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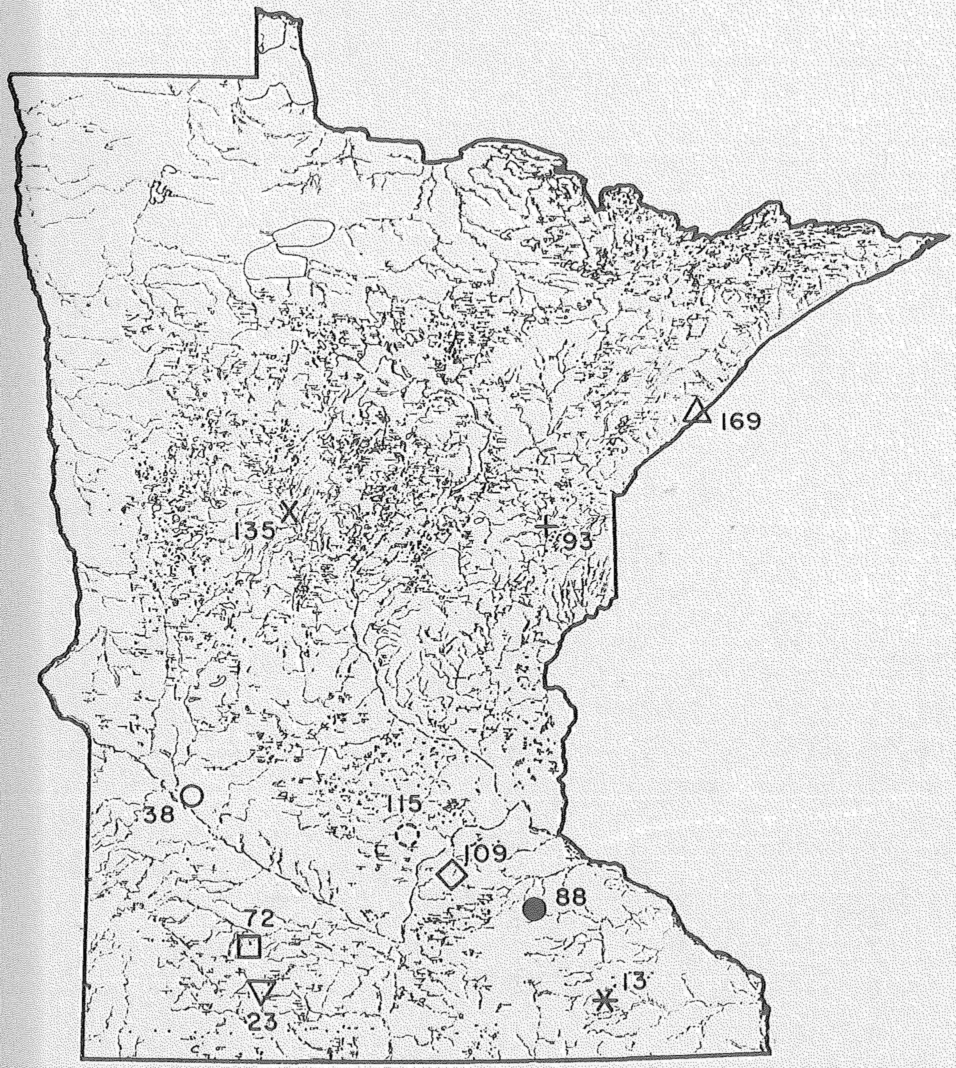


# Hydrologic Evaluation of Small Watersheds in Minnesota Using TR-20 Model

MN Department of Natural Resources
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# HYDROLOGIC EVALUATION OF SMALL WATERSHEDS IN MINNESOTA USING TR-20 MODEL

by

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# I. INTRODUCTION

## A. Need for Study

In Minnesota, as in all the states of the Union, hydrologic modeling of watersheds is done to generate a data base of runoff and hydrograph characteristics of a watershed to facilitate planning for implementation of water resources programs and projects. Some of the most used hydrologic models, at least among governmental agencies in Minnesota, are the TR-20 of the U.S. Soil Conservation Service and the HEC-1 of the U.S. Army Corps of Engineers.

This study deals with some of the input data parameters of the TR-20 model. There are three input parameters that one must estimate when modeling using TR-20. These are the time of concentration ($T_c$) in hours, the routing coefficient (C), and the runoff curve number (CN). The runoff curve number is estimated from soil information available in county soil surveys. The time of concentration and the routing coefficient, however, are more difficult to estimate without extensive field surveys. Most hydrologists do not have the time and the resources to do extensive field work. In this effort selected watersheds in Minnesota were studied in order to derive a range of values that will be of use to persons engaged in doing hydrologic modeling of Minnesota watersheds.

The writer has done hydrologic modeling in Minnesota in the last eight years. Usually since there is little time or staff to do extensive field surveys to gather data to conduct the studies, the writer felt that the difficulty of not having sufficient data may be ameliorated by deriving regionalized values of the time of concentration (Tc) and the routing coefficient (C). Therefore this study was undertaken to provide methods of estimating the time of concentration and routing coefficient.

B. Scope of Study

The scope of the study is limited primarily to deriving values for the time of concentration and the routing coefficient. Each watershed was modeled using an observed precipitation event. Then the input parameters - the time of concentration, the routing coefficient and the runoff curve number(s) were adjusted so that the resulting hydrograph that nearly reproduces the observed hydrograph was completed.

## II. DEFINITION OF HYDROGRAPH CHARACTERISTICS

The definitions for the time of concentration (Tc) and the routing coefficient (C) are those stated in the SCS National Engineering Handbook Section 4 (1). Accordingly the time of concentration (Tc) is "the time it takes for runoff to travel from the hydraulically most distant part of the storm area to the watershed outlet or other point of reference downstream. In hydrograph analysis, Tc is the time from the end of excess rainfall to the point on the falling link of the hydrograph (point of inflection) where the recession curve begins" (1).

Figure 1 shows a definition of the various characteristics of a hydrograph.

The routing coefficient (C) is defined by

$$C = \frac{O_2 - O_1}{I_1 - O_1} \qquad [1]$$

Where $O_1$ = outflow rate at time $t_1$, $O_2$ = outflow rate at time $t_2$, $I_1$ = inflow rate at time $t_1$.

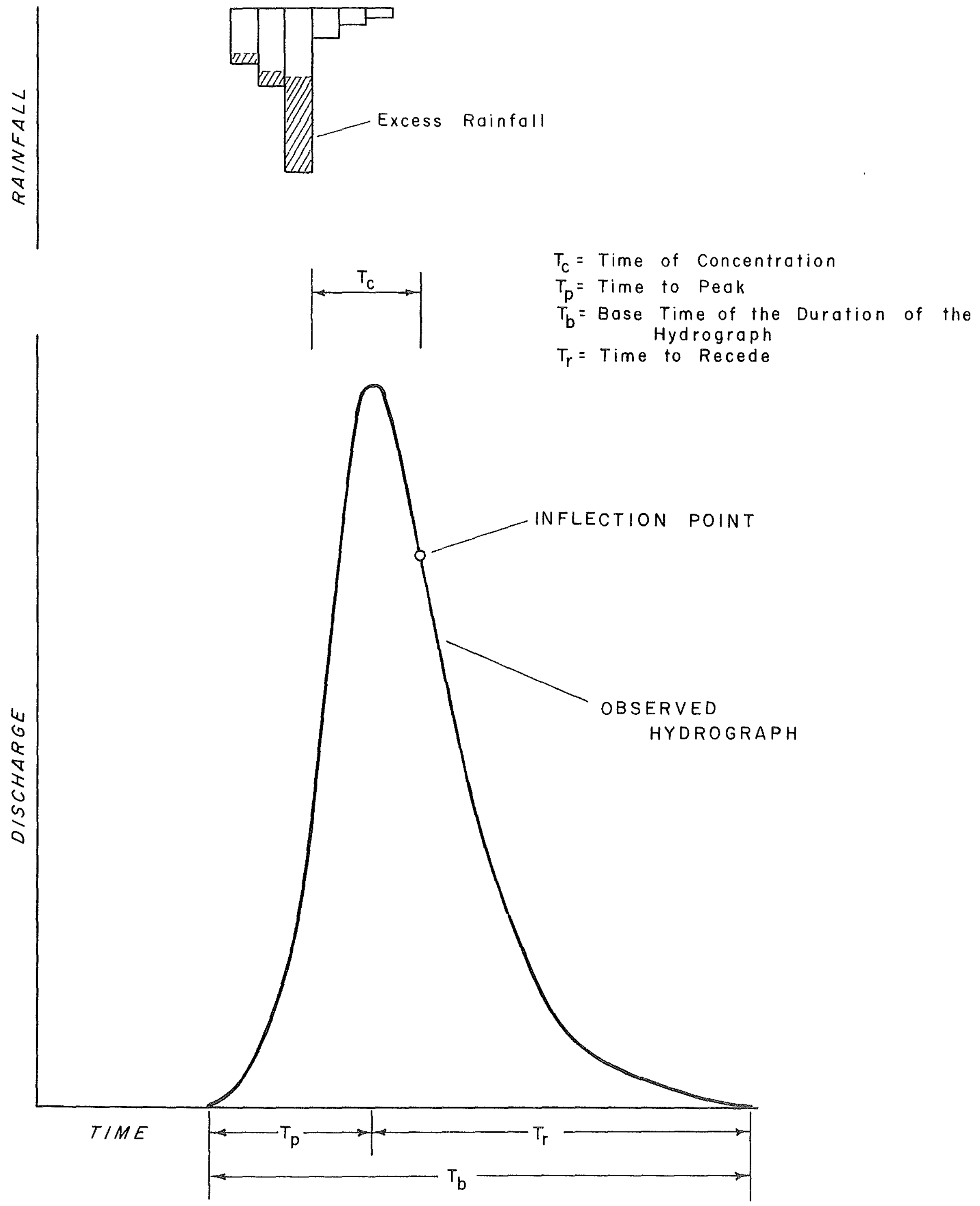


Figure 1 Definition of Hydrograph Characteristics

## III. DATA

### A. Availability of Data

The U.S. Geological Survey, Water Resources Division, Minnesota District in St. Paul in cooperation with Minnesota Department of Transportation, Minnesota Department of Natural Resources, and the U.S. Army Corps of Engineers collects crest-gage data of small streams. Some of the sites are equipped with continuous gage recorders and continuous rainfall recorders. The highest annual crest-gage height and the corresponding peak discharge are published by the U.S. Geological Survey (2). The continuous stage and rainfall data are available for a few sites; however these data are not published. Hydrographs were developed and the corresponding runoff computed from this unpublished data. The continuous rainfall data that produced the hydrograph was tabulated and totaled.

Nine watersheds ranging in area from 0.73 sq.mi. to 49.2 sq.mi. were modeled using the TR-20 program. The number of watersheds studied and their geographic location were dictated by the availability of both a hydrograph with significant discharge and continuously recorded rainfall data that produced the observed hydrograph. The main watershed characteristics such as area, length of main channel, slope of main channel, main watershed altitude, percent of forest cover, percent of area of lakes and swamps are shown in Table 1. The Buffalo Creek tributary near Brownton, was used only in the multiregression analysis; since it did not have a continuous rainfall record. The general geographic location of the watersheds and specifically the crest-gage site location for each of the watersheds studied is shown on Figure 2.

### B. Limitations of Data

Out of all the crest-gage sites in Minnesota, there were only nine sites

Table 1 General Characteristics of the Small Watersheds

| Stream Name | Site Number | Symbol | Gaging Station | Watershed Characteristics: Area | Main Channel Length | Main Channel Slope | Main Watershed Altitude | Forest Area | Area of Swamps & Lakes |
|---|---|---|---|---|---|---|---|---|---|
| | | | | sq. mi. | mi. | ft/mi. | ft. | percent | percent |
| North Branch, Root River tributary near Stewartville, MN | 13 | * | 0538360 | 0.73 | 2.0 | 47.3 | 1,252 | 1 | 0 |
| Warren Lake tributary near Windom, MN | 23 | ▽ | 0547540 | 1.39 | 2.45 | 17.4 | 1,401 | 1 | 0 |
| Little Cannon River tributary near Kenyon, MN | 88 | ● | 0535510 | 2.20 | 2.58 | 53.4 | 1,090 | 2 | 0 |
| Dry Creek near Jeffers, MN | 72 | □ | 0531690 | 3.13 | 4.62 | 61.4 | 1,332 | 2 | 0 |
| Silver Creek tributary near Two Harbors, MN | 169 | △ | 0401525 | 3.72 | 3.00 | 11.0 | 962 | 91 | 0 |
| Spring Creek near Montevideo | 38 | ○ | 0530520 | 16.0 | 7.51 | 5.7 | 991 | 2 | 1 |
| Raven Stream tributary near New Prague, MN | 109 | ◇ | 0533055 | 25.1 | 10.4 | 10.0 | 978 | 8 | 10 |
| Glaisby Brook near Kettle River, MN | 93 | + | 0533620 | 27.5 | 12.2 | 11.5 | 1,180 | 80 | 17 |
| Buffalo Creek tributary near Brownton, MN | 115* | | 0527870 | 30.2 | 14.3 | 3.3 | 1,030 | 4 | 4 |
| Cat River near Nimrod, MN | 135 | × | 0524420 | 49.2 | 13.9 | 6.9 | 1,375 | 33 | 15 |

* TR-20 model for site No. 115 was not completed due to incomplete rainfall data input.

NOTE: The data of Table 1 were compiled from reference (2).

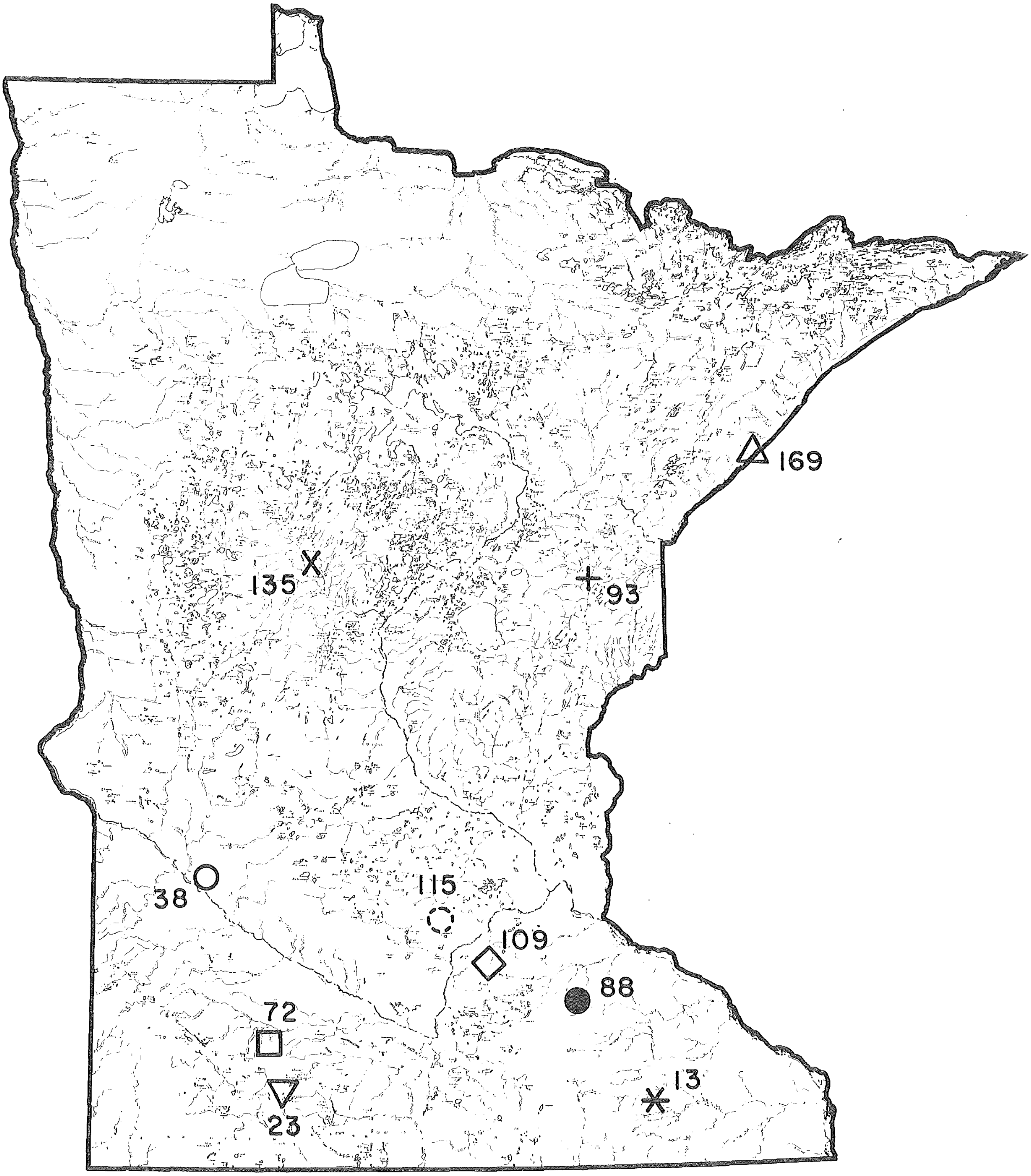


Figure 2 Map of Minnesota with Site Locations of Watersheds

where both usable continuous hydrograph and the corresponding continuous rainfall records existed for the period of record of the small stream gage program. Thus the number of watersheds modeled, their geographic location and the size of the watersheds was dictated by the availability of usable data.

## IV. ANALYSIS OF DATA

### A. TR-20 Modeling

Each of the watersheds listed in Table 1 were delineated on topographic maps and subdivided into subwatersheds as suggested by the Soil Conservation Service procedures for use of the TR-20 program. For each watershed the runoff curve number(s) was derived using the U.S. Soil Conservation Service's county soil surveys. The time of concentration and the routing coefficient for each subwatershed were estimated using U.S. Soil Conservation Service guidelines (1).

For each site two rainfall events that produced significant peak discharges were selected. The corresponding hydrographs were developed and plotted and designated as observed hydrographs. The rainfall was tabulated using selected intervals suitable for modeling.

The actual rainfall, the runoff curve number(s), and the watershed parameters - area of subwatersheds, length of reach, time of concentration, and routing coefficients were part of the input data.

The antecedent soil moisture (ASM) is 1 for dry soil moisture condition, 2 for normal soil moisture condition, and 3 for wet soil moisture condition. The value 1,2, or 3 for each rainfall event was determined using the guidelines developed by the U.S. Soil Conservation Service (1).

The time of concentration, the routing coefficient and the runoff curve number, were estimated values. After each run of the TR-20 model the resulting hydrograph was plotted and compared with the observed hydrograph. The time of concentration, the routing coefficient and the runoff curve numbers were adjusted one at a time until the best hydrograph that simulated the observed hydrograph was derived. The values of time of concentration and routing coefficient that produced the computed hydrograph are near the correct values for that watershed.

B. Results of TR-20 Modeling

The following is a brief presentation of the TR-20 modeling done on the nine watersheds. The rainfall events simulated were divided into two broad categories: those that happened in the growing season (June to September) and the dormant season (March through May and September through November). The results of TR-20 modeling on the nine watersheds for the growing and dormant seasons are shown on Tables 2 and 3 respectively. First, Tables 2 and 3, show comparisons of the observed peak discharge (Qp) and the observed runoff (R) with the computed discharge (Qp) and computed runoff (R). Further, the total rainfall event that produced both hydrographs and the total time of concentration that was used in producing the computed hydrograph are shown in Tables 2 and 3.

Figures 3 through 29 show the shape of each watershed and subwatershed and a comparison of the observed and computed hydrographs of the watershed. The resulting time of concentrations and routing coefficient are shown with the hydrographs.

A TR-20 run was made with the U.S. Soil Conservation Service's 24-hour duration rainfall table, Type I Distribution, using the optimized values of the time of concentration ($T_c$), the routing coefficient (C). For example, looking at Figure 4, the hydrograph produced by using 24-hour duration table has about 55 cfs as compared to 170 and 171 cfs of the observed and optimized hydrographs respectively and the peak discharge occurs about 6.6 hours later than the optimized peak discharge.

Table 2 Observed and Computed Hydrologic Characteristics for Growing Season (June to September)

| Stream Name | Site Number | Symbol | Area Sq. Mi. | Observed | | | Computed | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Qp(cfs) | P(in.) | R(in.) | Qp(cfs) | R(in.) | Tc(hrs) |
| North Branch, Root River tributary near Stewartville, MN | 13 | * | 0.73 | 172 | 2.6 | 1.06 | 171 | 0.80 | 3.2 |
| Warren Lake tributary near Windom, MN | 23 | ▽ | 1.39 | 122 | 0.7 | 0.13 | 133 | 0.10 | 1.0 |
| Little Cannon River tributary near Kenyon, MN | 88 | ● | 2.20 | 280 | 1.5 | 0.33 | 282 | 0.04 | 2.5 |
| Dry Creek near Jeffers, MN | 72 | □ | 3.13 | 365 | 1.7 | 0.99 | 366 | 0.94 | 4.2 |
| Silver Creek tributary near Two Harbors, MN | 169 | △ | 3.72 | 72 | 1.1 | 0.15 | 79 | 0.08 | 7.5 |
| Spring Creek near Montevideo | 38 | ○ | 16.0 | 111 | 3.0 | 0.15 | 119 | 0.14 | 32.5 |
| Raven Stream tributary near New Prague, MN | 109 | ◇ | 25.1 | 263 | 2.5 | 0.97 | 280 | 0.99 | 70 |
| Glaisby Brook near Kettle River, MN | 93 | + | 27.5 | 265 | 2.1 | 0.98 | 275 | 0.70 | 80 |
| Cat River near Nimrod, MN | 135 | × | 49.2 | 410 | 6.1 | 2.08 | 415 | 1.57 | 329 |

Qp = peak discharge
P = precipitation
R = runoff
C = routing coefficient
Tc = time of concentration

Table 3 Observed and Computed Hydrologic Characteristics for Dormant Season (April through May and September through November)

| Stream Name | Site Number | Symbol | Area Sq. Mi. | Observed Qp(cfs) | Observed P(in.) | Observed R(in.) | Computed Qp(cfs) | Computed R(in.) | Computed Tc(hrs) |
|---|---|---|---|---|---|---|---|---|---|
| North Branch, Root River tributary near Stewartville, MN | 13 | * | 0.73 | 28 | 1.3 | 0.21 | 29 | 0.21 | 3.2 |
| Warren Lake tributary near Windom, MN | 23 | ▽ | 1.39 | 370 | 5.8 | 1.10 | 375 | 3.38 | 4.4 |
| Little Cannon River tributary near Kenyon, MN | 88 | ● | 2.20 | 74 | 2.2 | 0.16 | 108 | 0.17 | 4.4 |
| Dry Creek near Jeffers, MN | 72 | □ | 3.13 | 440 | 5.0 | 2.53 | 456 | 2.53 | 4.2 |
| Silver Creek tributary near Two Harbors, MN | 169 | △ | 3.72 | 203 | 1.0 | 0.94 | 195 | 0.35 | 7.68 |
| Spring Creek near Montevideo | 38 | ○ | 16.0 | 40 | 1.3 | 0.15 | 47 | 0.06 | 3.25 |
| Raven Stream tributary near New Prague, MN | 109 | ◇ | 25.1 | 173 | 2.0 | 0.82 | 187 | 0.69 | 70 |
| Glaisby Brook near Kettle River, MN | 93 | + | 27.5 | 397 | 3.2 | 2.45 | 394 | 0.98 | 68 |
| Cat River near Nimrod, MN | 135 | × | 49.2 | 173 | 2.2 | 0.04 | 197 | 0.04 | 100 |

Qp = peak discharge
P = precipitation
R = runoff
C = routing coefficient
Tc = time of concentration

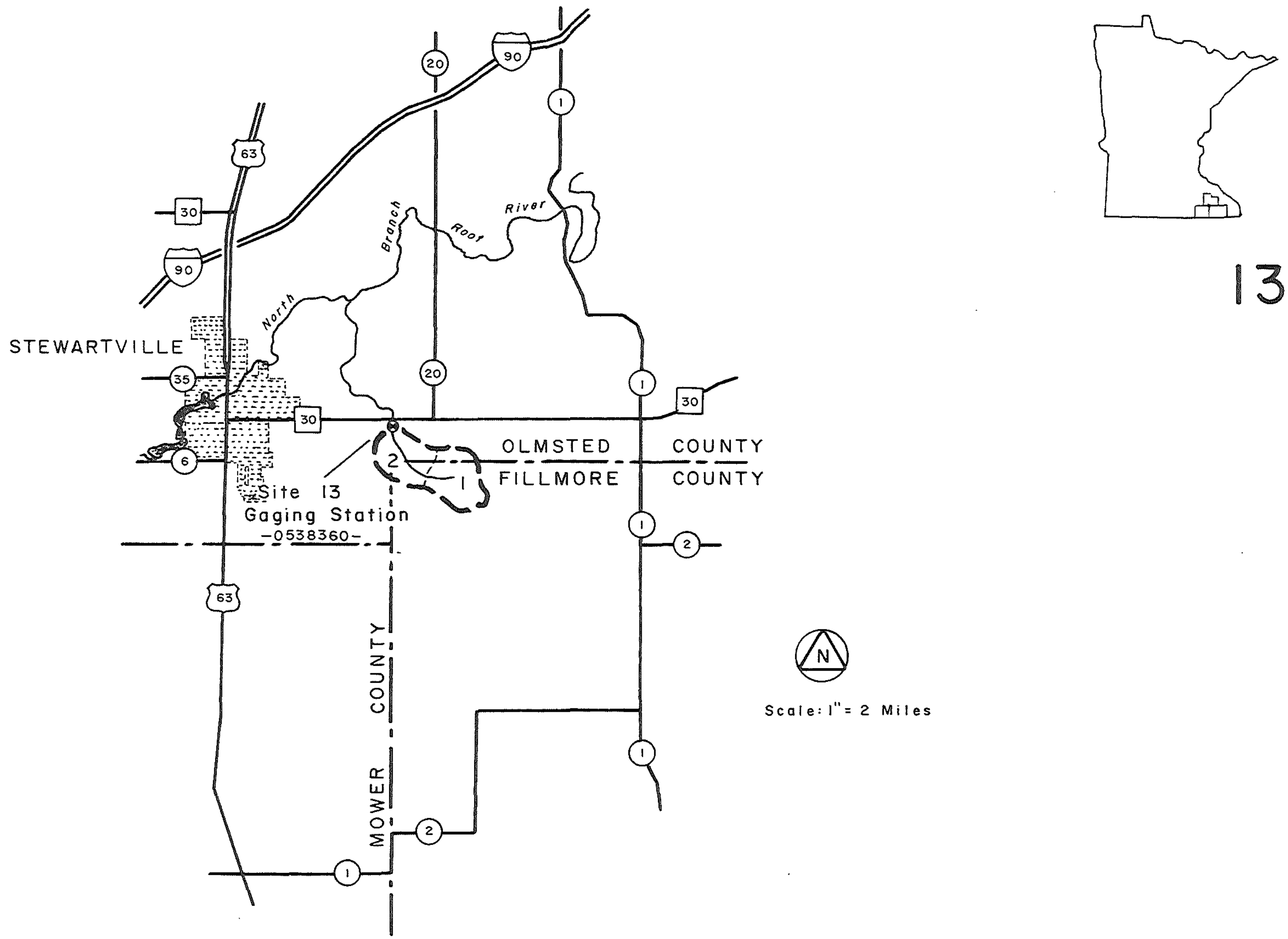


Figure 3 Map of North Branch Root River tributary Watershed, near Stewartville, MN

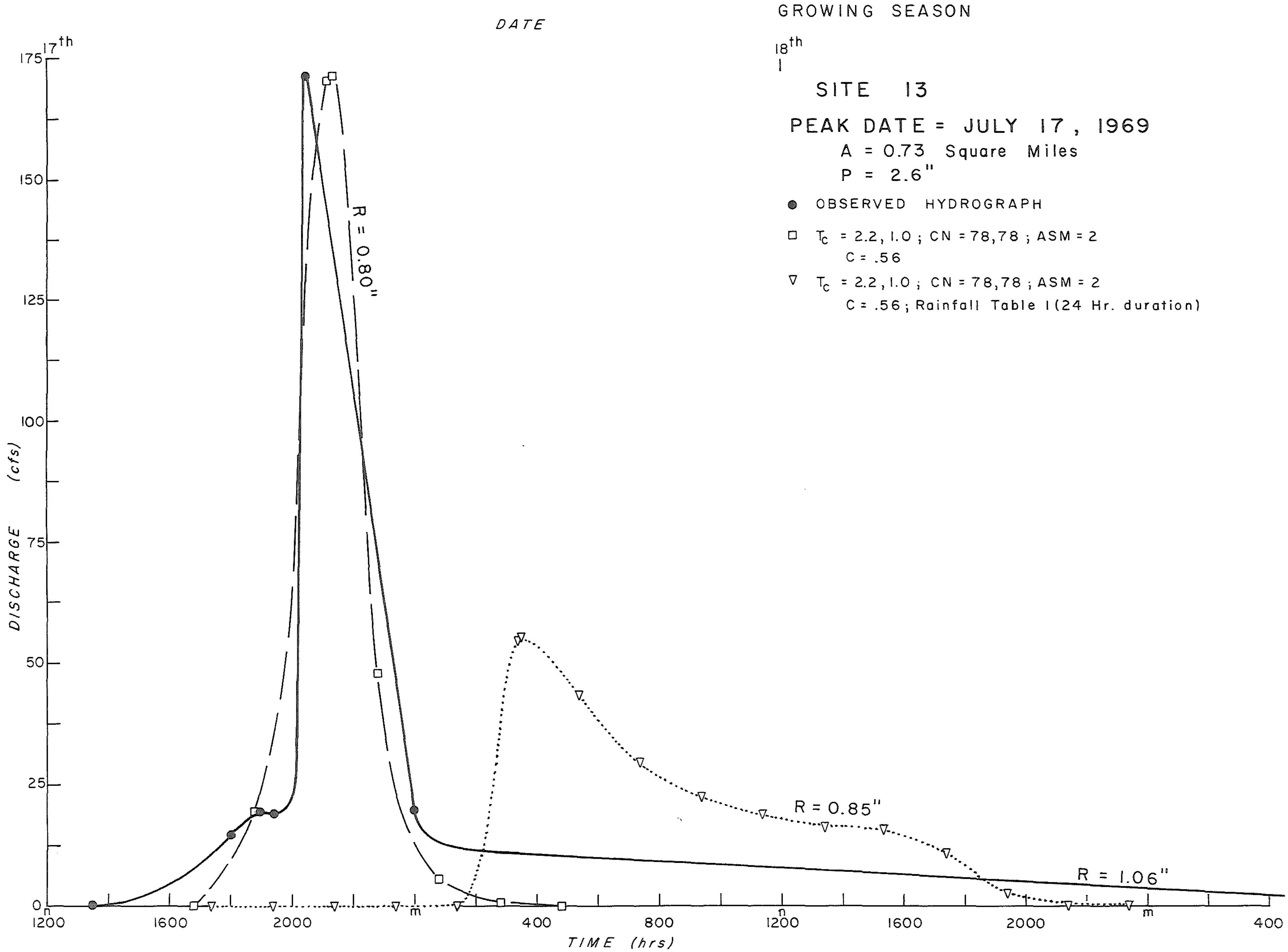


Figure 4 Observed and Computed Hydrographs for Growing season of North Branch Root River tributary, near Stewartville, MN

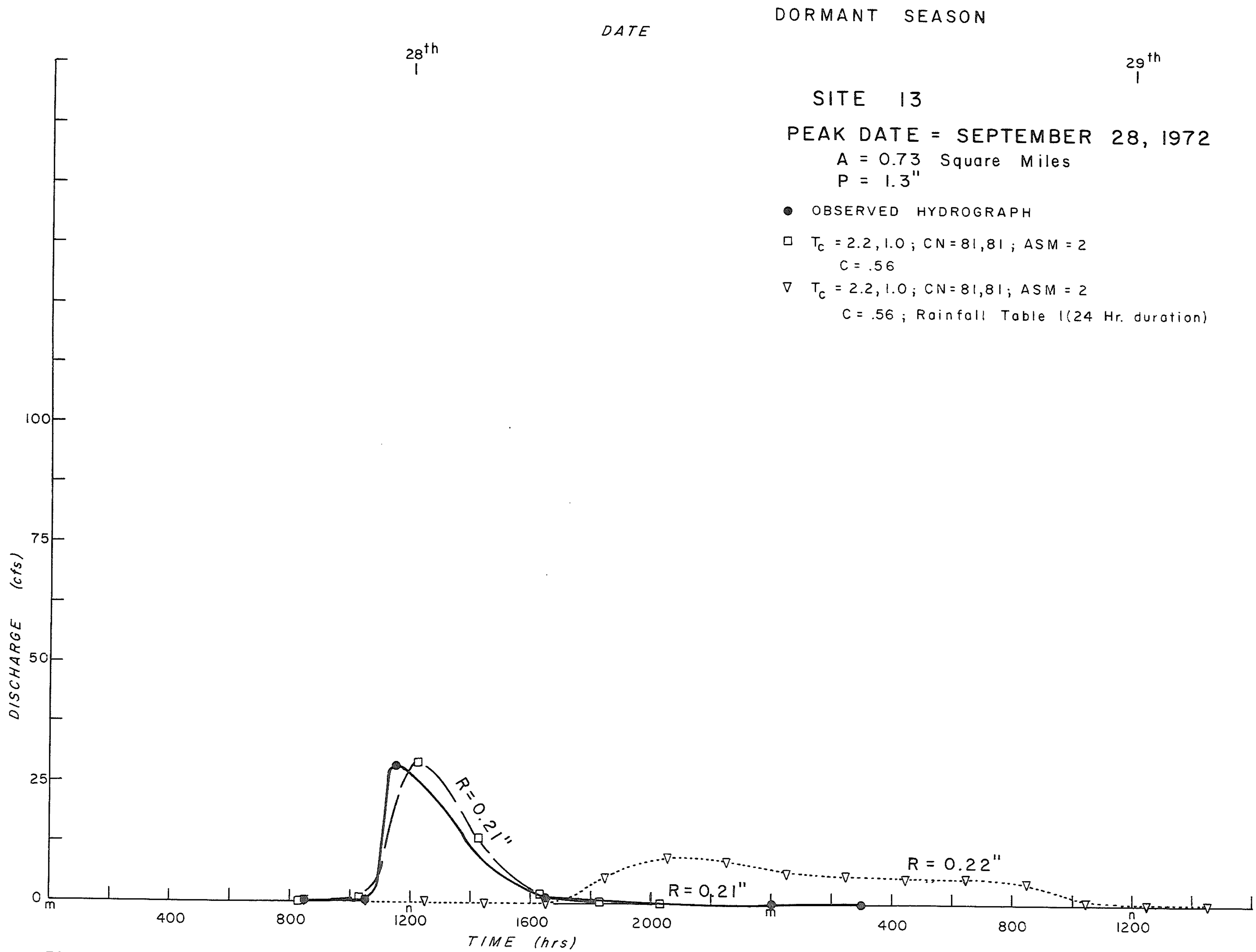


Figure 5 Observed and Computed Hydrographs for Dormant Season of North Branch Root River tributary, near Stewartville, MN

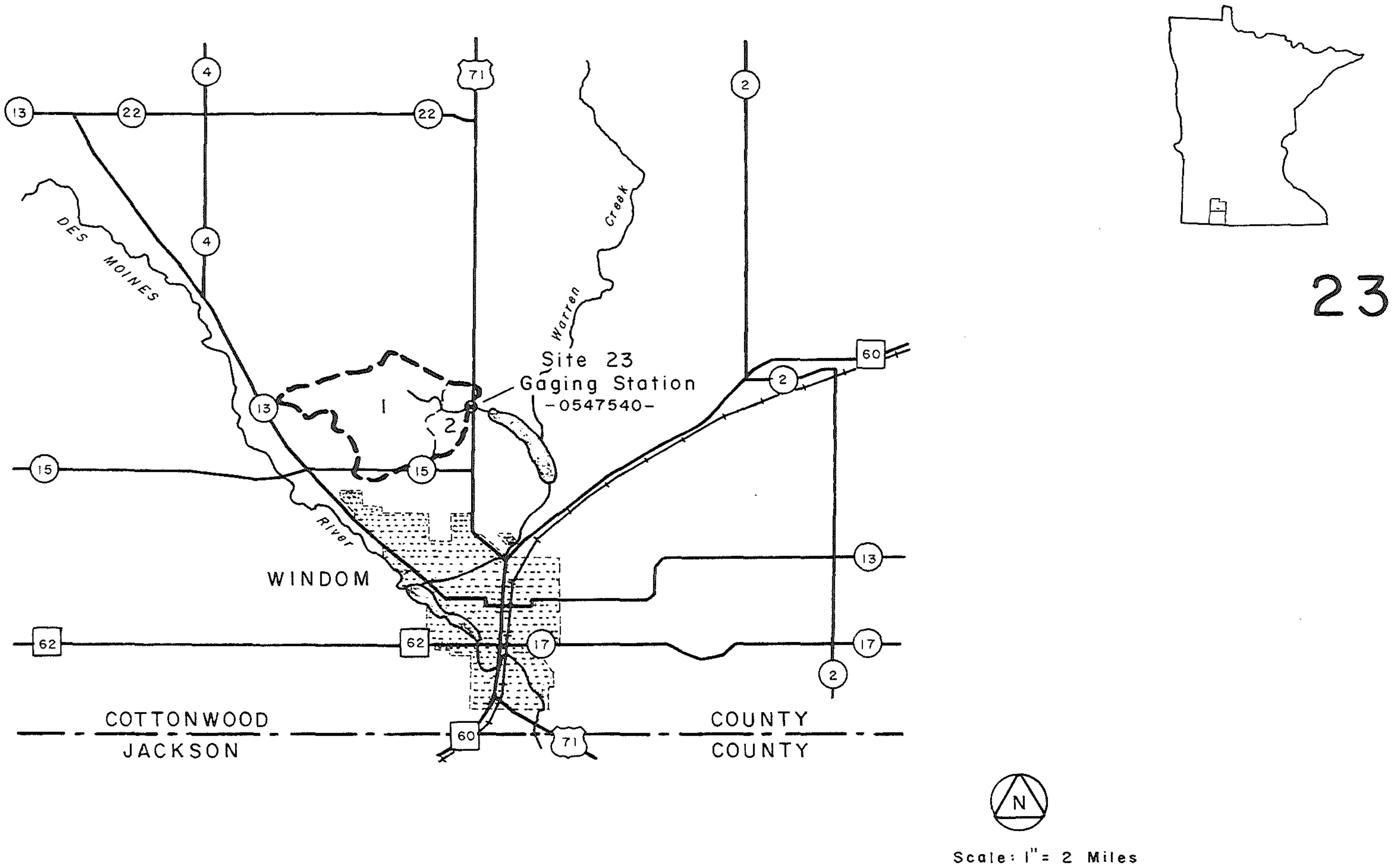


Figure 6  Map of Warren Lake tributary Watershed, near Windom, MN

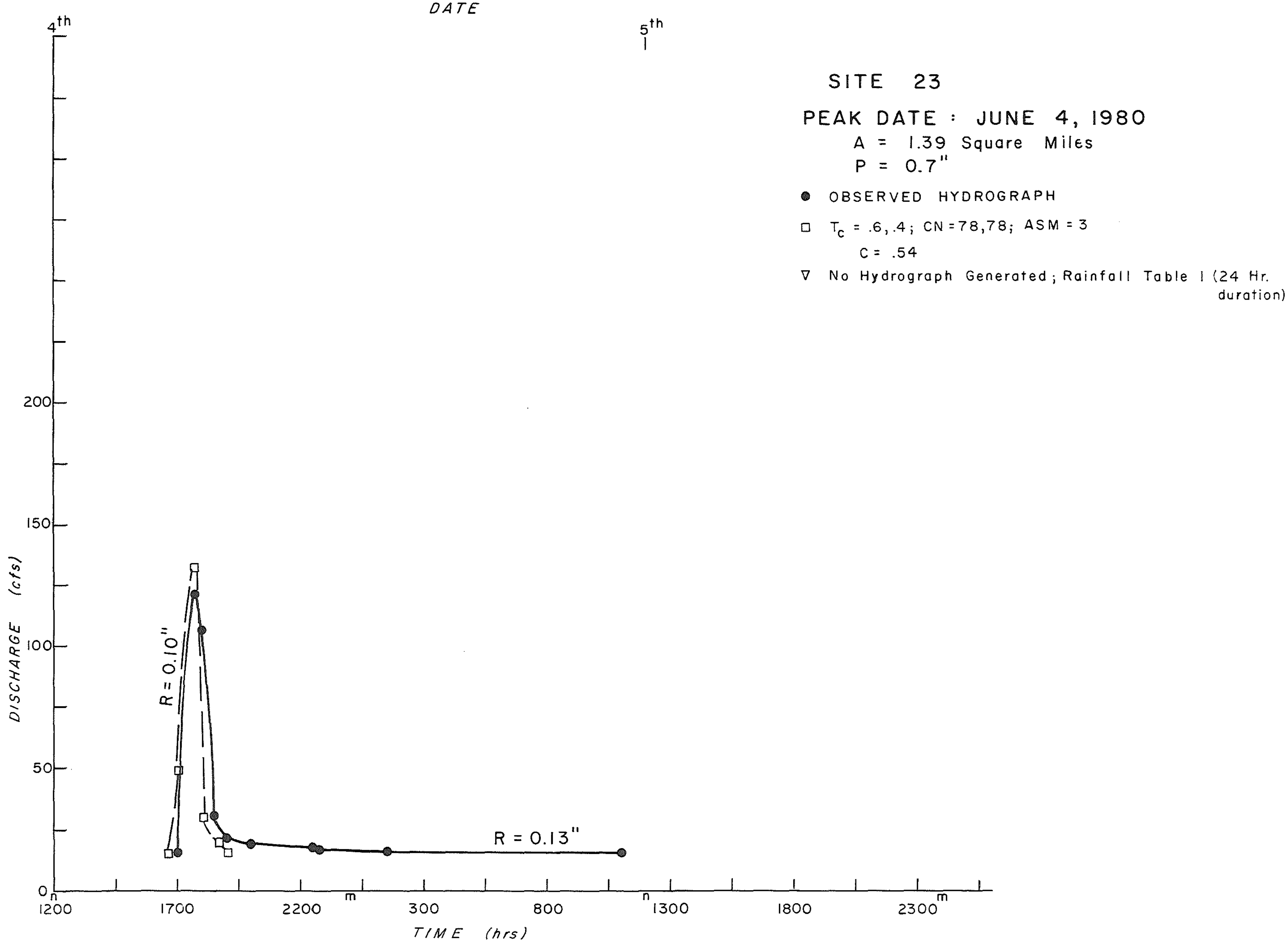


Figure 7 Observed and Computed Hydrographs for Growing Season of Warren Lake tributary, near Windom, MN

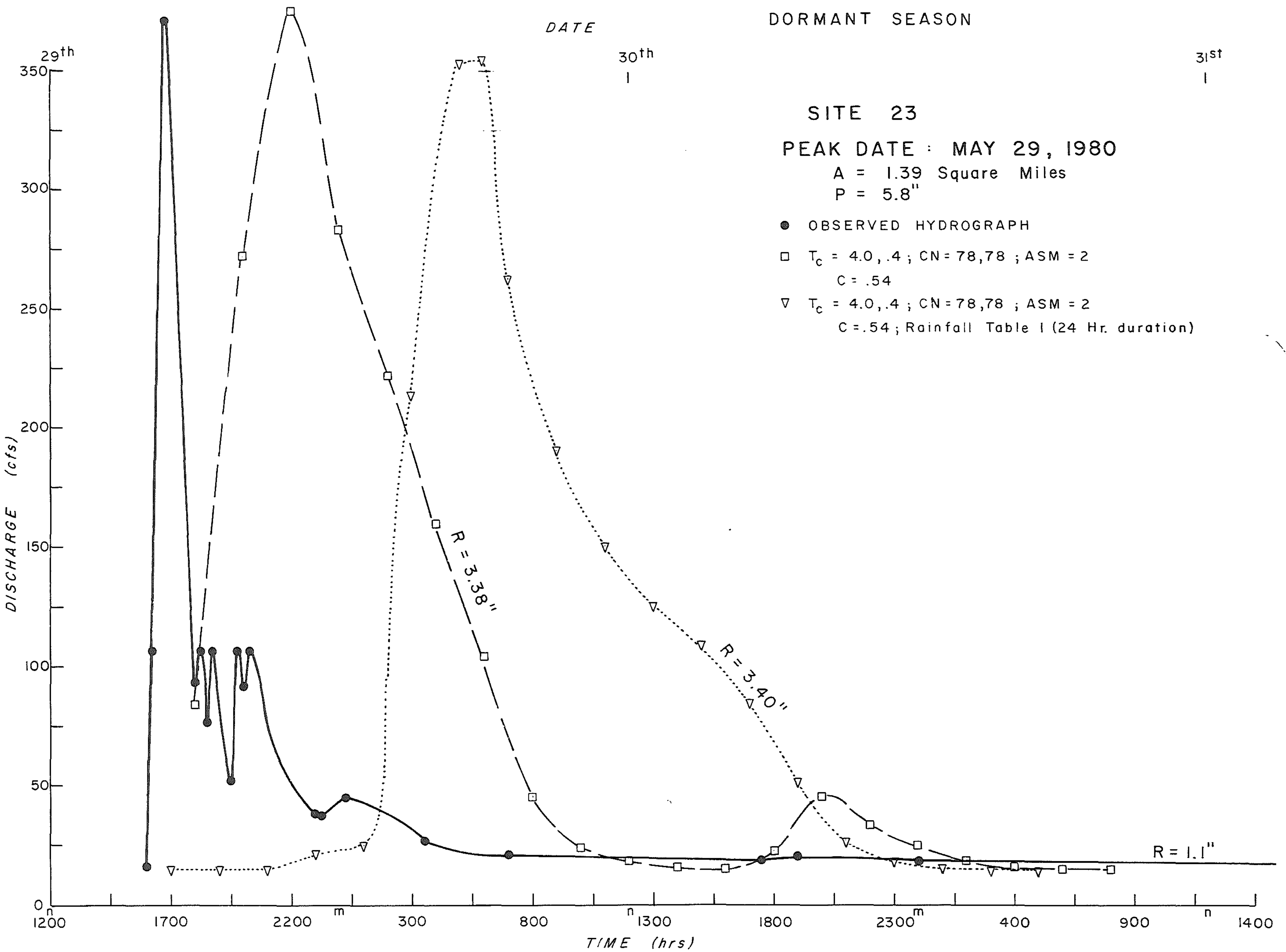


Figure 8 Observed and Computed Hydrographs for Dormant Season of Warren Lake tributary, near Windom, MN

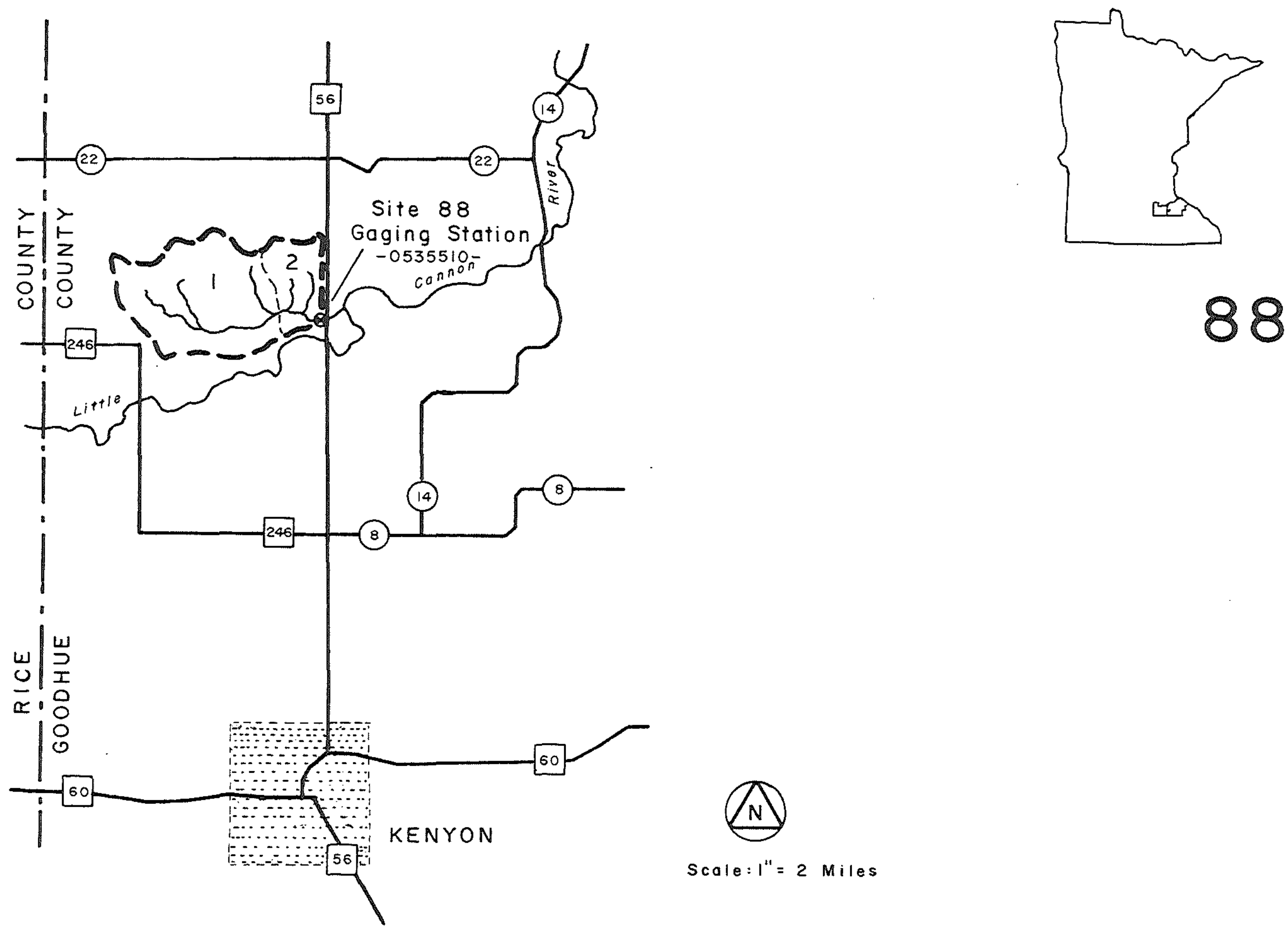


Figure 9 Map of Little Cannon River tributary Watershed, near Kenyon, MN

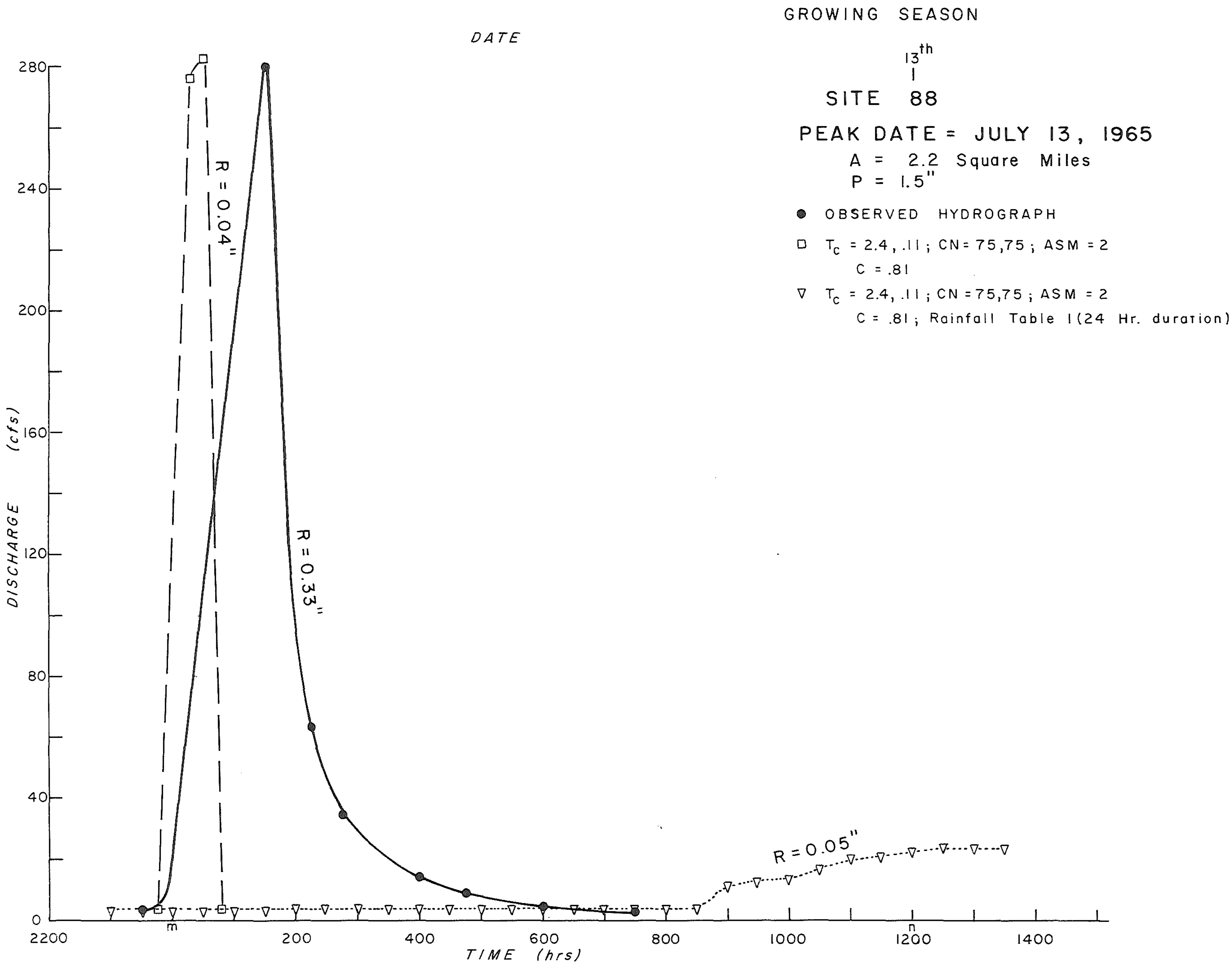


Figure 10 Observed and Computed Hydrographs for the Growing Season of Little Cannon River tributary, near Kenyon, MN

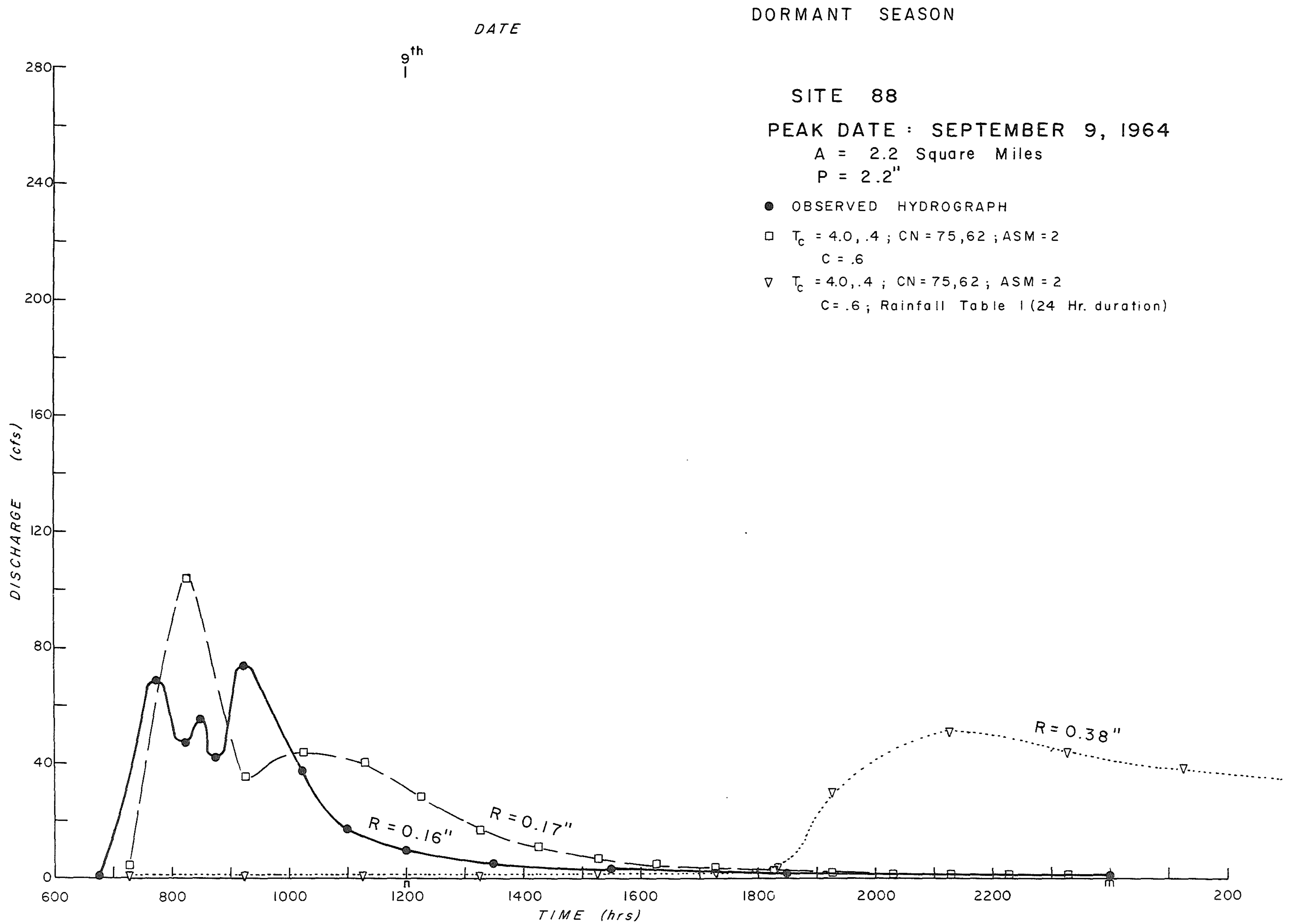


Figure 11 Observed and Computed Hydrographs for the Dormant Season of Little Cannon River tributary, near Kenyon, MN

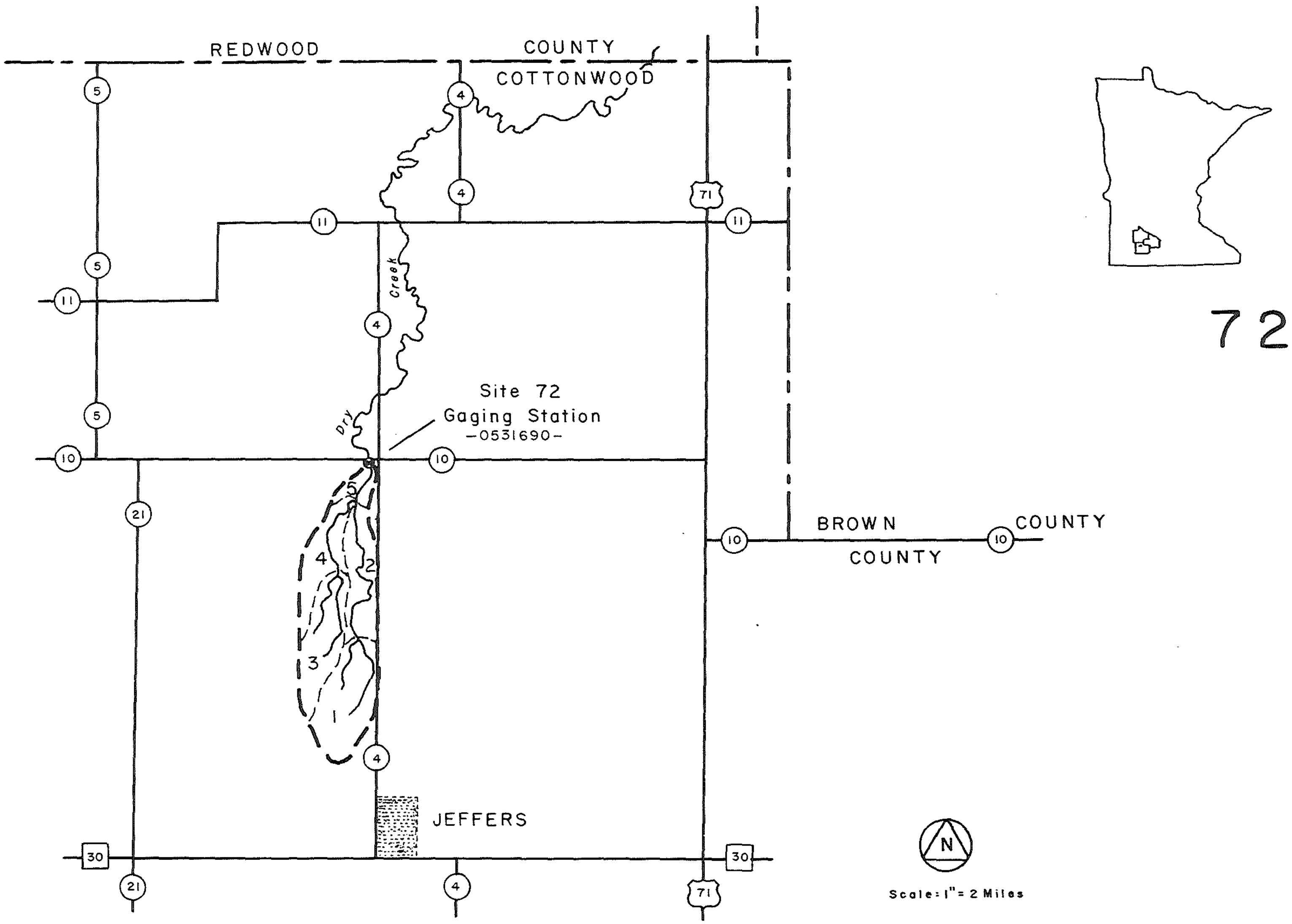


Figure 12 Map of Dry Creek Watershed, near Jeffers, MN

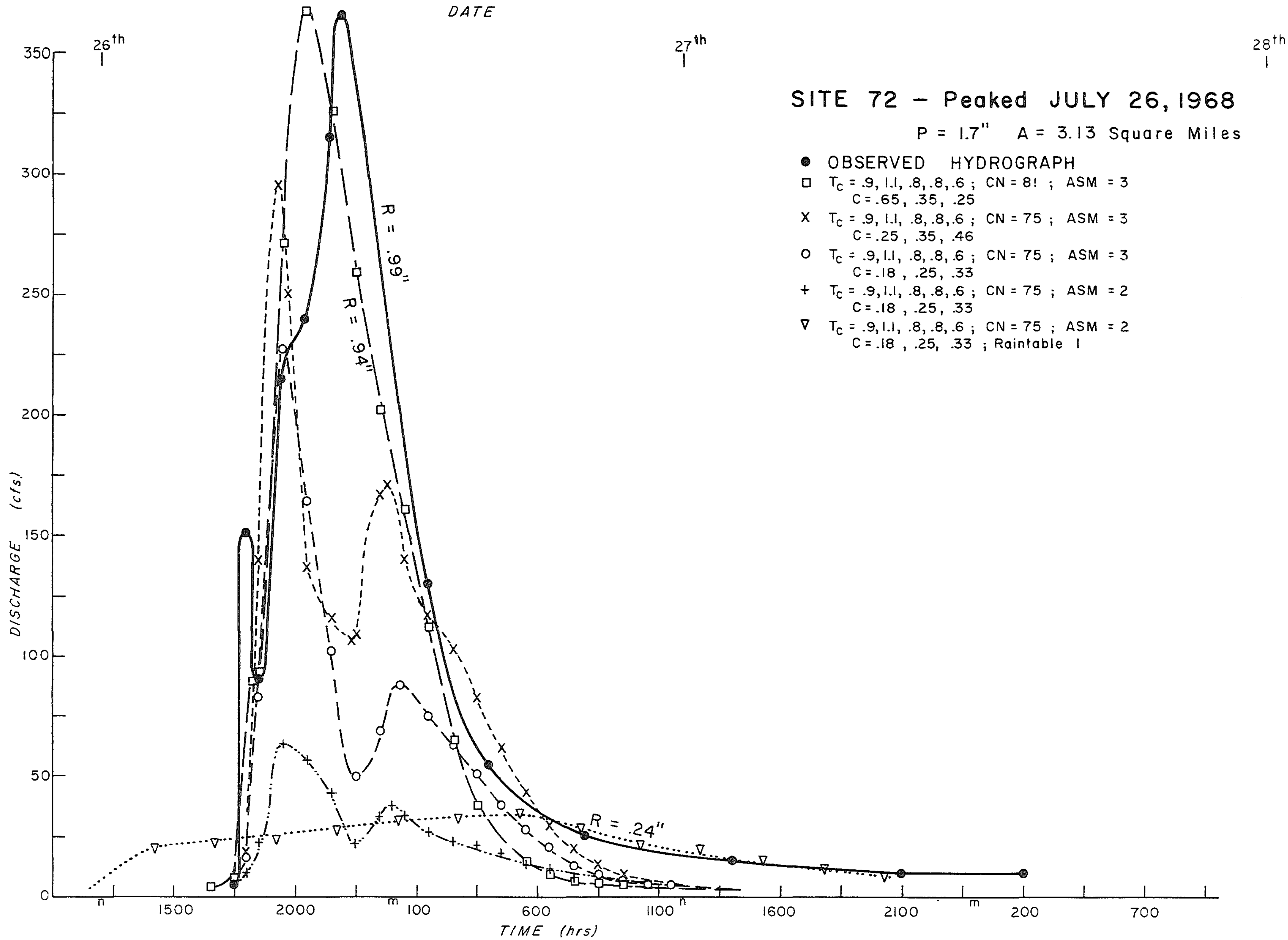


Figure 13 Observed and Computed Hydrographs for the Growing Season of Dry Creek, near Jeffers, MN

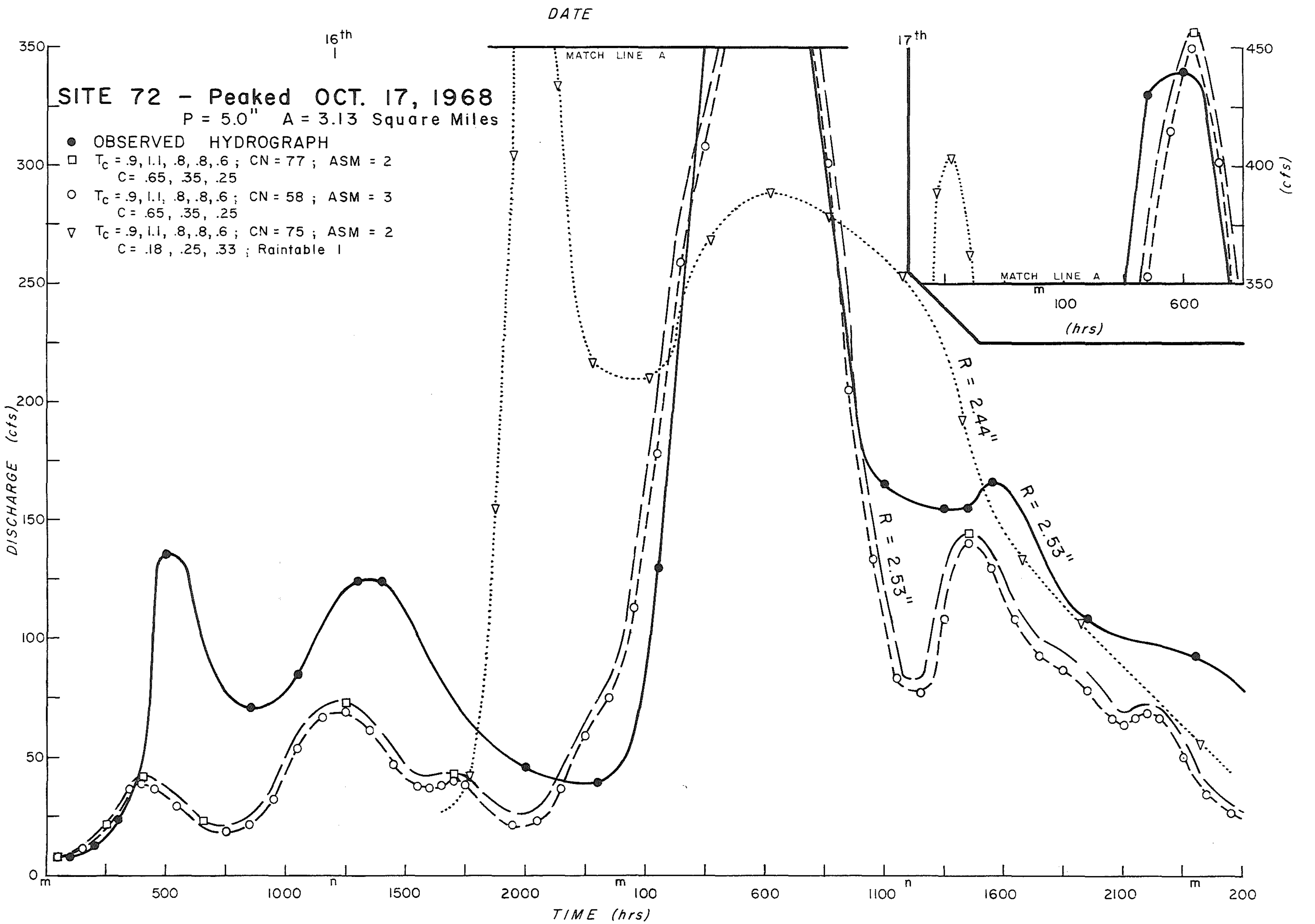


Figure 14 Observed and Computed Hydrographs for the Dormant Season of Dry Creek, near Jeffers, MN

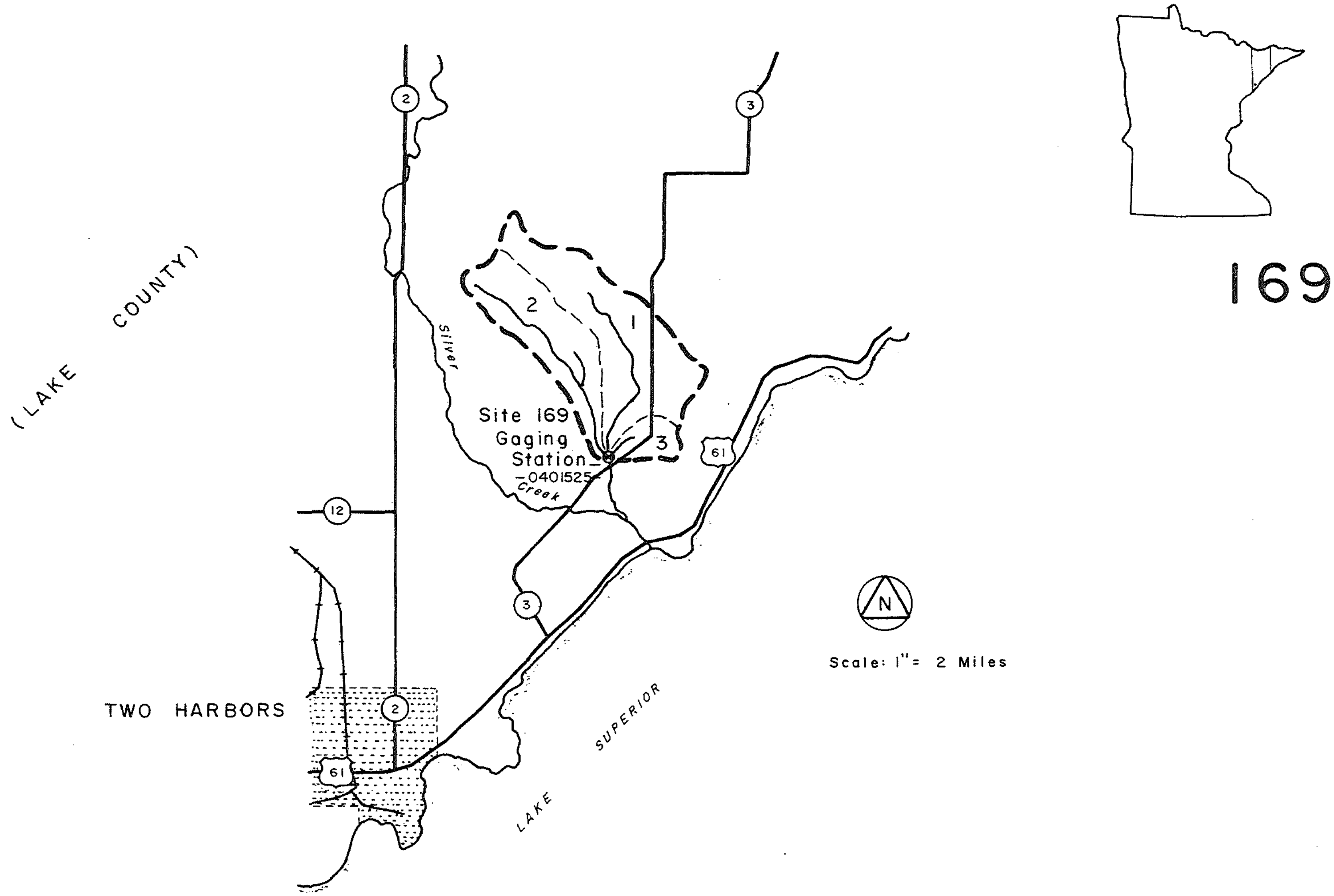


Figure 15 Map of Silver Creek tributary watershed, near Two Harbors, MN

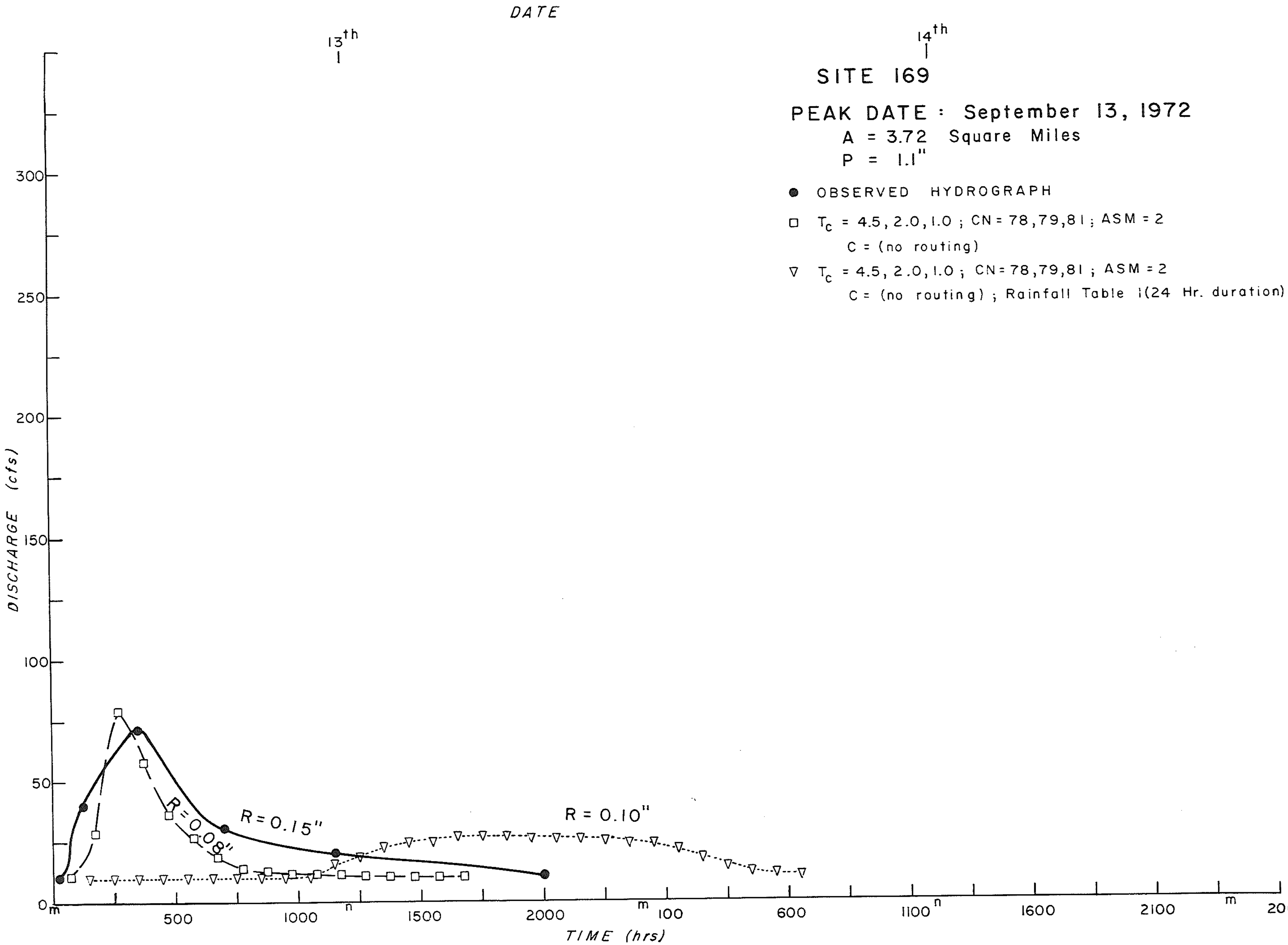


Figure 16 Observed and Computed Hydrographs for the Growing Season of Silver Creek tributary, near Two Harbors, MN

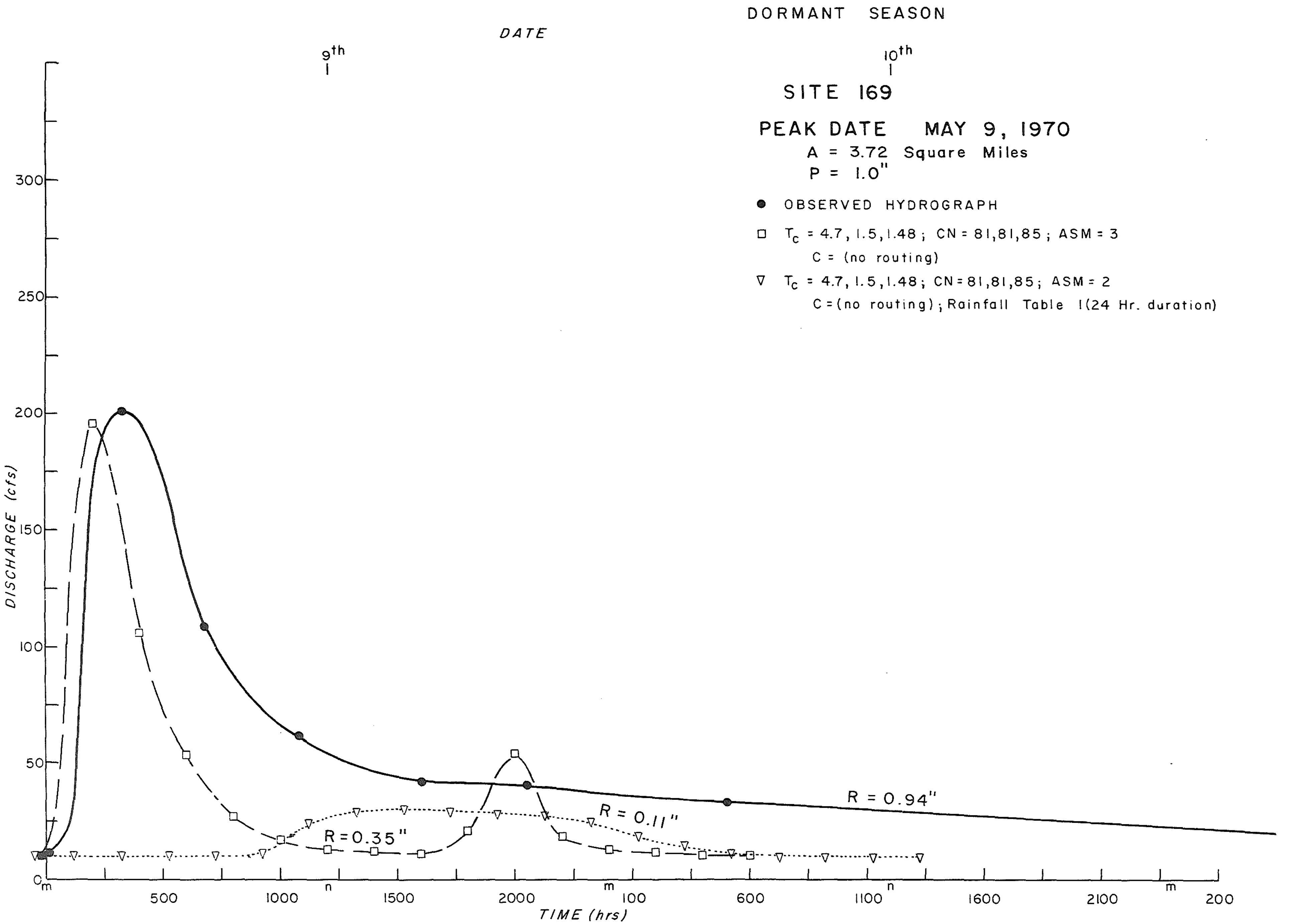


Figure 17 Observed and Computed Hydrographs for the Dormant Season of Silver Creek tributary, near Two Harbors, MN

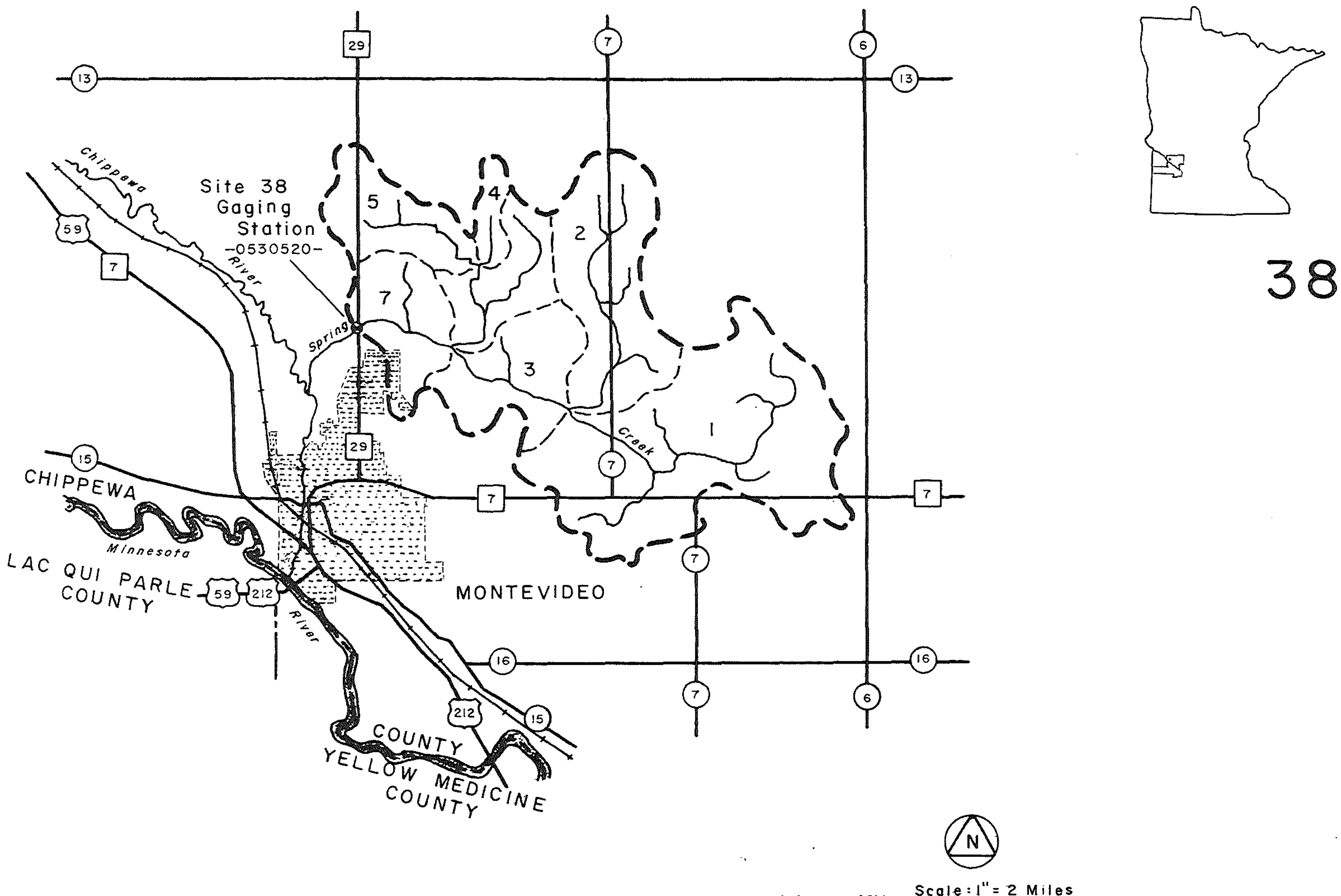


Figure 18 Map of Spring Creek Watershed, near Montevideo, MN

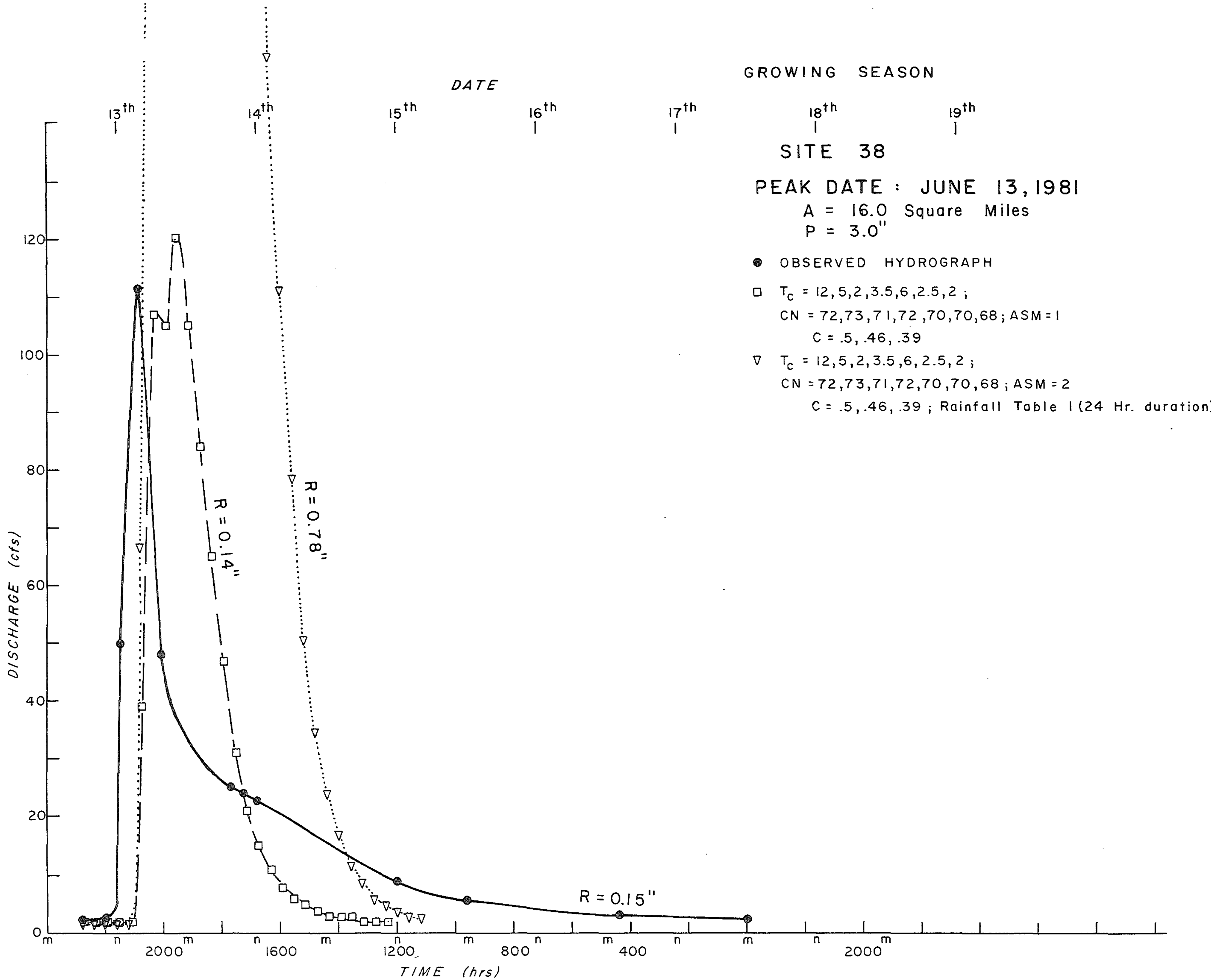


Figure 19 Observed and Computed Hydrographs for the Growing Season of Spring Creek, near Montevideo, MN

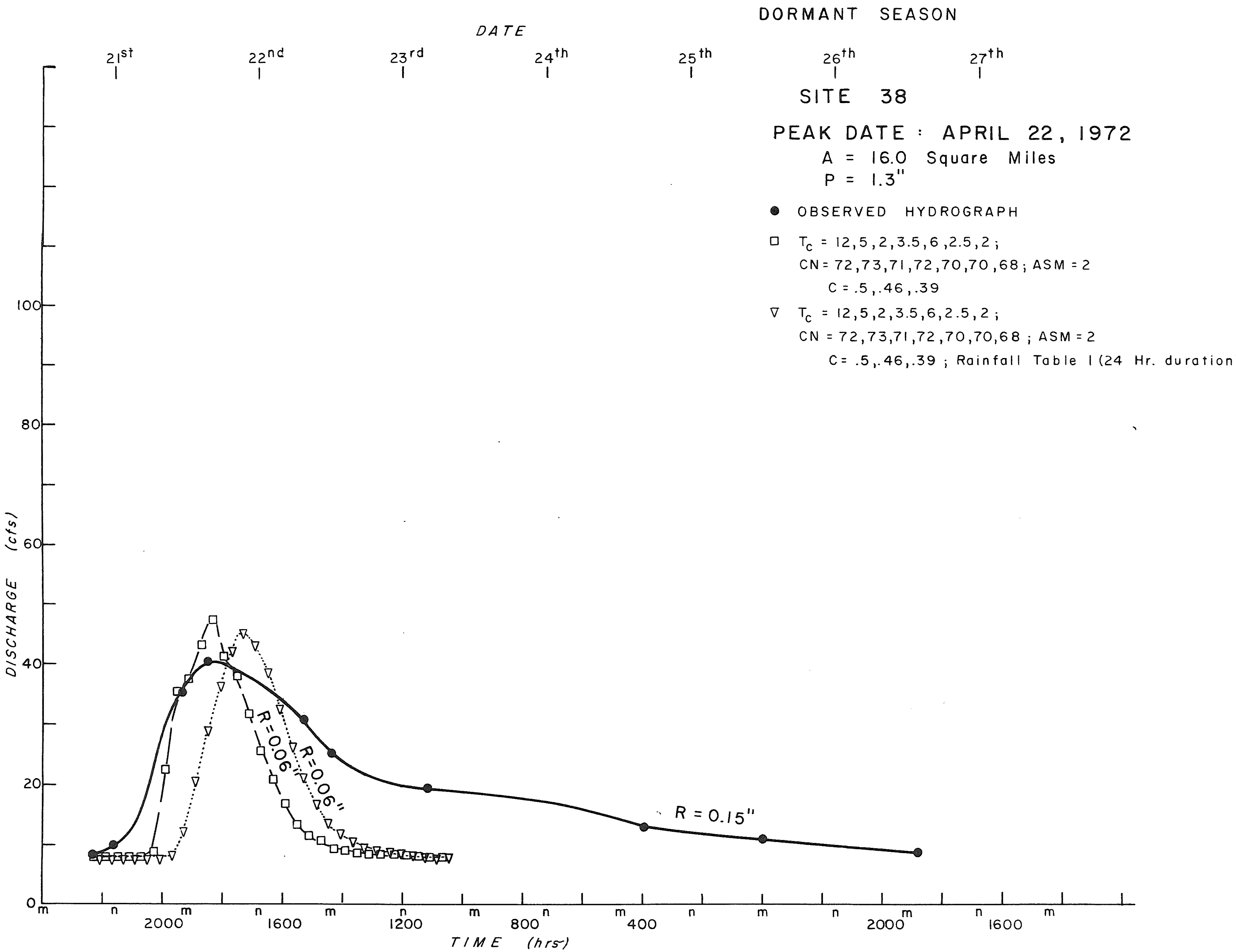


Figure 20 Observed and Computed Hydrographs for the Dormant Season of Spring Creek, near Montevideo, MN

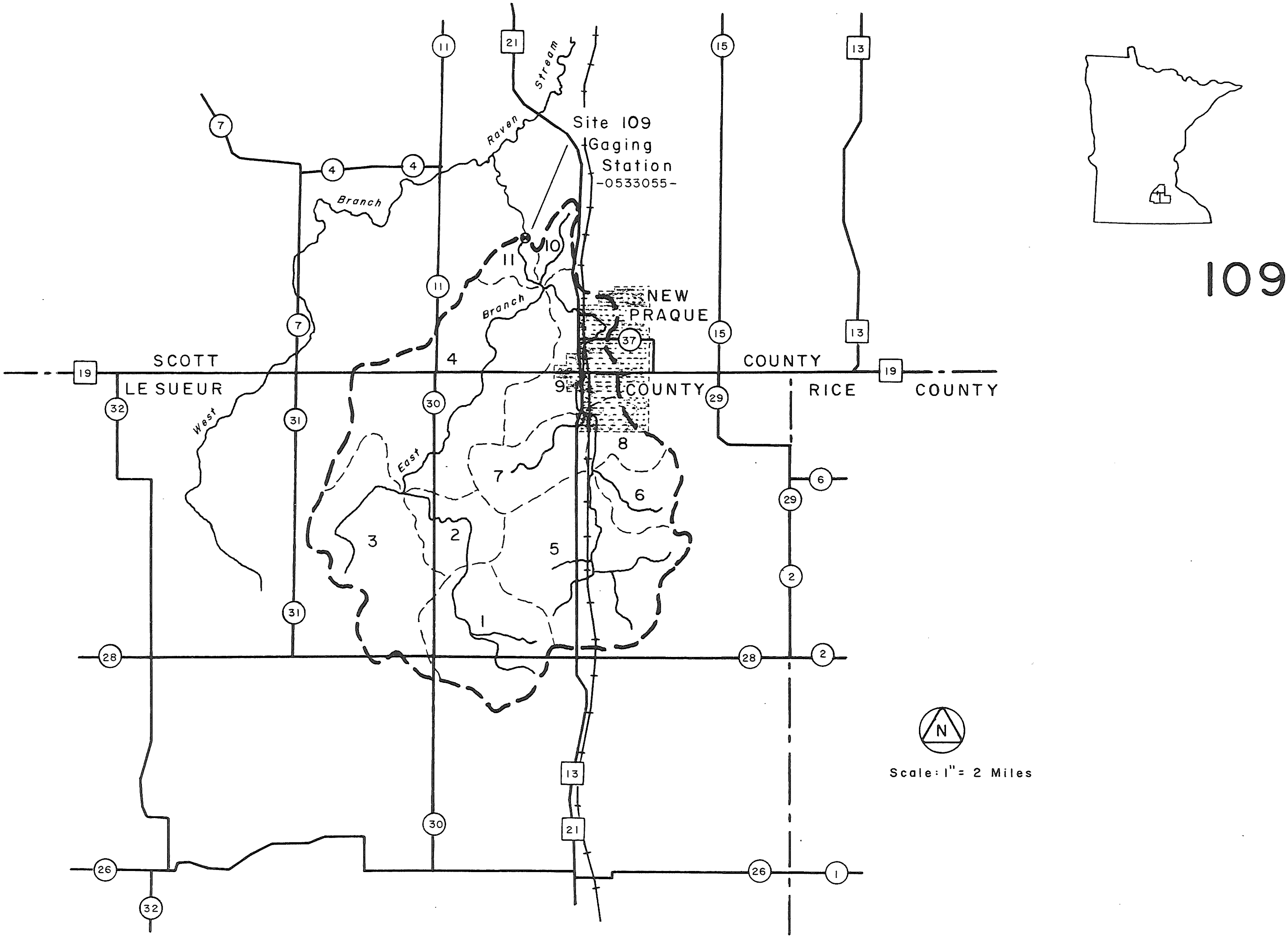


Figure 21 Map of Raven Stream tributary watershed, near New Prague, MN

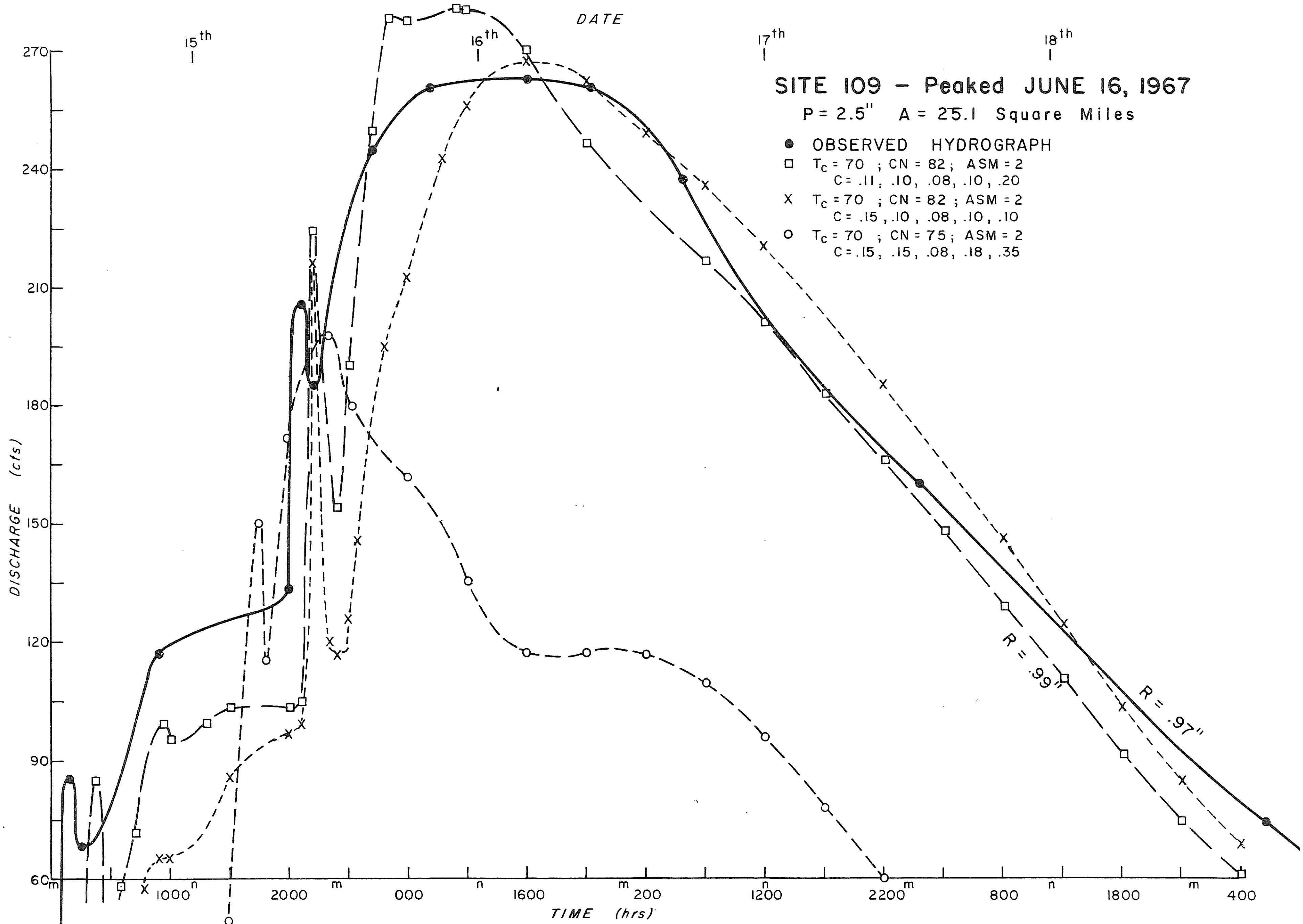


Figure 22 Observed and Computed Hydrographs for the Growing Season of Raven Stream tributary, near New Prague, MN

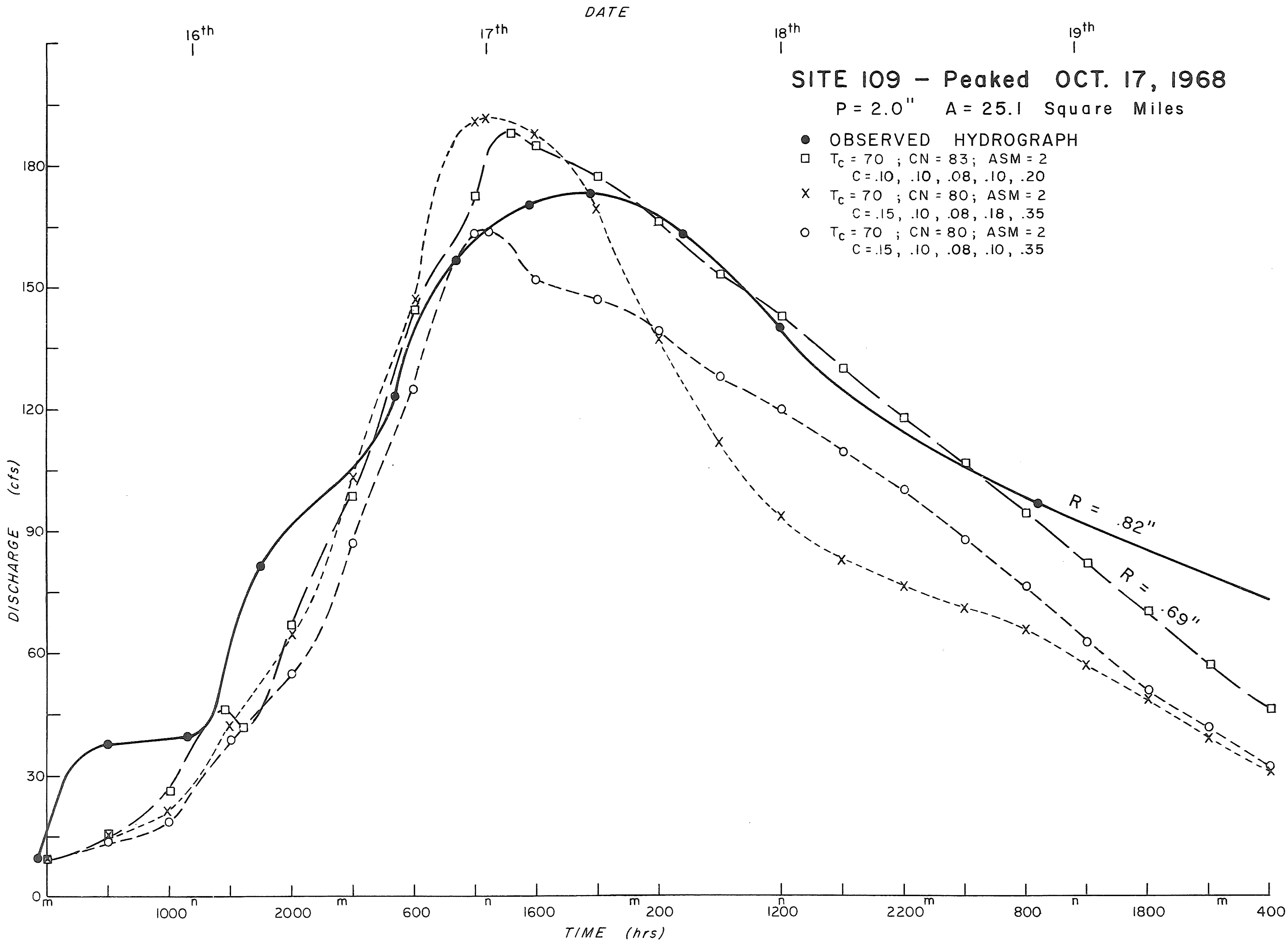


Figure 23 Observed and Computed Hydrographs for the Dormant Season of Raven Stream tributary, near New Prague, MN

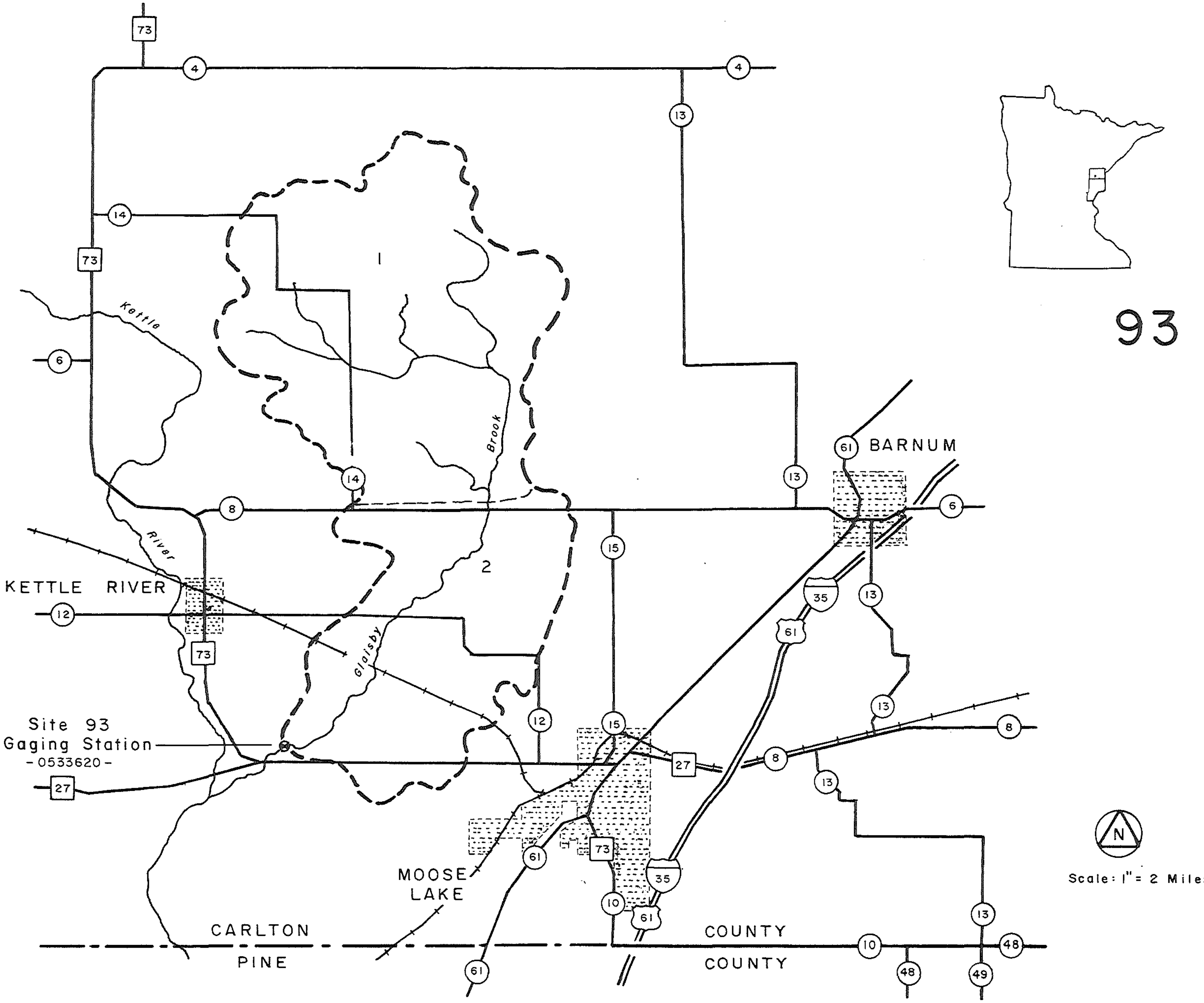


Figure 24 . Map of Glaisby Brook Watershed, near Kettle River, MN

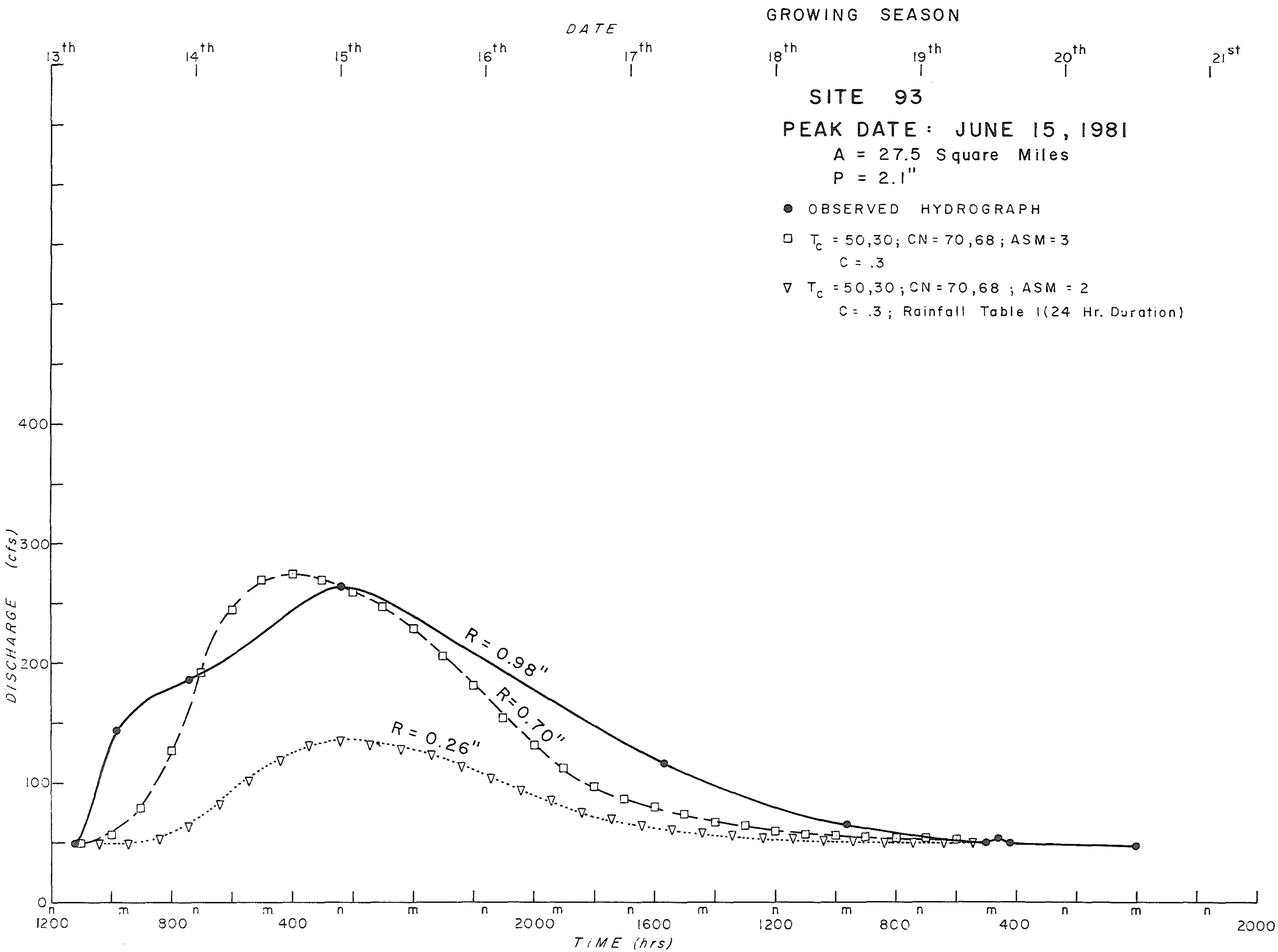


Figure 25 Observed and Computed Hydrographs for the Growing Season of Glaisby Brook, near Kettle River, MN

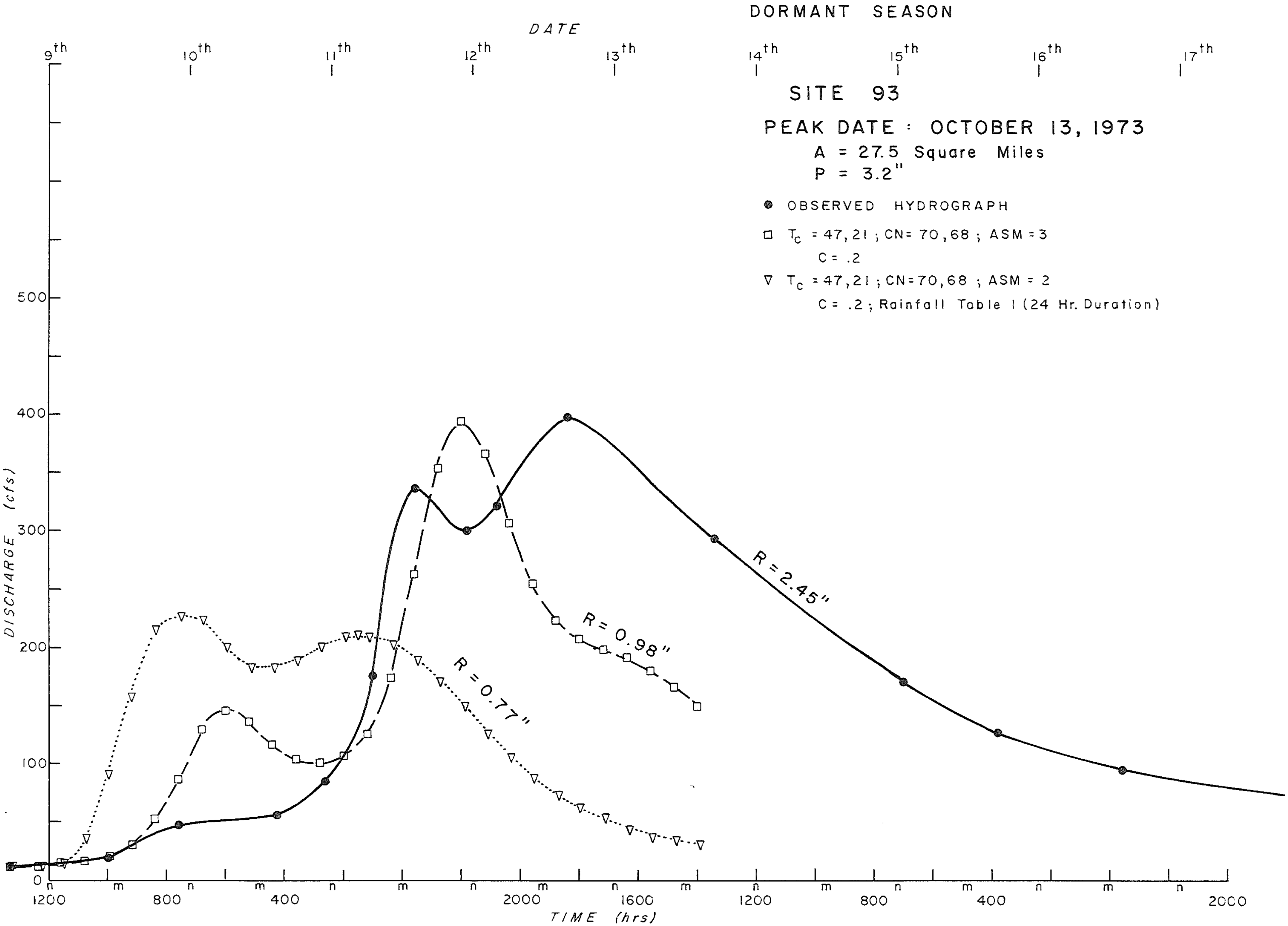


Figure 26 Observed and Computed Hydrographs for the Dormant Season of Glaisby Brook, near Kettle River, MN

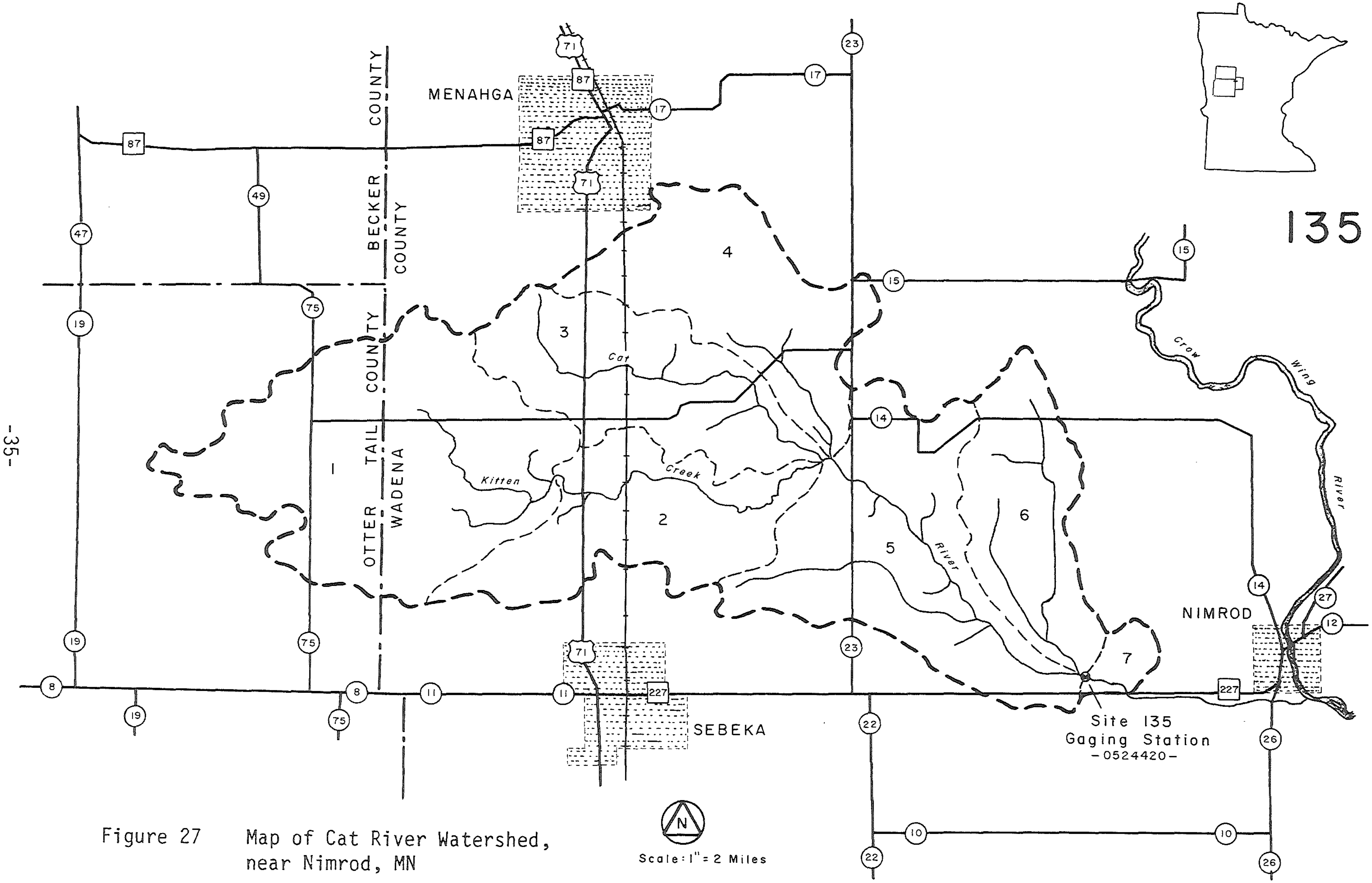


Figure 27 Map of Cat River Watershed, near Nimrod, MN

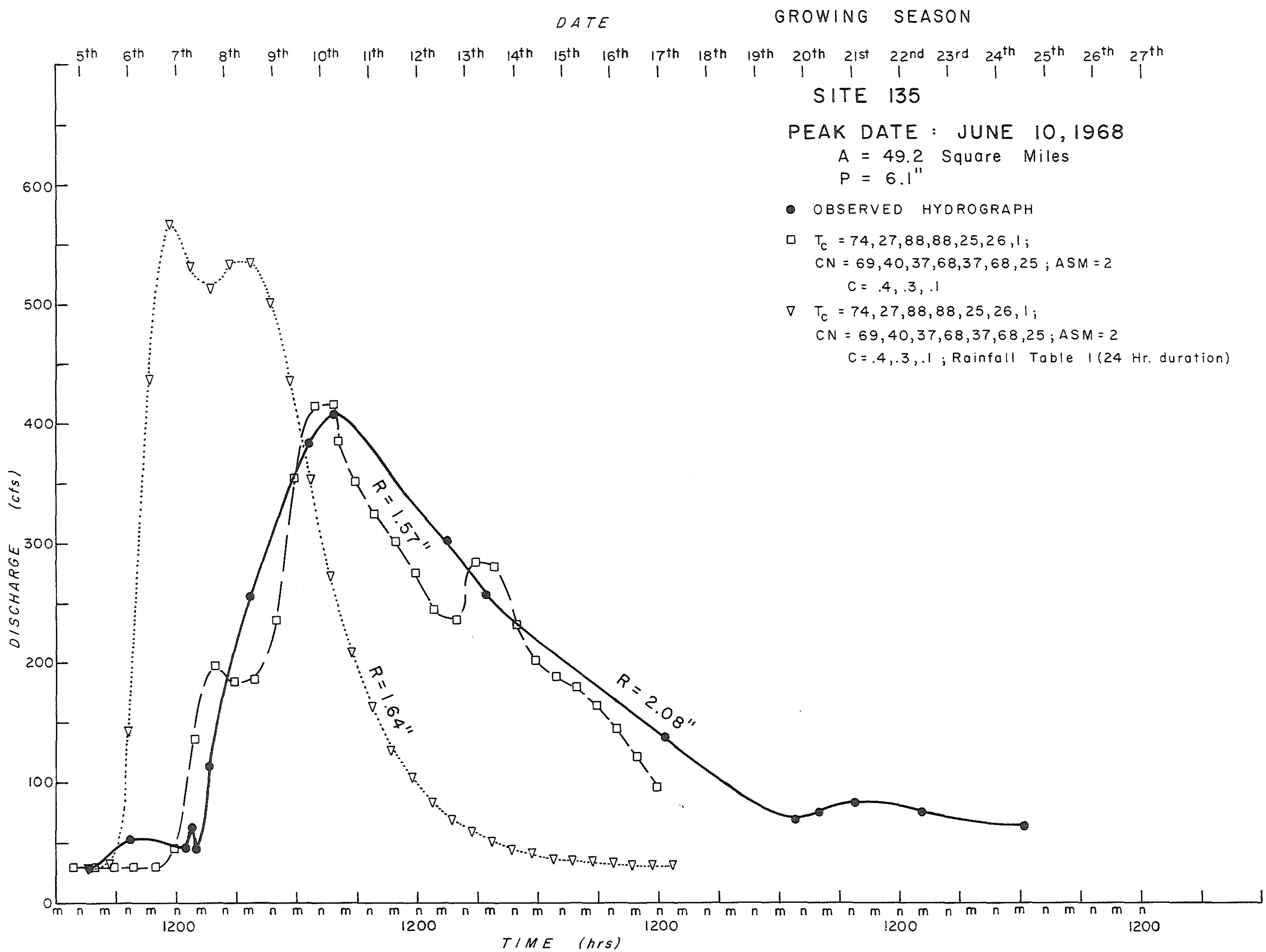


Figure 28 Observed and Computed Hydrographs for the Growing Season of Cat River, near Nimrod, MN

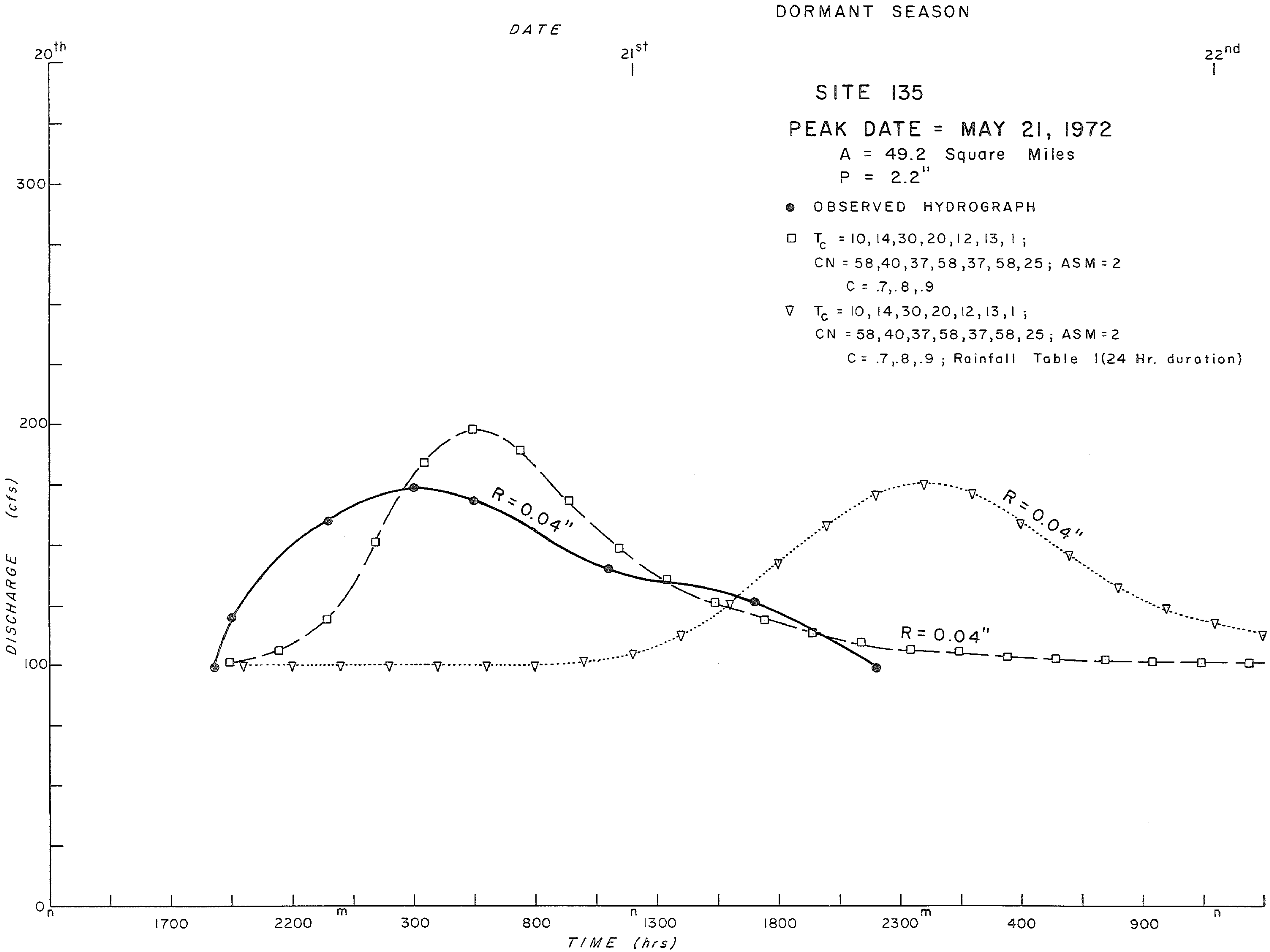


Figure 29 Observed and Computed Hydrographs for the Dormant Season of the Cat River, near Nimrod, MN

C. Regression Model

Several attempts were made to develop relationships of the time of concentration and routing coefficient with the watershed physical characteristics. Using data of the nine watersheds a relationship of the time of concentration with length of reach and the routing coefficient with the slope of the reach are derived using a regression model of the following form:

$$Tc = a_0 (L)^{a_1} \qquad [2]$$

where Tc = time of concentration in hours, L = reach length in feet, and $a_0$ and $a_1$, = regression coefficients. The data was plotted on log-log paper. A logarithm transform of equation [2] results in

$$\log Tc = \log a_0 + a_1 \log L \qquad [3]$$

Similarly for the routing coefficient the regression model is:

$$C = b_0 (S)^{b_1} \qquad [4]$$

where C = coefficient of velocity, S = slope of reach in feet/mile, and $b_0$ and $b_1$ = regression models.

The log transform of equation [4] is:

$$\log C = \log b_0 + b_1 \log S \qquad [5]$$

D. Results of Regression Model

Equations [3] and [5] were used to derive values for $a_0$, $a_1$, $b_0$, and $b_1$ for given values of Tc and L, and C and S respectively. Figure 30 shows a relationship of Tc with L for the nine watersheds without breaking them into subwatersheds. The length of reach considered in this case is the total main channel length of the whole watershed as shown on Table 1 and the time of concentration of the growing season as shown on Table 2. The results are:

$$Tc = 3 \times 10^{-10} (L)^{2.416} \qquad [6]$$

where

$10{,}000 \leq L \leq 100{,}000$, Tc is in hours and L is in feet.

A relationship of Tc with L for the subwatersheds which includes both overland flow and channel flow is shown in Figure 31. The results are:

$$Tc = 1.28 \times 10^{-14} (L)^{3.432} \qquad [7]$$

where

$10{,}000 \leq L \leq 50{,}000$, Tc is in hours and L is in feet.

and

$$Tc = 9.98 \times 10^{-6} (L)^{1.362} \qquad [8]$$

where

$1{,}000 \leq L \leq 10{,}000$ Tc is in hours and L is in feet.

Similarly, a relationship of C with S was developed as shown on Figure 32 and the results are:

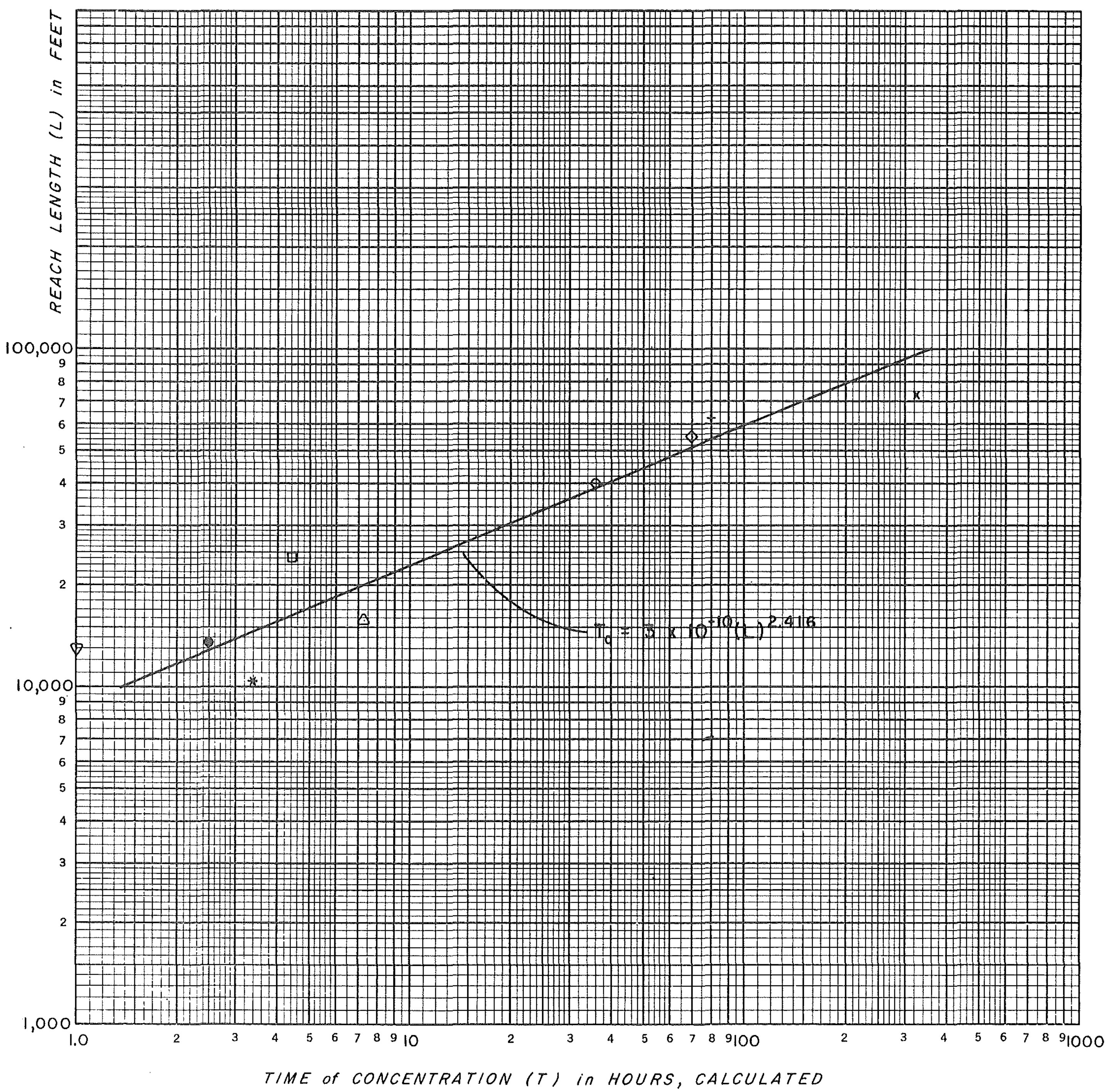


Figure 30 Relationship Between Time of Concentration (Tc) and Reach Length (L) for Channel Flow

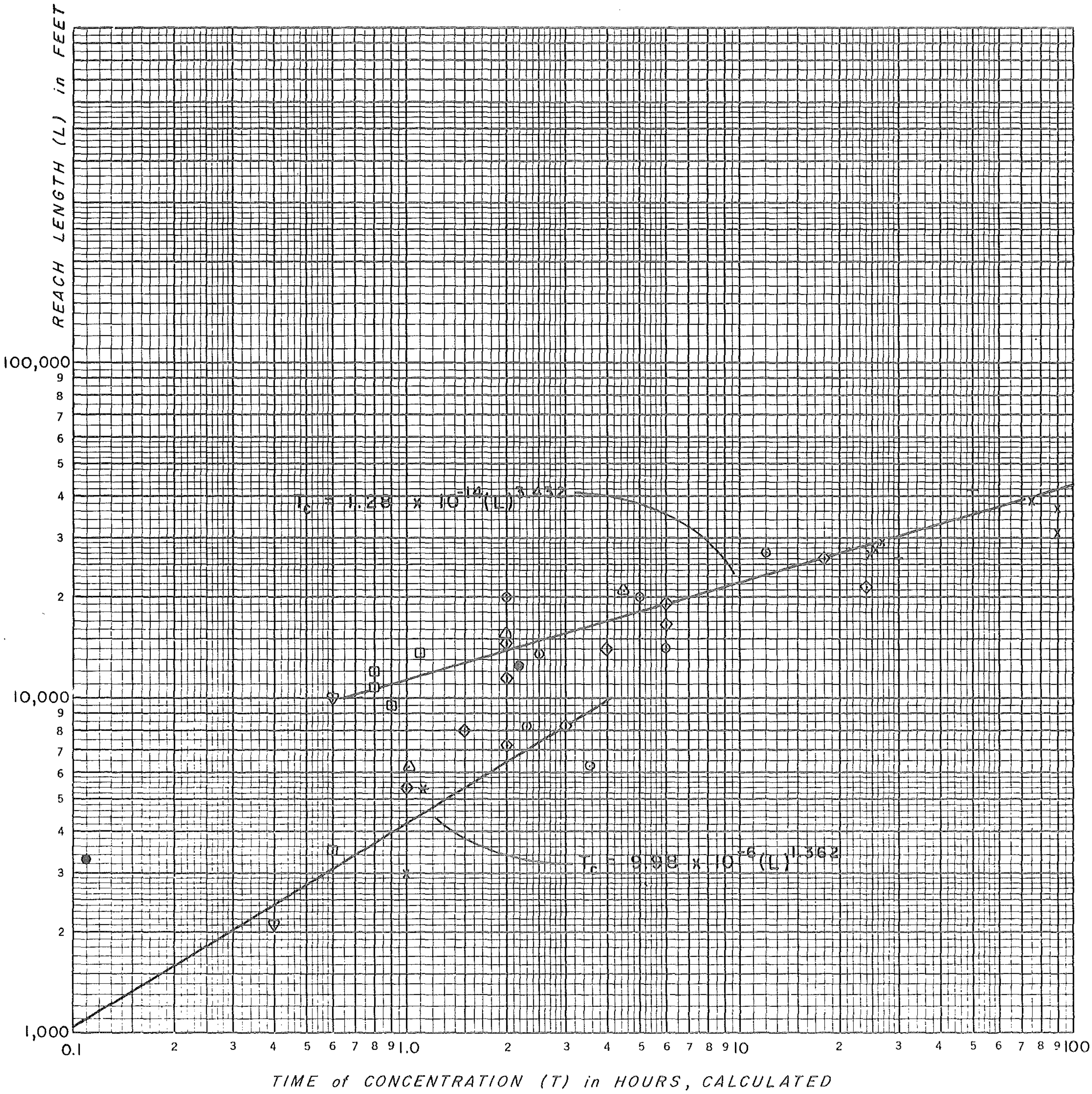


Figure 31 Relationship Between Time of Concentration (Tc) and Reach Length (L) for Overland and Channel Flow

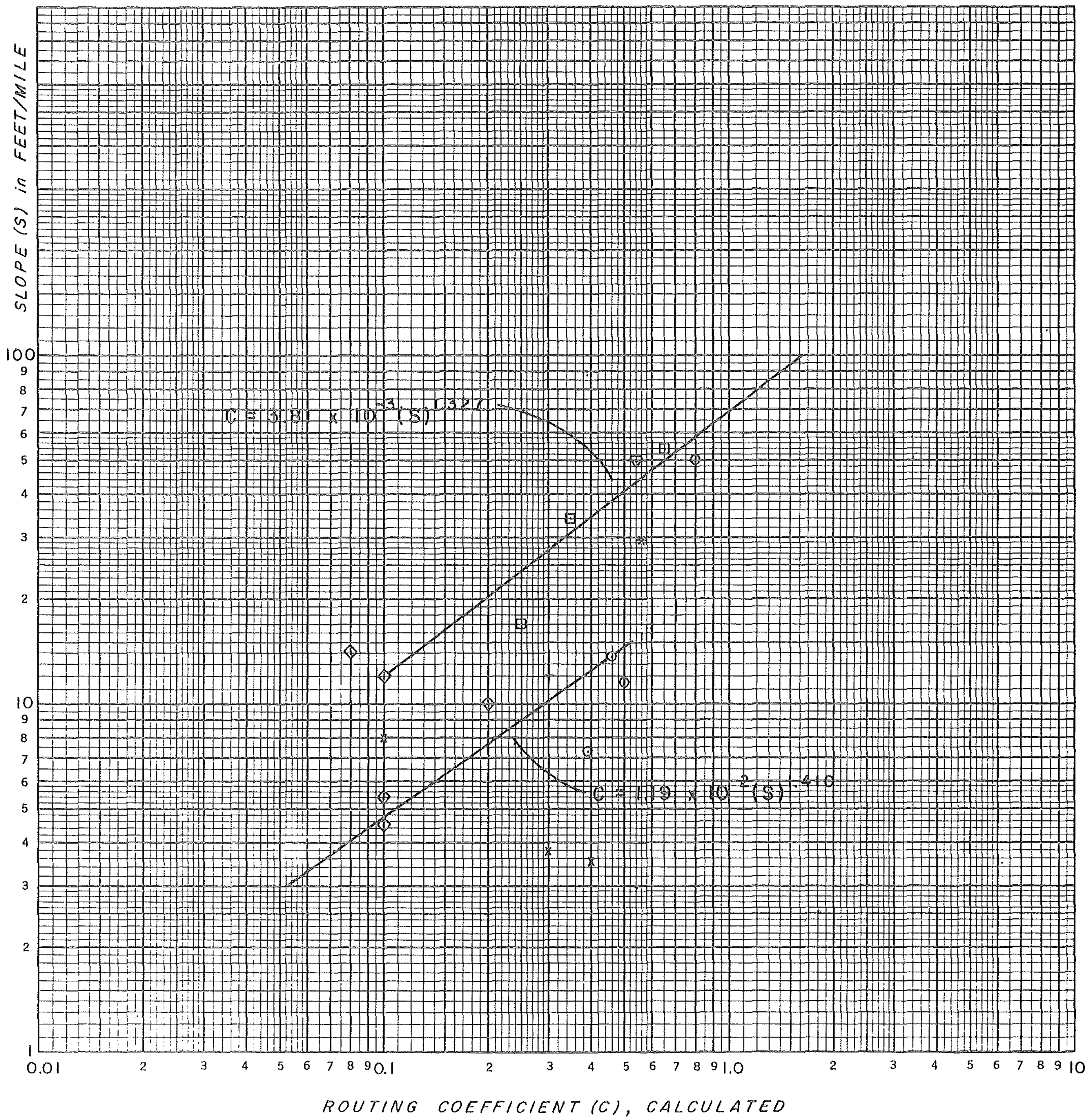


Figure 32 Relationship Between the Routing Coefficient (C) and Channel Slope (S) for Channel Flow

$$C = 3.81 \times 10^{-3} (S)^{1.327} \qquad [9]$$

where

$$12 \leq S \leq 100, \text{ S is in feet/mile,}$$

and

$$C = 1.19 \times 10^{-2} (S)^{1.410} \qquad [10]$$

where

$$3 \leq S \leq 15, \text{ S is in feet/mile.}$$

E. Multiregression Model

A multiregression model was used to analyze the interdependency of the climatic, hydrologic, and watershed characteristics. 12 variables were considered - the precipitation P in inches, the antecedent soil moisture ASM (1 for dry, 2 for normal, and 3 for wet), the peak observed discharge Qp in cubic feet per second, the observed runoff R (depth of runoff over the entire area of the watershed) in inches, the ratio of runoff to precipitation R/P in percent, the time of concentration Tc in hours, the time to peak Tp in hours, the watershed area A in square miles, the land use LU in percent of forest cover, the storage St (area of lakes and swamps over the area of watershed times 100 plus 1) in percent, the slope S of the main channel of the watershed in feet/mile, and the base of the hydrograph $T_b$ in hours.

The general form of the regression equation may be expressed:

$$U = a_o A^{a1} B^{a2} C^{a3} \ldots N^{an} \qquad [11]$$

where U = dependent variable in this case representing any one of the above 12 variables, and A, B, C...N = independent variables in this case representing the other 11 variables, n = number of independent variables, and $a_0, a_1, a_2, a_3 \ldots a_n$ = regression coefficients.

Equation [11] is linearized by a log transform expressed in the following form:

$$\log U = \log a_0 + a_1 \log A + a_2 \text{Log } B + a_3 \text{Log } C + \ldots + a_n \text{Log } N \quad [12]$$

The general form of equation [12] was used to derive the desired relationships between the variables. No more than four variables at a time were used in one equation so that the derived relationships can be practical.

The rainfall events were divided into two seasons - the growing season, June to September and the dormant season March through May and September through November. 25 rainfall events (at least two events for each of the 10 watersheds listed in Table 1) were considered for multiregression of the 12 variables for the growing season. Similarly, 20 rainfall events were considered for multiregression for the dormant season. The rainfall for the growing season varied from 0.7" to 6.1" and for the dormant season from 1.0" to 5.8".

The multiregression model (3) through its screen routine allowed to determine which of the 11 independent variables are significant on each of the 12 variables considered as dependent variables one at a time.

This routine screen enabled the determination of the dominant independent variables for a given dependent variable. For example given Qp, which one of the 11 independent variables describes best Qp; which two of the 11 independent variables describe best Qp; which three of the 11 independent variables describe Qp, and so on. Once the dominant independent variables for each dependent variable are determined, then the multiregression was run for each dependent variable with the one, two, three and four independent variables separately. Since R and %R/P, are not independent of each other, R and %R/P were not used together as independent variables, although P and R/P were used together as independent variables. For example, for the growing season, the one dominant variable that describes best Qp out of the 10 independent variables (excluding the 1st independent variable %R/P) is R, the two dominant independent variables that describe Qp are R and Tc, and the three dominant independent variables that describe Qp are R, A, and $T_b$, and the four dominant independent variables that describe Qp are R, A, S, and $T_b$ as shown in Table 4.

The average percent of standard error of estimate (%SEE) was estimated by the following procedure.

$$SEE = \sqrt{\frac{\Sigma(Qpo - Qpp)^2}{N-1-p}} \qquad [13]$$

where Qpo = observed peak discharge, Qpp = computed peak discharge, N=number of events, p=number of independent variables of the regression equation. Then the average percent of standard error of estimate was found by

$$\text{Average \% SEE} = \frac{(10^{SEE}-1) + (1-10^{-SEE})}{2} \qquad [14]$$

where $10^{SEE}-1$ = the upper limit of standard error of estimation, and $1-10^{-SEE}$ = the lower limit of standard error of estimate (4).

The average percent of standard error of estimation for each equation is shown in Tables 4 and 5.

The coefficient of determination $r^2$ is defined by:

$$r^2 = \frac{\Sigma (Qpp - \overline{Qpo})^2}{\Sigma (Qpo - \overline{Qpo})^2} \qquad [15]$$

where Qpo = observed peak discharge, Qpp = predicted peak discharge, and $\overline{Qpo}$ = (Qpo)/N observed peak discharge, and N = number of events. $r^2$ is shown for each regression equation in Tables 4 and 5.

F. Results of Multiregression Model

The results of the regression model are shown on Tables 4 and 5 for the rainfall events that occurred in the growing season and dormant season respectively.

$r^2$ reflects the overall accuracy of the prediction equation (5). The $r^2$ value of 0.77 for Equation [16] in Table 4 for instance, indicates the proportion of variation of Qp by R (runoff) and 0.23 (1-r = 1-0.77=0.23) is the proportion not explained by R. The value $r^2$ gets better as the number of independent variables in the equation increases. For example, $r^2$ = 0.89 in Equation [23] in Table 4. These values of $r^2$ indicate that 77% of the variation in Qp can be explained by the runoff R, and 89% of the variation in Qp can be explained by P, %R/P, A, and $T_b$.

Table 4 RELATIONSHIP OF CLIMATIC-HYDROLOGIC AND WATERSHED CHARACTERISTICS FOR THE GROWING SEASON (APRIL THROUGH SEPTEMBER)

| REGRESSION EQUATIONS | EQUATION NO. | $r^2$ | AVERAGE %SEE |
|---|---|---|---|
| $Qp = 2.49x10^{2} R^{0.6096}$ | [16] | .77 | 148 |
| $Qp = 4.14x10^{2} R^{0.6505} T_b^{-0.1151}$ | [17] | .80 | 34 |
| $Qp = 1.09x10^{3} R^{0.7335} (A)^{0.3650} T_b^{-0.4979}$ | [18] | .88 | 26 |
| $Qp = 2.642x10^{3} R^{0.8158} A^{0.3257} S^{-0.1387} T_b^{-0.5767}$ | [19] | .89 | 26 |
| $Qp = 20 (R/P)^{0.7051}$ | [20] | .69 | 42 |
| $Qp = 22(R/P)^{0.5756} T_c^{0.1796}$ | [21] | .80 | 230 |
| $Qp = 18 P^{0.2490} (R/P)^{0.6073} T_s^{0.1195}$ | [22] | .82 | 33 |
| $Qp = 33P^{0.6303} (R/P)^{0.7678} A^{0.3739} T_b^{-0.4774}$ | [23] | .89 | 26 |
| $R = 8x10^{-4} Qp^{1.2588}$ | [24] | .76 | 790 |
| $R = 1.0x10^{-3} P^{0.5571} Qp^{1.1091}$ | [25] | .83 | 46 |
| $R = 1.0x10^{-3} Qp^{0.8836} S^{0.5051} T_b^{0.5570}$ | [25] | .91 | 34 |
| $R = 9x10^{-3} Qp^{0.9816} A^{-0.3148} S^{0.3346} T_b^{0.7485}$ | [27] | .94 | 29 |
| $Tc = 3.2x10^{-1} Tp^{0.8300}$ | [28] | .74 | 83 |
| $Tc = 4x10^{-2} Qp^{0.6670} Tp^{0.6871}$ | [29] | .83 | 66 |
| $Tc = 4.9x10^{-2} P^{-0.6679} Qp^{0.6830} Tp^{0.8626}$ | [30] | .85 | 64 |
| $Tc = 1.32(R/P)^{0.5906} Tp^{0.8057} A^{0.7032} T_b^{-0.8197}$ | [31] | .88 | 57 |

Table 4 continued

| REGRESSION EQUATIONS | EQUATION NO. | $r^2$ | AVERAGE %SEE |
|---|---|---|---|
| $Tp = 1.83Tc^{0.8928}$ | [32] | .74 | 86 |
| $Tp = 2.1x10^{-1}Tc^{0.5842}T_b^{0.6349}$ | [33] | .91 | 48 |
| $Tp = 0.23P^{0.6044}Tc^{0.5234}T_b^{0.5006}$ | [34] | .93 | 49 |
| $T_b = 1.12x10^2(St)^{0.2985}$ | [35] | .82 | 56 |
| $T_b = 58xP^{0.6243}(St)^{0.2502}$ | [36] | .87 | 48 |
| $T_b = 4.26x10^3Q^{-0.9874}R^{0.8470}A^{0.7583}$ | [37] | .92 | 38 |
| $T_b = 3.2x10^4Qp^{-0.6836}R^{0.8322}(LU)^{0.2444}S^{-0.842}$ | [38] | .94 | 32 |
| $ASM = 1.30(LU)^{0.1157}$ | [39] | .16 | 47 |
| $ASM = 1.93(R/P)^{-0.1553}(LU)^{0.1157}$ | [40] | .22 | 46 |
| $ASM = 2.9x10^{-1}R^{-0.3534}Tp^{0.3531}S^{0.2463}$ | [41] | .29 | 45 |
| $P = 1.46Tp^{0.2627}$ | [42] | .60 | 34 |
| $P = 1.44Tc^{-0.1177}Tp^{0.3655}$ | [43] | .63 | 34 |
| $P = 1.79R^{0.1446}Tc^{-0.1766}Tp^{0.3572}$ | [44] | .68 | 32 |
| $\%(R/P) = 0.13Qp^{0.9869}$ | [45] | .69 | 50 |
| $\%(R/P) = 0.12Q^{0.8694}S^{0.2035}$ | [46] | .76 | 45 |
| $\%(R/P) = 0.07\ Qp^{0.9752}A^{-0.4545}T_b^{0.3671}$ | [47] | .81 | 40 |

Table 5 RELATIONSHIP OF CLIMATIC HYDROLOGIC AND WATERSHED CHARACTERISTICS FOR DORMANT SEASON (APRIL THROUGH MAY AND SEPTEMBER THROUGH NOVEMBER)

| REGRESSION EQUATIONS | EQUATION NO. | $r^2$ | AVERAGE %SEE |
|---|---|---|---|
| $Qp = 81P^{1.042}$ | [48] | .51 | 81 |
| $Qp = 26P^{0.9871}(LU)^{.2746}$ | [49] | .71 | 62 |
| $Qp = 13P^{0.9597}(R/P)^{0.2478}(LU)^{0.2653}$ | [50] | .79 | 54 |
| $Qp = 3.54P^{0.8990}(R/P)^{0.4168}(A)^{0.9270}(st)^{-0.2105}$ | [51] | .84 | 48 |
| $Qp = 32P^{0.7424}R^{0.1989}(LU)^{0.3013}(St)^{-0.2451}$ | [52] | .79 | 56 |
| $R = 4Sx10^{-3}Qp^{0.8804}$ | [53] | .42 | 132 |
| $R = 1.03x10^{-4}S^{1.1777}T_b^{1.0954}$ | [54] | .72 | 86 |
| $R = 9x10^{-4}Q^{0.8304}A^{-0.7438}T_b^{0.8075}$ | [55] | .84 | 65 |
| $R = 5x10^{-5}Qp^{0.5872}(LU)^{-0.3388}S^{0.9620}T_b^{1.0847}$ | [56] | .88 | 56 |
| $Tc = 1.67A^{0.7004}$ | [57] | .67 | 80 |
| $Tc = 7.32x10^{-1}Tp^{0.4201}A^{0.4447}$ | [58] | .75 | 70 |
| $Tc = 2.46R^{0.3643}A^{0.9984}(LU)^{-0.2446}$ | [59] | .81 | 62 |
| $Tc = 2.53x10^{-1}Qp^{0.3860}Tp^{0.3715}A^{0.6026}(LU)^{-0.2445}$ | [60] | .84 | 58 |
| $Tp = 2.56Tc^{0.7821}$ | [61] | .62 | 86 |
| $Tp = 5.63x10^{-10}Tc^{0.5882}T_b^{0.4380}$ | [62] | .70 | 78 |
| $Tp = 2.93x10^{-10}(ASM)^{0.7217}Tc^{0.6532}T_b^{0.4177}$ | [63] | .75 | 71 |
| $Tp = 5.2x10^{-1}(ASM)^{0.9381}(R/P)^{0.3744}Tc^{0.5533}(St)^{0.1196}$ | [64] | .81 | 64 |

Table 5 continued

| REGRESSION EQUATIONS | EQUATION NO. | $r^2$ | AVERAGE %SEE |
|---|---|---|---|
| $T_b = 57P^{0.1589}$ | [65] | .01 | 114 |
| $T_b = 1.33x10^3R^{0.5491}S^{-0.8201}$ | [66] | .70 | 58 |
| $T_b = 5.03x10^2R^{0.5096}(LU)^{0.1846}S^{-0.7650}$ | [67] | .81 | 47 |
| $T_b = 1.87x10^3Qp^{-0.3044}R^{0.6523}(LU)^{0.2655}S^{-0.7697}$ | [68] | .85 | 43 |
| $ASM = 4.45\ Qp^{0.1243}$ | [69] | .11 | 40 |
| $ASM = 2.24\ Tc^{-0.2402}Tp^{0.2080}$ | [70] | .21 | 39 |
| $ASM = 1.25\ R^{-0.1606}Tp^{0.2204}(St)^{-0.6990}$ | [71] | .29 | 38 |
| $P = 0.133Qp^{0.5074}$ | [72] | .51 | 55 |
| $P = 0.144Qp^{0.6390}(LU)^{-0.1686}$ | [73] | .63 | 49 |
| $P = 0.141\ Qp^{0.6792}(LU)^{-0.2118}(St)^{0.2317}$ | [74] | .65 | 50 |
| $P = 0.128Qp^{0.7957}(tc)^{-0.1971}(LU)^{-0.2524}(St)^{0.6730}$ | [75] | .68 | 48 |
| $\%R/P = 4.05S^{0.5418}$ | [76] | .29 | 114 |
| $\%R/P = 4.5x10^{-2}S^{0.9041}T_b^{0.8326}$ | [77] | .66 | 75 |
| $\%R/P = 2.7x10^{-2}P^{-0.3785}S^{1.001}T_b^{0.9256}$ | [78] | .71 | 71 |
| $\%R/P = 2.26x10^{-2}P^{-0.4100}(LU)^{-0.1755}S^{1.0592}T_b^{1.1077}$ | [79] | .76 | 65 |

The standard error of estimate reflects the prediction accuracy of the equation in absolute units. For example the value of Qp predicted by Equation [16] in Table 4 will be within 148% more or less of the true value of Qp. The accuracy of the predicting equations improves as indicated by the %SEE values as the number independent variables increases. For example, the %SEE for Equation [18] is 26%.

Equations [16] to [79] explain the relationship between the variables. First of all one can see the dominant independent variables for each given dependent variable. A positive power of an independent variable indicates that if the variable increases in magnitude then the predicted value of the dependent variable will increase. If R in Equation [16] in Table 4 increases, for instance, the value of Qp will increase. On the other hand if $T_b$ in Equation [18] in Table 4 increases the value of Qp will decrease since the power of $T_b$ is negative. For these two cases, Equations [16] and [18], the behavior is known before, without deriving these equations. What was unknown, however, was how exactly these equations are formulated, how many dominant independent variables to include, and what the values of the regression coefficients were.

Predictive equations for Qp, R, Tc, Tp, $T_b$, ASM, P, and %R/P were developed and can be used depending on the magnitude of %SEE. An equation with %SEE of 50 or less may be used to estimate the desired value of the dependent variable.

A comparison of Tables 4 and 5 for each dependent variable shows that there is a difference between the independent variables for the same dependent variable for the growing and dormant seasons. For example, the independent variable in Equation [16] is R, and in Equation [48] it is P for the dependent variable $Q_p$. In other words the runoff R is more dominant variable during growing season than P and explains more the variation of Qp. In the dormant season, however, the reverse is true. The land use percent LU and percent storage St are dominant independent variables in the dormant season equations and $T_b$ and S and are dominant independent variables in the growing season equations.

## V. CONCLUSIONS

The nine watersheds modeled using TR-20 hydrologic models are small in area ranging from 0.73 to 4.92 square miles. The TR-20 model was primarily developed for smaller watersheds to help in the planning and implementing watershed management programs. Equations, [6] to [10], are applicable in Minnesota to determine the time of concentration and routing coefficient C, which are needed as input data in TR-20 program in performing hydrologic modeling.

Equation [6] can be used to determine the time of concentration Tc where the flow is entirely channel flow. This determination can be done by simply figuring out the channel reach length in feet of the watershed or subwatershed and using Equation [6]. Furthermore, Equation [6] is used for channel reach lengths of more than 10,000 feet and less than 100,000 feet. Reach lengths of watersheds will usually be less than 100,000 feet in performing TR-20 modeling because larger watersheds are broken into smaller watersheds to do an adequate job in hydrologic modeling.

For subwatersheds that include overland and channel flow Equations [7] and [8] can be used to determine the time of concentration Tc. Equation [7] is used when the subwatershed length (overland and channel) is more than 10,000 feet and less than 50,000 feet, whereas Equation [8] is used when the watershed length (overland and channel) is more than a 1000 feet and less than 10,000 feet.

Similarly, Equations [9] and [10] can be used to determine the routing coefficient by figuring the slope of the overland and channel slope in feet per mile. Equation [9] is used when the slope S is more than 12 feet per mile and less than 100 feet per mile, whereas equation [10] is used when the slope S is more than 3 feet per mile and less than 12 feet per mile.

Equation [6] to [8] were developed from watersheds that had no swamps and watersheds that have swamps up to two-thirds of their channel reach length. Therefore, Equations [6] and [8] are applicable in watersheds where the reach lengths go through marshes. In developing Equations [9] and [10], however, the data from marshy reaches did not fit well (see Figure 32) and therefore were not used in developing these Equations [9] and [10] and as such it may not be advisable to use them in a reach where significant length of the channel passes through a marsh.

Finally, when modeling a watershed one can always compare the watershed characteristics such as size, shape, reach length, and slope with the one of the nine watersheds in Table 1, and then estimate the time of concentration and routing coefficient from the corresponding watershed in Tables 2 and 3 and/or the results shown in the Figures where the observed and computed hydrographs are displayed.

The relationships expressed by equation [16] through [79] are very significant results. A look at the independent variables of a dependent variable and by considering the corresponding value of $r^2$ and %SEE tells which factors are important in doing hydrologic modeling. Any of the predictive equations for Qp, R, Tc, Tp, %R/P and $T_b$ may be used if %SEE is less than about 50%.

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