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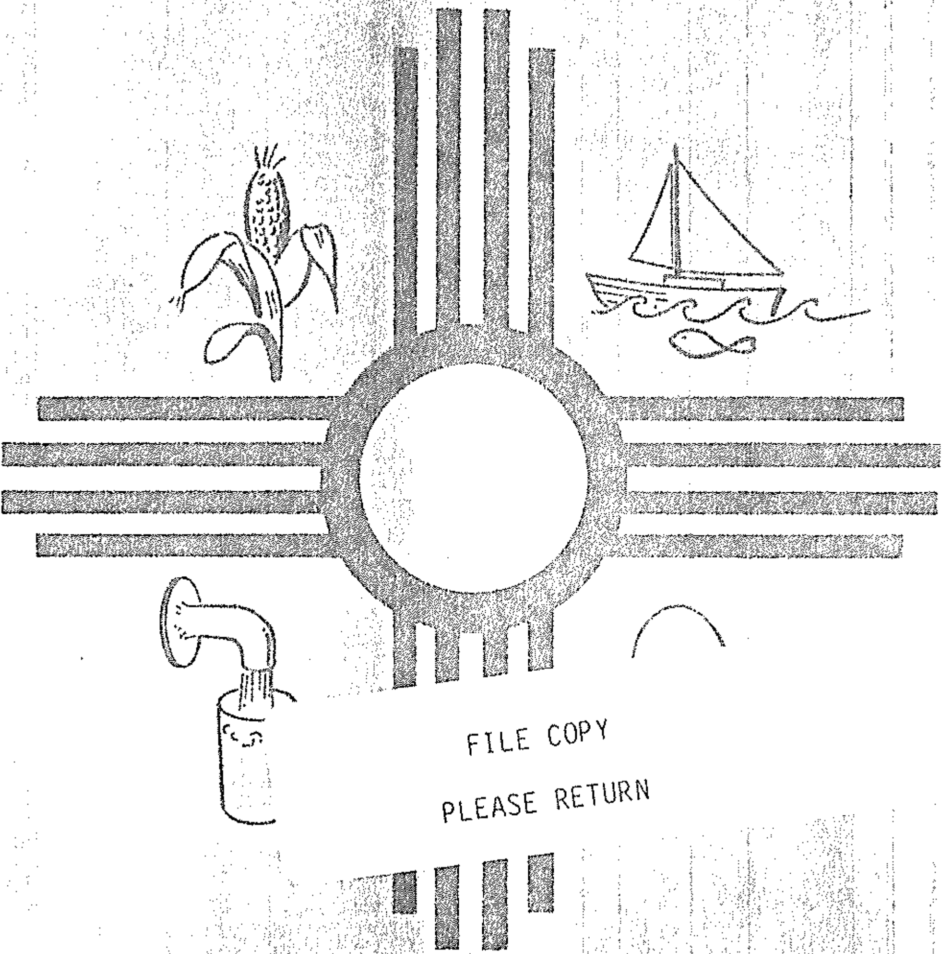
STUDIES ON RAINFALL-RUNOFF MODELING

4. ESTIMATION OF PARAMETERS OF TWO MATHEMATICAL MODELS OF SURFACE RUNOFF

Partial Technical Completion Report

Project No. 3109-206



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STUDIES ON RAINFALL-RUNOFF MODELING

4. Estimation of Parameters of Two Mathematical Models of Surface Runoff

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Partial Technical Completion Report

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New Mexico Water Resources Research Institute
in cooperation with
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LIST OF SYMBOLS

Symbol	Definition
A	The watershed area
API	Antecedent precipitation index
α	Kinematic wave parameter of frictional relationship
CONV	Kinematic converging section model
c	Coefficient: 0.8 to 2.2
CS	Channel slope
C_p	Coefficient: 0.56 to 0.69
C_t	Coefficient: 1.8 to 2.2
DD	Drainage-density
D_1	Infiltration capacity
D_5	Cook's ΣW reflecting soils, land use and topography
e	Base of the natural logarithm
F	Form factor
G	The time difference between the peak of runoff and the center of mass of runoff
h	Local depth of flow
I(t)	Input
IUH	Instantaneous unit hydrograph
K_2	Coefficient constant = 23
K_3	Coefficient constant = 545
K	Storage coefficient (Nash's Model)
K_f	Shape factor
K_1	Coefficient constant = 106
K_s	Storage constant
L or XLR	Length of mainstream
L_o	Radius of flow region (converging section)
m_1	First moment about the origin of the IUH
m_2	A dimensionless second moment
N	Number of reservoirs (Nash's Model)
n	Kinematic wave parameter of friction relationship

Symbol	Definition
NASH	Nash model of linear cascading reservoirs
P_i	The precipitation i days before the event of interest
q_o	The peak discharge
$q(x,t)$	Lateral inflow
Q_{p_e}	Estimated peak discharge
Q_{p_o}	Observed peak discharge
Q_p	Peak discharge of the unit hydrograph
$Q(t)$	Instantaneous discharge rate at time t
R	Multiple correlation coefficient
R_6	Total rainfall
R_{11}	The maximum 30 minute rainfall intensity
S_L	The mean channel slope
t	Time element
T_B	Length of the base of the unit hydrograph
t_L	Time difference between centroid of rainfall and the hydrograph peak
t_{LR}	Lag time
t_p	Time from beginning of rainfall to peak discharge
t_R	Rainfall duration
T_2	The length of the longest tributary
T_3	The length along the mainstream from the watershed outlet to the center of mass in feet.
T_5	The average main channel slope
T_6	The average overland slope in percent
T_9	The time of concentration
U	Local average velocity
V	Rainfall-excess volume
W	The total runoff volume
W_{sa}	Average width of source area
y	Recession constant
z	Exponent dependent upon the time-area concentration curve

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ESTIMATION OF PARAMETERS OF TWO MATHEMATICAL MODELS OF SURFACE RUNOFF

ABSTRACT

A methodology is developed to estimate the parameters of the Nash model (1957) and the converging overland flow model (Singh, 1974) of surface runoff, utilizing physically measurable watershed characteristics. These characteristics are investigated and used to derive equations to estimate the model parameters for small natural agricultural watersheds. Runoff hydrographs are predicted for several rainfall events on several of these watersheds. A comparison of the predictive performance of the two models indicates that both models performed equally well on these watersheds.

CHAPTER 1

INTRODUCTION

1.1 General Remarks

The importance of surface runoff is exemplified by the abundance of surface runoff prediction models in the hydrologic literature. A fundamental problem common to most of the models is: how to estimate the model parameters from physically measurable watershed characteristics? The traditional approach has been to bypass this problem by optimizing the model parameters for some selected rainfall-runoff events over a given watershed, using a suitable optimization algorithm and an objective function. These optimized parameter values are then utilized in the model to predict runoff for the rainfall events of interest not used in the optimization. This, however, does not offer a solution to the basic problem, and has other serious shortcomings. For example, the optimized parameters can best represent the system only for the events used in the optimization; as soon as the optimization set of rainfall events is changed, the optimum parameter values will also change. The extensive amount of data normally required for optimization is often lacking and may prove prohibitive in the widespread applicability of the model. Equally important, optimization is a costly operation.

An approach to solve this basic problem is to relate the model parameters to those watershed characteristics which can be obtained from the topographic map. It is implicitly assumed that such characteristics remain unchanged throughout the period of study. One obvious advantage of this is that it is readily applicable to ungaged watersheds or watersheds with insufficient data for optimization.

1.2 Objectives

The objective of this study is to develop a methodology to estimate apriori the parameters of the linear Nash model and the nonlinear converging overland flow model for small agricultural watersheds. A comparison of the predictive performance of the two models is also made.

CHAPTER 2

REVIEW OF LITERATURE

In this chapter we provide a comprehensive survey of investigations that have utilized watershed geomorphology in rainfall-runoff modeling. It will be apparent from the ensuing discussion that most investigations have been confined to estimating unit hydrograph parameters from watershed geomorphology.

Quantitative geomorphic methods provide a means whereby the physiographic and topographic characteristics of a watershed are analysed to define their relationship with the unit hydrograph characteristics. Numerous methods have been developed for constructing the unit hydrograph for ungaged watersheds utilizing watershed characteristics. These methods differ from one another either in the relationships established or the methodology employed. The following discussion summarizes several of the more commonly used methods. Many of the methods are merely modifications of existing procedures, modified so as to account for variations in regional geomorphology.

Sherman (1932a) defined the unit hydrograph as the discharge-time relationship resulting from steady effective rainfall of unit duration uniformly distributed over a watershed. It follows, therefore, that the unit hydrograph should reflect translation and storage effects of the watershed, and these effects would be expected to be related to its physical characteristics. Sherman (1932b) studied the relationship of runoff hydrographs to size and character of drainage basins, and suggested the dominant factors controlling the distribution of runoff-rates to be: (1) drainage-area size and shape, (2) distribution of watercourses, (3) slope of the valley sides or general land slope, (4) slope of the mainstream, and (5) pondage resulting from surface or channel obstructions forming natural detention reservoirs.

Snyder (1938) was probably the first to relate the physical geometry of a basin to the unit hydrograph characteristics. From his study of the watersheds in the Appalachian Highland which varied in size from 10-10,000 square miles, he defined three points of the unit hydrograph as:

$$t_L = C_t(LL_{ca})^{0.3} \tag{2-1}$$

$$Q_p = (640AC_p)/t_L \tag{2-2}$$

$$T_B = 3 + 3(t_L/24) \tag{2-3}$$

where t_L is the basin lag time (difference between the centroid of rainfall and the hydrograph peak), L length of the mainstream in miles from the outlet to the divide, L_{ca} the distance in miles from the outlet to a point on the mainstream nearest the center of the watershed, C_p and C_t coefficients depending upon units and drainage-basin characteristics (C_p = 0.56 to 0.69; C_t = 1.8 to 2.2), Q_p peak discharge of the unit hydrograph in cfs, A area of drainage basin in square miles, and T_B length of the base of the unit hydrograph in days.

Equations (2-1), (2-2), and (2-3) hold for an excess rain of duration t_r:

$$t_r = t_L/5.5 \tag{2-4}$$

Lag period t_{LR} for a different rainfall duration t_R can be calculated as:

$$t_{LR} = t_L + (t_R-t_r)/4.0 \tag{2-5}$$

Once the values for t_L, Q_p, and T_B are known, the unit hydrograph can be sketched. It is drawn so that the area under the graph represents a one inch volume of direct runoff from the watershed.

A few years later, Clark (1945) derived the unit hydrograph of a watershed by routing its time-area concentration curve through a linear reservoir $S = KQ$, where S is storage, Q discharge, and K storage coefficient. Clark utilized in his derivation the Muskingham method of flood routing (McCarthy, 1939). He estimated the parameter K from the relation:

$$K = c \quad L/\sqrt{S_L} \tag{2-6}$$

where S_L is mean channel slope, and c coefficient varying from 0.8 to 2.2.

Thereafter, Edson (1951) derived an expression for the shape of the instantaneous unit hydrograph:

$$Q(t) = \frac{V\ y}{\Gamma(z+1)} \quad (yt)^z\ e^{-yt} \tag{2-7}$$

where Q(t) is the instantaneous discharge rate at time t, V the rainfall excess volume, y the recession constant, z the exponent whose value depends upon the shape of the time-area concentration curve of the watershed, e the base of the natural logarithm, and Γ the gamma function. Edson observed that the failure encountered in correlating basin characteristics with hydrograph properties, peak discharge and time of rise, may be attributable to the complex relationship of y and z.

About the same time, Taylor and Schwarz (1952) analyzed data from 20 watersheds in the North and Middle Atlantic States and developed an expression for lag t_L as:

$$t_L = C_t e^{mt_R} \tag{2-8}$$

where m is:

$$m = \frac{0.212}{(LL_{ca})^{0.36}} \tag{2-9}$$

and the coefficient C_t is:

$$C_t = \frac{0.6}{\sqrt{S_L}} \tag{2-10}$$

where S_L is the weighted slope of the channel. Several parameters of watershed size and shape were investigated, but the quantity LL_{ca} with an exponent very nearly equal to Snyder's value was found best. The influence of slope on C_t was indicated earlier by Snyder (1938). Taylor and Schwarz also developed an expression for the unit hydrograph peak in the form of Eq. (2-8) but with more complex expressions for the coefficient and exponent.

In 1957 the Soil Conservation Service (SCS) developed a method for hydrograph synthesis which was later modified by using the dimensionless hydrograph. From an analysis of a large number of hydrographs for natural watersheds varying widely in size and geographical location it was concluded that a unit hydrograph could be represented by a simple triangular shape. Thus the method requires only the determination of the time to peak t_p and the peak discharge Q_p as:

$$t_p = t_R/2 + t_L \tag{2-11}$$

$$Q_p = 484\ A/t_p \tag{2-12}$$

where t_p is time from beginning of rainfall to peak discharge in hours, t_R duration of rainfall in hours, and t_L lag time from centroid of rainfall to peak discharge in hours. Values of t_L were determined for various geographic regions. The dimensionless hydrograph had its ordinate values expressed as the ratio Q/Q_p, and its abscissa values as the ratio t/t_p. These ratios were tabulated by the Soil Conservation Service. Once Q_p and t_p are known, a unit graph can be constructed.

The hydrograph synthesis method developed by Hickok, et al (1959) is very similar to that of SCS. The primary difference between the two methods is that the former is restricted to very small watersheds varying in size from 11 to 790 acres located in semiarid regions. The dimensionless graph has its ordinate in units of Q/Q_p and its abscissa in units of t/t_L. Here the lag t_L was taken as the time difference between the centroid of a limited block of intense rainfall and the resultant peak discharge. Two different methods for determining the lag time, depending upon geographic and climatological conditions, were presented:

For homogeneous semiarid rangelands up to approximately 1000 acres in area the lag is:

$$t_L = K_1 (A^{0.3}/S_L \quad DD)^{0.61} \tag{2-13}$$

where t_L is lag time in minutes, S_L average land slope of the watershed in percent, DD drainage density in feet per acre, and K_1 constant coefficient = 106.

For watersheds of widely different physiographic characteristics t_L is:

$$t_L = K_2 \frac{\sqrt{T_3 + W_{sa}}}{S_L \sqrt{DD}} \tag{2-14}$$

where T_3 is the length from the outlet of the watershed to the center of gravity of the source area in feet, W_{sa} available width of the source area in feet, and

K_2 coefficient = 23. The source area was considered to be the half of the watershed with the highest average land slope.

The authors determined Q_p(cfs) from the relation:

$$\frac{Q_p}{V} = \frac{K_3}{t_L} \tag{2-15}$$

where V is given in acre-feet, t_L in minutes, and K_3 taken equal to 545.

For his model (Nash, 1958) Nash expressed the parameters in terms of moments of the instantaneous unit hydrograph. Two years later, he attempted to relate the moments to watershed characteristics (Nash, 1960). For a sample of 30 British watersheds the following relationships were obtained:

$$m_1 = 27.6\ A^{0.3}\ S_L^{-0.3} \tag{2-16}$$

$$m_1 = 20(L)^{0.3}\ (CS)^{-0.33} \tag{2-17}$$

$$m_2 = 1.0(m_1)^{-0.2}\ (S_L)^{-0.1} \tag{2-18}$$

$$m_2 = 0.41(L)^{-0.1} \tag{2-19}$$

where m_1 is the first moment about the origin of the IUH (hours), m_2 a dimensionless second moment, CS mainstream channel slope in parts per 10,000, and S_L overland slope in parts per 10,000.

In 1961 Gray employed the two-parameter gamma distribution to define a modified form of the unit hydrograph for small watersheds. The method was developed on the rationalization of the runoff process proposed by Edson (1951). He then established correlations of hydrograph characteristics with watershed physiography. His method has since been used in several investigations (Hanson and Johnson, 1964).

About the same time, Reich (1962) chose three parameters to describe the runoff hydrograph. Regression analysis was performed to estimate these parameters from soil, land use, rainfall and antecedent moisture. The following equations were given:

$$W = 0.1315 - 0.5792\ D_1 + 0.902\ T_9 + 0.4261\ R_6 \tag{2-20}$$

$$q_o = -0.2917 + 0.46\ R_{11} - 0.0004\ T_3 + 0.00018\ T_2 \tag{2-21}$$

$$G = \frac{7.313 * 10^{-9}\ D^5}{T_5^{0.727}\ S_L^{0.939}} \tag{2-22}$$

where W is total runoff volume in inches, q_o peak discharge in inches per hour, G time difference in minutes between the peak of runoff and the center of mass of runoff, D_1 infiltration capacity in inches per hour, T_9 time of concentration in hours, R_6 total rainfall in inches, R_{11} maximum 30 minute rainfall intensity in inches per hour, T_3 length in feet along the mainstream from the watershed outlet to the center of mass, T_2 length of the longest tributary in feet, D Cook's ΣW parameter describing the soil, land use, and topography, and T_5 average main channel slope in feet per foot.

Another study conducted by Dyhr-Nielson and Schulz (1972) considered numerous watershed parameters that affected the shape of the runoff hydrograph. By means of factor analysis the original list of parameters was reduced to eight significant watershed parameters: (1) area of the basin, (2) total length of streams, (3) form factor, (4) compactness coefficient, (5) drainage-density, (6) dimensionless standard deviation of travel distance, (7) mainstream slope, and (8) basin slope.

Black (1975) used a laboratory rainfall simulator to study the effects of watershed size on the hydrograph parameters: (1) maximum peak, (2) time of rise, (3) time of recession, and (4) time of runoff. Experimental results indicated that runoff per unit area decreases as size increases because larger areas take longer to concentrate the runoff into a peak, and rainfall intensity and duration decrease over larger areas. Another finding was that the decay time, as an index to the time of recession, increases and is related exponentially to the level of maximum peak.

The preceeding investigations suggested the use of the following characteristics in this study: (1) AREA, basin area in hectares, (2) WIDTH, basin width in kilometers, (3) XLR, length of the mainstream in kilometers, (4) SHAPE, shape factor, (5) DD, drainage-density in meters^{-1}, (6) SLOPE, average basin slope in percent, (7) CSLOPE, average mainstream channel slope in percent, and (8) SO, stream order.

CHAPTER 3

DISCUSSION OF MODELS

This chapter provides a brief description of the two models used in the present study. The model parameters and their possible physical interpretations are indicated.

3.1 Converging Overland Flow Model (CONV)

The converging overland flow model considers surface runoff as unsteady, gradually varied free surface flow and approximates its dynamic behavior by the kinematic wave theory (Lighthill and Whitham, 1955). The complex geometry of a natural watershed is transformed into a simple linearly converging geometry as shown in Fig. 3-1. This transformation is based on the premise that the simplified geometry will have a hydrologic response similar to that of the natural geometry and is, hence, equivalent to some extent (Woolhiser, 1969; Singh, 1974, 1975a, 1975b).

From Fig. 3-1 it is clear that the converging section has four geometric parameters including L_o, r, θ, and S_o, where L_o is the length of the section, S_o the slope, r a parameter related to the degree of convergence, and θ the interior angle. Because of radial symmetry, θ does not affect the relative response characteristics; since the watershed area must be preserved, it is dependent on L_o and r only. It will be shown later that these geometric paramaters can be estimated from watershed topography; thus a topographic map is sufficient to transform the complex watershed geometry into a simplified equivalent converging geometry.

The mathematical representation of the model consists of a continuity equation and a kinematic-momentum equation. These equations, as derived by Singh (1974), are:

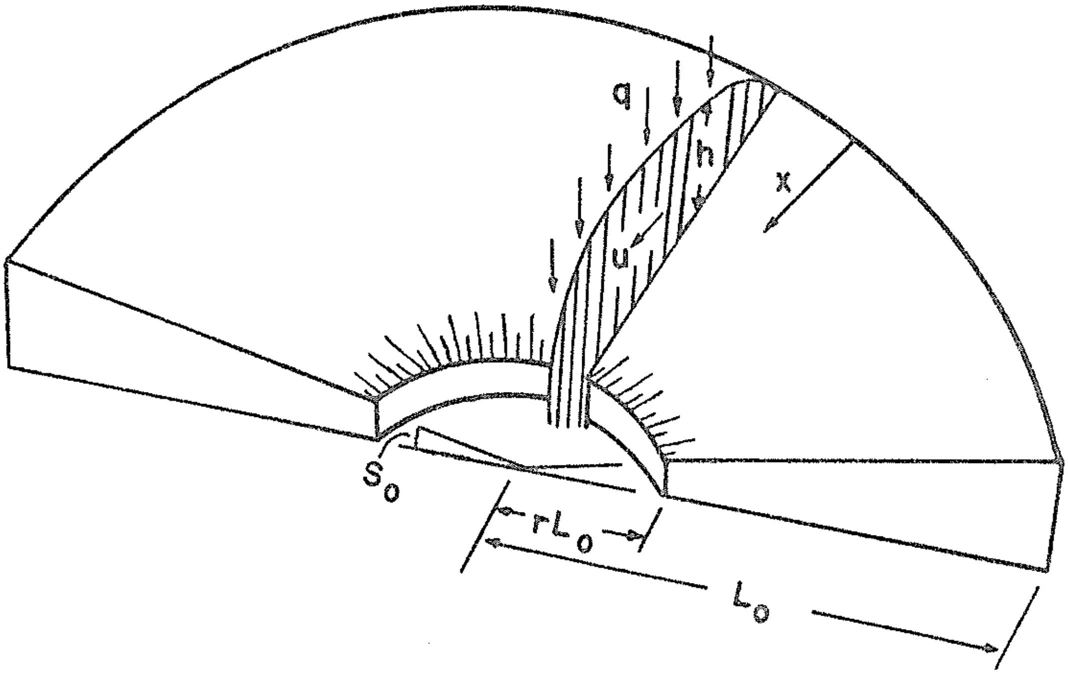

Fig. 3-1. Geometry of converging section, CONV model.

$$\frac{\partial h}{\partial t} + U\frac{\partial h}{\partial x} + h\frac{\partial U}{\partial x} = q(x,t) + \frac{Uh}{(L_o - x)} \quad (3\text{-}1)$$

$$Q = \alpha h^n \quad (3\text{-}2)$$

where h is local depth, U local velocity, Q rate of outflow per unit width, q(x,t) lateral inflow rate in volume per unit time per unit area, L_o radius of the converging section, α,n parameters of frictional relationship, x space coordinate, and t time coordinate.

Because of their nonlinear nature it is not possible to solve Eqs. (3-1) and (3-2) explicitly analytically for space-time variable inflow q (Singh, 1974). However, numerical and hybrid solutions (Singh, 1975b, 1975e) are relatively simple to develop, and will be utilized in the present investigation.

It is clear from Eq. (3-2) that the model has two parameters n and α. In a laboratory study Singh (1974, 1975a) showed that these two parameters were strongly correlated and that it would be reasonable to keep n fixed at 1.5, thus reducing the 2-parameter model to a 1-parameter model. In the present study this 1-parameter model was used. The dynamical basis of the parameter α strongly suggests that it has physical significance and that it should be plausible to estimate it from watershed characteristics. For further details see Singh (1974, 1975a, 1975b, 1975c, 1975d, 1975e).

3.2 Nash Model (NASH)

The Nash model (Nash, 1958) represents a watershed by a cascade of linear reservoirs as shown in Fig. 3-2. It is noteworthy that the model does not explicitly account for the geometric configuration of a given watershed. The runoff dynamics is represented by a spatially lumped continuity equation and a linear storage law; for time interval Δt, these can be written as:

$$q(t) = Q(t) + \frac{dS(t)}{dt} \quad (3\text{-}3)$$

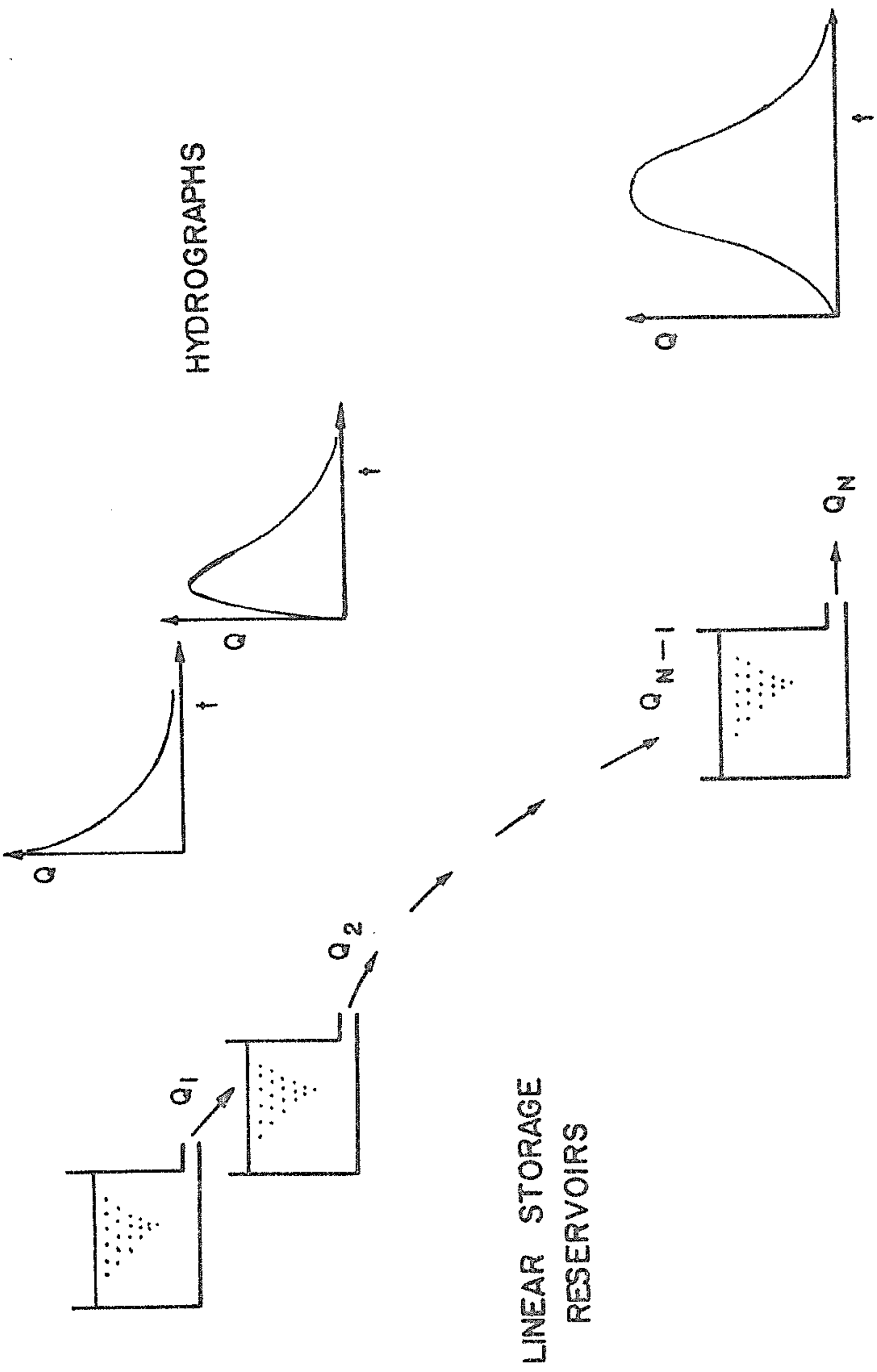

Fig. 3-2. Nash's cascade of linear reservoirs.

$$S = KQ \tag{3-4}$$

where S is storage and K storage coefficient or watershed characteristic lag time. The basis of Nash model emerges principally from the notion of linearity inherent in Eq. (3-4). By routing an instantaneous unit inflow through a cascade of N equal linear reservoirs Nash (1958) derived an expression for the instantaneous unit hydrograph (IUH) W(t):

$$W(t) = \frac{1}{K(N-1)!} (t/K)^{N-1} e^{-t/K} \tag{3-5}$$

For an inflow q(t), outflow Q(t) at time t can be computed by the convolution integral:

$$Q(t) = \int_{o}^{t} W(t-z)\, q(z)\, dz \tag{3-6}$$

From Eq. (3-5) it is seen that the model has two parameters N and K. The precise physical significance of these parameters is unclear, but it appears plausible to establish links between these parameters and watershed characteristics. To be specific, K is a lag time parameter and will depend mainly on the length of the mainstream, slope, drainage-density and shape factor; whereas N accounts for the overland and channel phases and will largely depend on the area, the drainage-density and the shape factor. It is conceivable that by fixing N, the 2-parameter Nash model can be reduced to a 1-parameter model. Although N will change from one watershed to another, it is quite likely that it may be more or less the same for watersheds in the same size group. This contention will be explored in the present study. For further details on Nash model see the references by Nash (1958, 1960).

CHAPTER 4

ASSEMBLAGE AND ANALYSIS OF RESEARCH DATA

This chapter deals with the collection and analysis of research data. A brief description of agricultural watersheds, selected for the study, is provided. For optimization of model parameters, the watershed characteristics are identified and determined. Finally, equations are developed for estimating the model parameters from these characteristics.

4.1 Selection of Agricultural Watersheds

Thirty eight agricultural watersheds were selected for this study as shown in Table 4-1. These watersheds represent several regions of the United States encompassing diverse geologic, topographic and hydrologic conditions. These are small agricultural watersheds varying in area from about 0.5 hectares to 3,055 hectares. Two factors were considered in the selection of these watersheds: (1) rainfall-runoff data was adequate, (2) slope of a watershed was reasonably high.

Deep, fine-textured, granular, slowly permeable, alkaline throughout, and slow internal drainage are typical characteristics of soils of watersheds near Riesel(Waco), Texas. The dominance of Houston black clay is notable. These soils are also noted for the formation of large extensive cracks upon drying. Surface drainage is, by and large, good but no well-defined drainageways exist on the watersheds. Usually, water is drained by rills and poorly defined field gullies.

Most of the time these watersheds are covered with an agricultural crop. Because of low permeability of the soils, the watersheds respond rapidly to rainfall and produce quickly rising hydrographs. For the events under consideration, the major part of rainfall was observed as surface runoff; the infiltration losses did not dominate.

The watersheds near Hastings, Nebraska, have loessial soils. The top soil is normally a mixture of silt loam and silt clay. The internal drainage is medium, and the permeability of subsoil is moderately slow. Surface drainage is good. The watersheds develop arterial flow toward a central drainageway. Channel meandering is noticeable and leads to impounding some water.

These are also agricultural watersheds, and have agricultural cover on the surface. A major part of the rainwater seeps into the ground, thus infiltration losses are predominant. Their response to rainfall input is not as fast as that of watersheds near Riesel (Waco), Texas, especially for events under consideration.

The watersheds near Coshocton, Ohio, have residual soils developed from shale and sandstone. Topsoils are silt loam to loam in texture, moderate fine crumb in structure. Subsoils have moderate permeability with medium internal drainage and no impeding layers. Surface drainage is good with flow to one main channel. Area is highly dissected and has occasional small gullies and valleys which are narrow and have high gradients except in lower reaches of the main channel.

These watersheds have a mixture of surface coverage, all under conservation practices. A significant portion of rainfall is absorbed by infiltration, thus effectively reducing the rainfall-excess volume. Response to rainfall input is similar to that experienced by the watersheds near Hastings, Nebraska.

The soils of the Watkinsville, Georgia, watershed consist of piedmont material ranging in texture from sandy loam to clay loam. Fine-textured, red and friable material of moderately rapid permeability is typical. Internal drainage is medium to rapid. Surface drainage is good along a well defined drainageway meandering through breaks in the bench terraces for about two-thirds the length of the watershed; some pocketing of water above terraces occurs, however.

This old style bench terraced watershed is usually cultivated in row crops generally on the contours. Infiltration is a predominant factor over runoff; small rainfall-excess is typical.

Soils of the McCredie, Missouri, watershed are deep loessial and glacial material of silt loam texture and fine crumb structure. Permeability and internal drainage of subsoils are very slow. Surface drainage over the gently rolling or undulating claypan prairie is good.

Surface cover on this agricultural watershed consists of rotational crops cultivated in rows on generally contoured slopes. The low permeability of the soils results in a rapid response to rainfall input.

Loessial soils of medium texture, granular structure and moderate permeability are typical of the Ralston Creek, Iowa, and Fennimore, Wisconsin, watersheds. Surface drainage of the well dissected watersheds, with ill-defined boundaries, is good. Some ponding near gaging location occurs.

General diversified farming without soil conserving practices, results in moderate to severe erosion on these watersheds. Runoff response to rainfall input is typically moderate indicating the minor to medium role played by infiltration.

Soils of the Oxford, Mississippi, watersheds are loessial and coastal plains material of silt loam texture and weak fine granular structure, and have moderate to moderately slow permeability with an impeding subsoil layer; internal drainage is medium to slow. Surface drainage is good. Portions of the watershed (6-19%) are non-contributory due to the presence of small desilting and retention dams.

Table 4-1. Characteristics of agricultural watersheds.

Watershed Identification	Area (Hectares)	Weighted Average Slope (%)	Soil Characteristics	Surface Drainage
Riesel (Waco), Texas				
Watershed C	234.32	2.040	Soils of varying texture and structure; slow internal drainage; deep, fine textured, slowly permeable soils noteworthy; cracks upon drying	Good, few well-defined waterways, much of drainage by field gullies and rills
Watershed D	449.22	2.100	-do-	-do-
Watershed G	1,772.59	2.055	-do-	-do-
Watershed W-1	71.23	2.185	Deep, fine textured, granular, slowly permeable, alkaline throughout, slow internal drainage; Houston black clay notable; extensive cracks upon drying	-do-
Watershed W-2	52.61	2.550	-do-	-do-
Watershed W-6	17.12	2.025	-do-	-do-
Watershed W-10	7.97	1.620	-do-	-do-
Watershed SW-12	1.20	3.950	-do-	-do-
Watershed SW-17	1.21	1.830	-do-	-do-

Table 4-1. (continued)

Watershed Identification	Area (Hectares)	Weighted Average Slope (%)	Soil Characteristics	Surface Drainage
Watershed Y	125.05	2.405	-do-	-do-
Watershed Y-2	53.42	2.585	-do-	-do-
Watershed Y-4	32.34	2.855	-do-	-do-
Watershed Y-6	8.46	3.225	-do-	-do-
Watershed Y-7	16.19	1.865	-do-	-do-
Watershed Y-8	8.42	1.945	-do-	-do-
Watershed Y-10	8.50	2.375	-do-	-do-
Hastings, Nebraska				
Watershed 2-H	1.38	6.135	Loessial; internal drainage medium; silt loam predominant; permeability moderate	Good; overland flow predominant
Watershed 4-H	1.47	5.960	Loessial; moderate internal drainage; mixture of silt loam and clay; permeability moderate	Good; surface flow to a well-defined waterway
Watershed W-3	194.66	5.305	-do-	Good; arterial flow to a central drainageway; channel meandering present

Table 4-1. (continued)

Watershed Identification	Area (Hectares)	Weighted Average Slope (%)	Soil Characteristics	Surface Drainage
Watershed W-8	844.20	5.500	-do-	-do-
Watershed W-11	1,412.40	5.095	-do-	-do-
Coshocton, Ohio				
Watershed 5	141.42	15.505	Residual soils developed from shale and sandstone, moderate fine crumb structure; moderate permeability, medium internal drainage, no impeding layers	Good, well-defined waterways feeding one main channel, area highly dissected, valleys are narrow and have high gradients
Watershed 92	372.32	15.400	-do-	-do-
Watershed 94	615.14	15.900	-do-	-do-
Watershed 95	104.01	16.890	-do-	-do-
Watershed 97	1,853.53	17.210	-do-	-do-
Watershed 177	30.59	15.325	-do-	Good, surface flow to one main channel with no major divisions or tributaries; natural boundaries

Table 4-1. (continued)

Watershed Identification	Area (Hectares)	Weighted Average Slope (%)	Soil Characteristics	Surface Drainage
<u>Oxford, Mississippi</u>				
Watershed W-5	457.31	7.720	Loessial and coastal plain soils, silt loam texture, fine grain structure; moderate to moderately slow permeability with an impeding subsoil layer	Good, 6-19% of the watershed areas are non-contributory due to desilting and retention dams
Watershed W-10	2,237.99	10.140	-do-	-do-
Watershed W-24	206.80	12.415	-do-	-do-
Watershed W-35	3,055.48	7.355	-do-	-do-
Watershed WC-1	1.57	7.765	-do-	-do-
Watershed WC-2	0.58	7.130	-do-	-do-
Watershed WC-3	0.65	5.930	-do-	-do-
Watershed WP-4	1.22	9.375	-do-	-do-
<u>Watkinsville, Georgia</u>				
Watershed W-1	7.77	10.625	Piedmont soils, sandy to clay loam texture, fine textured, red and friable material; moderately rapid permeability, internal drainage medium	Good, well-defined drainage-ways meandering through breaks in bench terraces

Table 4-1. (continued)

Watershed Identification	Area (Hectares)	Weighted Average Slope (%)	Soil Characteristics	Surface Drainage
<u>Mc Credie, Missouri</u>				
Watershed W-1	62.32	3.420	Deep glacial and loessian material, silt loam texture, fine crumb structure; very slow permeability and internal drainage	Good, drainage over gently rolling or undulating claypan prairies
<u>Iowa City, Iowa</u>				
Ralston Creek	781.07	10.250	Loessial soils, medium texture, granular structure; moderate permeability and internal drainage	Good, well dissected drainage network, ill-defined boundaries
<u>Fennimore, Wisconsin</u>				
Watershed W-1	133.55	5.975	-do-	-do-

Surface coverage on these agricultural watersheds consists of equal portions of cultivation, pastures, woods, and idle land. Low permeability and impeding subsoil layers restrict infiltration resulting in fairly rapid response to rainfall input.

4.2 Selection of Rainfall-Runoff Data

The guidelines proposed by Barnes (1959), Bernard (1935), and Brater (1939) for the selection of hydrologic data suitable for hydrograph development were followed in this study. These can be summarized as follows:

1. The rain must have fallen within the selected time unit.
2. The storm must have been well distributed over the watershed, all stations showing an appreciable amount.
3. The storm period must have occupied a place of comparative isolation in the record.
4. The runoff following a storm must have been uninterrupted by the effects of low temperatures and unaccompanied by melting snow or ice.
5. The hydrographs must have a sharp, defined rising limb culminating in a single peak and followed by an uninterrupted recession. In a multipeaked hydrograph peaks must be distinctly defined.

Rainfall-runoff data for the agricultural watersheds were obtained from two sources:

1. USDA publications entitled "Hydrologic Data For Experimental Agricultural Watersheds in the United States."
2. The USDA Hydrologic Data Center, USDA-ARS, Beltsville, Maryland.

Rainfall-runoff data for watersheds near Hastings, Nebraska, were obtained from the USDA Hydrologic Data Center. For the remaining watersheds, data were obtained directly from the USDA publications on hydrolgic data. These publications are released almost every year and contain one event per year for each watershed. This event is generally the largest runoff producing event in that year. Eight to twelve events per watershed were normally available; some watersheds had even fewer events. The watershed name, location and date of rainfall-runoff event, used in this analysis, are given in Table 4-2.

USDA publications on hydrologic data usually list readings of only one raingage, although the watershed may have more than one raingage. This raingage is supposedly taken to be representative of watershed rainfall, a situation not often attained. In order to be consistent throughout, this practice was followed for each watershed.

4.3 Determination of Rainfall-Excess

The conventional ϕ-index method of determining rainfall-excess was used in this study. The ϕ-index method assumes a time invariant infiltration rate for the duration of rainfall (see Fig. 4-1). The ϕ-index method simplifies the rainfall-excess calculation, and its simplicity is the primary reason for its use in hydrologic modeling. For this same reason it was used in the present study. Several disadvantages are, however, associated with this method and will be discussed in a later section.

4.4 Selection of Topographic Characteristics

The topographic characteristics selected for this study include average watershed slope, slope of the mainstream, watershed area, width of the watershed, length of the mainstream, drainage-density, shape factor and stream order. Fundamental concepts inherent in CONV called for consideration of the first two characterisitcs. The remainder of the characteristics have been found influential in determining the shape of the runoff hydrograph (Sherman, 1932b; Gray, 1961; Black, 1975). These characteristics are given for each watershed in Table 4-3. We now define these characteristics and discuss how to obtain them.

4.4.1 Average Watershed Slope (SLOPE)

Average watershed slope was obtained directly from the USDA hydrologic data publications. Slope was given in these publications for several portions

Table 4-2. Watershed name, location, and runoff dates.

Location and Name	Watershed	Runoff Event Number						
		1	2	3	4	5	6	7
Albuquerque, New Mexico	W-II	8-24-57	8-21-58	5-23-59	8-15-61	6-10-66	8-13-67	
Coshocton, Ohio	5	6-28-40	6-12-57	9-23-45	4-25-61	8-21-60	6-28-57	1-21-59
	92	9-23-45	6-12-57	6-28-57	1-21-59	4-25-61	6-28-40	6-18-40
	94	9-23-45	6-12-57	6-28-57	1-21-59	4-25-61	8-21-60	6-28-40
	95	9-23-45	6-28-57	4-25-61	6-28-40	3-9-64	6-12-57	6-18-40
	97	6-12-57	4-25-61	6-28-40	6-18-40	3-9-64	6-4-41	9-23-45
	177	4-25-61	9-23-45	6-12-57	6-28-57	1-21-59	6-28-40	6-18-40
Fennimore, Wisconsin	W-1	8-3-40	6-28-45	8-12-43	7-11-44	6-24-49	7-26-40	6-3-43
Hastings, Nebraska	2-H	8-13-39	6-22-42	8-7-42	9-7-42	8-23-44	8-7-47	9-5-46
	4-H	8-11-39	6-20-42	8-7-42	9-7-42	8-29-44	8-7-46	9-5-46
	W-3	6-10-42	9-5-46	5-20-46	6-5-49	9-19-50	6-25-51	7-10-51
	W-8	6-5-48	6-14-43	5-11-44	6-5-45	7-16-45	9-19-50	6-1-51
	W-11	5-11-44	9-19-50	6-1-51	7-10-51	6-26-52	7-13-52	5-22-54
Mc Credie, Missouri	W-1	7-3-41	6-10-42	5-16-43	6-8-43	5-14-45	7-22-48	9-12-49

Table 4-2. (continued)

Location and Name	Watershed	Runoff Event Number						
		1	2	3	4	5	6	7
Oxford, Mississippi	W-5	4-3-58	6-10-59	6-11-59	1-17-60	8-31-61	9-4-62	1-22-57
	W-10	1-17-60	8-31-61	4-3-58	6-11-59	8-29-63	3-6-64	3-3-65
	W-24	11-18-57	5-9-58	1-17-60	7-25-62	3-6-64	3-4-65	5-24-66
	W-35	11-18-57	4-15-58	5-23-59	3-4-60	3-4-64	3-4-65	5-24-66
	WC-1	5-26-59	6-11-59	8-9-60	8-31-61	6-11-62	7-20-63	4-13-64
	WC-2	5-26-59	6-11-59	8-9-60	8-31-61	6-11-62	7-20-63	4-13-64
	WC-3	5-26-59	6-11-59	8-9-60	8-31-61	6-11-62	7-20-63	4-13-64
	WP-4	5-26-59	6-11-59	8-9-60	8-31-61	6-11-62	7-20-63	4-13-64
Riesel (Waco), Texas	C	6-10-41	4-24-57	5-9-57	5-13-57	6-23-59	7-9-61	7-16-61
	D	5-6-55	5-3-57	6-23-59	12-31-59	7-16-61	7-23-61	6-4-62
	G	7-14-41	2-14-59	8-23-59	11-4-59	12-31-59	7-16-61	7-23-61
	W-1	3-12-53	5-13-57	6-4-57	6-23-59	6-15-61	7-16-61	6-9-62
	W-2	5-22-51	3-12-53	4-24-57	5-13-57	6-23-57	6-25-61	6-9-61
	W-6	4-27-49	4-24-57	5-13-57	6-23-57	6-18-57	6-25-61	6-9-62

Table 4-2. (continued)

Location and Name	Watershed	Runoff Event Number						
		1	2	3	4	5	6	7
	W-10	3-12-53	4-24-57	6-4-57	6-23-59	5-22-61	6-25-61	6-9-62
	Y	4-27-49	3-31-57	4-24-57	6-4-57	6-23-59	7-16-61	6-26-61
	Y-2	3-26-46	4-24-57	5-13-57	6-4-57	6-23-59	7-16-61	6-25-61
	Y-4	3-12-53	4-24-57	5-13-57	6-4-57	6-23-59	7-16-61	6-25-61
	Y-6	5-6-55	4-24-57	5-13-57	6-4-57	6-23-59	5-25-61	6-15-61
	Y-7	5-6-55	4-24-57	5-13-57	6-4-57	6-23-59	5-22-61	7-16-61
	Y-8	3-12-53	4-24-57	5-13-57	6-4-57	6-23-59	6-18-61	6-9-62
	Y-10	5-6-55	4-24-57	5-13-57	6-4-57	6-23-59	5-25-61	6-9-62
	SW-12	3-12-53	6-4-57	6-23-59	6-9-62	3-29-65		
	SW-17	3-12-53	3-31-57	4-24-57	5-13-57	6-23-59	6-26-61	7-16-61
Ralston Creek, Iowa		6-1-43	7-21-48	7-1-50	7-18-56	8-31-56	11-15-60	11-15-61
Watkinsville, Georgia	W-1	7-11-41	5-15-42	4-24-45	11-26-48	8-13-58	8-1-61	6-26-63

Table 4-2. (continued)

Location and Name	Watershed	Runoff Event Number						
		8	9	10	11	12	13	14
Albuquerque, New Mexico	W-II							
Coshocton, Ohio	5	6-18-40	3-10-64					
	92	8-21-60	3-10-64					
	94	6-18-40	3-10-64					
	95	6-12-57	3-10-64					
	97	7-11-46	6-28-57					
	177							
Fennimore, Wisconsin	W-1	6-22-44	6-17-44	6-21-54				
Hastings, Nebraska	2-H	5-20-49	6-16-50	6-1-51	6-26-52	7-13-52	5-22-54	6-12-58
	4-H	5-20-49	6-16-50	6-1-51	6-26-52	7-13-52	5-22-54	6-12-58
	W-3	5-21-52	6-26-52	7-13-52	6-7-53	6-15-57	6-29-57	7-16-57
	W-8	7-10-51	6-26-52	6-29-52	7-6-52	6-7-53	6-16-57	7-3-59
	W-11	6-16-57	6-14-61	5-21-65				
Mc Credie, Missouri	W-1	6-29-57	4-6-65					

Table 4-2. (continued)

Location and Name	Watershed	Runoff Event Number						
		8	9	10	11	12	13	14
Oxford, Mississippi	W-5	12-7-57	8-30-63	3-6-64	3-7-65	3-4-66	6-1-67	
	W-10	12-28-66	6-1-67					
	W-24	8-29-63	6-3-67					
	W-35	6-3-67						
	WC-1	7-8-65	9-30-66	7-9-67				
	WC-2	7-8-65	9-30-66	7-9-67				
	WC-3	7-8-65	9-30-66	7-9-67				
	WP-4							
Riesel (Waco), Texas	C	6-4-62	5-10-65					
	D	5-10-65						
	G	6-9-61	3-29-65					
	W-1	3-29-65						
	W-2	3-29-65						
	W-6	3-29-65						

Table 4-2. (continued)

Location and Name	Watershed	Runoff Event Number						
		8	9	10	11	12	13	14
	W-10	3-29-65						
	Y	6-9-62	3-29-65					
	Y-2	6-9-62	3-29-65					
	Y-4	6-9-62	3-29-65					
	Y-6	6-9-62	3-29-65					
	Y-7	6-9-62	3-20-65					
	Y-8	3-29-65						
	Y-10	6-9-62	3-29-65					
	SW-12							
	SW-17	6-9-62	3-29-65					
Ralston Creek, Iowa		7-13-62	9-20-65	6-10-66	6-7-67			
Watkinsville, Georgia	W-1	3-25-64	5-4-64					

Table 4-2. (continued)

Location and Name	Watershed	Runoff Event Number				
		15	16	17	18	19
Hastings, Nebraska	2-H	7-3-59	5-15-60	3-23-62	6-16-65	6-29-65
	4-H	5-15-60	8-23-62	6-12-65	6-19-65	
	W-3	7-3-59				
	W-8	7-3-59				

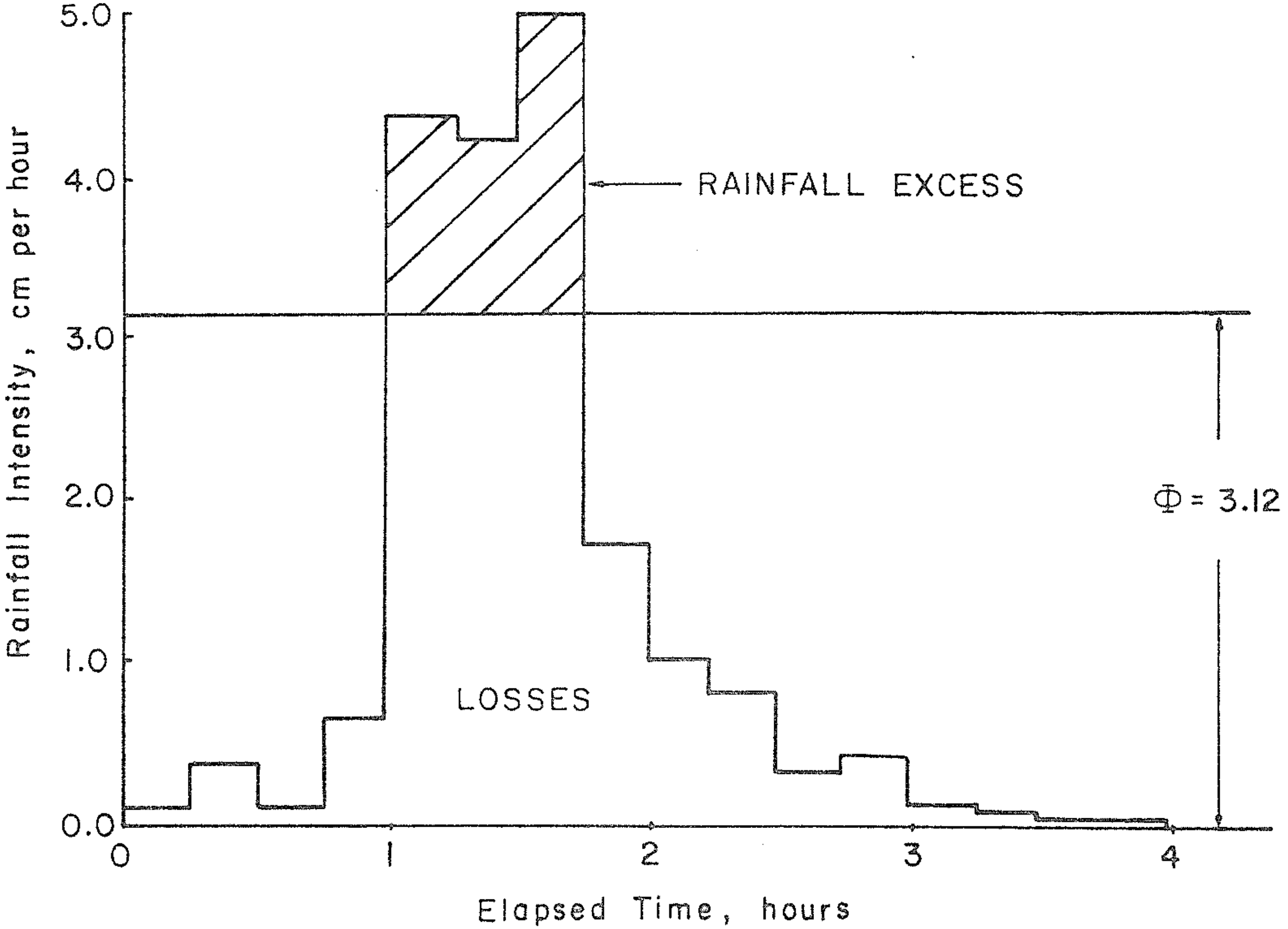

Fig. 4-1. ϕ-index separation method Oxford, Mississippi, W-5, 8-31-61.

of the watershed. An average slope was obtained by weighting each slope with respect to the proportion of watershed comprising this slope.

4.4.2 Average Mainstream Slope (CSLOPE)

The slope of the principal drainage channel was determined from the topographic map. The length of the mainstream was divided by the difference in elevation between its upper and lower ends. Small basin areas and the relatively straight channel reaches justified this simplistic method.

4.4.3 Basin Area (AREA), Basin Width (WIDTH), and Length of Mainstream (XLR)

Area and width of the basin were given in the USDA publications, as was the length of the mainstream. The length of the principle watercourse was defined as the distance from the gaging station to the upstream watershed boundary measured along the floodplain of the watercourse.

4.4.4 Drainage-Density (DD)

Drainage-density was determined from the topographic map. Drainage-density is defined as the cumulative length of all streams, shown in the drainage-basin, divided by the drainage-basin area:

$$DD = \frac{\Sigma L}{A} \tag{4-1}$$

where DD is drainage-density, A area of drainage-basin, and L length of watercourses.

4.4.5 Shape Factor (SHAPE)

The shape factor proposed by Chorley, Malm, and Pagorzelski (1957) was utilized in this study:

$$K_f = \frac{\pi L^2}{4.0 A} \tag{4-2}$$

where K_f is the dimensionless shape factor, and L length of the mainstream.

4.4.6 Stream Order (SO)

The method of designating stream order developed by Strahler (1954a) was applied. Strahler's method assumes that the channel-network map includes all intermittent and permanent flow lines located in clearly defined valleys, the smallest finger-tip tributaries are designated order 1. Where two first-order channels join, a channel segment of order 2 is formed; where two channels of order 2 join, a segment of order 3 is formed; and so forth. The mainstream through which all discharge of water passes is therefore the stream segment of the highest order.

The usefulness of the stream order system is dependent upon the assumption that, on the average, order number is directly proportional to relative watershed dimensions, channel size, and stream discharge at that place in the system. Due to the dimensionless nature of stream order, drainage-basins differing greatly in size can be compared provided the problem of linear map scaling is resolved.

4.5 Determination of Converging Geometry

The transformation of the complex watershed geometry into a simplified converging geometry requires the determination of the geometric parameters L_o, r, and θ. These geometric parameters were estimated from topographic characteristics including width and area of the basin, and length of the mainstream. L_o was considered equal to the length of the mainstream along its course. θ was defined as:

$$\theta = 2 \arctan \left(\frac{W}{2L_o}\right) \tag{4-3}$$

where W is the horizontal projection of the watershed width. Then r can be determined from the watershed area:

Table 4-3. Watershed characteristics.

Location and Name	Watershed	Area (Hectares)	Width (Km)	Length of Mainstream (Km)	Slope (%)	Shape	Drainage Density (m^{-1})	Stream Order	Slope of Mainstream (%)
Albuquerque, N.M.	W-II	16.39	0.234	0.814	12.260	3.1752	0.0065	3	5.168
Coshocton, Ohio	5	141.24	0.671	2.415	15.505	3.2431	0.0063	3	1.770
	92	372.32	0.518	2.898	15.400	1.7716	0.0007	3	2.368
	94	615.14	1.931	4.186	15.900	2.2372	0.0011	2	1.750
	95	104.01	3.460	5.635	16.890	2.3978	0.0018	3	1.353
	97	1,853.53	3.892	9.016	17.210	3.4444	0.0010	3	1.014
	177	30.59	0.465	0.854	15.325	1.8707	0.0031	2	5.357
Fennimore, Wisc.	W-1	133.55	0.914	1.768	5.975	1.8389	0.0022	2	1.724
Hastings, Neb.	2-H	1.38	0.076	0.189	6.135	2.0395	0.0078	2	2.581
	4-H	1.47	0.107	0.162	5.960	1.3921	0.0078	1	4.528
	W-3	194.66	1.207	2.720	5.305	2.9861	0.0039	3	0.430
	W-8	844.20	1.811	7.953	5.500	5.8850	0.0032	4	0.430
	W-11	1,412.40	2.012	11.673	5.576	7.5793	0.0032	4	0.430
Mc Credie, Mo.	W-1	62.32	0.415	1.036	3.420	1.3541	0.0028	3	1.176

Table 4-3. (continued)

Location and Name	Watershed	Area (Hectares)	Width (Km)	Length of Mainstream (Km)	Slope (%)	Shape	Drainage Density (m^{-1})	Stream Order	Slope of Mainstream (%)
Oxford, Miss.	W-5	457.31	2.347	2.415	7.720	1.0013	0.0009	1	0.630
	W-10	2,238.00	4.829	6.440	10.140	1.4555	0.0010	3	0.700
	W-24	206.80	1.207	2.012	12.420	1.5382	0.0038	3	3.030
	W-35	3,055.48	3.621	8.855	7.550	2.0155	0.0014	4	0.689
	WC-1	1.57	0.114	0.149	7.760	1.1163	0.0248	3	6.222
	WC-2	0.59	0.084	0.092	7.130	1.1197	0.0146	1	6.667
	WC-3	0.65	0.061	0.107	5.930	1.3725	0.0122	1	4.286
	WP-4	1.22	0.076	0.134	9.380	1.1602	0.0138	1	5.682
Riesel (Waco), Texas	C	234.32	1.402	2.366	2.040	1.3761	0.0023	3	0.570
	D	449.22	1.982	3.567	2.100	2.2246	0.0022	3	0.510
	G	1,772.59	2.592	7.829	2.055	2.7160	0.0020	4	0.369
	W-1	71.23	0.610	1.646	2.180	2.9887	0.0029	2	0.833
	W-2	52.61	0.823	0.945	2.550	1.3335	0.0034	2	1.290
	W-6	17.12	0.457	0.445	2.020	0.9090	0.0129	2	1.370

Table 4-3. (continued)

Location and Name	Watershed	Area (Hectares)	Width (Km)	Length of Mainstream (Km)	Slope (%)	Shape	Drainage Density (m^{-1})	Stream Order	Slope of Mainstream (%)
	W-10	7.97	0.305	0.323	1.620	1.0289	0.0041	1	1.500
	Y	125.05	0.915	1.537	2.405	1.4830	0.0026	2	0.990
	Y-2	53.42	0.854	1.000	2.585	1.4702	0.0027	2	1.220
	Y-4	32.34	0.595	0.610	2.850	0.9031	0.0011	2	1.750
	Y-6	8.46	0.259	0.338	3.225	1.0634	0.0015	1	1.804
	Y-7	16.19	0.381	0.543	1.865	1.4289	0.0017	1	0.840
	Y-8	8.42	0.183	0.244	1.945	0.5550	0.0016	1	1.100
	Y-10	8.50	0.381	0.338	2.375	1.0584	0.0038	1	1.300
	SW-12	1.20	0.119	0.116	3.950	0.8770	0.0171	1	2.894
	SW-17	1.21	0.122	0.116	1.830	0.8712	0.0066	1	1.579
Ralston Creek, Iowa		781.07	1.463	5.796	10.250	3.3780	0.0085	4	0.550
Watkinsville, Georgia		7.77	0.274	0.381	10.625	1.4763	0.0114	2	4.161

$$A = \frac{\theta}{360} \quad (\pi) \; L_o^2 \, \frac{(1+r)}{(1-r)} \qquad (4\text{-}4)$$

4.6 Methodology For Estimation of Model Parameters

The development of a procedure for estimating model parameters from watershed characteristics involved two basic operations: (1) the optimization of model parameters for a set of events for each watershed, and (2) the correlation of the optimized parameters with topographic characteristics by means of regression analysis. Each of these operations is discussed in the following sections.

4.6.1 Optimization of Model Parameters

The model parameters were optimized by the modified Rosenbrock method (Rosenbrock, 1960; Palmer, 1969; and Himmelblau, 1972), using the objective function based on the sum of squares of peak deviations:

$$F = \sum_{j=i}^{M} (Q_{p_o}(j) - Q_{p_e}(j))^2 \qquad (4\text{-}5)$$

where F is index of disagreement, or error, $Q_{p_o}(j)$ observed hydrograph peak for the jth event, $Q_{p_e}(j)$ estimated hydrograph peak for the jth event, and M number of runoff events in the optimization set. This objective function is particularly useful in flood studies and has other attractive features. Obviously, among peaks greater weight is placed on higher peaks. If F is divided by the number of events, the mean square error will result. This shows, on the average, how much error occurs as the optimization is performed over a set of events. Because it requires only the hydrograph peak from each event, it is efficient computationally. However, it is not recommended for use where hydrograph peak is not an important consideration, e.g., low flow studies. This objective function has been found useful in several studies (Singh, 1974, 1975a, 1975b, 1975e, 1975f).

In optimization of model parameters for a watershed all rainfall events, that were available on that watershed, were utilized. The optimized parameters of CONV and NASH are given in Table 4-4. To optimize parameters of NASH two cases were distinguished: (1) both N and K were considered parameters for optimization, (2) N was fixed at 3 and K was considered as the parameter for optimization. The reason to fix N at 3 will become clear later.

4.6.2 Correlation of Model Parameters with Topographic Characteristics

The UCLA Biomedical Statistical package, called BMD02R, was used to perform regression analyses of model parameters and watershed characteristics. This package is versatile, can handle a large number of variables, and is stepwise in nature.

1. Correlation of α

Regression analyses were performed to correlate α as dependent variable with aforementioned watershed characteristics as independent variables. Initially, a multiple linear regression analysis for all 38 watersheds was performed. The correlation coefficient was 0.9523 and the standard error of estimate 9.23. The regression equation is:

$$\alpha = 0.00942*AREA + 11.53795*WIDTH - 9.76167*XLR + 1.94925*SLOPE + 11.8994*SHAPE + 175.32422*DD + 0.89852*SO - 4.687079*CSLOPE \tag{4-6}$$

Figure 4-2 shows the computed values of α using Eq. (4-6) versus the optimized values of α.

These statistics indicate a relatively good linear relationship between α and watershed characteristics. In an attempt to improve the correlation coefficient, the independent variables were first logarithmically transformed and then α was linearly correlated with these transformed variables. The correlation coefficient and standard error of estimate were 0.9274 and 11.31 respectively. The logarithmic transformation obviously did not improve the correlation.

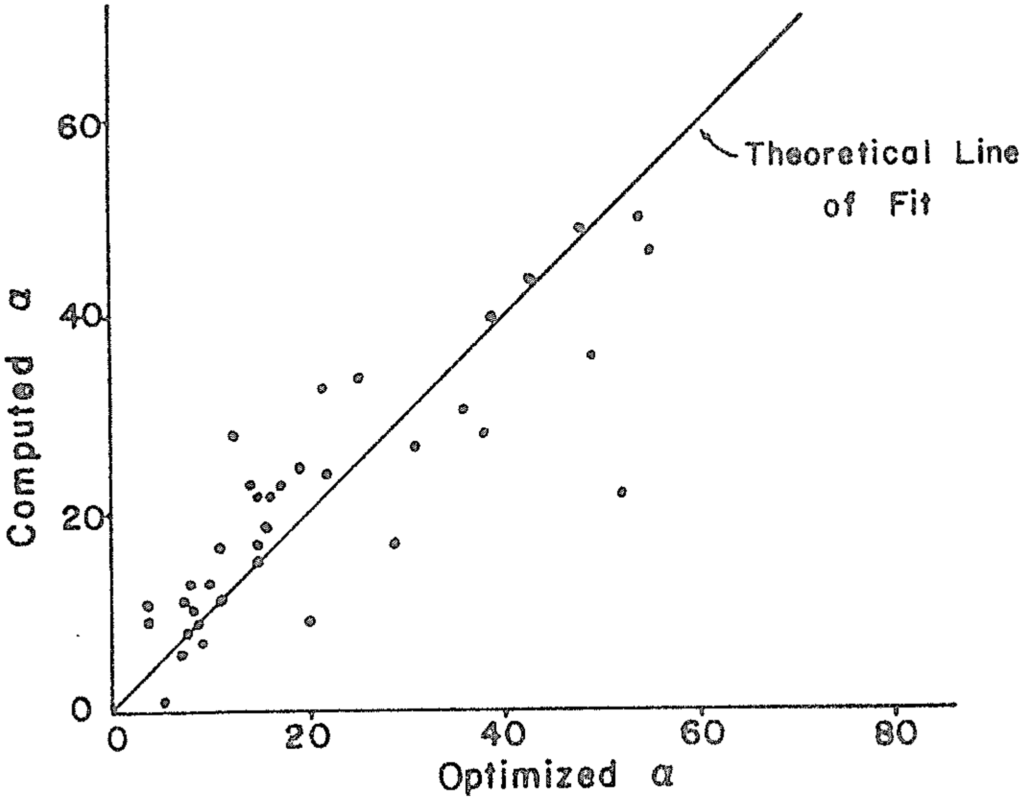

Fig. 4-2. Computed α vs. optimized α for equation 4-6.

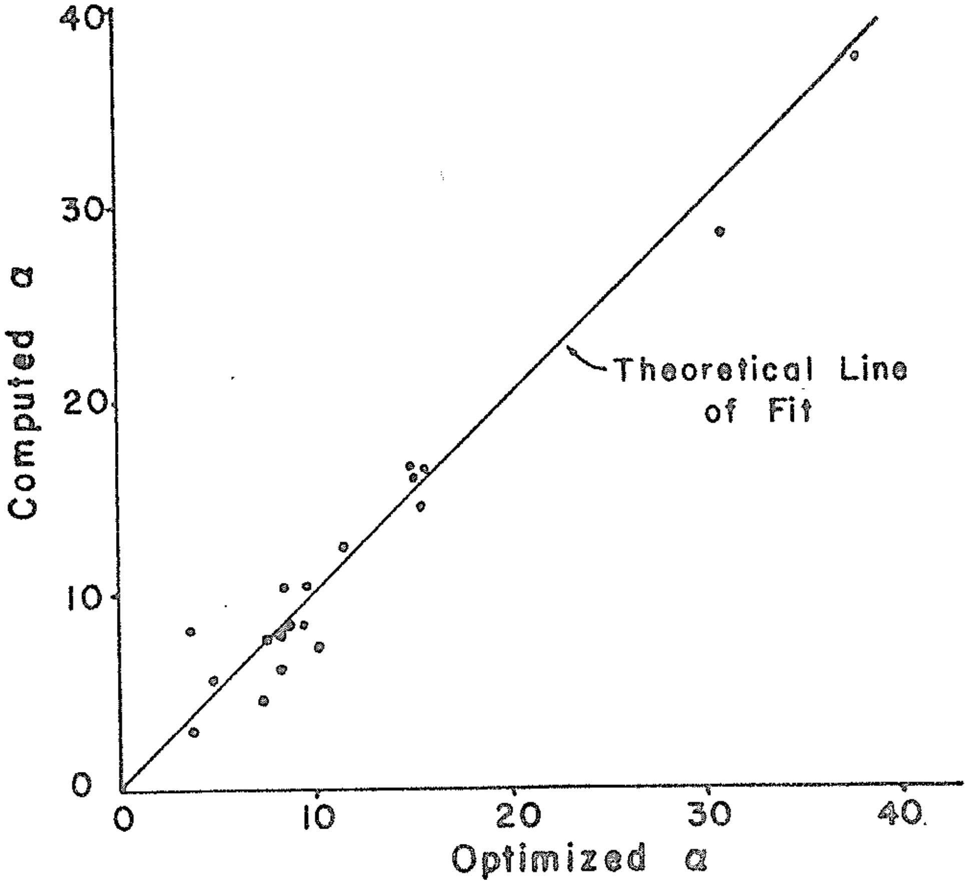

Fig. 4-3. Computed α vs. optimized α for equation 4-7.

Table 4-4. Optimized model parameters.

Name and Location	Watershed	Number of Events Used in Optimization	Model Parameters				
			CONV	NASH		NASH	
			α	N	K	N	K
Albuquerque	W-II	6	78.0000	4.7800	2.4100	3.0	3.3232
Coshocton	5	9	48.8750	1.5000	25.7968	3.0	14.5864
	92	9	22.3750	2.8724	30.3356	3.0	29.5001
	94	9	38.9500	1.8568	22.3749	3.0	18.6849
	95	9	43.0937	3.2400	26.7200	3.0	28.1287
	97	9	55.0624	1.9900	44.1920	3.0	32.4000
	177	7	30.8000	1.5640	12.7724	3.0	7.7105
Fennimore	W-1	10	52.3400	3.0097	9.5113	3.0	9.5682
Hastings	4-H	18	79.0690	4.6670	28.5347	3.0	33.5738
	W-3	15	49.3749	9.7200	6.5500	3.0	13.2689
	W-8	15	25.8750	7.6000	31.3400	3.0	56.0000
	W-11	10	18.6609	8.8200	48.5400	3.0	92.4900
Mc Credie	W-1	9	15.7250	8.1032	8.7962	3.0	16.0552
Oxford	W-5	13	21.5036	7.1700	16.2900	3.0	27.7590

Table 4-4. (continued)

Name and Location	Watershed	Number of Events Used in Optimization	Model Parameters				
			CONV	NASH		NASH	
			α	N	K	N	K
	W-10	9	54.0000	5.1400	20.9800	3.0	29.6953
	W-24	9	12.2500	6.5737	26.7571	3.0	43.5749
	W-35	8	14.5625	13.0163	24.1118	3.0	55.4570
	WC-1	10	9.4359	9.9425	1.1650	3.0	2.2129
	WC-2	10	4.9422	2.8457	0.4537	3.0	0.4310
	WC-3	10	8.2000	5.7725	1.4870	3.0	2.2166
	WP-4	7	8.6582	10.1636	0.3558	3.0	0.5313
Riesel (Waco)	C	9	16.0000	7.4154	14.4256	3.0	25.1217
	D	8	16.7509	5.9035	23.7226	3.0	36.0781
	G	9	20.0000	18.3300	22.8210	3.0	64.0000
	W-1	8	38.0000	2.9523	7.5340	3.0	7.3929
	W-2	8	15.4980	2.6355	10.8761	3.0	10.0000
	W-6	8	9.8125	1.3097	14.4921	3.0	8.0000
	W-10	8	10.1761	2.0000	8.0000	3.0	6.4000

Table 4-4. (continued)

Name and Location	Watershed	Number of Events Used in Optimization	Model Parameters				
			CONV	NASH		NASH	
			α	N	K	N	K
	Y	9	28.2910	3.1082	10.5666	3.0	10.9450
	Y-2	9	15.7500	3.3337	11.2625	3.0	12.0632
	Y-4	9	7.7789	2.0836	18.0438	3.0	14.0000
	Y-6	9	3.6250	4.6456	11.1878	3.0	14.8808
	Y-7	9	11.7937	2.1506	10.0582	3.0	8.0000
	Y-8	8	7.3684	4.0381	4.8423	3.0	5.8148
	Y-10	9	8.2937	4.6751	5.0457	3.0	6.7165
	SW-12	5	8.7315	10.9764	1.4455	3.0	2.9040
	SW-17	9	3.8516	5.4478	3.8314	3.0	5.8207
Ralston Creek		11	36.0781	5.6600	22.3700	3.0	33.5200
Watkinsville	W-1	9	15.1000	3.5983	5.7690	3.0	5.2500

It was then hypothesized that stratification of the data based on a watershed area criterion might improve the correlation. The area criterion was selected as the basis for stratification because the area parameter had larger range of values than any other parameter.

The watersheds were divided into two groups: (1) watersheds smaller than or equal to 75 hectares, and (2) watersheds larger than 75 hectares. The former group contained 20 watersheds and the latter 18 watersheds. Linear regression analyses were performed for both groups. The correlation coefficients for the small and large watersheds were 0.9932 and 0.9530 with standard error of estimate 2.29 and 14.31 respectively. It is clear that the data stratification significantly improved the correlation coefficient. The regression equations are:

For the small watersheds,

$$\alpha = -0.32453*AREA - 6.5572*WIDTH + 44.29964*XLR + 1.08668*SLOPE - 1.98314* SHAPE + 427.48218*DD - 2.45283*SO - 1.02488*CSLOPE \qquad (4\text{-}7)$$

For the large watersheds,

$$\alpha = 0.01011*AREA + 12.6032*WIDTH - 10.50376*XLR + 1.81744*SLOPE + 12.20712* SHAPE + 934.08984*DD + 0.79896*SO - 4.59683*CSLOPE \qquad (4\text{-}8)$$

Figures 4-3 and 4-4 show the distribution of computed α values using Eqs. (4-7) and (4-8) versus the optimized α values for small and large watersheds respectively.

In hope of further improving the correlation coefficient for the group of large watersheds the functional relationship between each independent variable and α was investigated. Table 4-5 lists the independent variables and the functional form which produced the highest correlation coefficient for α with that variable. By selectively combining the transformed independent variables and performing linear regression analyses, the best equation was

Table 4-5. Functional form of variables for CONV.

	Large Watersheds	
Variable	Functional Form	Correlation Coefficient Between α and Individual Variable
AREA	Linear	0.621
WIDTH	Linear	0.830
XLR	Linear	0.764
SLOPE	Log_e	0.917
SHAPE	Log_e	0.808
DD	Log_e	0.902
SO	Linear	0.851
CSLOPE	Linear	0.754

Table 4-6. Functional form of variables for NASH.

Variable	Functional Form	Correlation Coefficient Between K and Individual Variable
AREA	Linear	0.786
WIDTH	Linear	0.816
XLR	SQRT	0.930
SLOPE	Linear	0.614
SHAPE	Log_e	0.832
DD	Linear	0.279
SO	Linear	0.842
CSLOPE	Linear	0.289

obtained for the large watersheds with a correlation coefficient of 0.9714 and the standard error of estimate 11.22. The regression equation is:

$$\alpha = 0.01233*\mathrm{AREA} + 11.82528*\mathrm{WIDTH} - 10.50765*\mathrm{XLR} + 8.38607*\mathrm{Log}_e(\mathrm{SLOPE}) + 51.27583*\mathrm{Log}_e(\mathrm{SHAPE}) - 1.99823*\mathrm{Log}_e(\mathrm{DD}) - 7.06871*\mathrm{SO} - 2.51323*\mathrm{CSLOPE} \quad (4\text{-}9)$$

A comparison of Figs. 4-5 and 4-4 illustrates the improved correlation between computed and optimized α values, and corresponds to a higher correlation coefficient for Eq. (4-9).

Statistical F tests were applied to the regression equations to determine at what point variables ceased to be statistically significant, and could therefore be deleted from the equation. Values of F were calculated at each regression step using the following equation:

$$F = \frac{(SSR_1 - SSR_2)/p}{MSE_1} \quad (4\text{-}10)$$

where SSR_1 is the sum of squares due to regression from the full model, SSR_2 the sum of squares due to regression in the reduced model, where variables are deleted, p number of variables deleted, and MSE_1 the mean square error associated with deviations from regression in the full model. Calculated F values at each step of regression were compared to tabulated F values, $F_{.05}(p, n-k-1)$, where n is the sample size and k is the degrees of freedom due to regression. If the calculated F values equalled or exceeded the tabulated F value the variable was retained in the regression equation. Table 4-7 gives the F value comparison. By deleting relatively non-contributory variables the degrees of freedom were increased thereby enhancing the statistical significance. The final regression equation for the small watersheds is:

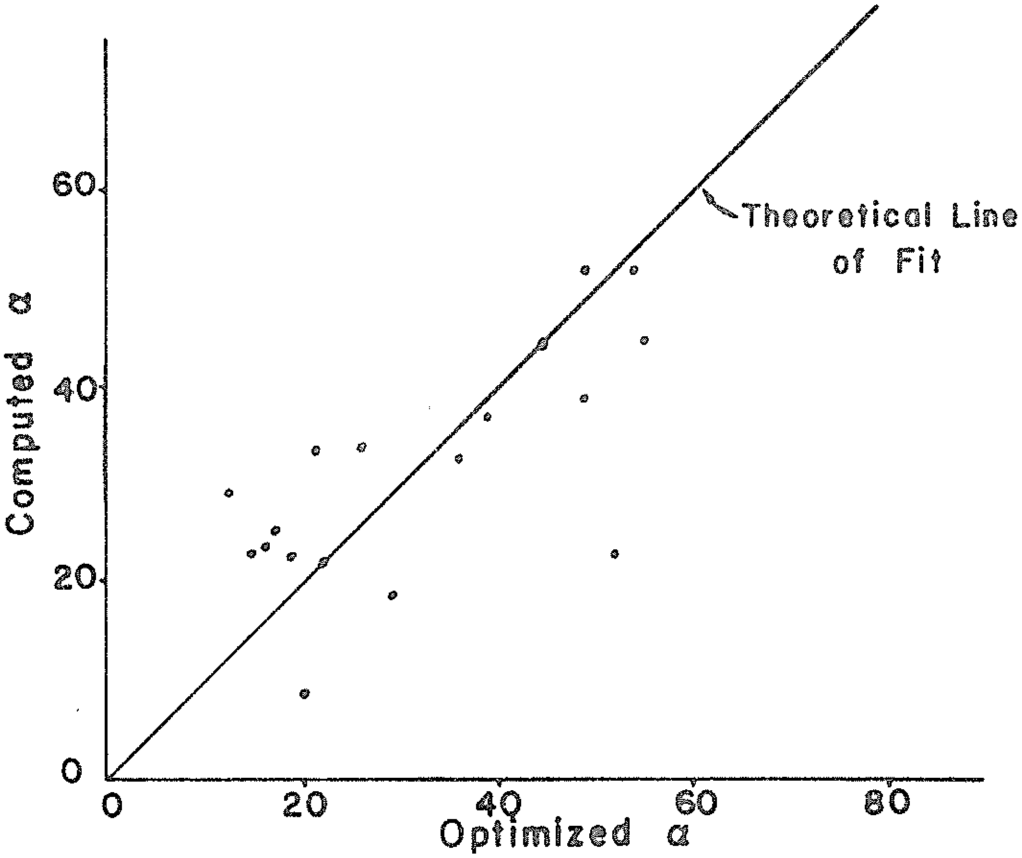

Fig. 4-4. Computed α vs. optimized α for equation 4-8.

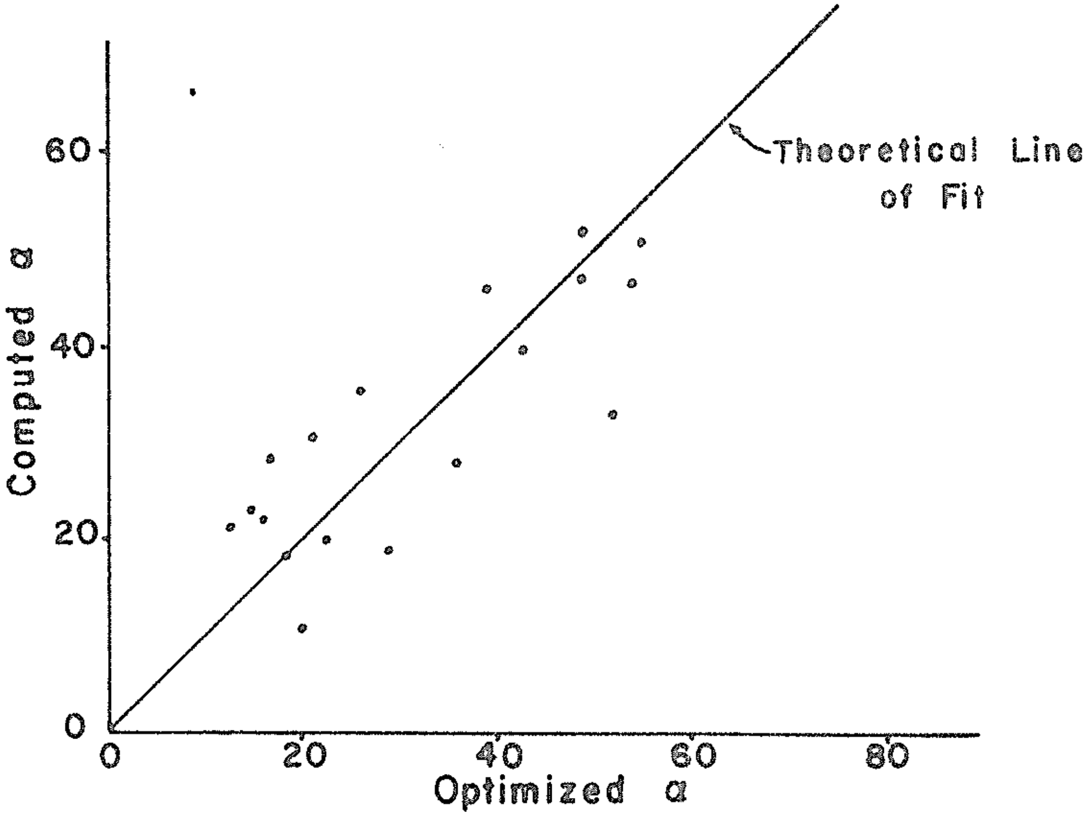

Fig. 4-5. Computed α vs. optimized α for equation 4-9.

Table 4-7. Statistical F tests for CONV.

Small Watersheds				Large Watersheds			
Step	Variable To Be Added	Calculated F	Tabulated F $F_{.05}(p,n-k-1)$	Step	Variable To Be Added	Calculated F	Tabulated F $F_{.05}(p,n-k-1)$
1	SHAPE	–	–	1	SLOPE	–	–
2	XLR	17.83	4.45	2	DD	18.38	4.67
3	SLOPE	5.04	4.49	3	CSLOPE	8.16	4.75
4	AREA	4.98	4.54	4	XLR	7.93	4.84
5	WIDTH	4.72	4.60	5	SHAPE	6.53	4.96
6	DD	4.69	4.67	6	WIDTH	5.98	5.12
7	SO	1.31	4.75	7	AREA	5.08	5.32
8	CSLOPE	0.19	4.84	8	SO	4.83	5.59

$$\alpha = -0.45817*AREA - 9.54289*WIDTH + 50.53227*XLR + 0.59317*SLOPE - 3.13773*SHAPE + 148.47112*DD \qquad (4-11)$$

with a correlation coefficient of 0.9905 and standard error of estimate 2.49. Figure 4-6 shows the computed versus optimized values of α for Eq. (4-11) A comparison of Figs. 4-3 and 4-6 shows that Eqs. (4-7) and (4-11) produce essentially the same results although two variables have been deleted from Eq. (4-11).

The final regression equation for the large watersheds is:

$$\alpha = 10.91814*WIDTH - 6.96391*XLR + 10.764*Log_e(SLOPE) + 28.933*Log_e(SHAPE) - 0.70065*Log_e(DD) - 5.89831*CSLOPE \qquad (4-12)$$

with a correlation coefficient of 0.9625 and standard error of estimate 11.69. Figure 4-7 shows the computed versus optimized values of α for Eq. (4-12). A comparison of Figs. 4-5 and 4-7 shows that Eqs. (4-9) and (4-12) produce essentially the same results although two variables have been deleted from Eq. (4-12).

2. Correlation of N and K

Regression analyses were performed to correlate the parameters N and K as dependent variables with the aforementioned watershed characteristics as the independent variables. Initially, a linear regression analysis, for all 38 watersheds, was performed separately for N and K. The correlation coefficient for N and K was 0.6858 and 0.9038 with standard error of estimate 2.96 and 5.79 respectively. The regression equations are:

$$N = -0.63439*WIDTH + 1.2826*XLR - 0.38665*SLOPE - 1.33649*SHAPE + 142.8307*DD + 1.08697*SO + 0.68069*CSLOPE + 0.58631*AREA \qquad (4-13)$$

$$K = -0.001*AREA - 4.25605*WIDTH + 4.23147*XLR + 0.988*SLOPE - 1.22699*SHAPE - 280.94189*DD - 1.22258*SO - 1.89397*CSLOPE \qquad (4-14)$$

Figures 4-8 and 4-9 are plots of computed versus optimized N and K values for Eqs. (4-13) and (4-14) respectively.

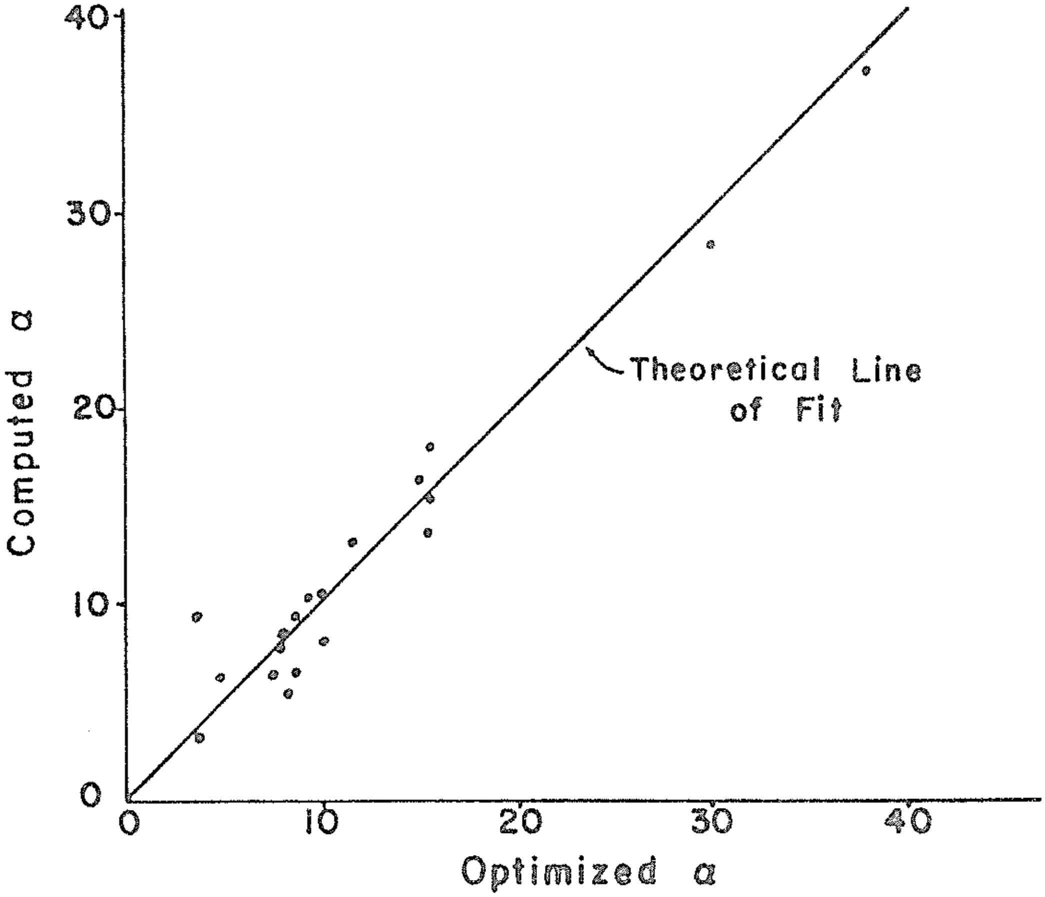

Fig. 4-6. Computed α vs. optimized α for equation 4-11.

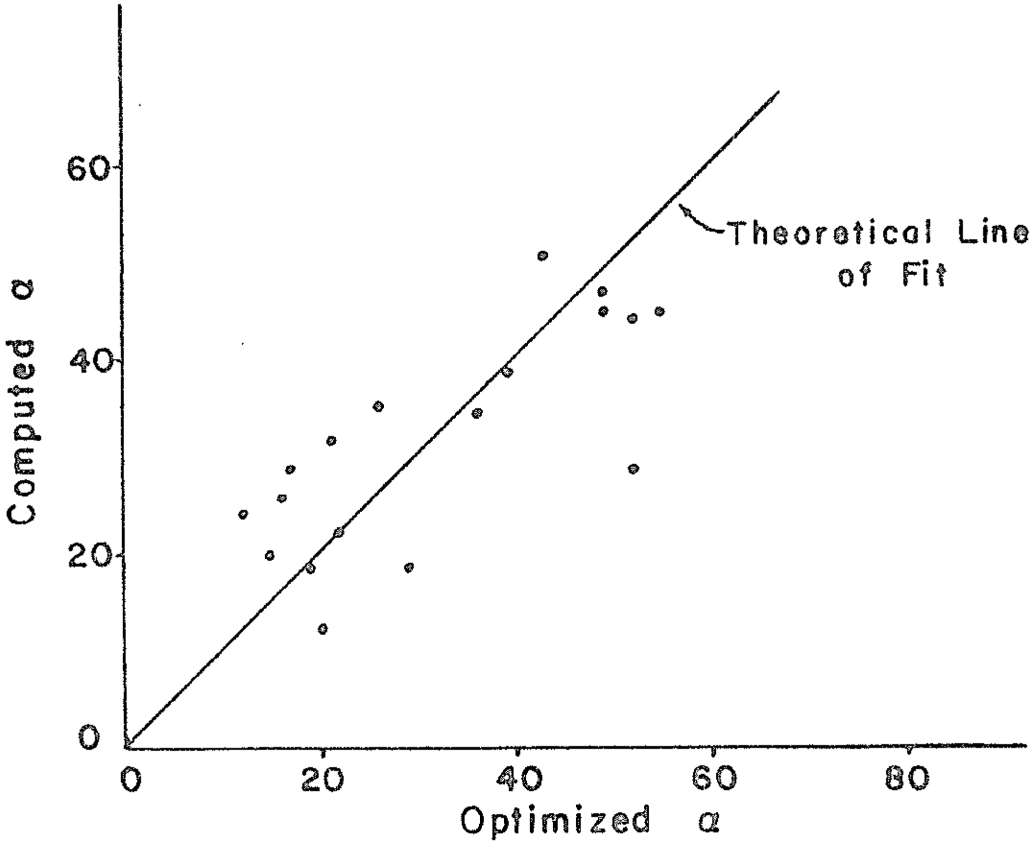

Fig. 4-7. Computed α vs. optimized α for equation 4-12.

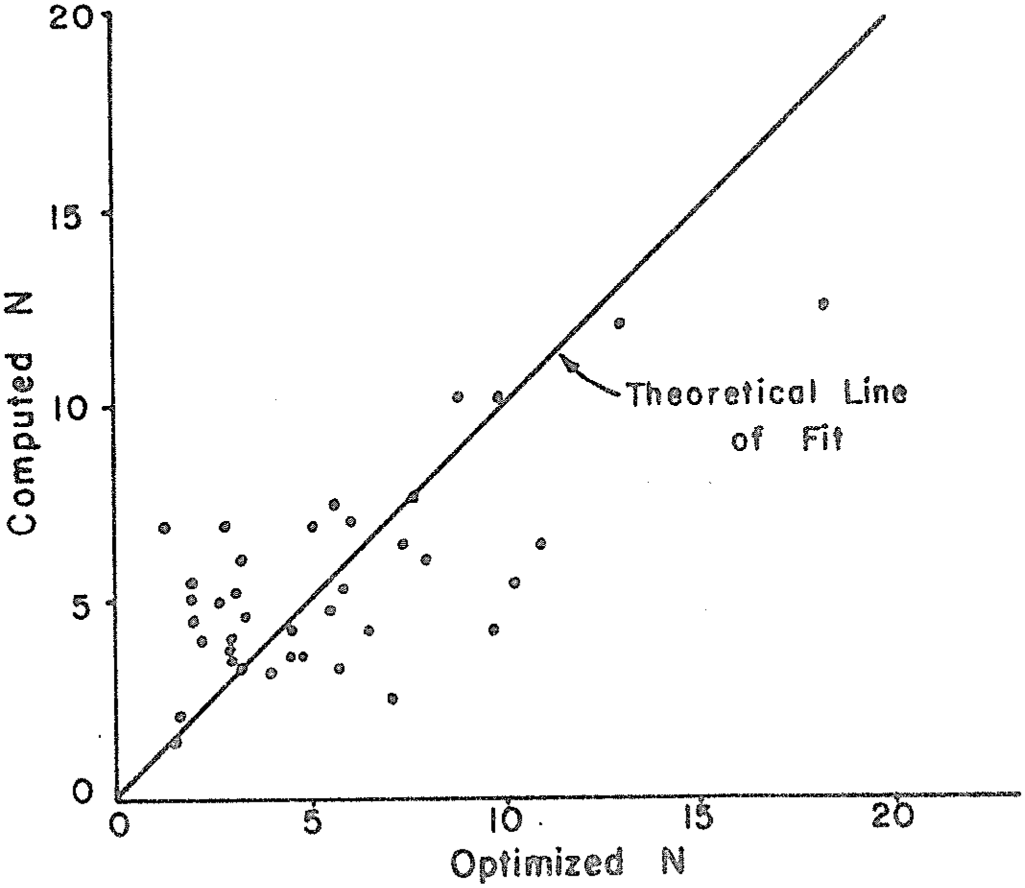

Fig. 4-8. Computed N vs. optimized N for equation 4-13.

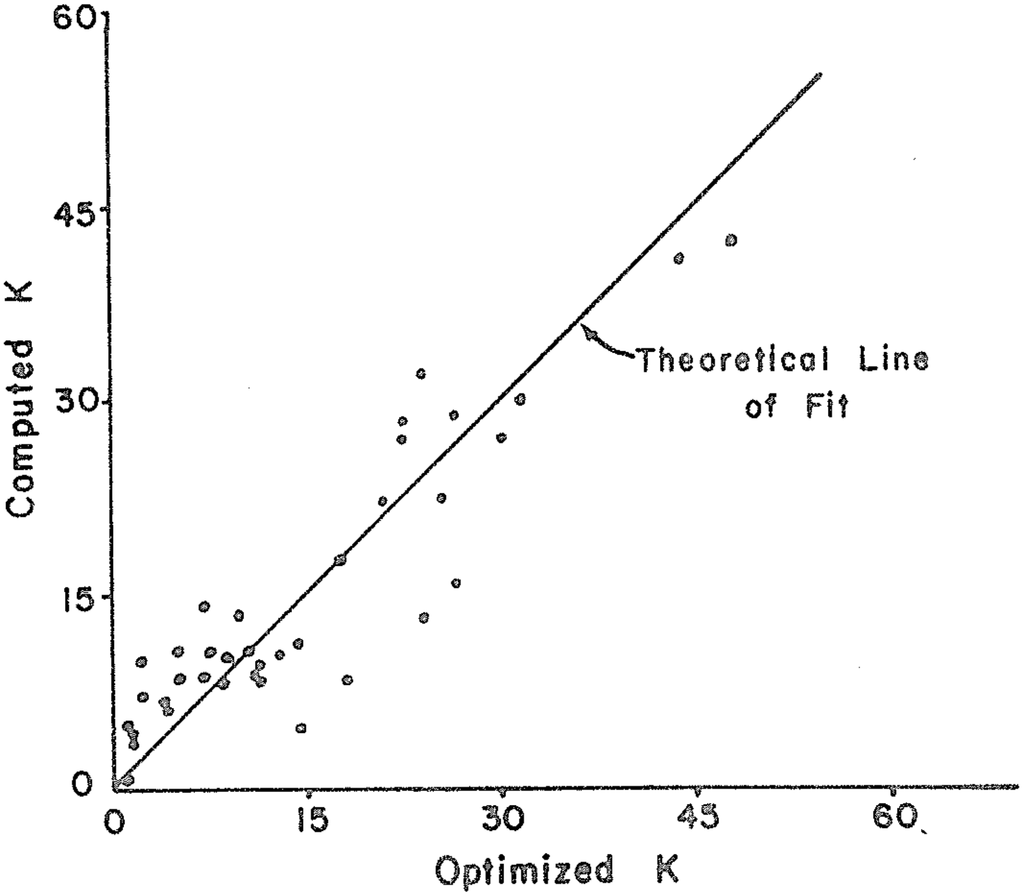

Fig. 4-9. Computed K vs. optimized K for equation 4-14.

These statistics indicate a poor linear relationship between N and the watershed characteristics, and a good linear relationship for K. To improve the correlation coefficient for N, the independent variables were first logarithmically transformed and then N was linearly correlated with these transformed variables. The correlation coefficient and the standard error of estimate were 0.7098 and 12.38 respectively. Although some improvement in the correlation coefficient was realized, it was not as high as desired.

Once again, in an effort to improve the correlation coefficient stratification of the data was performed using the same area criterion that resulted in two groups of watersheds as in case of α. Regression analyses for parameter N were then performed for both small and large watersheds yielding correlation coefficients 0.7301 and 0.7545 with standard error of estimate 12.20 and 11.82 respectively. The regression equations are:

For the small watersheds,

$$N = -0.73154*WIDTH + 1.86349*XLR - 0.54877*SLOPE - 2.0598*SHAPE + 140.3692*DD + 1.1248*SO + 0.59374*CSLOPE + 0.64973*AREA \tag{4-15}$$

For the large watersheds,

$$N = -0.73154*WIDTH + 1.73621*XLR - 0.60135*SLOPE - 2.2563*SHAPE + 149.355*DD + 1.5438*SO + 0.38441*CSLOPE + 0.49284*AREA \tag{4-16}$$

Figures 4-10 and 4-11 show the graphs of computed versus optimized values of N for Eqs. (4-15) and (4-16). A comparison of these plots with Fig. 4-8 clearly shows that no significant improvement in the correlation coefficient results from the data stratification.

These results clearly indicated that in this case no significant improvement resulted from the data stratification. In view of the generally weak correlation between parameter N and the watershed characteristics it was decided to fix N, thus reducing the NASH model to a 1-parameter model. This would simplify the determination of parameter K, and also expedite the costly optimization process.

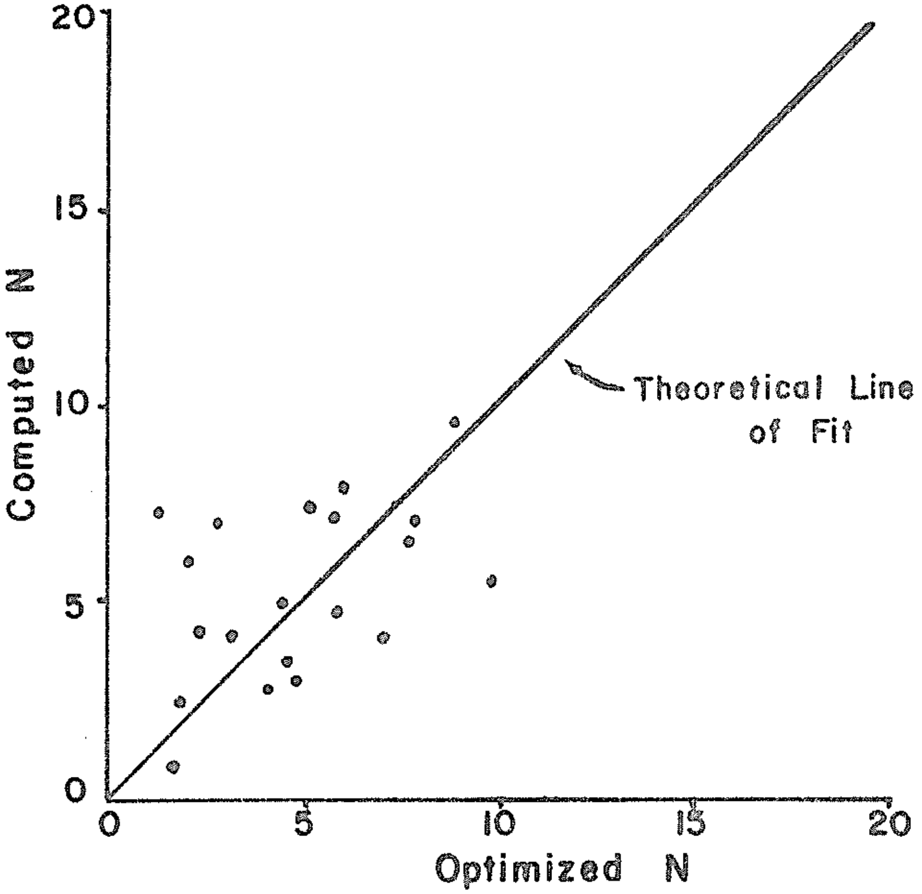

Fig. 4-10. Computed N vs. optimized N for equation 4-15.

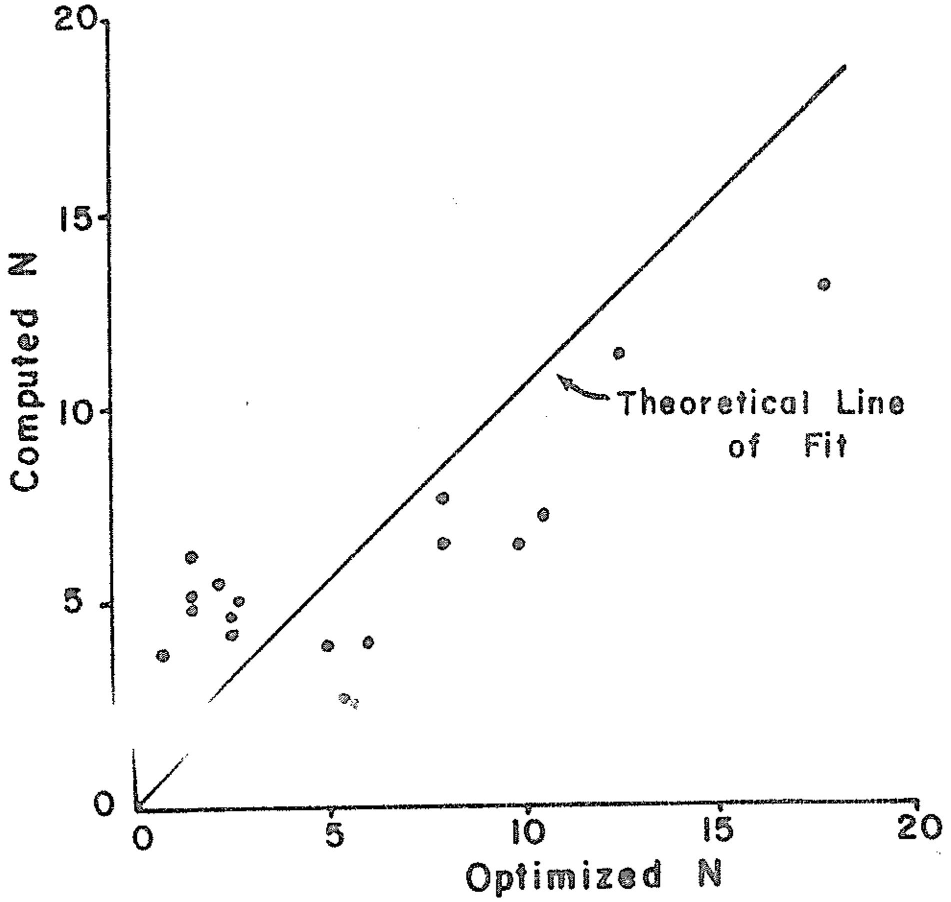

Fig. 4-11. Computed N vs. optimized N for equation 4-16.

Two questions naturally arise: (1) what justification can be made for fixing N, and (2) what value should N be assigned? To answer the first question, the functional nature of N should be emphasized. The parameter N signifies the number of linear reservoirs, and thus accounts for the effect of storage on the watershed response characteristics. Channel storage and overland storage always exist in most watersheds. The characteristics of these storage elements will naturally depend on the watershed topography. For smaller watersheds where topographic characteristics do not change drastically from one watershed to another, it seems plausible that N will not change drastically either. Therefor it appears that N can be specified for watersheds that fall within a certain area range.

As to a particular value of N, one can choose any value of N equal to or greater than 2. The value of N higher than 1 is required to get the right shape of runoff hydrograph. For smaller watersheds with relatively small channel development, it may be appropriate to fix N at 3. This choice of N seems to be consistent with Table 4-4 entailing optimized N for each watershed under consideration.

Holding N constant necessitated re-optimization of parameter K. The new optimized values of K are given in Table 4-4. Linear regression analysis for all 38 watersheds was then performed for new values of parameter K. The multiple correlation coefficient and standard error of estimate were 0.9375 and 10.59 respectively. The regression equation for K is:

$$K = 0.59631*AREA - 6.03594*WIDTH + 38.8672*XLR - 13.5118*SLOPE - 10.6385*SHAPE - 183.9712*DD - 4.8446*SO + 1.89*CSLOPE \tag{4-17}$$

Figure 4-12 shows the graph of computed versus optimized values of K for Eq. (4-17).

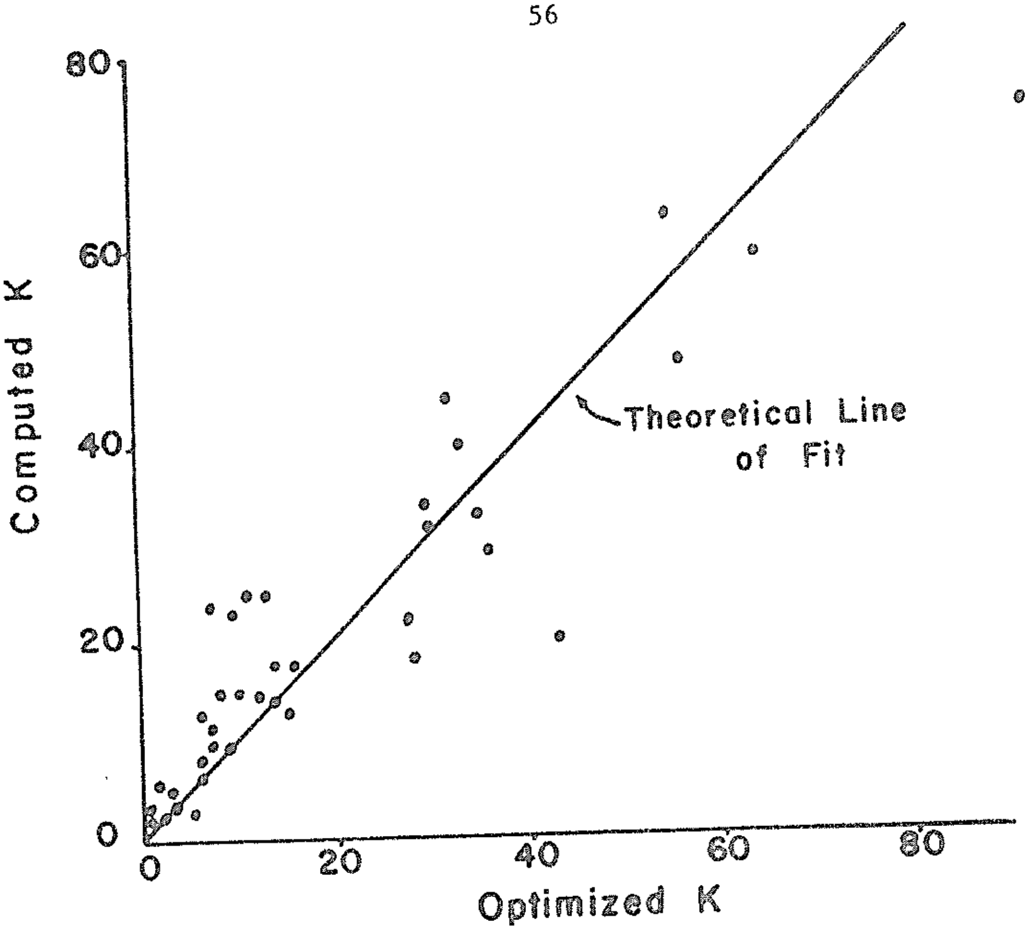

Fig. 4-12. Computed K vs. optimized K for equation 4-17.

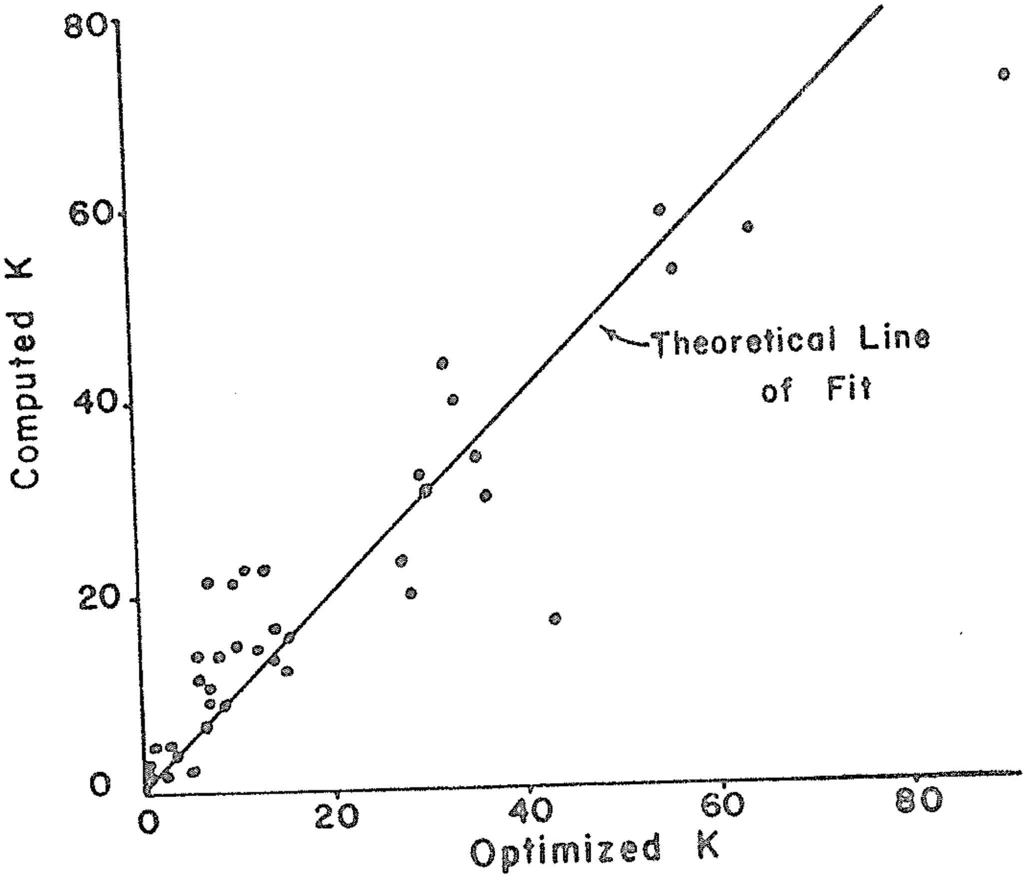

Fig. 4-13. Computed K vs. optimized K for equation 4-18.

Identification of the functional relationships between each independent variable and K was attempted to increase the correlation coefficient. Table 4-6 lists the independent variables and the functional form which produced the highest correlation coefficient between K and that variable. By selectively combining the transformed variables and performing linear regression analysis the highest correlation coefficient 0.9592 was obtained with a standard error of estimate of 8.96. The regression equation is:

$$K = 0.00545*\mathrm{AREA} - 9.08041*\mathrm{WIDTH} + 32.78809*\mathrm{SQRT(XLR)} - 0.79334*\ \mathrm{SLOPE} - 5.57113*\mathrm{Log}_e(\mathrm{SHAPE}) - 274.99609*\mathrm{DD} - 3.10247*\mathrm{SO} + 1.06*\ \mathrm{CSLOPE} \quad (4\text{-}18)$$

Figure 4-13 shows the plot of computed versus optimized values of K for Eq. (4-18). A comparison of Figs. 4-12 and 4-13 clearly illustrates the improvement in the correlation after the variables were transformed.

Statistical F tests were again employed in an effort to delete comparatively non-contributory variables from the regression equation. Table 4-8 lists calculated and tabulated F values for each step of the regression. As Table 4-8 indicates variables SHAPE, CSLOPE, SO, and DD were deleted from the regression equation for K. The final form of the regression equation is:

$$K = 0.00666*\mathrm{AREA} - 6.26551*\mathrm{WIDTH} + 22.70943*\mathrm{SQRT(XLR)} - 0.7722*\mathrm{SLOPE} \quad (4\text{-}19)$$

with correlation coefficient of 0.9541 and standard error of estimate 8.91. Figure 4-14 shows the computed versus optimized values of K for Eq. (4-19). A comparison of Figs. 4-13 and 4-14 shows that Eqs. (4-18) and (4-19) produce essentially the same results although several variables have been deleted from Eq. (4-19).

Table 4-8. Statistical F tests for NASH.

Step	Variable To Be Added	Calculated F	Tabulated F $F_{.05}(p,n-k-1)$
1	XLR	-	-
2	SLOPE	10.10	4.11
3	WIDTH	5.28	4.12
4	AREA	4.20	4.13
5	SO	1.83	4.14
6	SHAPE	1.38	4.15
7	CSLOPE	0.13	4.16
8	DD	0.43	4.17

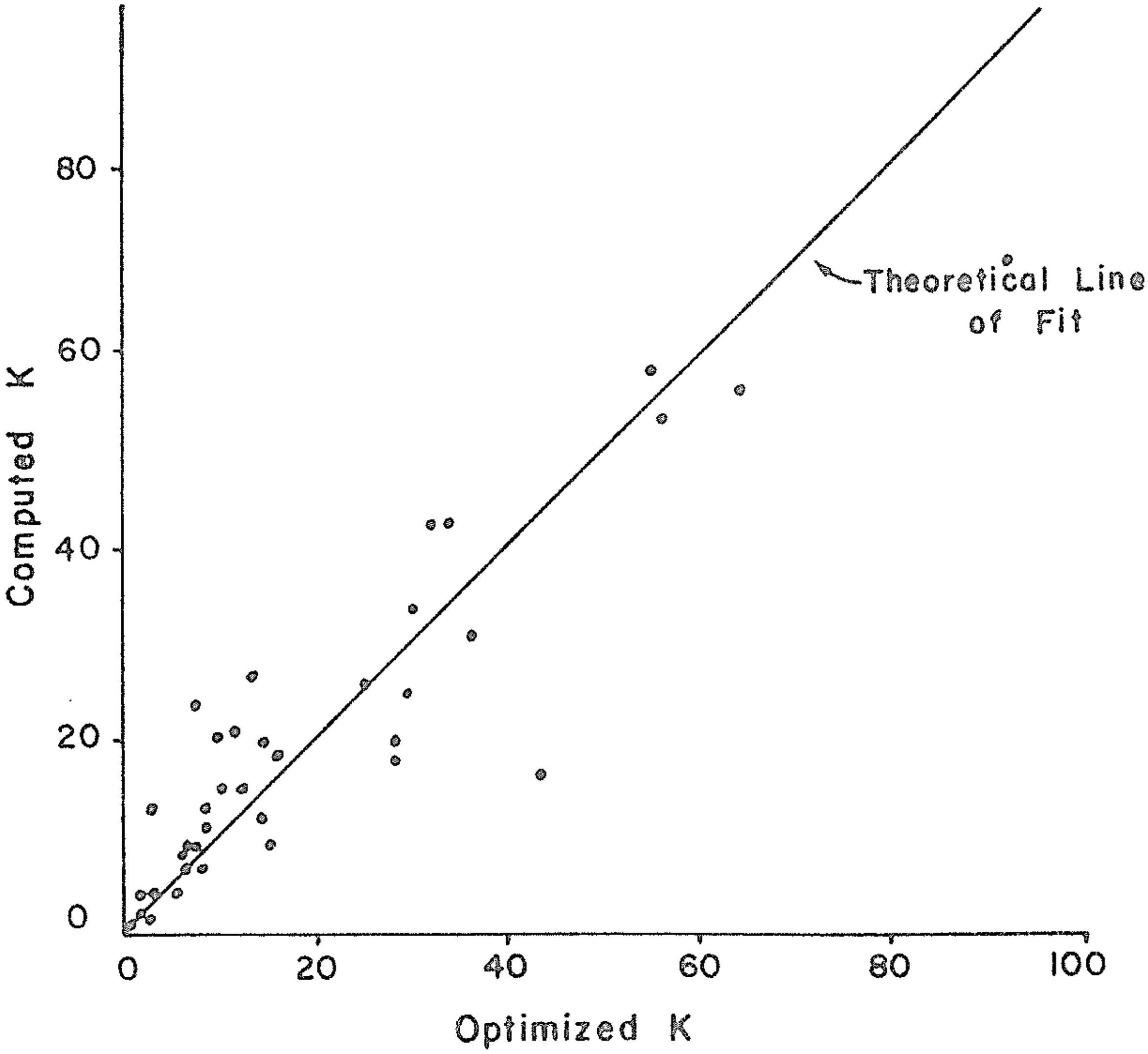

Fig. 4-14. Computed K vs. optimized K for equation 4-19.

Table 4-9. Regression analyses (CONV).

Regression Trial	Multiple Correlation Coefficient: R	Standard Error of Estimate
Linear regression, sample size 38	0.9523	9.23
Logarithmic regression, sample size 38	0.9274	11.31
Stratification of samples:		
1. Watersheds larger than 75 hectares, sample size 18	0.9530	14.31
2. Watersheds smaller than or equal to 75 hectares, sample size 20	0.9932	2.29

Table 4-10. Regression analyses (NASH).

Regression Trial	Parameter	Multiple Correlation Coefficient: R	Standard Error of Estimate
Linear regression, sample size 38	N	0.6858	2.96
	K	0.9038	5.79
Logarithmic regression, sample size 38	N	0.7098	12.38
Stratification of samples:			
1. Watersheds larger than 75 hectares, sample size 18	N	0.7545	11.82
2. Watersheds smaller than or equal to 75 hectares, sample size 20	N	0.7301	12.20
Linear regression with fixed N, sample size 38	K	0.9375	10.59
Manipulation of individual variables: SQRT(XLR) and Log_e(SHAPE)	K	0.9592	8.96

CHAPTER 5

HYDROGRAPH PREDICTION AND DISCUSSION OF RESULTS

After the derivation of equations for model parameters, the predictive ability of the models was considered. Three hydrograph features were of primary concern: (1) hydrograph peak, (2) time to peak, and (3) the hydrograph shape. Hydrograph predictions were performed by CONV and NASH for several events on a few watersheds selected from each of the two groups. Test data were comprised of events of two types: (1) events previously used in the optimization, and (2) events not previously used in the optimization.

5.1 Hydrograph Prediction

Using estimated values of α, hydrographs were predicted by CONV for several events on both large and small watersheds, as shown in Figs. 5-1 - 5-6 and Tables 5-1 and 5-2. These figures show a relatively good agreement of predicted hydrographs with observed hydrographs for small watersheds and not so good an agreement for large watersheds. The prediction error for both large and small watersheds varied widely reflecting model sensitivity to input errors. Poor prediction on large watersheds was largely due to errors in rainfall-excess and poor synchronization between rainfall and runoff observations. Predictions were particularly poor for multipeaked hydrographs.

Identical data was used for predictions by NASH. Figures 5-7 - 5-9 show the hydrographs by NASH. As evident from Table 5-3, NASH consistently underpredicted the hydrograph peak.

5.2 Discussion of Results

Figures 5-1 to 5-9 show the predictive performance of both models, and Tables 5-1 to 5-3 give statistics of their performance. These indicate that hydrograph shape and time characteristics are generally predicted well by NASH and CONV, although their parameters are estimated from watershed characteristics. Due to its non-linear nature, CONV is very sensitive to spatial

Table 5-1. Comparison of observed and predicted hydrograph peak and its timing for small agricultural watersheds.

CONV MODEL

Watershed Name	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Hastings 2-H	7-13-52	4.724	2.731	42.20	11.0	28.5	-159.23
	6-20-42	1.453	0.285	80.35	18.0	48.2	-168.00
	8-29-44	1.252	0.170	86.43	11.0	54.2	-392.31
	6-12-58	2.157	0.497	76.97	12.0	37.8	-215.37
	5-22-54	4.801	0.947	80.27	61.0	100.0	- 63.93
	7- 3-59	6.401	6.558	- 2.46	41.0	24.0	41.46
	5-15-60	3.937	2.232	43.30	22.0	39.1	- 77.89
	6- 1-51	2.972	0.945	68.19	145.0	149.5	- 3.11
	6-26-52	2.157	0.716	66.81	20.0	36.9	- 84.51
	8-23-62	3.124	1.777	43.11	40.0	31.1	22.30
	8-11-39	2.819	0.327	88.41	10.0	30.0	-200.00
	6-12-65	8.814	5.113	41.97	9.0	33.3	-269.54
	6-29-65	2.067	0.764	63.04	9.0	36.1	-301.25
McCredie	7- 3-41	2.362	1.971	16.58	90.0	99.7	- 10.83
	6-10-42	2.342	2.162	7.70	60.0	57.5	4.12
	5-14-45	2.088	1.632	21.82	92.0	84.0	8.70
	5- 1-48	0.500	0.320	36.07	82.0	68.3	16.76
	7-22-48	1.003	1.771	-76.47	80.0	65.0	18.47
	9-12-49	1.392	2.163	-55.38	53.0	50.7	4.41
	6-29-57	2.642	3.084	-16.73	50.0	45.3	9.36
	4- 5-65	1.465	1.538	- 4.95	60.0	76.2	- 26.98
	6- 8-43	1.689	1.691	- 0.09	91.0	93.0	- 2.20
Riesel (Waco) Y-2	3-26-46	1.270	0.993	21.85	66.0	50.9	22.85
	6-23-49	2.022	1.337	33.86	84.0	112.7	- 34.17
	7-16-61	0.183	0.134	26.89	79.0	89.0	- 12.72
	6-25-61	0.643	0.497	22.74	84.0	66.4	21.00
	6- 9-62	2.284	1.693	25.85	49.0	64.9	- 32.42
	4-24-57	4.267	5.293	-24.05	37.0	48.0	- 29.73
	5-13-57	3.150	3.681	-16.87	35.0	46.0	- 31.46
	6- 4-57	4.547	3.990	12.25	34.0	43.3	- 27.47

Table 5-1. (continued)

CONV MODEL

Watershed Name	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Riesel (Waco)							
Y-7	5- 6-55	1.499	0.480	67.97	6.0	47.5	- 691.83
	6- 4-57	3.480	3.568	- 2.53	33.0	32.2	2.49
	5-22-61	0.386	0.119	69.10	6.0	77.7	-1195.18
	6- 9-62	2.421	3.513	-45.13	37.0	43.2	- 16.73
	4-24-57	5.994	6.418	- 7.07	31.0	37.6	- 21.28
	5-13-57	5.156	5.128	0.55	33.0	37.9	- 14.74
	6-23-59	4.470	2.362	47.17	57.0	107.0	- 87.72
	3-29-65	5.778	7.204	-24.69	79.0	77.4	2.03
Y-10	5- 6-55	1.511	0.538	64.37	12.0	50.1	- 317.16
	6- 4-57	6.096	5.873	3.65	26.0	32.8	- 25.97
	6-23-59	1.786	1.723	3.49	70.0	102.6	- 46.64
	5-25-61	0.930	0.264	71.57	17.0	56.1	- 229.87
	6-15-61	0.858	0.216	74.90	26.0	67.2	- 158.33
	4-24-57	6.858	6.648	3.07	35.0	36.7	- 4.82
	5-13-57	4.851	4.698	3.16	26.0	35.9	- 38.05
	6- 9-62	1.001	1.129	-12.77	38.0	46.4	- 22.13
	3-29-65	6.925	7.781	-12.36	69.0	81.2	- 17.69
W-10	3-12-53	2.718	1.128	58.50	49.0	42.0	14.20
	6- 4-57	2.167	1.308	39.62	48.0	52.4	- 9.07
	4-24-57	7.087	6.243	11.90	28.0	34.8	- 24.38
	4-24-57	7.087	5.607	20.88	28.0	34.9	- 24.61
	5-22-61	1.072	0.352	67.18	41.0	64.4	- 57.05
	6-25-61	0.838	0.551	35.03	41.0	66.4	- 62.07
	6- 9-62	2.093	1.706	18.51	32.0	41.0	- 28.04
	6-23-59	4.978	3.822	23.23	63.0	56.0	11.11
	3-29-65	4.495	6.387	-42.09	71.0	75.3	- 6.09

Table 5-2. Comparison of observed and predicted hydrograph peak and its timing for large agricultural watersheds.

CONV MODEL

Watershed Name	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Oxford W-5	1-22-57	0.383	0.522	-36.19	115.0	111.4	3.14
	12- 6-57	0.713	0.917	-28.60	255.0	496.0	-94.50
	4- 3-58	0.780	1.064	-36.33	65.0	76.3	-17.36
	6-11-59	1.269	2.186	-72.33	53.0	50.6	4.56
	1-17-60	0.323	0.449	-38.70	150.0	133.3	11.10
	8-31-61	0.861	0.665	22.71	55.0	86.8	-57.81
Ralston Creek	11-15-61	0.328	0.598	-82.46	450.0	286.0	36.44
	7-13-62	1.397	1.864	-33.44	411.0	210.0	48.91
	9-20-65	0.927	1.434	-54.72	160.0	113.0	29.37
	6- 8-66	0.465	0.315	32.27	470.0	423.8	9.83
	6- 6-67	1.384	1.062	23.25	620.0	314.5	49.27
	7- 1-50	1.649	1.444	12.40	120.0	104.7	12.75
	7-21-48	0.862	0.683	20.78	225.0	130.0	42.22
	6- 1-43	1.242	1.317	- 6.03	90.0	102.1	-13.49
	8-30-56	1.011	0.746	26.24	185.0	161.0	12.97
	11-15-60	0.587	0.533	9.12	168.0	163.7	2.55
Coshocton 5	6-18-40	0.290	0.225	22.41	54.0	66.4	-22.95
	1-21-59	0.737	1.294	-75.70	674.0	320.0	52.52
	8-21-60	2.438	1.902	21.99	162.0	53.2	67.14
	4-25-61	0.699	1.011	-44.73	114.0	87.0	23.68
	9-23-45	0.815	0.853	- 4.65	78.0	134.2	-72.05
	3- 9-64	0.295	0.586	-98.48	382.0	396.0	- 3.66
	6-12-57	1.097	0.922	16.00	116.0	50.0	56.90
Riesel (Waco) C	4-24-57	2.205	3.051	-38.36	68.0	56.5	16.87
	5-13-57	1.438	2.319	-61.35	92.0	57.5	37.46
	7-16-61	0.379	0.602	-59.13	133.0	82.6	37.88
	6- 4-62	0.798	1.120	-50.39	126.0	79.0	37.30
	5- 9-57	0.285	0.387	-35.86	104.0	88.5	14.95
	6-10-41	2.240	2.897	-29.32	81.0	74.8	7.64
	7- 9-61	0.127	0.101	20.11	30.0	131.5	-337.26
	5-10-65	3.512	5.370	-52.92	45.0	50.7	-12.56

Table 5-2. (continued)

CONV MODEL

Watershed Name	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Hastings W-3	6-10-43	0.884	1.537	-73.93	35.0	47.1	-34.50
	5-27-44	1.194	0.981	17.80	29.0	53.0	-82.76
	5-20-49	0.528	0.719	-36.13	99.0	106.1	- 7.16
	7-10-51	4.420	2.686	39.23	41.0	80.0	-95.12
	5-21-52	1.466	1.065	27.35	40.0	53.0	-32.50
	6-26-52	1.455	2.261	-55.36	50.0	47.4	5.18
	6- 7-53	1.824	2.526	-38.52	40.0	49.9	-24.82
	6-15-57	2.997	2.451	18.22	62.0	61.0	1.61
	7- 3-59	5.080	4.729	6.92	34.0	38.0	-11.76
	9- 5-46	1.298	0.993	23.53	146.0	177.6	-21.61
	5- 6-49	0.358	0.290	19.08	74.0	87.0	-17.57
	6-25-51	1.697	1.194	29.64	129.0	176.7	-36.97
	7-13-52	3.378	4.120	-21.96	124.0	129.0	- 4.03
	6-15-57	2.487	2.753	-10.69	64.0	84.0	-31.25
	6-16-57	1.727	1.542	10.74	154.0	162.4	- 5.49
W-11	5-11-44	0.285	0.002	99.94	145.0	250.0	-72.41
	9-19-50	0.527	0.201	61.87	316.0	375.0	-18.67
	7-10-51	0.663	0.951	-43.38	189.0	296.0	-56.63
	5-22-54	0.721	0.292	59.52	214.0	300.0	-40.19
	6-14-61	0.257	0.222	13.19	212.0	300.0	-41.51
	6- 1-51	0.831	0.258	68.90	247.0	400.0	-61.94
	6-26-52	0.205	0.204	0.29	555.0	386.7	30.33
	7-13-52	0.772	0.485	37.20	256.0	378.2	-47.73
	6-16-57	0.582	0.587	- 0.74	349.0	342.0	2.01
	5-21-65	1.064	1.393	-30.92	560.0	249.7	55.42

Table 5-3. Comparison of observed and predicted hydrograph peak and its timing for agricultural watersheds.

NASH MODEL

Watershed Name	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Hastings 2-H	7-13-52	4.724	3.822	19.09	11.0	20.0	-81.82
	6-20-42	1.453	1.001	31.14	18.0	14.0	22.22
	8-29-44	1.252	0.710	43.29	11.0	12.0	- 9.09
	6-12-58	2.157	1.500	30.46	12.0	12.0	0.00
	5-22-54	4.801	2.048	57.35	61.0	106.0	-73.77
	7- 3-59	6.401	7.015	- 9.60	41.0	16.0	60.98
	5-15-60	3.937	3.315	15.80	22.0	28.0	-27.27
	6- 1-51	2.972	2.147	27.75	145.0	134.0	7.59
	6-26-52	2.157	1.898	11.97	20.0	12.0	40.00
	8-23-62	3.124	3.012	3.60	40.0	18.0	55.00
	8-11-39	2.819	1.326	52.96	10.0	12.0	-20.00
	6-12-65	8.814	6.113	30.65	9.0	28.0	-211.11
	6-29-65	2.067	1.937	6.32	9.0	12.0	-33.33
McCredie	7- 3-41	2.362	1.667	29.47	90.0	102.0	-13.33
	6-10-42	2.342	1.748	25.36	60.0	64.0	- 6.67
	5-14-45	2.088	1.477	29.27	92.0	98.0	- 6.52
	5- 1-48	0.500	0.496	0.85	82.0	38.0	53.66
	7-22-48	1.003	1.514	-50.87	80.0	70.0	12.50
	9-12-49	1.392	1.793	-28.79	53.0	52.0	1.89
	6-29-57	2.642	2.295	13.13	50.0	50.0	0.00
	4- 5-65	1.465	1.326	9.50	60.0	80.0	-33.33
	6- 8-43	1.689	1.435	15.03	91.0	104.0	-14.29
Riesel (Waco)Y-2	3-26-46	1.270	1.210	4.71	66.0	36.0	45.45
	6-23-49	2.022	1.420	29.79	84.0	116.0	-38.10
	6-25-61	0.643	0.715	-11.29	84.0	36.0	57.14
	6- 9-62	2.284	1.671	26.81	49.0	60.0	-22.45
	4-24-57	4.267	3.799	10.97	37.0	56.0	-51.35
	5-13-57	3.150	2.893	8.16	35.0	50.0	-42.86
	6- 4-57	4.547	3.056	32.78	34.0	48.0	-41.18
Y-7	5- 6-55	1.499	0.680	54.60	6.0	30.0	-400.00
	6- 4-57	3.480	2.546	26.82	33.0	36.0	- 9.09
	5-22-61	0.386	0.264	31.72	6.0	38.0	-533.33
	6- 9-62	2.421	2.464	- 1.77	37.0	48.0	-29.73
	4-24-57	5.994	4.178	30.31	31.0	50.0	-61.29
	5-13-57	5.156	3.474	32.62	33.0	48.0	-45.45
	6-23-59	4.470	2.037	54.43	57.0	116.0	-103.51
	3-29-65	5.778	5.468	5.35	79.0	102.0	-29.11

Table 5-3. (continued)

NASH MODEL

Watershed	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Riesel (Waco)W-10	5- 6-55	1.511	1.035	31.51	12.0	26.0	-116.67
	6- 4-57	6.096	4.813	21.04	26.0	34.0	- 30.77
	6-23-59	1.786	1.781	0.28	70.0	28.0	60.00
	5-25-61	0.930	0.643	30.79	17.0	22.0	- 29.41
	6-15-61	0.858	0.556	35.26	26.0	30.0	- 15.38
	4-24-57	6.858	5.500	19.82	35.0	42.0	- 20.00
	5-13-57	4.851	4.040	16.75	26.0	38.0	- 46.15
	6- 9-62	1.001	1.417	-41.62	38.0	34.0	10.53
	3-29-65	6.925	6.746	2.58	69.0	88.0	- 27.54
W-10	3-12-53	2.718	1.490	45.17	49.0	28.0	42.86
	6- 4-57	2.167	1.365	37.00	48.0	54.0	- 12.50
	4-24-57	7.087	4.886	31.06	28.0	40.0	- 42.86
	4-24-57	7.087	4.463	37.03	28.0	40.0	- 42.86
	5-22-61	1.072	0.719	32.88	41.0	36.0	12.20
	6-25-61	0.848	0.786	7.31	41.0	62.0	- 51.22
	6- 9-62	2.093	1.790	14.49	32.0	36.0	- 12.50
	6-23-59	4.978	3.548	28.73	63.0	60.0	4.76
	3-29-65	4.495	5.131	-14.15	71.0	82.0	- 15.49
Oxford W-5	1-22-57	0.383	0.582	-51.88	115.0	88.0	23.48
	12- 6-57	0.713	1.008	-41.29	255.0	492.0	- 92.94
	4- 3-58	0.780	1.204	-54.32	65.0	62.0	4.62
	6-11-59	1.269	2.019	-59.18	53.0	44.0	16.98
	1-17-60	0.323	0.456	-40.94	150.0	114.0	24.00
	8-31-61	0.861	0.860	0.10	55.0	64.0	- 16.36
Ralston Creek	11-15-61	0.328	0.571	-74.10	450.0	338.0	24.89
	7-13-62	1.397	1.500	- 7.39	411.0	262.0	36.25
	9-20-65	0.927	1.095	-18.07	160.0	146.0	8.75
	6- 8-66	0.465	0.373	19.75	470.0	422.0	10.21
	6- 6-67	1.384	0.908	34.37	620.0	316.0	49.03
	7- 1-50	1.649	1.089	33.94	120.0	134.0	- 11.67
	7-21-48	0.862	0.658	23.75	225.0	118.0	47.56
	6- 1-43	1.242	1.034	16.75	90.0	114.0	- 26.67
	8-30-56	1.011	0.699	30.89	185.0	178.0	3.78
	11-15-60	0.587	0.561	4.47	168.0	142.0	15.48
Coshocton 5	6-18-40	0.290	0.318	- 9.97	54.0	42.0	22.22
	1-21-59	0.737	1.038	-40.87	674.0	334.0	50.45
	8-21-60	2.438	1.292	47.02	162.0	70.0	56.79
	4-25-61	0.699	0.793	-13.50	114.0	106.0	7.02

Table 5-3. (continued)

NASH MODEL

Watershed Name	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Coshocton 5	9-23-45	0.815	0.765	6.13	78.0	134.0	-71.79
	3- 9-64	0.295	0.549	-85.95	382.0	406.0	- 6.28
	6-12-57	1.097	0.807	26.48	116.0	48.0	58.62
Riesel (Waco) C	4-24-57	2.205	2.011	8.81	68.0	70.0	- 2.94
	5-13-57	1.438	1.389	3.39	92.0	66.0	28.26
	7-16-61	0.379	0.674	-78.17	133.0	62.0	53.38
	6- 4-62	0.798	1.063	-33.25	126.0	80.0	36.51
	5- 9-57	0.285	0.498	-75.13	104.0	62.0	40.38
	6-10-41	2.240	1.967	12.21	81.0	76.0	6.17
	7- 9-61	0.127	0.204	-61.47	30.0	58.0	-93.33
	5-10-65	3.512	2.927	16.64	45.0	68.0	-51.11

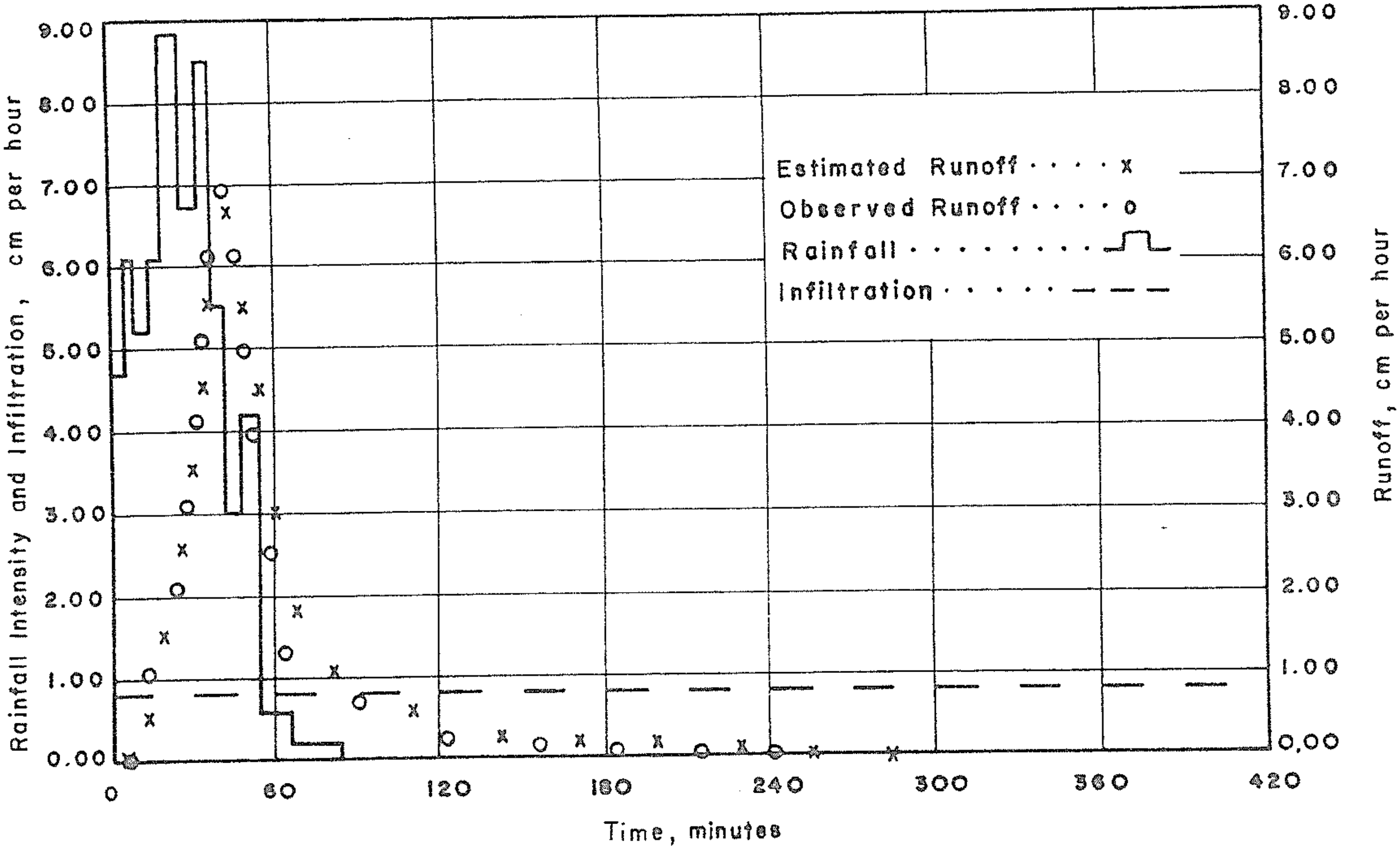

Fig. 5-1. Hydrograph prediction by CONV, using ϕ-index, for rainfall event of 4-24-57 on watershed Y-10, Riesel (Waco), Texas.

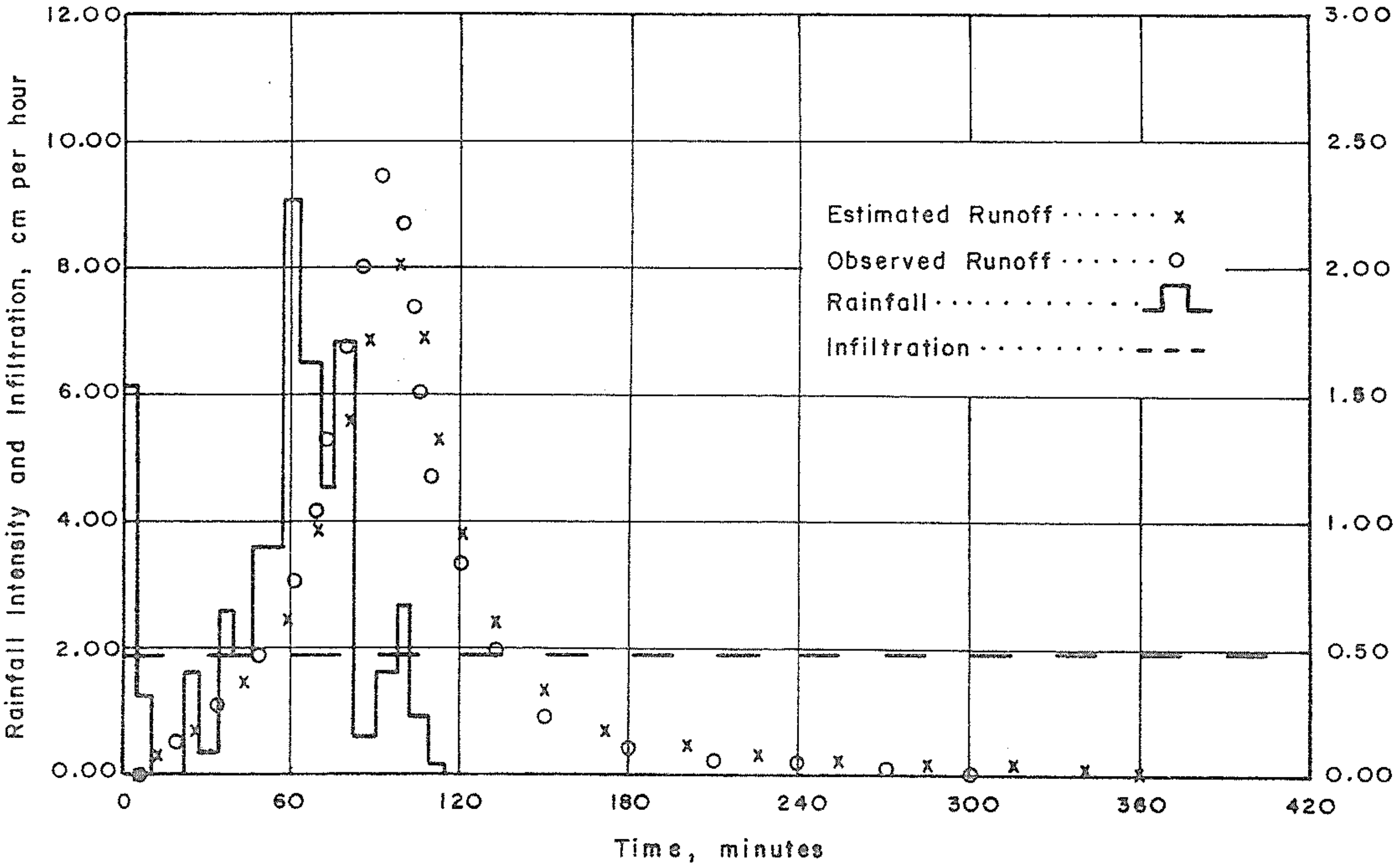

Fig. 5-2. Hydrograph prediction by CONV, using ϕ-index, for rainfall event of 7-3-41 on watershed W-1, McCredie, Missouri.

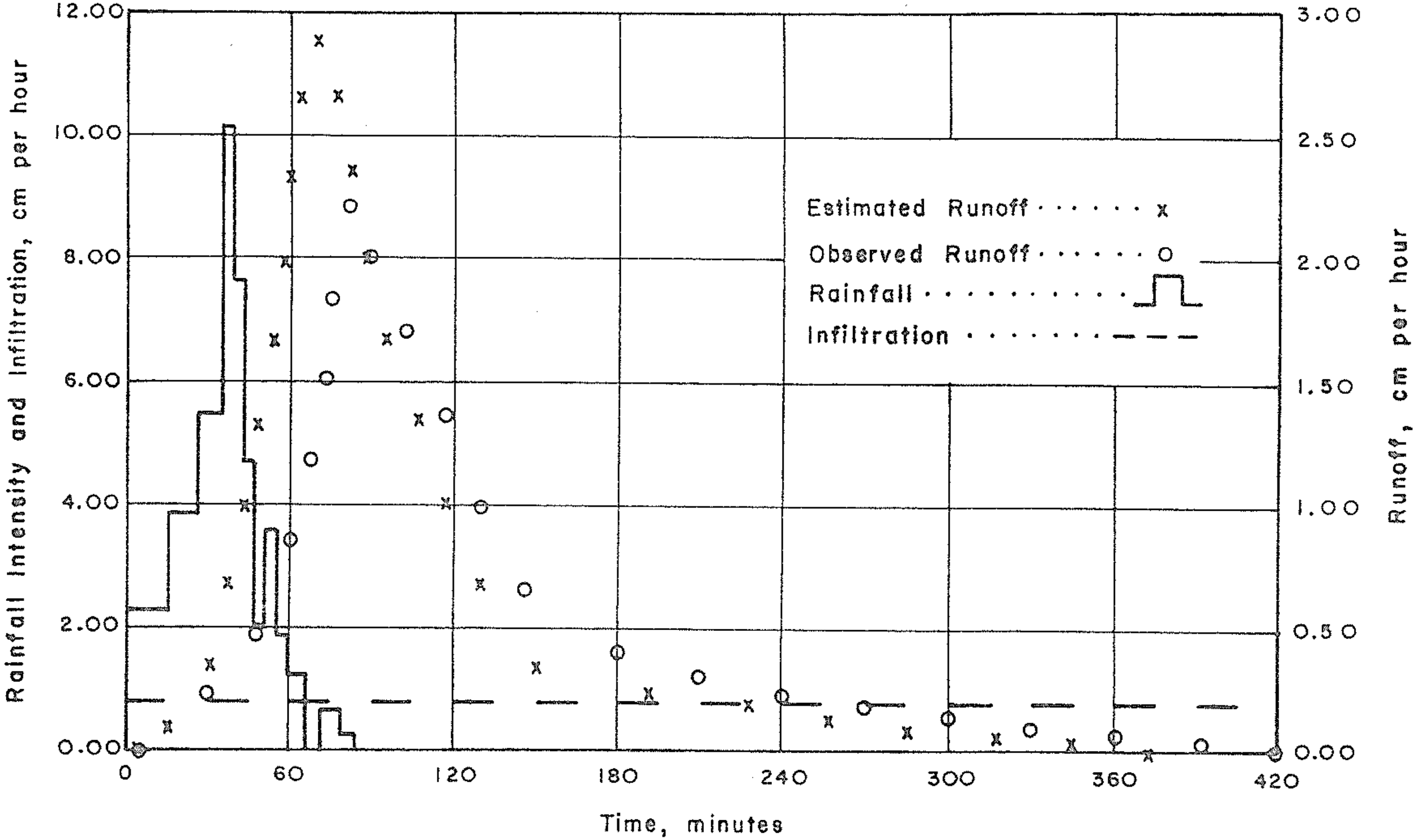

Fig. 5-3. Hydrograph prediction by CONV, using ϕ-index, for rainfall event of 6-10-41 on watershed C, Riesel (Waco), Texas.

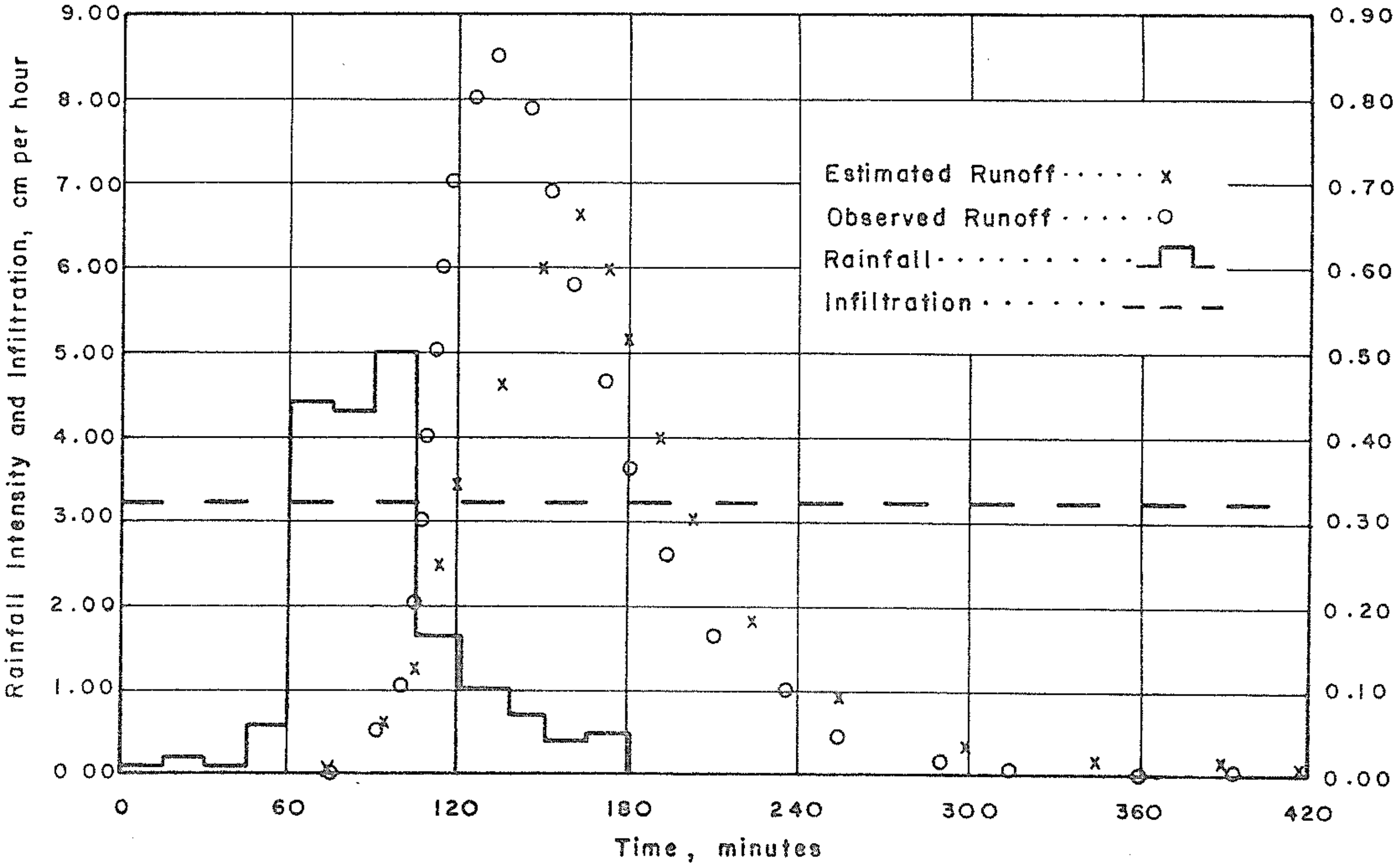

Fig. 5-4. Hydrograph prediction by CONV, using φ-index, for rainfall event of 8-31-61 on watershed W-5, Oxford, Mississippi.

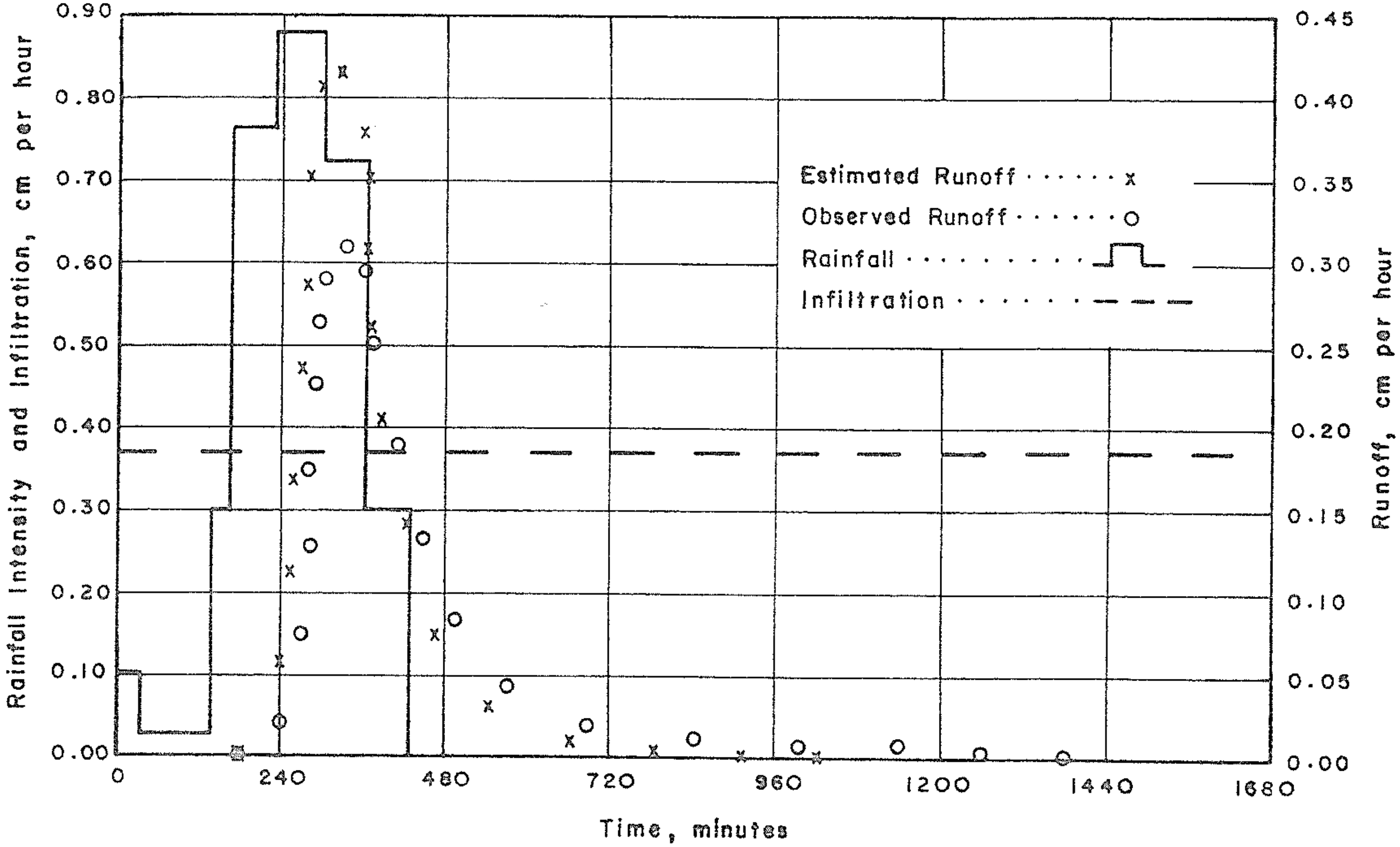

Fig. 5-5. Hydrograph prediction by CONV, using ϕ-index, for rainfall event of 1-17-60 on watershed W-5, Oxford, Mississippi.

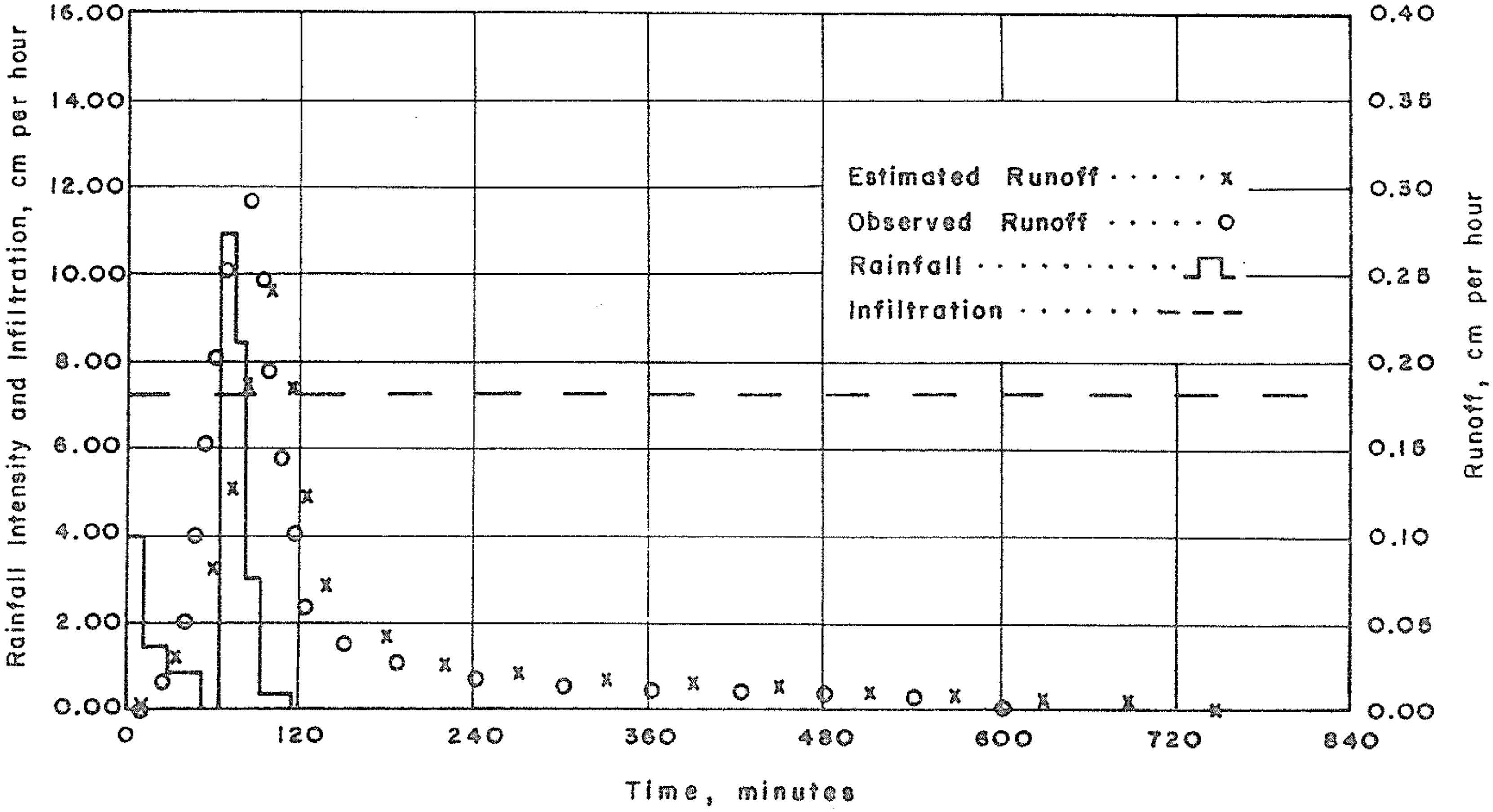

Fig. 5-6. Hydrograph prediction by CONV, using ϕ-index, for rainfall event of 6-18-40 on watershed 5, Coshocton, Ohio.

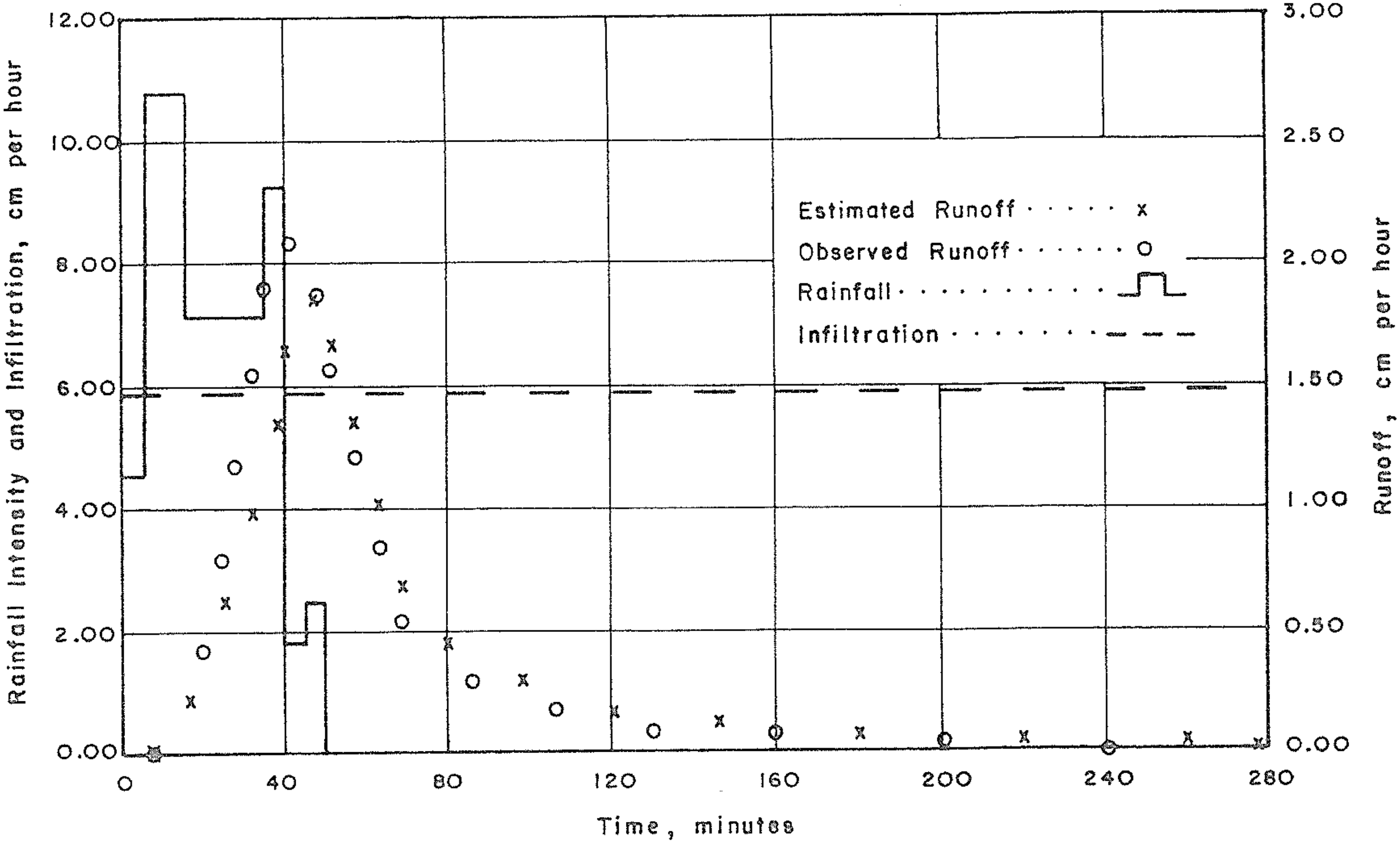

Fig. 5-7. Hydrograph prediction by NASH, using ϕ-index, for rainfall event of 6-9-62 on watershed W-10, Riesel (Waco), Texas.

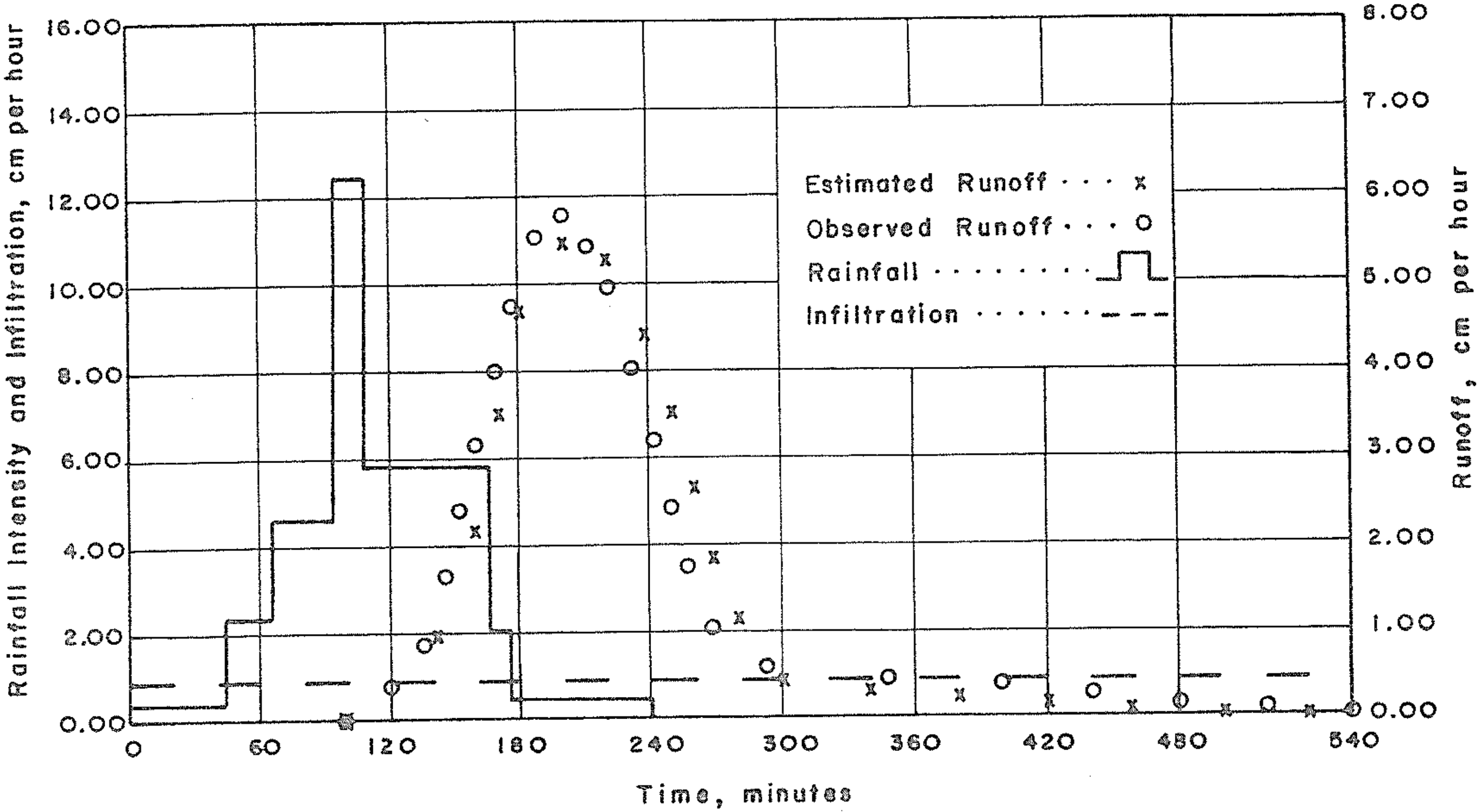

Fig. 5-8. Hydrograph prediction by NASH, using ϕ-index, for rainfall event of 3-29-65 on watershed Y-7, Riesel (Waco), Texas.

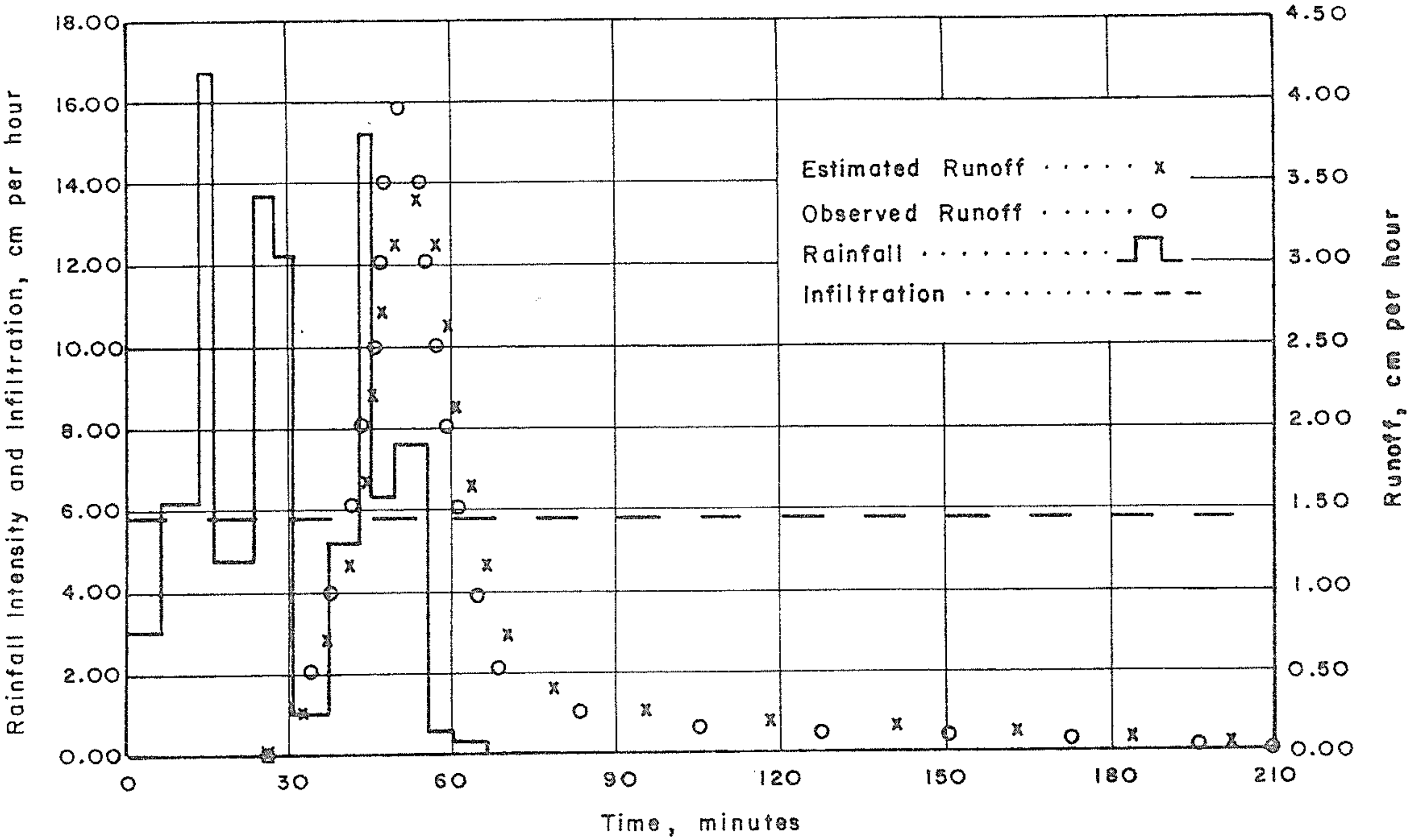

Fig. 5-9. Hydrograph prediction by NASH, using ϕ-index, for rainfall event of 5-15-60 on watershed 2-H, Hastings, Nebraska.

and temporal distribution of rainfall. The best prediction results were obtained when rainfall was almost normally distributed in time and occurred for a minimum of 30 minutes. For almost every non-normally distributed rainfall event, peak times were either over predicted or under predicted. The significance of the minimum 30 minute rainfall duration seems to be in the satisfaction of initial abstractions.

NASH was also found to be sensitive to spatial and temporal rainfall distribution, but to a lesser degree than CONV. NASH, like CONV, performed better when rainfall was almost normally distributed, occurring for a minimum of 30 minutes.

5.3 Sources of Errors

Now the question arises regarding the probable sources of errors in model results. Of all, input errors are probably most important.

Inaccurate measurements of rainfall and subsequent estimation of mean areal rainfall may cause considerable error. On the watersheds in question a centrally located raingage was assumed to represent the mean areal rainfall. However, this is seldom the case because rainfall varies in time and space. This situation was exemplified by several events in which runoff volume exceeded rainfall volume, which of course is physically impossible. This meant that such rainfall events, tabulated in the USDA publications, may not have been representative of the mean areal rainfall which actually caused the runoff. This improper correspondence between rainfall and runoff would cause error in model predictions.

Rainfall-excess forms the input to the model and was determined by subtracting from rainfall infiltration which was estimated by ϕ-index. An examination of Figs. 5-10 - 5-13 shows that the large prediction errors

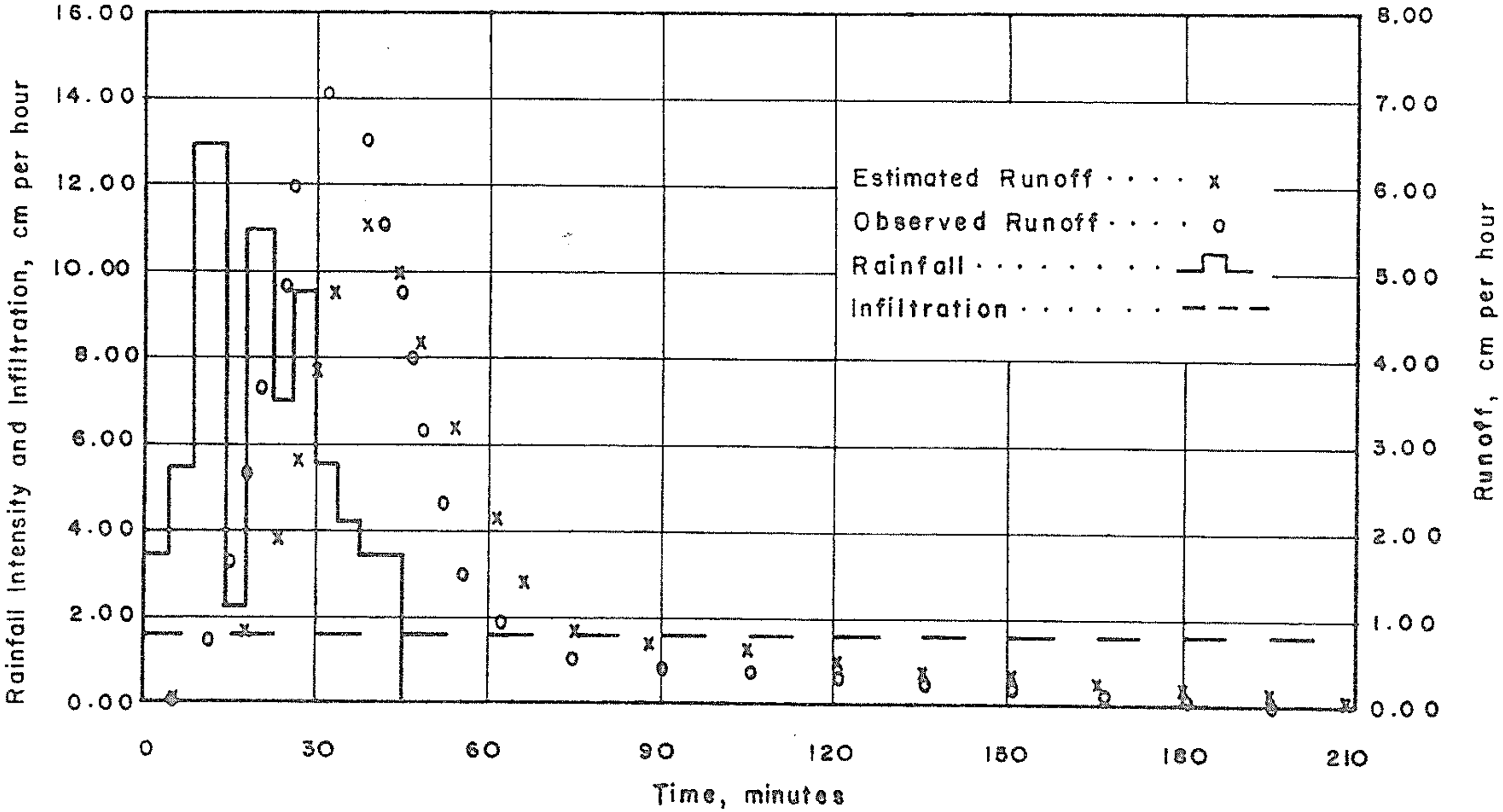

Fig. 5-10. Hydrograph prediction by CONV, using ϕ-index, for rainfall event of 4-24-57 on watershed W-10, Riesel (Waco), Texas.

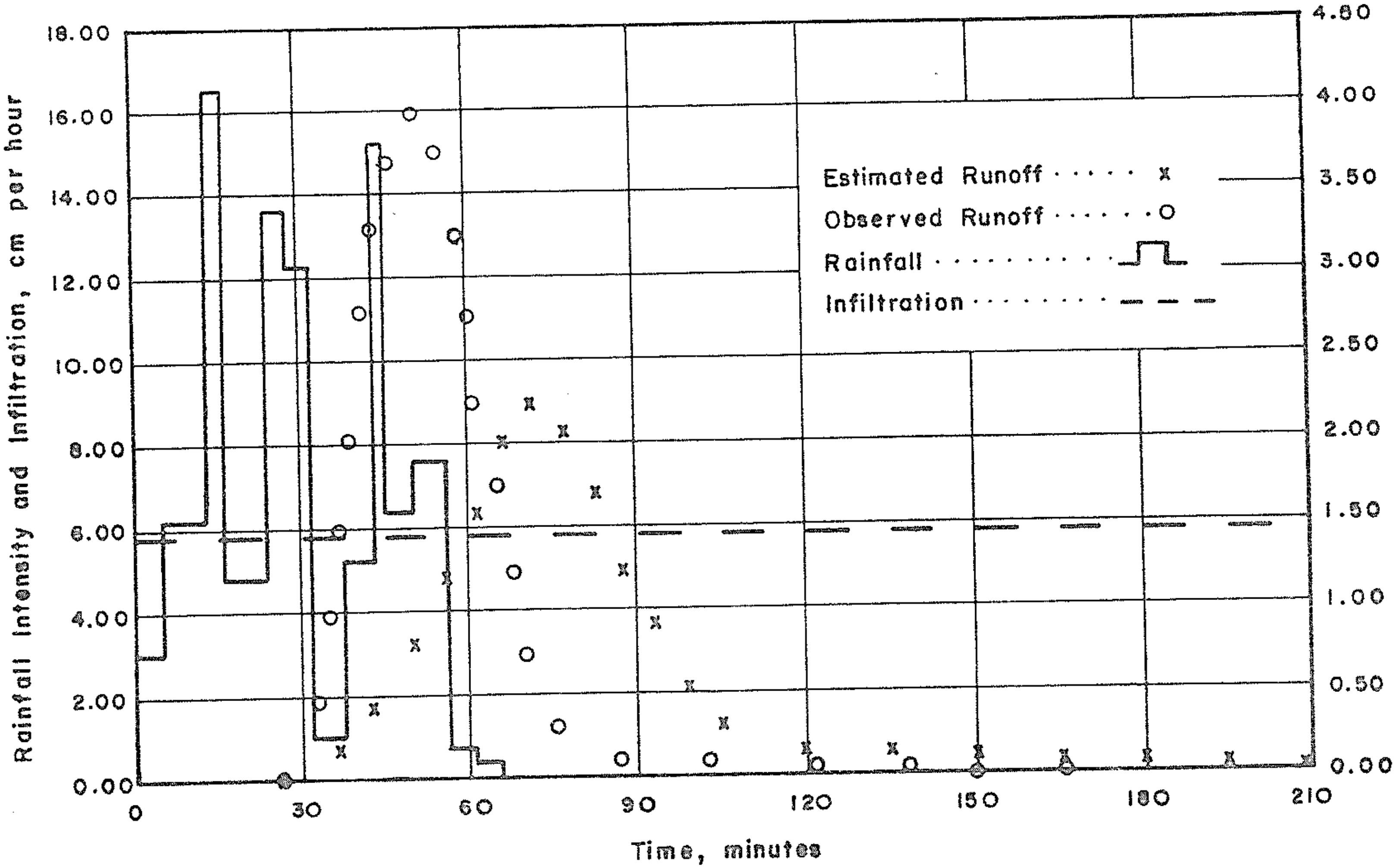

Fig. 5-11. Hydrograph prediction by CONV, using ϕ-index, for rainfall event of 5-15-60 on watershed 2-H, Hastings, Nebraska.

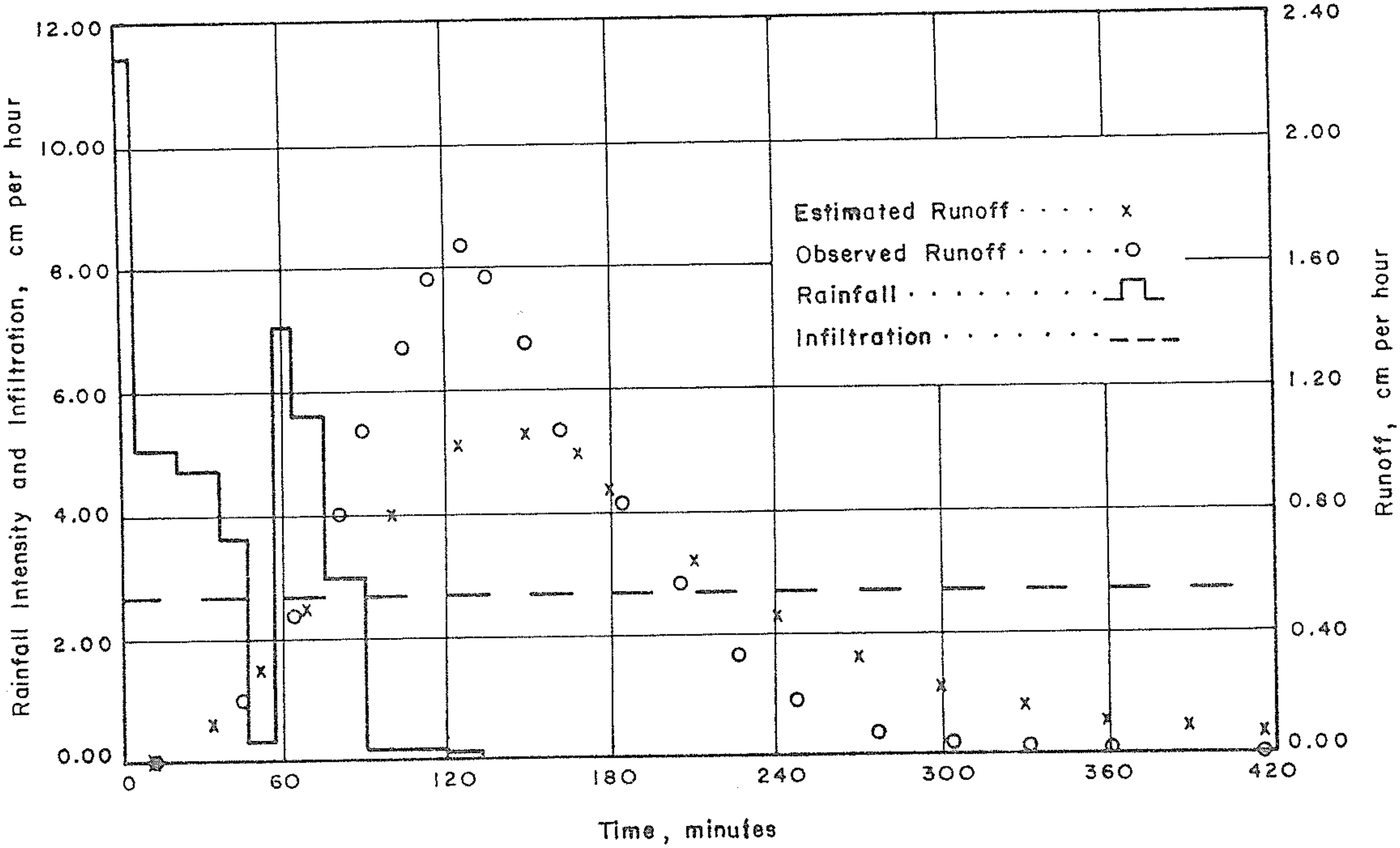

Fig. 5-12. Hydrograph prediction by NASH, using ϕ-index, for rainfall events of 7-1-50 on watershed Ralston Creek, Iowa.

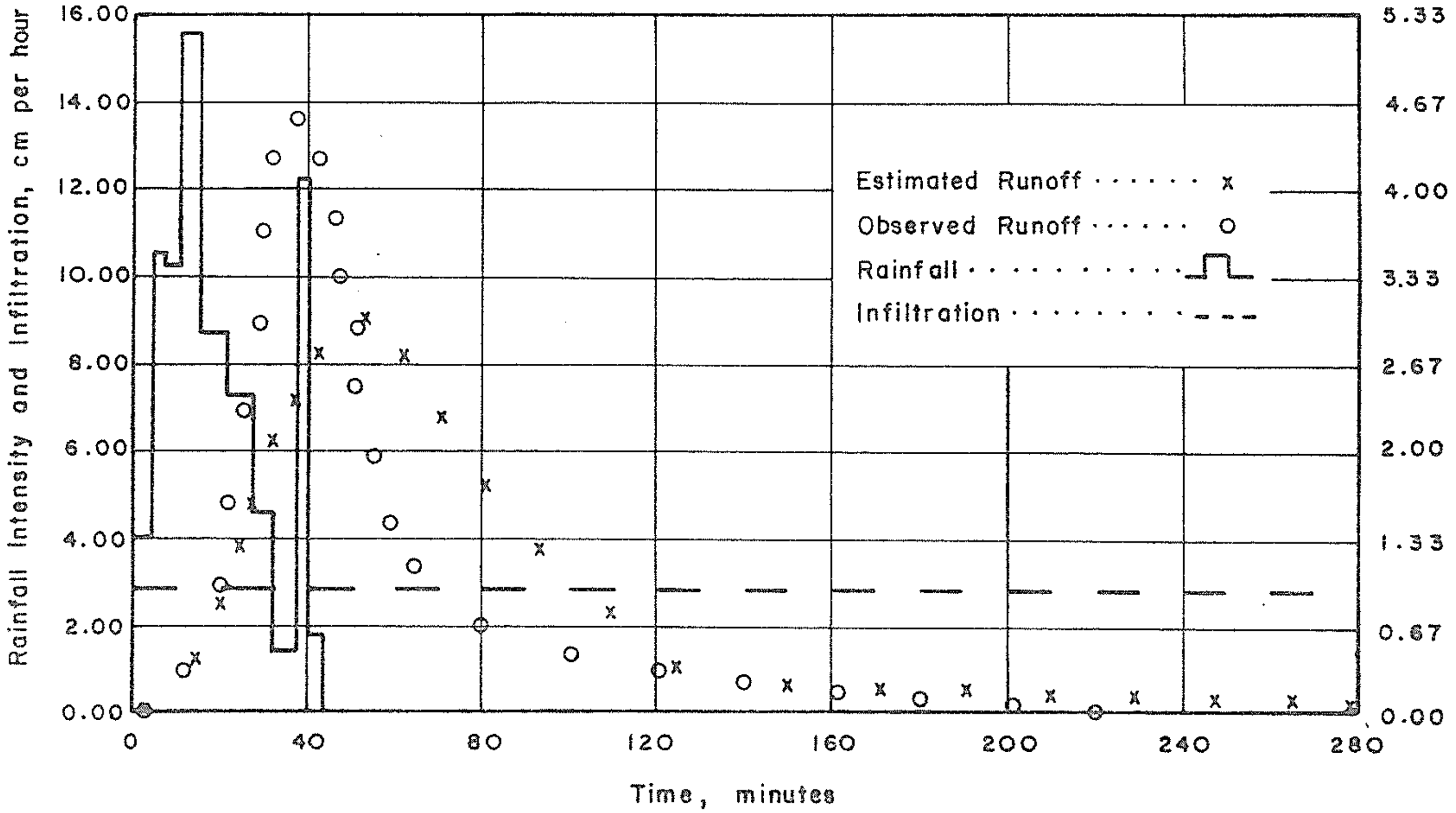

Fig. 5-13. Hydrograph prediction by NASH, using ϕ-index, for rainfall event of 6-4-57 on watershed Y-2, Riesel (Waco), Texas.

are likely due to error in rainfall-excess.

To corroborate this hypothesis the Philip infiltration scheme was substituted for the ϕ-index method in the prediction models. Predicted hydrographs were then computed for a few watersheds. Tables 5-4 - 5-6 show observed and predicted hydrograph peak and its time. Sample predicted hydrographs are shown in Figs. 5-14 - 5-17. A comparison of Tables 5-1 - 5-3 with Tables 5-4 - 5-6 shows that errors in both runoff peak and its time are consistently smaller for the predicted hydrographs utilizing the Philip's infiltration scheme. In particular, multipeaked hydrographs showed the greatest reduction in peak and peak time errors. Comparison of Figs. 5-3, 5-7, 5-10, 5-13, and with Figs. 5-14, 5-15, 5-16, and 5-17 respectively, shows that predicted hydrographs, utilizing the Philip's infiltration scheme, match the observed hydrographs closer than the predicted hydrographs using the ϕ-index method.

For simplicity the following assumptions, which would cause some error, were employed in runoff modeling:

(1) The spatial variability of infiltration was neglected. No allowance was made for depression storage or for infiltration during rainless periods. Point determination of infiltration at the raingage location seldom represents the mean condition.

(2) It was assumed that 100% of watershed area contributed to runoff. This may not be true, especially for large watersheds where spatial rainfall variability is high.

(3) Evaporation and transpiration were neglected. These losses are not always negligible.

(4) Complex watershed configurations were transformed into simpler ones.

(5) Spatial variability of rainfall was not taken into consideration in the determination of mean areal rainfall.

Table 5-4. Comparison of observed and predicted hydrograph peak and its timing for small agricultural watersheds.

CONV MODEL; PHILIP EQUATION FOR INFILTRATION

Watershed	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Riesel(Waco)Y-2	3-26-46	1.270	1.284	-1.07	66.0	47.8	27.56
	6-23-59	2.022	2.289	-13.22	84.0	101.0	-20.24
	7-16-61	0.183	0.167	8.93	79.0	86.6	- 9.62
	6-25-61	0.643	0.482	25.04	84.0	74.5	11.32
	6- 9-62	2.284	1.800	21.22	49.0	65.3	-33.21
	4-24-57	4.267	4.993	-17.01	37.0	48.0	-29.73
	5-13-57	3.150	3.600	-14.16	35.0	46.1	-31.69
	6- 4-57	4.547	3.951	13.11	34.0	43.0	-26.45
W-10	3-12-53	2.718	1.158	57.39	49.0	41.8	14.64
	6- 4-57	2.167	1.367	36.90	48.0	50.6	- 5.51
	4-24-57	7.087	6.280	11.39	28.0	34.8	-24.37
	4-24-57	7.087	5.564	21.49	28.0	36.8	-31.44
	5-22-61	1.072	0.358	66.61	41.0	52.3	-27.67
	6-25-61	0.848	0.578	31.85	41.0	70.5	-71.86
	6- 9-62	2.093	1.700	18.79	32.0	43.9	-37.04
	6-23-59	4.978	4.431	10.99	63.0	58.2	7.61
	3-29-65	4.495	6.448	-43.47	71.0	75.3	- 6.07
Y-7	5- 6-55	1.499	0.749	50.04	6.0	33.5	-458.64
	6- 4-57	3.480	4.292	-23.34	33.0	25.1	24.01
	5-22-61	0.386	0.196	49.20	6.0	52.7	-778.16
	6- 9-62	2.421	4.432	-83.11	37.0	24.6	33.39
	4-24-57	5.994	7.201	-20.13	31.0	25.9	16.38
	5-13-57	5.156	5.772	-11.94	33.0	28.8	12.78
	6-23-59	4.470	3.86	13.65	57.0	110.2	-93.28
	3-29-65	5.778	7.948	-37.56	79.0	72.6	8.13
Y-10	5- 6-55	1.511	0.589	61.00	12.0	42.2	251.36
	6- 4-57	6.096	6.217	- 1.99	26.0	31.0	-19.23
	6-23-59	1.786	2.494	-39.66	70.0	87.2	-24.58
	5-25-61	0.930	1.004	- 7.99	17.0	39.8	-133.85
	6-15-61	0.858	0.236	72.50	26.0	58.8	-126.21
	4-24-57	6.858	6.806	0.76	35.0	35.0	0.00
	5-13-57	4.851	4.705	3.03	26.0	35.8	-37.62
	6- 9-62	1.001	1.258	-25.68	38.0	45.4	-19.52
	3-29-65	6.925	7.842	-13.25	69.0	81.0	-17.40

Table 5-5. Comparison of observed and predicted hydrograph peak and its timing for large agricultural watersheds.

CONV MODEL; PHILIP EQUATION FOR INFILTRATION

Watershed	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Hastings W-3	6-10-43	0.884	1.512	-71.02	35.0	46.1	-31.69
	5-27-44	1.194	0.980	17.91	29.0	53.0	-82.76
	5-20-49	0.528	0.685	-29.59	99.0	80.5	18.72
	7-10-51	4.420	5.284	-19.56	41.0	46.1	-12.42
	5-21-52	1.466	1.066	27.24	40.0	53.0	-32.50
	6-26-52	1.455	1.894	-30.13	50.0	47.8	4.45
	6- 7-53	1.824	2.346	-28.61	40.0	52.7	-31.68
	6-15-57	2.997	2.635	12.07	62.0	66.1	- 6.68
	7- 3-59	5.080	4.789	5.73	34.0	42.0	-23.53
	9- 5-46	1.298	1.538	-18.47	146.0	161.0	-10.27
	5- 6-49	0.358	0.292	18.52	74.0	87.0	-17.57
	6-25-51	1.697	1.319	22.25	129.0	169.7	-31.57
	7-13-52	3.378	4.240	-25.50	124.0	128.9	- 3.98
	6-15-57	2.487	2.524	- 1.52	64.0	62.6	2.18
	6-16-57	1.727	1.575	8.84	154.0	162.3	- 5.39
W-11	5-11-44	0.285	0.062	78.08	145.0	250.0	-72.41
	9-19-50	0.527	0.445	15.66	316.0	357.0	-12.97
	7-10-51	0.663	0.954	-43.87	189.0	233.4	-23.47
	5-22-54	0.721	0.303	58.03	214.0	300.0	-40.19
	6-14-61	0.257	0.221	13.94	212.0	300.0	-41.51
	6- 1-51	0.831	0.279	66.36	247.0	400.0	-61.94
	6-26-52	0.205	0.204	0.54	555.0	419.2	24.47
	7-13-52	0.772	0.488	36.86	256.0	338.5	-32.22
	6-16-57	0.582	0.584	- 0.19	349.0	342.0	2.01
	5-21-65	1.064	1.403	-31.81	560.0	249.4	55.46

Table 5-6. Comparison of observed and predicted hydrograph peak and its timing for small agricultrual watersheds.

NASH MODEL: PHILIP EQUATION FOR INFILTRATION

Watershed Name	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Riesel (Waco)							
Y-2	3-26-46	1.270	1.437	- 13.15	66.0	36.0	45.45
	6-23-59	2.022	2.058	- 1.78	84.0	106.0	-26.19
	7-16-61	0.183	0.368	-100.98	79.0	34.0	56.96
	6-25-61	0.643	0.588	8.51	84.0	62.0	26.19
	6- 9-62	2.284	1.772	22.40	49.0	58.0	-18.37
	4-24-57	4.267	3.634	14.84	37.0	56.0	-51.35
	5-13-57	3.150	2.844	9.71	35.0	50.0	-42.86
	6- 4-57	4.547	3.990	12.24	34.0	46.0	-35.29
Y-7	5- 6-55	1.499	0.683	54.43	6.0	32.0	-433.33
	6- 4-57	3.480	2.476	28.85	33.0	38.0	- 15.15
	5-22-61	0.386	0.273	29.19	6.0	36.0	-500.00
	6- 9-62	2.421	2.465	- 1.85	37.0	38.0	- 2.70
	4-24-57	5.994	4.143	30.88	31.0	46.0	- 48.39
	5-13-57	5.156	3.418	33.72	33.0	48.0	- 45.45
	6-23-59	4.470	2.833	36.64	57.0	120.0	-110.53
	3-29-65	5.778	5.700	1.38	79.0	102.0	- 29.11
Y-10	5- 6-55	1.511	1.037	31.37	12.0	22.0	- 83.33
	6- 4-57	6.096	4.808	21.12	26.0	34.0	- 30.77
	6-23-59	1.786	2.390	- 33.86	70.0	94.0	- 34.29
	5-25-61	0.930	0.645	30.63	17.0	24.0	- 41.18
	6-15-61	0.858	0.559	34.87	26.0	24.0	7.69
	4-24-57	6.858	5.475	20.16	35.0	44.0	- 25.71
	5-13-57	4.851	3.903	19.54	26.0	38.0	- 46.15
	6- 9-62	1.001	1.481	- 48.02	38.0	36.0	5.26
	3-29-65	6.925	6.656	3.88	69.0	88.0	- 27.54
W-10	3-12-53	2.718	1.518	44.14	49.0	28.0	42.86
	6- 4-57	2.167	1.536	29.09	48.0	46.0	4.17
	4-24-57	7.087	4.899	30.86	28.0	40.0	- 42.86
	4-24-57	7.087	4.451	37.19	28.0	42.0	- 50.00
	5-22-61	1.072	0.740	31.00	41.0	24.0	41.46
	6-25-61	0.848	0.859	- 1.29	41.0	62.0	- 51.22
	6- 9-62	2.093	1.980	5.39	32.0	38.0	- 18.72
	6-23-59	4.978	3.877	22.12	63.0	60.0	4.76
	3-29-65	4.495	5.171	- 15.05	71.0	82.0	- 15.49

Table 5-7. Comparison of observed and predicted hydrograph peak and its timing for large agricultural watersheds.

NASH MODEL: PHILIP EQUATION FOR INFILTRATION

Watershed Name	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Hastings W-3	6-10-43	0.884	1.003	-13.52	35.0	56.0	-60.00
	5-27-44	1.194	0.766	35.80	29.0	56.0	-93.10
	5-20-49	0.528	0.566	- 7.12	99.0	76.0	23.23
	7-10-51	4.420	2.654	39.96	41.0	74.0	-80.49
	5-21-52	1.466	0.788	46.89	40.0	56.0	-40.00
	6-26-52	1.455	1.180	18.93	50.0	80.0	-60.00
	6- 7-53	1.824	1.364	25.19	40.0	70.0	-75.00
	6-15-57	2.997	1.514	49.49	62.0	84.0	-35.48
	7- 3-59	5.080	2.498	50.82	34.0	70.0	-105.88
	9- 5-46	1.298	1.071	17.50	146.0	168.0	-15.07
	5- 6-49	0.358	0.328	8.47	74.0	70.0	5.41
	6-25-51	1.697	1.129	33.49	29.0	174.0	-34.88
	7-13-52	3.378	2.374	29.74	124.0	162.0	-30.65
	6-15-57	2.487	1.573	36.73	64.0	86.0	-34.38
	6-16-57	1.727	1.136	34.27	154.0	170.0	-10.39
W-11	5-11-44	0.285	0.271	4.72	145.0	186.0	-28.28
	9-19-50	0.527	0.609	-15.49	316.0	248.0	21.52
	7-10-51	0.663	1.155	-74.10	189.0	166.0	12.17
	5-22-54	0.721	0.558	22.61	214.0	202.0	5.61
	6-14-61	0.257	0.462	-80.21	212.0	190.0	10.38
	6- 1-51	0.831	0.497	40.20	247.0	274.0	-10.93
	6-26-52	0.205	0.320	-56.22	555.0	208.0	62.52
	7-13-52	0.772	0.708	8.28	256.0	230.0	10.16
	6-16-57	0.582	0.707	-21.40	349.0	264.0	24.36
	5-21-65	1.064	1.437	-35.02	560.0	220.0	60.71

(6) The models accounted for only one-dimensional space variability in surface runoff along the direction of flow.

Some error may be due to model parameters. Errors, incurred in the process of parameter determination, are principally from two sources: (1) poor selection of data used in parameter optimization, and (2) choice of an unrealistic objective function for use in the optimization procedure. These sources of errors can be effectively minimized through the strict application of the guidelines previously outlined for the selection of hydrologic data and choosing an appropriate objective function that will serve the intended purpose.

Watershed characteristics may yet be another source of error. The most serious error in determination of topographic features is that of map scaling. Differing linear map scales can result in the disproportionate determination of identical parameters. The watershed characteristics, drainage-density and stream order were especially vulnerable to this problem. As an example, a stream of order 3 on a small scale map may be interpreted as a stream of order 1 on a large scale map. However, since watersheds of similar size were generally mapped to similar scales, data stratification based on size tended to reduce this error.

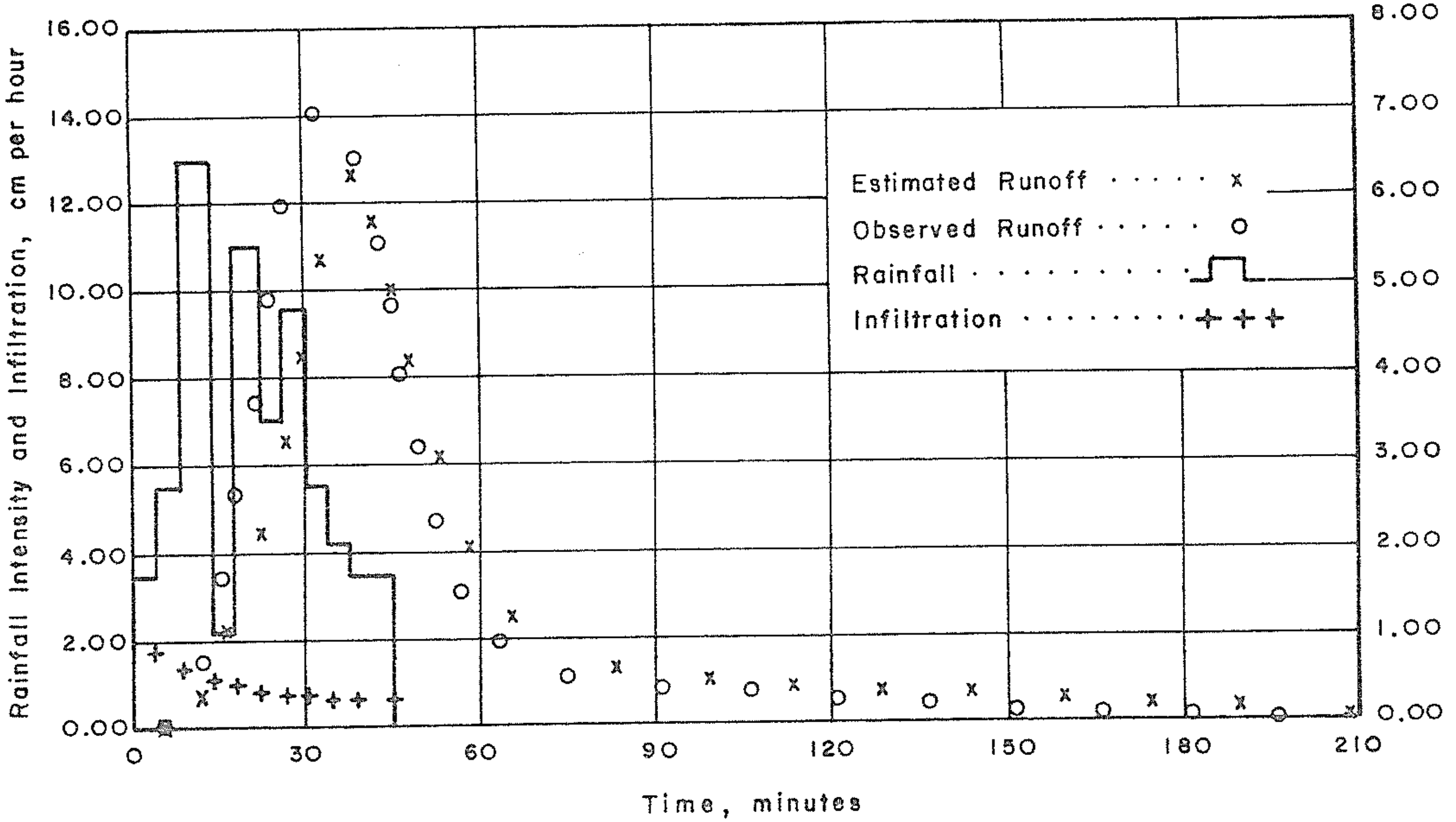

Fig. 5-14. Hydrograph prediction by CONV, using Philip's infiltration method, for rainfall event of 4-24-57 on watershed W-10, Riesel (Waco), Texas.

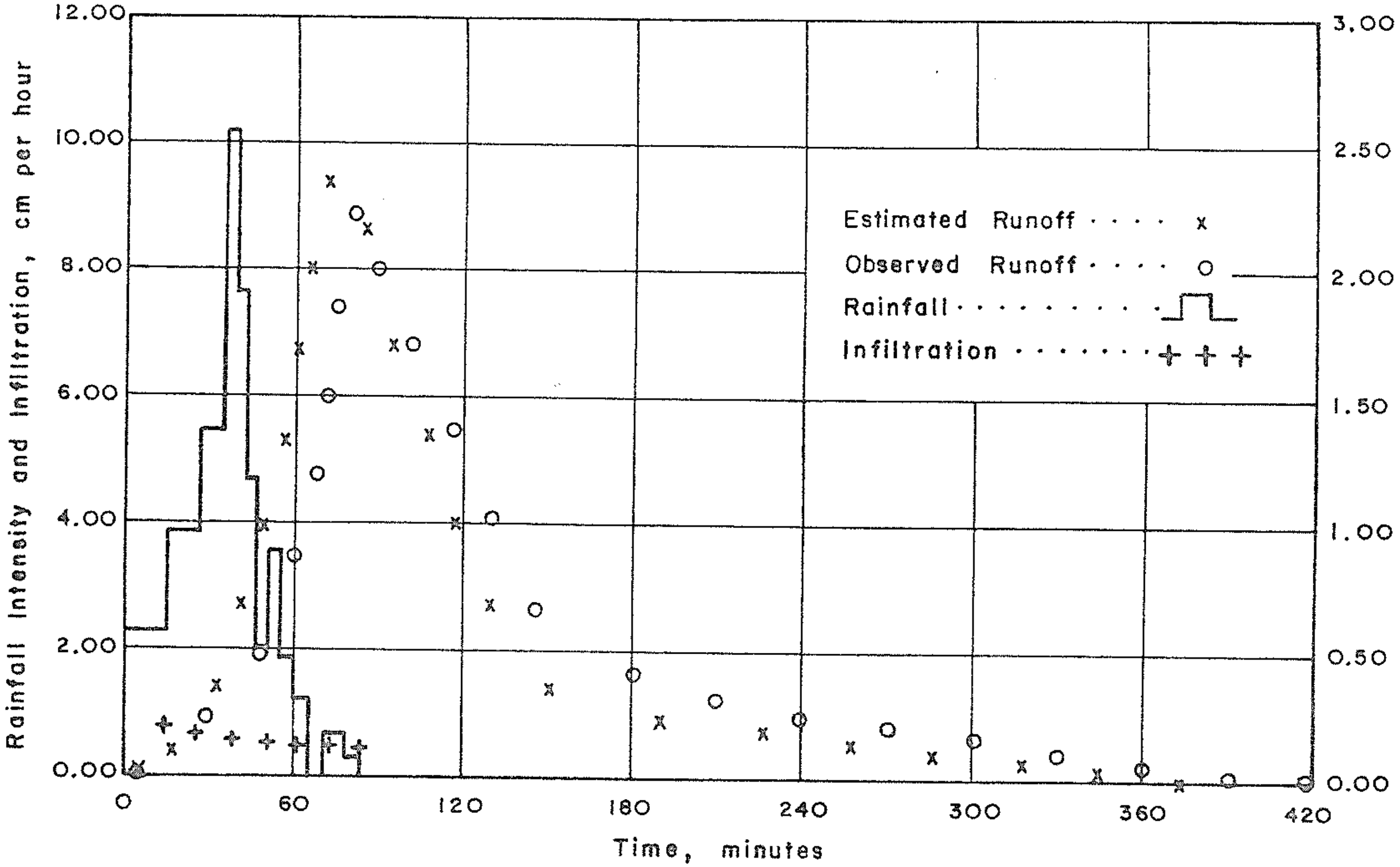

Fig. 5-15. Hydrograph prediction by CONV, using Philip's infiltration method, for rainfall event of 6-10-41 on watershed C, Riesel (Waco), Texas.

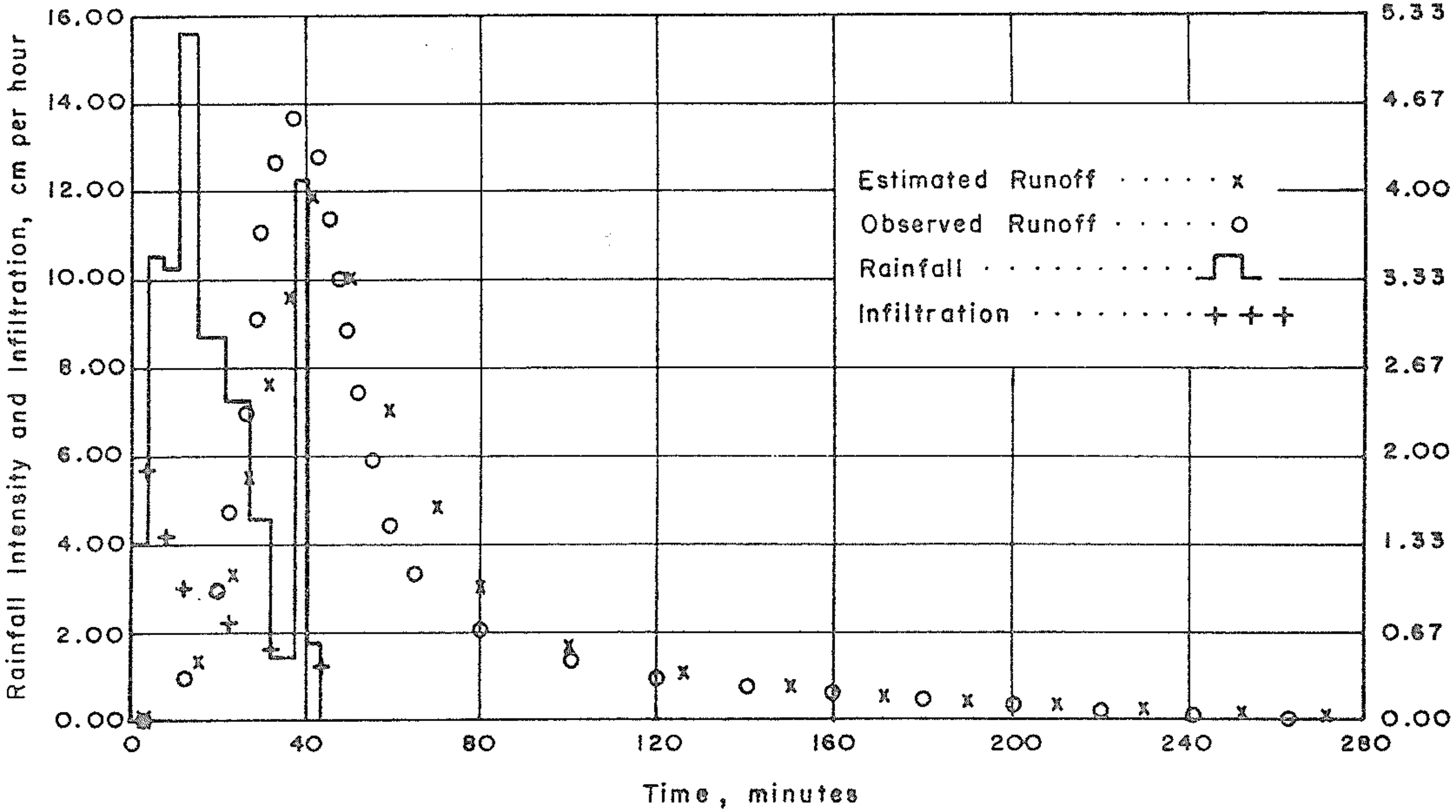

Fig. 5-16. Hydrograph prediction by NASH, using Philip's infiltration method, for rainfall event of 6-4-57 on watershed Y-2, Riesel (Waco), Texas.

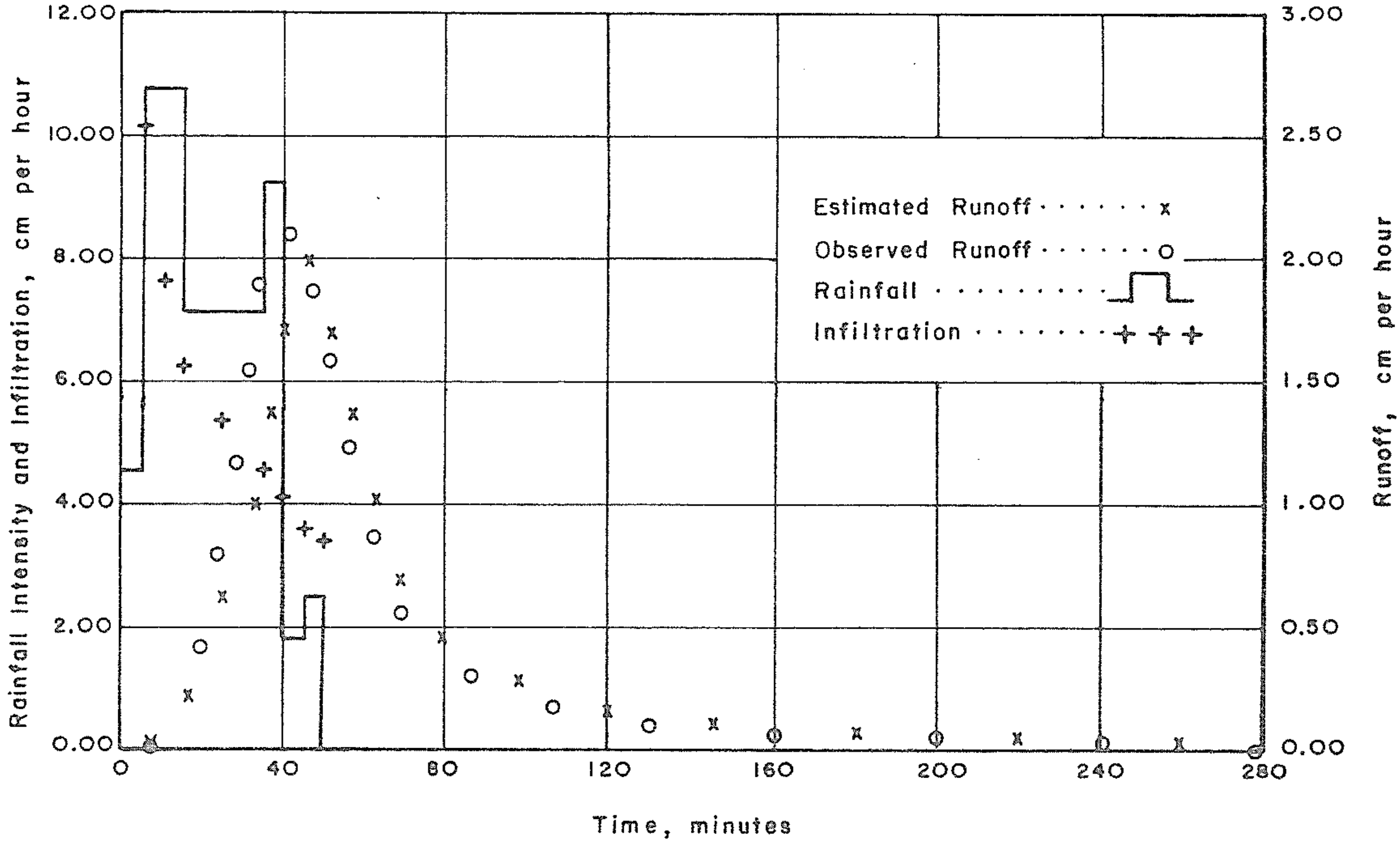

Fig. 5-17. Hydrograph prediction by NASH, using Philip's infiltration method, for rainfall event of 6-9-62 on watershed W-10, Riesel (Waco), Texas.

CHAPTER 6

CONCLUSIONS

The following conclusions are drawn from this study:

(1) The model parameters α and K were reliably estimated from watershed physiography.

(2) In deriving equations for these parameters it is desirable to include a large number of watersheds having diverse physiographic conditions, and to estimate infiltration for determination of rainfall-excess by a reliable procedure.

(3) Estimation of the parameters of physically based models is easier and more reliable than that of the parameters of operational models.

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