODS AND SOIL C

```
Product= (A/L^2)^b2*Sb^b3*(P/L)^b4
  b1=    12.50000
  b2=     0.02624
  b3=     0.13385
  b4=     0.28421

Total number of events       4.00000
                            Average  13.68257 sum=      54.73030
=========================================================================
Obsev'd    A/L^2      Sb     P/L *E-number                          Predicted
Runoff Co  shape     slope   dpt/lgth    number  Product   Coeff    Runoff Cp
=========================================================================
 0.30224  0.22938  0.00769  0.58185  5.00000  0.01631 18.53501  0.20025
 0.13769  0.19145  0.04247  0.13077  5.00000  0.01335 10.31620  0.16391
 0.11661  0.19145  0.04247  0.63996  6.00000  0.01089 10.70432  0.13378
 0.20870  0.18438  0.02356  0.19246  5.00000  0.01375 15.17477  0.16890
=========================================================================
```

Appendix III

Case Study
and
Comparisons
of
Peak Flow Predictions
Among
Different Methods.

Case I

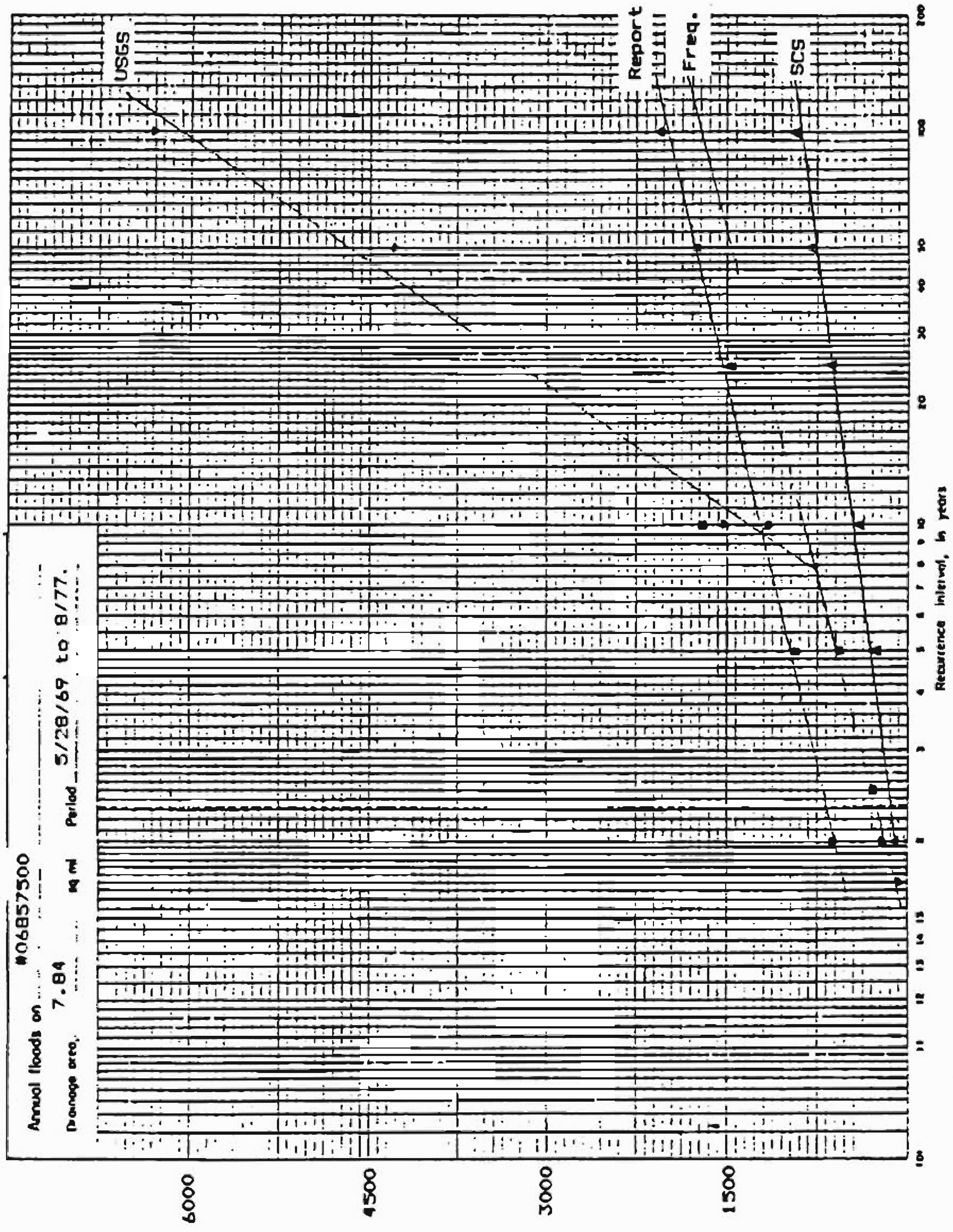
Kansas River Basin

Gaging Station: #06857500
Big Timber Creek Tributary near
Arapahoe, Colo.

Location: Lat. 38°59'36", Long. 102°17'06", in NE 1/4, Sec 24-T12S-R44W, Cheyenne County, on right bank, 800 feet upstream from unnamed tributary, 11.5 miles northwest of Arapahoe and 13 miles northeast of Cheyenne Wells.

Drainage Area: 7.84 sq. mile.
Period of Records: 5/28/69 to 8/77.
Remarks: Basin cover is natural prairie vegatation and cultivated crops.

Basin Area: 7.84 sq. mile
Basin Slope: 0.00785
Basin Length: 22,300 feet
Tc: 2.7 hour
A/L^2: 0.4395


Annual floods on #06857500
Drainage area, 7.84 sq mi
Period 5/28/69 to 8/77.
6000
4500
3000
1500
Recurrence interval, in years
USGS
Report
Freq.
SCS

Rainfall Distribution

Tr	1	2	3	6	24	Pc	i=Pc/Tc
2	1.26	1.44	1.58	1.80	2.20	1.50	0.56
5	1.80	2.04	2.22	2.50	3.00	2.17	0.80
10	2.10	2.41	2.64	3.00	3.60	2.57	0.95
25	2.50	2.91	3.22	3.70	4.40	3.13	1.16
50	2.90	3.31	3.62	4.10	4.90	3.53	1.31
100	3.28	3.73	4.07	4.60	5.40	4.00	1.48

Predicted Peak Runoff

Tr	Freq.	USGS	SCS II	Report
2	200	-	93	595
5	600	80	242	930
10	870	1493	389	1153
25	1200	3300	616	1490
50	1450	4266	772	1742
100	1730	6326	935	2036

Case II

Platte River Basin

Gaging Station: #06760430

Spring Canyon Creek near Peetz,

Colorado.

Location: Lat. 40°58'12", Long. 103°00'34", in NW 1/4, SE 1/4 Sec 36-T12N-R51W, Logan County, on right bank, 500 feet downstream from access road to windmill and 5 miles east of Peetz.

Drainage Area: 10.0 sq. mile.

Period of Records: 5/23/69 to 10/79.

Remarks: Basin cover is natural prairie vegatation and cultivated crops.

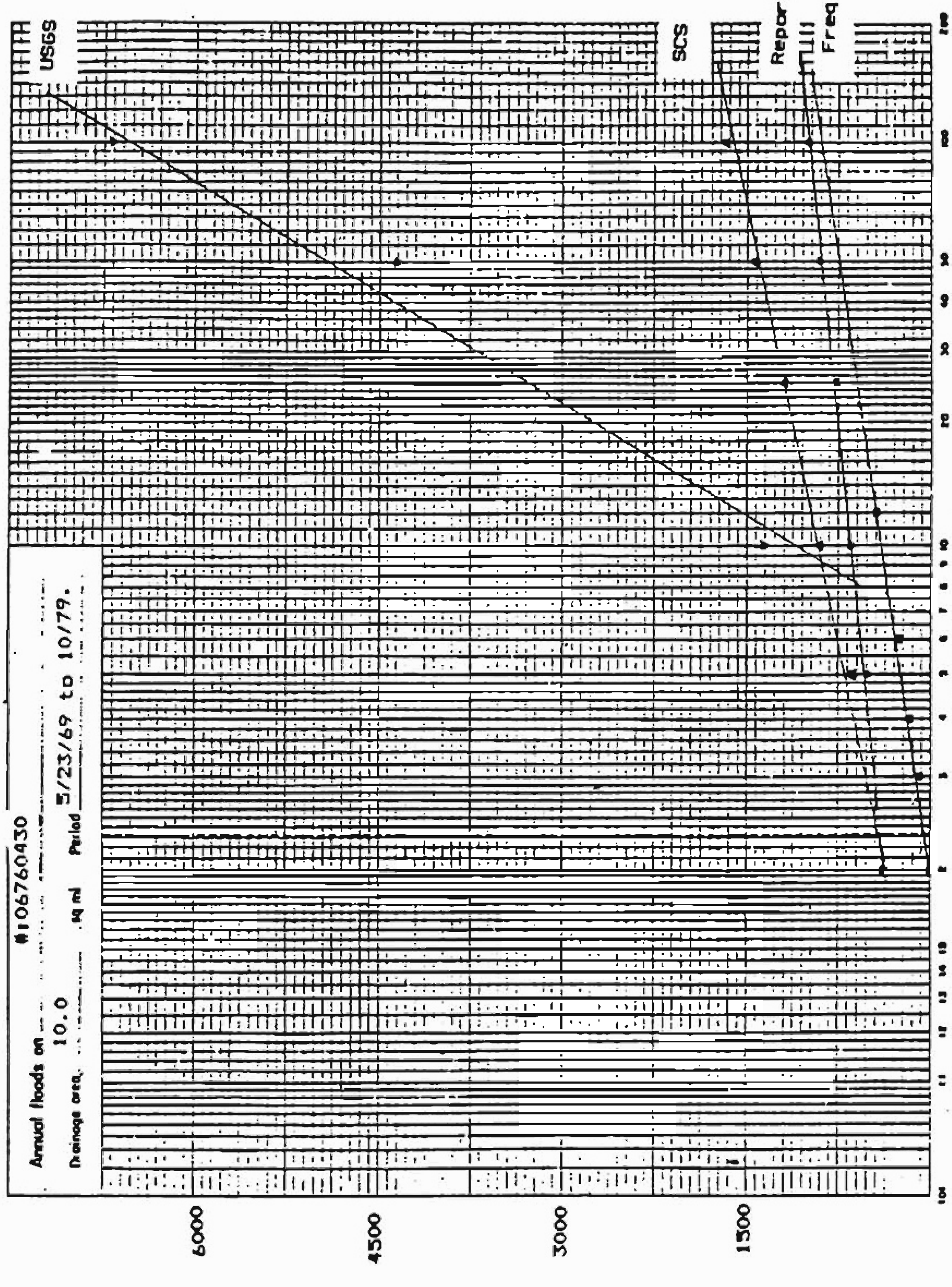
Basin Area: 10.0 sq. mile

Basin Slope: 0.00414

Basin Length: 29,000 feet

Tc: 5.2 hour

A/L^2: 0.3315


Annual floods on #106760430
Drainage area, 10.0 sq mi
Period 5/23/69 to 10/79.
USGS
SCS
Report
T.111
Freq.
6000
4500
3000
1500
1.01
1.1
1.2
1.3
1.4
1.5
2
3
4
5
6
7
8
9
10
20
30
40
50
100
200
Recurrence interval, in years

Rainfall Distribution

Tr	1	2	3	6	24	Pc	i=Pc/Tc
2	1.31	1.48	1.60	1.80	2.10	1.75	0.34
5	1.75	1.90	2.02	2.20	2.65	2.15	0.41
10	2.00	2.21	2.36	2.60	3.00	2.54	0.49
25	2.30	2.54	2.72	3.00	3.50	2.93	0.56
50	2.70	2.92	3.09	3.35	3.90	3.28	0.63
100	2.91	3.16	3.35	3.65	4.30	3.57	0.69

Predicted Peak Runoff

Tr	Freq.	USGS	SCS II	Report
2	10	-	410	399
5	250	-	650	510
10	400	1369	920	638
25	580	3300	1200	762
50	750	4347	1460	886
100	880	6702	1690	992

Case III

Arkansas River Basin

Gaging Station: #07107600
St. Charles River Tributary near
Goodpasture, Colorado.

Location: Lat. 38°04'05", Long. 104°46'33", in NE 1/4, NE 1/4 Sec 09-T23S-R66W, Pueblo County, on left bank, 600 feet upstream from bridge on Burnt Mill Road, 8 miles southeast of Pueblo.

Drainage Area: 2.87 sq. mile.

Period of Records: 3/20/70 to 11/78.

Remarks: Basin cover is natural prairie vegatation and scattered forested areas.

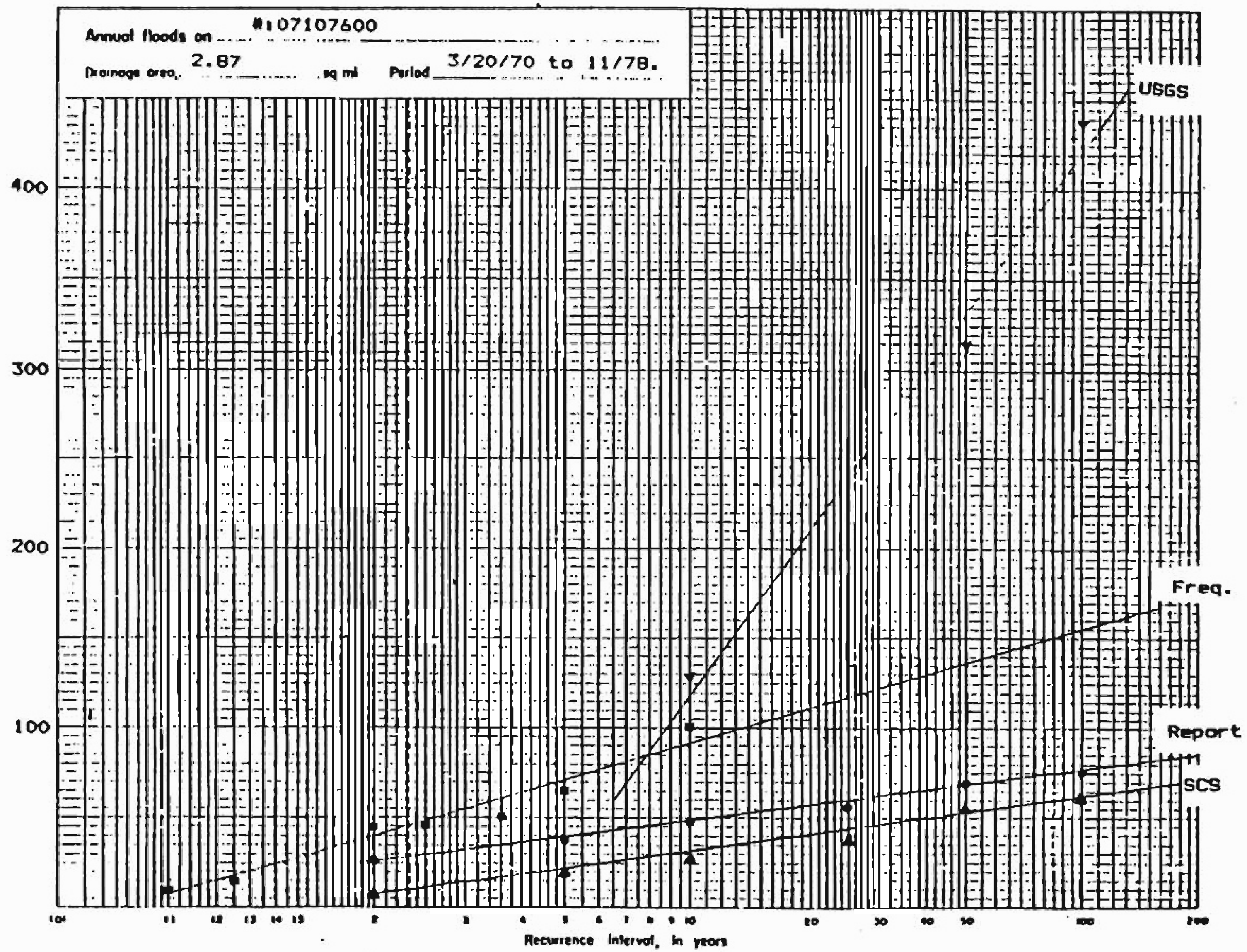
Basin Area: 2.87 sq. mile

Basin Slope: 0.025

Basin Length: 20,100 feet

Tc: 1.4 hour

A/L^2: 0.198


Annual floods on #107107600
Drainage area, 2.87 sq mi
Period 3/20/70 to 11/78.
USGS
Freq.
Report
SCS
400
300
200
100
1.01
1.1
1.2
1.3
1.4
1.5
2
3
4
5
6
7
8
9
10
20
30
40
50
100
200
Recurrence interval, in years

Rainfall Distribution

Tr	1	2	3	6	24	Pc	i=Pc/Tc
2	0.77	1.07	1.30	1.65	2.17	0.89	0.64
5	1.10	1.46	1.73	2.15	2.65	1.24	0.89
10	1.30	1.70	1.99	2.45	3.10	1.46	1.04
25	1.50	1.96	2.31	2.85	3.70	1.68	1.20
50	1.75	2.25	2.62	3.20	4.20	1.95	1.39
100	1.91	2.45	2.86	3.50	4.60	2.13	1.52

Predicted Peak Runoff

Tr	Freq.	USGS	SCS II	Report
2	400	-	72	247
5	700	300	194	379
10	870	1294	273	464
25	1250	2400	373	555
50	1350	3139	517	672
100	1550	4387	603	754

Case IV

Arkansas River Basin

Gaging Station: #07126400 Red Rock Canyon Creek near Bloom, Colorado.

Location: Lat. 37°33'24", Long. 103°50'20", in SE 1/4, SE 1/4 Sec 36-T28S-R58W, Las Animas County, on left bank, 1000 feet upstream from county road crossing, 11 miles southeast of Bloom.

Drainage Area: 4.14 sq. mile.

Period of Records: 5/18/70 to 9/77.

Remarks: Basin cover is natural prairie vegatation.

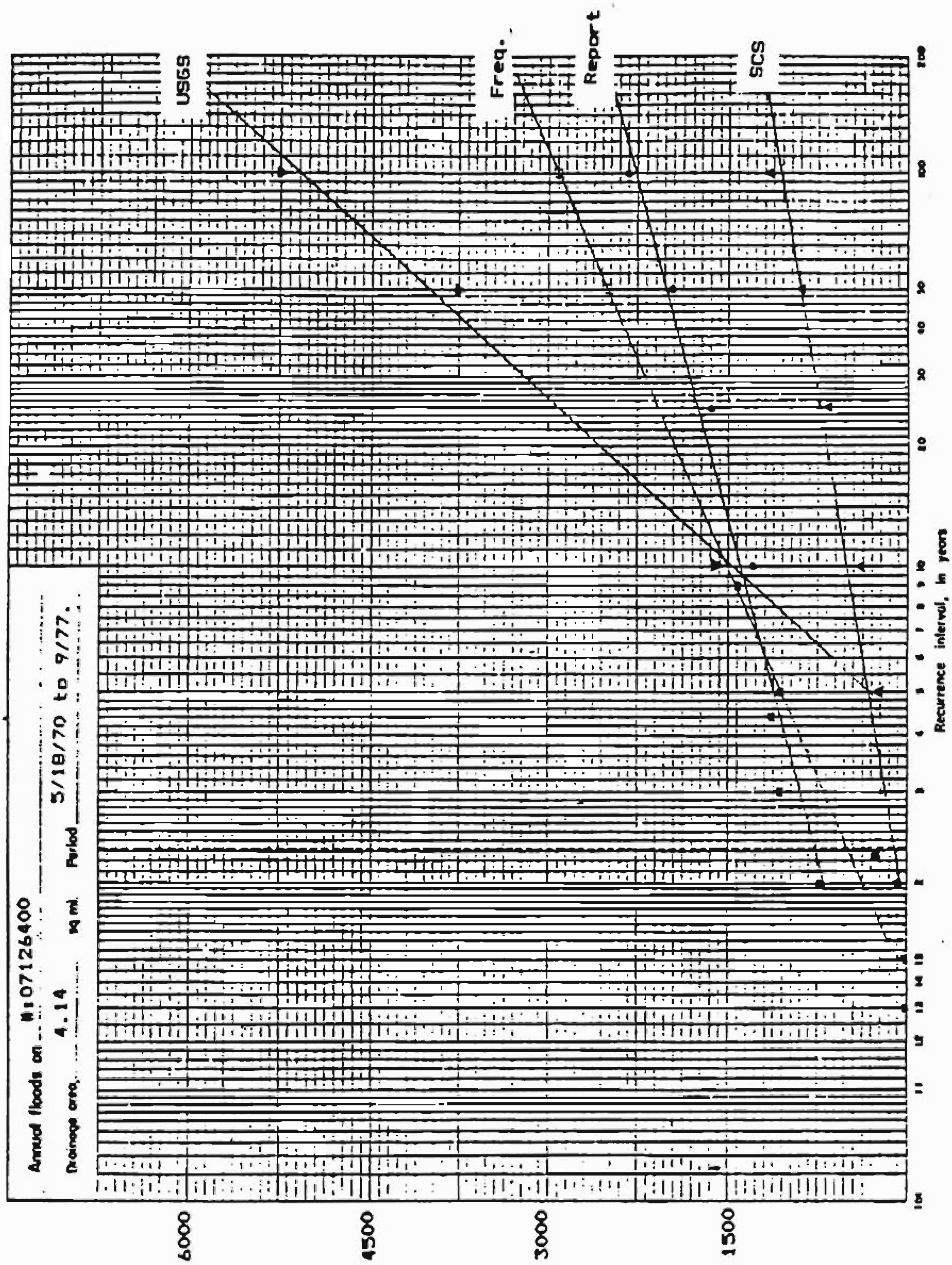
Basin Area: 4.14 sq. mile

Basin Slope: 0.0268

Basin Length: 17,800 feet

Tc: 1.1 hour

A/L^2: 0.28


Annual floods on #:07126400
Drainage area, 4.14 sq mi.
Period 5/18/70 to 9/77.
USGS
Freq.
Report
SCS
6000
4500
3000
1500
1.01
1.1
1.2
1.3
1.4
1.5
2
3
4
5
6
7
8
9
10
20
30
40
50
100
200
Recurrence interval, in years

Rainfall Distribution

Tr	1	2	3	6	24	Pc	i=Pc/Tc
2	1.22	1.38	1.68	1.70	2.05	1.24	1.13
5	1.65	1.87	2.03	2.28	2.80	1.67	1.52
10	1.90	2.17	2.38	2.70	3.25	1.93	1.95
25	2.30	2.67	2.93	3.35	3.94	2.34	2.13
50	2.65	3.03	3.31	3.75	4.40	2.69	2.45
100	3.00	3.41	3.72	4.20	5.10	3.04	2.76

Predicted Peak Runoff

Tr	Freq.	USGS	SCS II	Report
2	400	-	87	730
5	1100	300	261	1072
10	1550	1610	397	1285
25	2100	2900	646	1649
50	2500	3789	894	1963
100	2900	5231	1155	2307

Case V

Arkansas River Basin

Gaging Station: #07120600 Timpas Creek Tributary near Thatcher, Colorado.

Location: Lat. 37°34'24", Long. 104°06'10", in NE 1/4, Sec 34-T28S-R60W, Las Animas County, on right bank, 150 feet downstream frome destroyed bridge on old road, 0.7 miles upstream from mouth and 1.5 miles north of Thatcher.

Drainage Area: 6.56 sq. miles of which 1.97 is noncontributing.

Period of Records: 3/19/70 to 8/77.

Remarks: Basin cover is natural prairie vegetation and scattered forested areas.

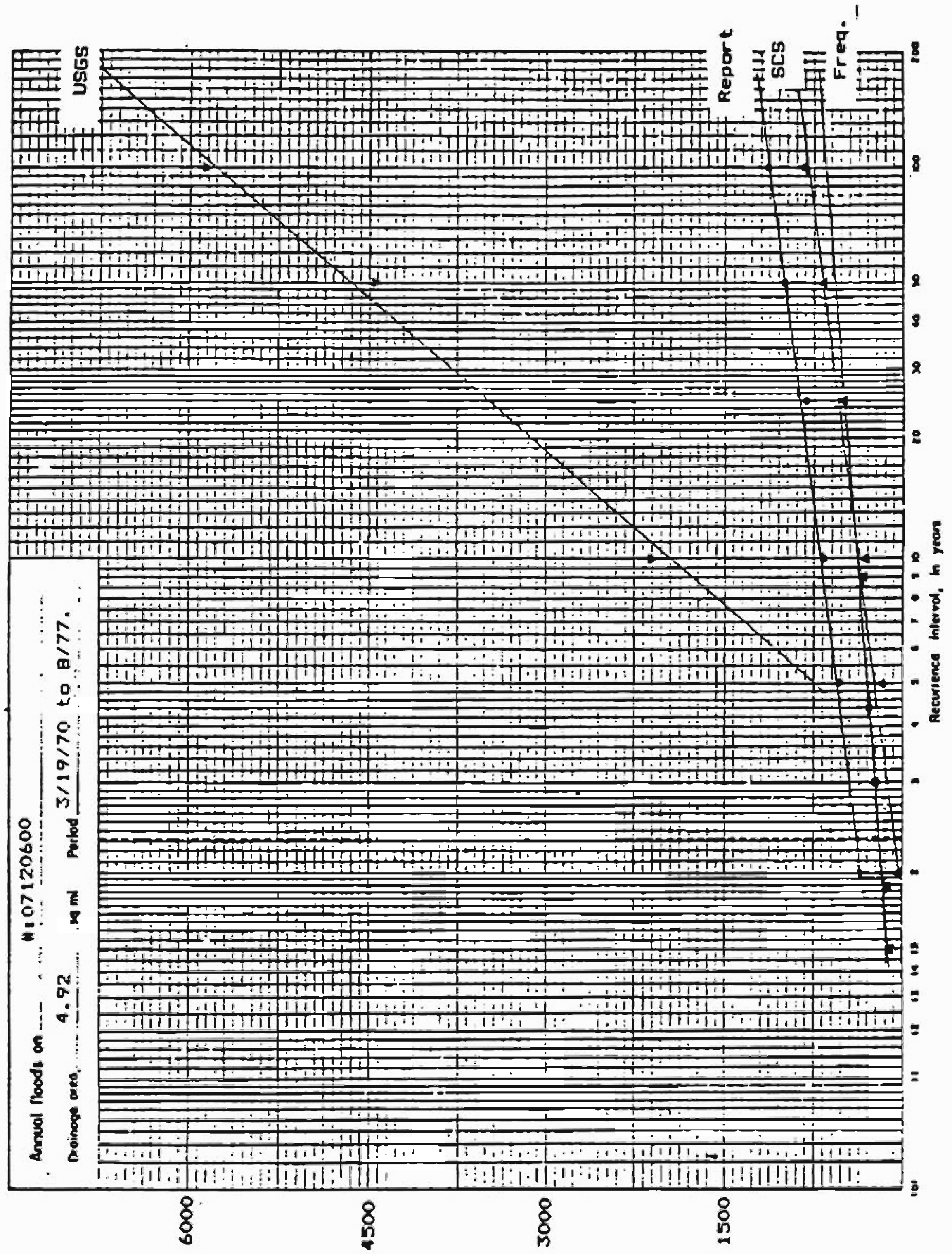
Basin Area: 4.92 sq. mile

Basin Slope: 0.043

Basin Length: 35,200 feet

Tc: 2.36 hour

A/L^2: 0.1476


Annual floods on
#:07120600
Drainage area, 4.92 sq mi
Period 3/19/70 to 8/77.
6000
4500
3000
1500
1.01
1.1
1.2
1.3
1.4
1.5
2
3
4
5
6
7
8
9
10
20
30
40
50
100
200
Recurrence interval, in years
USGS
Report
SCS
Freq.

Rainfall Distribution

Tr	1	2	3	6	24	Pc	i=Pc/Tc
2	1.15	1.31	1.44	1.63	2.03	1.36	0.57
5	1.50	1.74	1.92	2.20	2.69	1.98	0.84
10	1.85	2.11	2.30	2.60	3.10	2.41	1.02
25	2.15	2.46	2.69	3.05	3.80	2.82	1.19
50	2.60	2.89	3.11	3.45	4.20	3.23	1.37
100	2.85	3.19	3.45	3.85	4.68	3.59	1.52

Predicted Peak Runoff

Tr	Freq.	USGS	SCS II	Report
2	170	-	33.5	361
5	270	750	175.6	525
10	360	2067	317.8	662
25	435	3500	485.1	801
50	570	4428	660.8	1009
100	720	5902	844.8	1139

Case VI

Dolores River Basin

Gaging Station: #09175800

Dead Horse Creek near Naturita, Colo.

Location: Lat. 38°02'37", Long. 108°34'38", in NE 1/4 SE1/4, Sec 25-T44N-R16W, San Miguel County, on right bank at upstream end of culvert under state highway 141, 2.7 miles southwest of Basin General Store, and 12.1 miles south of Naturita.

Drainage Area: 5.33 sq. miles.

Period of Records: 4/30/71 to 9/80.

Remarks: Basin cover is natural prairie vegetation

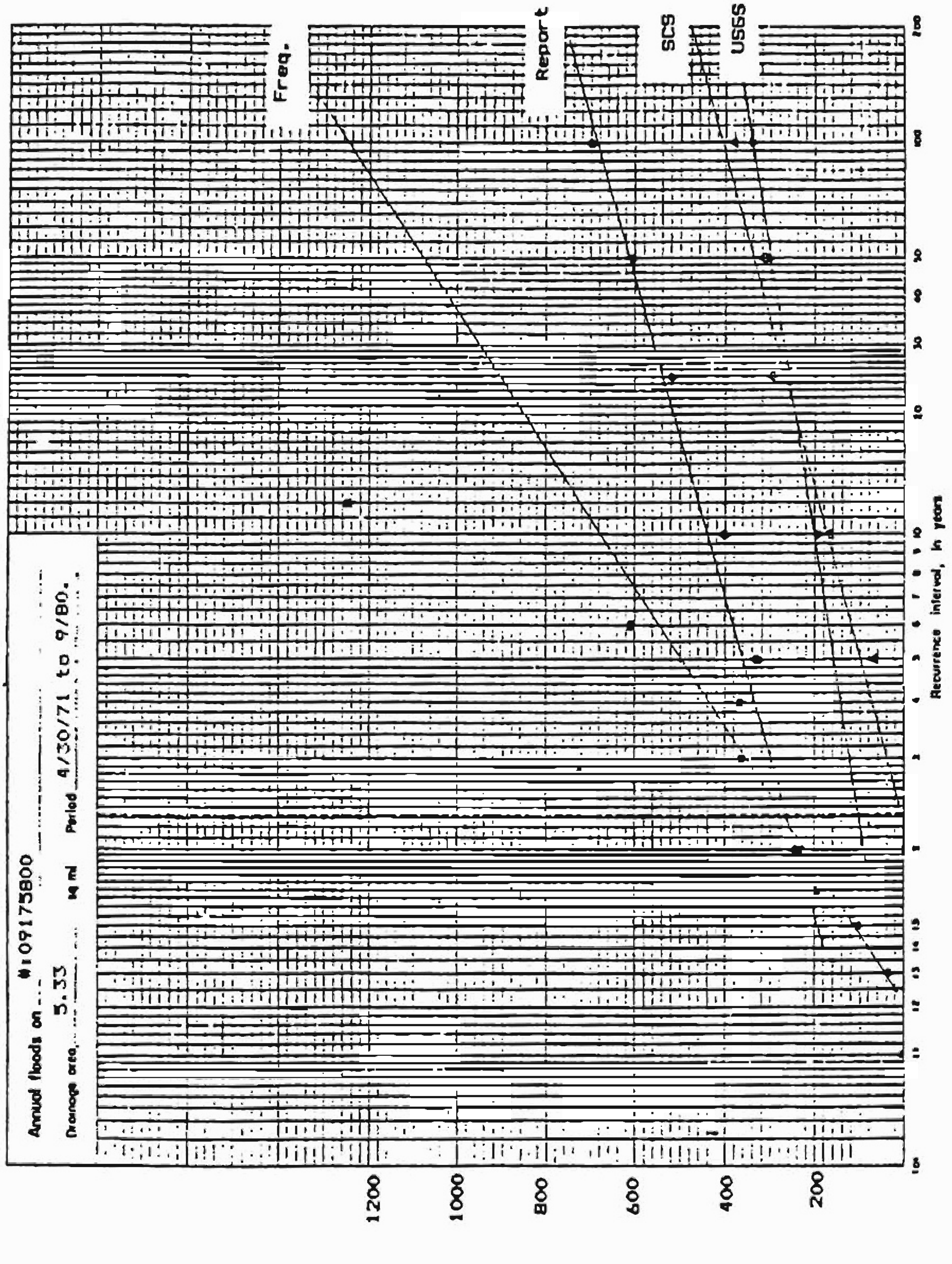
Basin Area: 5.33 sq. mile

Basin Slope: 0.535

Basin Length: 37,030 feet

Tc: 1.81 hour

A/L^2: 0.1084


Annual floods on #09175800
Drainage area 5.33 sq mi Period 4/30/71 to 9/80.
Freq.
Report
SCS
USGS
1200
1000
800
600
400
200
1.01
1.1
1.2
1.3
1.4
1.5
2
3
4
5
6
7
8
9
10
20
30
40
50
100
200
Recurrence interval, in years

Rainfall Distribution

Tr	1	2	3	6	24	Pc	i=Pc/Tc
2	0.63	0.72	0.78	0.90	1.19	0.71	0.39
5	0.80	0.93	1.02	1.19	1.60	0.91	0.50
10	0.92	1.08	1.18	1.38	1.98	1.05	0.58
25	1.15	1.31	1.41	1.61	2.38	1.28	0.71
50	1.30	1.47	1.58	1.80	2.76	1.44	0.80
100	1.49	1.66	1.77	1.99	2.99	1.63	0.90

Predicted Peak Runoff

Tr	Freq.	USGS	SCS II	Report
2	230	-	0	241
5	490	160	76	332
10	660	196	171	400
25	900	260	297	520
50	1070	292	310	605
100	1250	340	387	712

Appendix IV

Computer Source Code
for
Data Analysis.

APPENDIX II

DATA REDUCTION PROGRAM and DATA

THERE ARE 48 GAUGED STATIONS FOR SMALL WATERSHEDS IN COLORADO. EACH WATERSHED HAS A GAGING STATION #. (THE WATERSHED IDENTIFICATION #) THE FUNCTION OF THIS PROGRAM IS TO CALCULATE THE SHAPE FACTOR AND RUNOFF COEFFICIENT FOR A GIVEN EVENT OF EACH WATERSHED. PUT ALL THE INFORMATION. CALCULATED DATA INTO AN OUTFILE.

PROGRAM VARIABLES:
IN: NUMBER SEQUENCE OF WATERSHED
NO: WATERSHED ID #
A: WATERSHED AREA (SQR MILES)
OL: LENGTH OF OVERLAND FLOW (FT)
NCODE: OVERLAND FLOW GROUND SURFACE TYPE
  NCODE = 1: FOREST WITH HEAVY GROUND LITTLE AND MEADOW
  NCODE = 2: FALLOW OR MINIMUM TILLAGE CULTIVATION
  NCODE = 3: SHORT GRASS PASTURE AND LAWN
  NCODE = 4: NEARLY BARE GROUND
  NCODE = 5: GRASSED WATERWAY
MCODE: SOIL TYPE--> 1:TYPE A: 2:TYPE B: 3: TYPE C: 4:TYPE D.
CL: LENGTH OF CHANNEL FLOW (FT)
UB: WATERSHED UPPER BOUNDARY ELEVATION (FT)
CB: CHANNEL HEAD ELEVATION (FT)
OB: CHANNEL OUTLET ELEVATION (FT)
SO: SLOPE OF OVERLAND FLOW SECTION
SC: SLOPE OF CHANNEL FLOW SECTION
SB: SLOPE OF THE WHOLE BASIN
TO: TIME FOR OVERLAND FLOW (MIN)
TN: TIME FOR CHANNEL FLOW (MIN)
TC: TIME OF CONCENTRATION. = TO + TN
N: # OF EVENTS FOR EACH WATERSHED
NR: NUMBER OF PRECIPITATION BLOCKS
TP.TD: TIME OF DURATION FOR EACH RAIN BLOCK (MIN)
RMAX: STORAGE FOR MAX. PRECIPITATION
BLKMAX: STORAGE FOR MAX. RAINFALL BLOCK (RAIN BLOCKS IN 5)
P: PRECIPIATION (IN)
T: TIME OF CONCETRATION-ACTUAL (MIN)
JMAX: INDEX NO OF MAX. RAINFALL BLOCK IN BLKMAX.
JR. JL: INDEX NO
AVI: AVERAGE RAINFALL INTENSITY
NF: TOTAL NUMBER OF RUNOFF DATA FOR EACH RECORD OF RAINFALL

```
    DOUBLE PRECISION R(300).RMAX,BLKMAX,F(500),BLK(300)
    OPEN(UNIT=5, FILE='REGIONA')
    OPEN(UNIT=6, FILE='RATIOA')
        REWIND(6)
        ENDFILE(6)
    OPEN (UNIT=7, FILE='RATIOCA')
        REWIND(7)
        ENDFILE(7)
    READ (5.10) IN
 10 FORMAT(I10)


       ITOTAL = 0
       WRITE(6,11)
 11    FORMAT(//4X.'WATER'.8X,'LAND'.2X,'OVERLAND'.3X,'CHANNEL',
   1   3X,'UPPER',5X,'CHNNL.',4X,'OUTLET'1X,'SOIL')
       WRITE(6,12)
 12    FORMAT(4x.'-SHED',3X,'AREA',1X,'USAGE'.3X,'FLOW',
   2   14X,1X,'HEAD',6X, 'BNDRY',5X,'BNDRY')
       WRITE(6,13)
 13    FORMAT(4X,'ID#',10X,'CODE',3X,'LENGTH',4X,'LENGTH',
   1  4X,'ELEV',6X,'ELEV',6X,'ELEV',3X,'TYPE'//)
    DO 55  I= 1,IN
14     READ(5,15) NO,A,NCODE,OL,CL,UB,CB,OB,MCODE
 15    FORMAT(I10,F6.2,I4,5F10.1,I4)
       WRITE(6,15) NO,A,NCODE,OL,CL,UB,CB,OB,MCODE


            TL = OL + CL
            SO = (UB -CB) /OL
            SC = (CB - OB) /CL
            SB = (UB - OB ) /TL

     TO = 0.83 * (RN * OL /(SO**0.5))**0.467
        IF (NCODE .EQ. 1)  V = 2.61 * (SO **.51)
        IF (NCODE .EQ. 2)  V = 4.57 * (SO **.5)
        IF (NCODE .EQ. 3)  V = 6.95 * (SO**.5)
        IF (NCODE .EQ. 4)  V = 10. * (SO**.51)
        IF (NCODE .EQ. 5)  V = 15.2 * (SO**.5)
      TO = OL/(V*60)
            TN1 = ( (11.9 * ((CL/5280)**3)/(CB-OB))**0.385) * 60
            TN2 = CL/(15.2*(SC**.5) * 60)
              IF (TN1 .GT. TN2) THEN
                     TN = TN2
              ELSE
                     TN= TN1
              ENDIF
            TC = TO + TN
      READ(5.19) N
19    FORMAT(I10)
      ITOTAL = ITOTAL + N
```

```
            DO 50    K = 1. N
               READ(5,20) NR,TD
 20            FORMAT(I10.F10.2)
               READ(5,21)  (R(J), J= 1.NR)
 21            FORMAT(10F7.2)
               WRITE(6,22)
 22            FORMAT(/15X,'RAINFALL ARRAY')
               WRITE(6,21)  (R(J),  J=1.NR)
                   RMAX  = 0
                   BLKMAX  = 0
                     DO 27    J = 1. NR - 4
                       BLK(J)  = 0
                         DO 23    L = J. J+4
 23                        BLK(J)  = BLK(J)  +  R(L)
                         IF  (BLK(J)  .LT.  BLKMAX)  GOTO 27
                         BLKMAX  = BLK(J)
                         DO 24    M= J. J+4
                           IF(R(M)  .GE.  RMAX)   THEN
                               RMAX  = R(M)
                               JMAX  = M
                           ENDIF
 24                      CONTINUE
 27                   CONTINUE


                    T = 0
                    P = RMAX
                    JR = JMAX + 1
                    JL = JMAX - 1
 28                 T = T + TD
    IF (JR .GE. NR) GOTO 390
    IF (JL .LE. 0) GOTO 391
                    IF  (T .GT.  TC)  GOTO 39
                    IF  (R(JR)  .LT.  R(JL))  GO TO 38
                          P  = P + R(JR)
                          JR  = JR + 1
                          GOTO 28
 38                       P  = P + R(JL)
                          JL  = JL  - 1
                          GOTO 28
 390          P  = P  + R(JL)
            T = T + TD
          JL = JL  - 1
             IF  ((T .GE.  TC)  .OR.  (JL .EQ.  0))  GOTO 39
             IF  (JL .NE.  0)  GOTO 390
 391          P  = P  + R(JR)
             T = T + TD
           JR = JR + 1
             IF  ((T .GE.  TC)  .OR.  (JR .EQ.  NR))  GOTO 39
             IF  (JR .NE.  NR)  GOTO 391
 39                AVI  =  (P * 60)  /  T
```

```
                    READ(5.20) NF. TP
                    READ(5,21) (F(J), J = 1, NF)
                    WRITE(6,41)
   41               FORMAT(/15X,'RUNOFF ARRAY')

                     WRITE(6,21) (F(J), J = 1. NF)

                        FMAX = 0
                        DO 45   J = 1. NF
                          IF(F(J) .GT. FMAX)  FMAX = F(J)
   45                   CONTINUE
       WRITE(6,201)
201    FORMAT(//3X,'MAX. BK.'2X,'MAX. PPT',3X,'MAX. RUNOFF')
      WRITE(6,200) JMAX, RMAX, FMAX
  200 FORMAT(/3X,I5,2F12.3)
       WRITE(6,100)
  100     FORMAT(/2X,'VELOCITY',6X,'TO',7X,'TC',7X,'PRECIP',
     14X,'TIME',5X,'AVI')
      WRITE(6,101) V,TO,TC,P,T,AVI
01       FORMAT(4F10.5,F9.2,F10.5)

               IF ( T .GE. TC ) THEN
                     C = FMAX / (A * AVI * 645.33333)
              ELSE
                     C = FMAX /  ((A*AVI*645.3333)*(T/TC))
              ENDIF
                     WL = A * (5280**2) / (TL**2)
                    PL = 1.E5 * P / (TL * 12)
                     WRITE(6,47)
  47                 FORMAT(/4X,'ID #',3X,'WSD',1X,'N',2X,
    2               'RUNOFF C',2X,'BASIN SLP',4X,'W/P',
    2               7X,'P/L',6X,'T',5X,'TC',2X,'ND',1X,'MD')
           WRITE(6,49) NO,I,K,C,SB,WL,PL,T,TC,NCODE,MCODE
  49                FORMAT(I10,2I3,4F10.6,2F7.1,I2,I3)
           WRITE(7,49) NO,I,K,C,SB,WL.PL,T,TC,NCODE,MCODE
                   WRITE(7,777) C,FMAX,P,A,SB
7          FORMAT(5F15.5)
  50    CONTINUE
  55    CONTINUE
                     WRITE(7.60) ITOTAL
  60                 FORMAT(3X,'ITOTAL=',I10)
      STOP
      END
```

Appendix V

Computer Source Code
for
Regression Analysis.

APPENDIX III

LEAST-SQUARES PROGRAM and DATA

```
C  USE LEAST-SQUARES TO FIND B(0).B(1).B(2).B(3)....B(M) IN FORMULA
C  Y = B(0) + B(1) * X1 + B(2) * X2 +.....B(M) * XM

        DOUBLE PRECISION X(272. 0:6), SUM(6,6), SUMY(6),B(6),SUMINV(6,6)
        DOUBLE PRECISION Y(272), C(272),SB(272),WL(272),PL(272).CC(272)
        DOUBLE PRECISION YHAT(272), T(272),TC(272)
        DOUBLE PRECISION YBAR,SSY,SS,RES,RSQR,REGV,YV
        OPEN(UNIT=  5, FILE= 'RATIO')
        OPEN(UNIT = 6. FILE= 'LSQRATIO')
           REWIND(6)
           ENDFILE(6)
         OPEN(UNIT =7. FILE= 'LSQSTRA')
           REWIND(7)
           ENDFILE(7)
        OPEN(UNIT=8.FILE='PLTLU')
           REWIND(8)
           ENDFILE(8)
        READ (5.10) N
  10    FORMAT(I10)
        DO 9  I= 1,N
 210     READ(5.20,END=213) C(I),SB(I),WL(I),PL(I),T(I),TC(I)
         IF(C(I) .LT. 0.05 .OR. C(I) .GT. 0.75) GOTO 210
        IK = I
  9     CONTINUE
  20    FORMAT(16X. 4F10.6,2F7.1)
 213     M= 3
        DO 30  I=1,IK
        Y(I) = LOG10( C(I) )
        X(I,1) = LOG10 ( WL (I)  )
        X(I.2) = LOG10 ( SB (I)  )
        PL(I) = PL(I) * 0.00001
        X(I.3) = LOG10 ( PL (I)  )
  30    CONTINUE
         WRITE(6.11)
  11     FORMAT(//9X. 'REPORT OF DATA')
  12     FORMAT(//8X,'Q/AI',6X,'A/(L**2)',8X,'S',9X,'P/L',11X.'C'//)
        DO 50  K =1.IK
  50    X(K.0) = 1
        MP = M + 1
```

```
      DO 200  I= 1.MP
      DO 200  J= 1,MP
      SUM(I,J) = 0
      DO 100  K = 1, IK
100   SUM(I,J) = SUM(I,J) + X(K,I-1) * X(K, J-1)
      SUM(J,I) = SUM(I,J)
200   CONTINUE
      DO 300  I = 1,MP
      SUMY (I) = 0
      DO 350  K = 1,IK
350   SUMY(I) = SUMY(I) + Y(K) * X(K, I-1)
300   CONTINUE
      CALL MATR(MP,SUM,SUMINV)
      DO 500  I=1.MP
      B(I) = 0
      DO 550  J =  1. MP
550   B(I) = B(I) + SUMINV(I.J) * SUMY(J)
      WRITE(6,560) I.B(I)
     IF(I.EQ.1)BB=10.**B(I)
     IF(I.EQ.1)WRITE(6.561)BB
561 FORMAT(3X,' BB =',5X,F12.5)
560  FORMAT(3X,'B(',I1,')=',5X,F12.5)
500  CONTINUE
    YBAR=SUMY(1)/FLOAT(IK)
      PRINT *, YBAR
    SSY=0.
    SS=0.
    WRITE(8.10) IK
    DO 88 I=1,IK
    CC(I)=BB*WL(I)**B(2)*SB(I)**B(3)*FL(I)**B(4)
    WRITE(6,113)C(I),WL(I),SB(I),FL(I),CC(I)
    WRITE(8,113) C(I),WL(I),SB(I),FL(I),CC(I)
113 FORMAT(3F12.5,E12.5,F12.5)
    YHAT(I)=B(1)+B(2)*X(I,1)+B(3)*X(I,2)+B(4)*X(I,3)
    RES=Y(I)-YHAT(I)
    SS=SS+RES*RES
    SSY=SSY+(Y(I)-YBAR)**2
 88 CONTINUE
      RSQR = (SSY - SS)/SSY
      REGV= SS/(IK-MP)
      YV= SSY/(IK-1)
      WRITE(6.115) SS,SSY,RSQR, REGV, YV
115   FORMAT(/1X,'SS=',F8.3,2X,'SSY=',F8.3,2X,'RSQR=',F8.3,2X,
  1    'REGV=', F8.3,2X,'YV=',F8.3)
     STOP
     END
```

```
      SUBROUTINE MATR(NMAT,S,T)
      DOUBLE PRECISION S(6,6),T(6,6),SP(6,6)
      DOUBLE PRECISION Z
      DO 8500  I= 1,NMAT
      Z= 0
      IF( I .EQ. 1)  GOTO 8200
      I1 = I -1
      DO 8100  J= 1. I1
8100  Z = Z + T (J,I) * T(J,I)
8200  IF (S(I,I) -Z .LE. 0) GOTO 9600
      T(I,I) = SQRT( S(I,I) - Z)
      IF ( I .EQ. NMAT) GOTO 8500
      J2 = I + 1
      DO  8450  J = J2. NMAT
      Z = 0
      IF (I .EQ. 1) GOTO 8400
      JJ1 = I - 1
      DO 8300  JJ = 1, JJ1
8300  Z = Z + T(JJ,I) * T(JJ, J)
8400  T (I,J) = ( S(I,J) - Z) / T(I,I)
8450  CONTINUE
8500  CONTINUE
      DO 9300  I1 = 1, NMAT
      I = NMAT - I1 + 1
      SP (I,I) = 1/ T(I,I)
      IF (I .EQ. NMAT) GOTO 9200
      J1 = I + 1
      DO 9100  J = J1 .NMAT
      SP(I, J) = 0
      DO 9100  JJ = J1, J
      SP(I,J) = SP(I,J) -T(I,JJ) * SP(JJ,J)/ T(I,I)
9100  CONTINUE
9200  IF (I .EQ. 1)  GOTO 9300
      J2 = I -1
      DO 9250  J = 1. J2
      SP(I.J) = 0
9250  CONTINUE
 300  CONTINUE
      DO 9400  I = 1. NMAT
      DO 9400  J = 1, I
      T (I,J) = 0
      DO 9500  K= 1. NMAT
 500  T(I.J) = T(I,J) + SP(I,K) * SP(J,K)
      T(J,I) = T(I,J)
 400  CONTINUE
      RETURN
 600  WRITE(6,9700)
 700  FORMAT( 20H TERMINATE IN MATINV)
      STOP
      END
```