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ST. ANTHONY FALLS HYDRAULIC LABORATORY

External Memorandum No. 155

HYDROLOGIC INVESTIGATIONS OF SELECTED WATERSHEDS IN THE COPPER-NICKEL REGION OF NORTHEASTERN MINNESOTA

by

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Addendum No. 1

PREDICTING INITIAL MOISTURE CONDITION FOR RUNOFF MODEL

by

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Prepared for

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ABSTRACT

The mathematical simulation models (1) SSARR, developed by the Corps of Engineers and the National Weather Service, and (2) the TR-20, developed by the Soil Conservation Service were applied to three watersheds in the Copper-Nickel region of noreastern Minnesota. The study was sponsored by the Minnesota Environmental Quality Council, Minnesota State Planning Agency.

The results indicate that the SSARR model provides a good basis for continuous synthesis of runoff, both high and low flow, for selected watersheds in the region. A proposed second phase of this study should include application of the model to portions of the Kawishiwi and Upper St. Louis Basins and additional fitting with large floods.

The TR-20 model was successfully fitted to the same 3 watersheds for selected storms. Due to the nature of the soils, vegetation and topography of this region, the response of the watersheds to rain and snowmelt moisture inputs is much slower than for agricultural watersheds. The use of considerable detail in the fitting process to simulate individual subwatersheds, swamps, and beaver dams produced no significant improvement over a coarser structure. The model has no procedure for drying the soil between storms or for the analysis of snowmelt. Its primary use in these investigations may be for the analysis of runoff from selected areas where the infiltration and runoff characteristics are modified by mining operations. Consideration should be given to a determination of curve numbers associated with the modified areas.

One weakness of the SSARR is the failure of the soil moisture index to transfer from the snow basin to the rain basin. This should be reviewed relative to possible improvement.

Information is provided on the results of an allied study of soil moisture predictions for use in the analysis of individual storm events. This is of interest for use of models such as the TR-20.

In calibrating these models, it appeared that the data on rain and water content of snow were the weakest part of the system. Raingages in this region are not spaced closely enough to provide reasonably accurate data on summer storms.

Hydrologic Investigation of Selected Watersheds in the Copper-Nickel Region of Northeastern Minnesota

by

Charles S. Savard,[1] Nels P. Nelson,[2]
and C. Edward Bowers[3]

INTRODUCTION

The primary objectives of this investigation include:

1. Evaluation of the performance of the Soil Conservation Service TR-20 and the Streamflow Synthesis and Reservoir Regulation (SSARR) mathematical simulation models in the Copper-Nickel Region of Northeastern Minnesota.
2. Application of the models to three selected watersheds in the region.

The evaluation involves a measure of the ability of the models to (1) predict runoff events with good estimates of peak flows and yearly volumes of runoff and (2) synthesize frequency events such as the 100 year flood.

The SSARR was chosen over other continuous synthesis mathematical simulation models because of its favorable performance record in the Columbia River basin by the Corps of Engineers and in other areas, including Minnesota.

The TR-20 has been widely used in Minnesota by the Soil Conservation Service and by others interested in determination of both computed peak flows and changes in peak flows due to changes in land use. The TR-20 utilizes unit hydrograph theory and the SCS-Mockus curves relating rainfall and runoff volumes. Antecedent moisture conditions can be considered in terms of "dry", "normal", and "wet" conditions, AMC I, II, and III, respectively. These choices affect the curve numbers in the runoff analysis. As the TR-20 is design oriented, the user would

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normally select one of these conditions for the desired future condition. In attempts to use the model to fit past events, it was considered desirable to develop a soil moisture model.

Professor Curtis Larson, of the Department of Agricultural Engineering, agreed to investigate methods of predicting initial soil moisture conditions for runoff event models. His report is Addendum No. 1 of this report.

Computer printouts of selected runs constitute Addendums No. 2 and No. 3.

While both the TR-20 and SSARR models were already operational at the St. Anthony Falls Hydraulic Laboratory, Department of Civil and Mineral Engineering, it was necessary to acquaint staff members with their use, and to determine the performance of the models in the Copper-Nickel area. Prior to this time, in this Department (CME), the models had been used primarily in the south-central part of the state in predominantly agricultural areas.

It should be noted that the SSARR model was developed starting about 1958 and that the TR-20 was probably initiated about or soon after this date. Use of the models on a daily operational basis would result in optimum performance of the models. In the current study the models have been used quite actively over an 8 month period. This has been very helpful in attempts to properly use the models but it must be noted that the authors of this report still have much to learn about their use.

It was considered desirable to evaluate the models with measured runoff data for earlier years. While the TR-20 could be utilized with existing regional data, it would be necessary to fit the SSARR model to the watersheds using past data and in the process, evaluate parameters such as the soil moisture index (SMI), the baseflow infiltration index (BII), and 'surface runoff'-'subsurface runoff' (S-SS) relationship. While this information is available for south central Minnesota, it was not known whether it was applicable to the Copper-Nickel Region. It was thought desirable to operate the TR-20 with data for earlier years to assist in an evaluation of its performance in the Copper-Nickel area.

In discussions with Mr. Alan Wald of the Environmental Quality Council Staff, the three watersheds selected for this phase of the program were: Filson Creek (9.6 sq. miles), the Stony River near Babbitt (180 sq. miles), and the Partridge River near Aurora (130 sq. miles above Second Creek). With the assistance of the

EQC, DNR, the USGS, and the Forest Service hydrologic data for 1961, 62, 63, 64, 75, and 77 were assembled for the Stony and Partridge Rivers. Data for portions of 1975, 76, and 77 were assembled for Filson Creek (1977 data are incomplete). Additional data would have been desirable.

The three watersheds are in close proximity to each other in the Hoyt Lakes - Babbitt - Ely area, shown in Figure 1. Filson Creek and the Stony River are north of the Laurentian Divide and part of the Kawishiwi River Basin, whereas the Partridge River is south of the Laurentian Divide and part of the St. Louis River Basin.

All three of the watersheds are in heavily forested areas with many lakes and swamps, resulting in considerable storage.

The following table lists some data on the watersheds:

Watershed	Area Sq. Mi.	Stream Slope*	Storage (% Area)
Filson Creek	8-10	15.3	11.0
Stony River near Isabella	180	12.6	28.1
Partridge River	130**	8.1	20.1

*ft/mile

**above Second Creek

The Partridge River Watershed has fairly extensive mining areas. This affects runoff to some extent but of more importance is the extensive pumping of water from mines to streams and from Colby Lake to the mining operations. Erie Mining Company is the primary firm involved in this activity. Runoff data were modified to account for these operations as described later in the report.

The bedrock in all three watersheds is crystalline consisting of gabbro, anorthosite, and granites from the Duluth complex. Outcrops are extensive in certain areas and cause high runoff due to their low permeabilities. Deep groundwater aquifers do not exist in the area. However, shallow aquifers exist

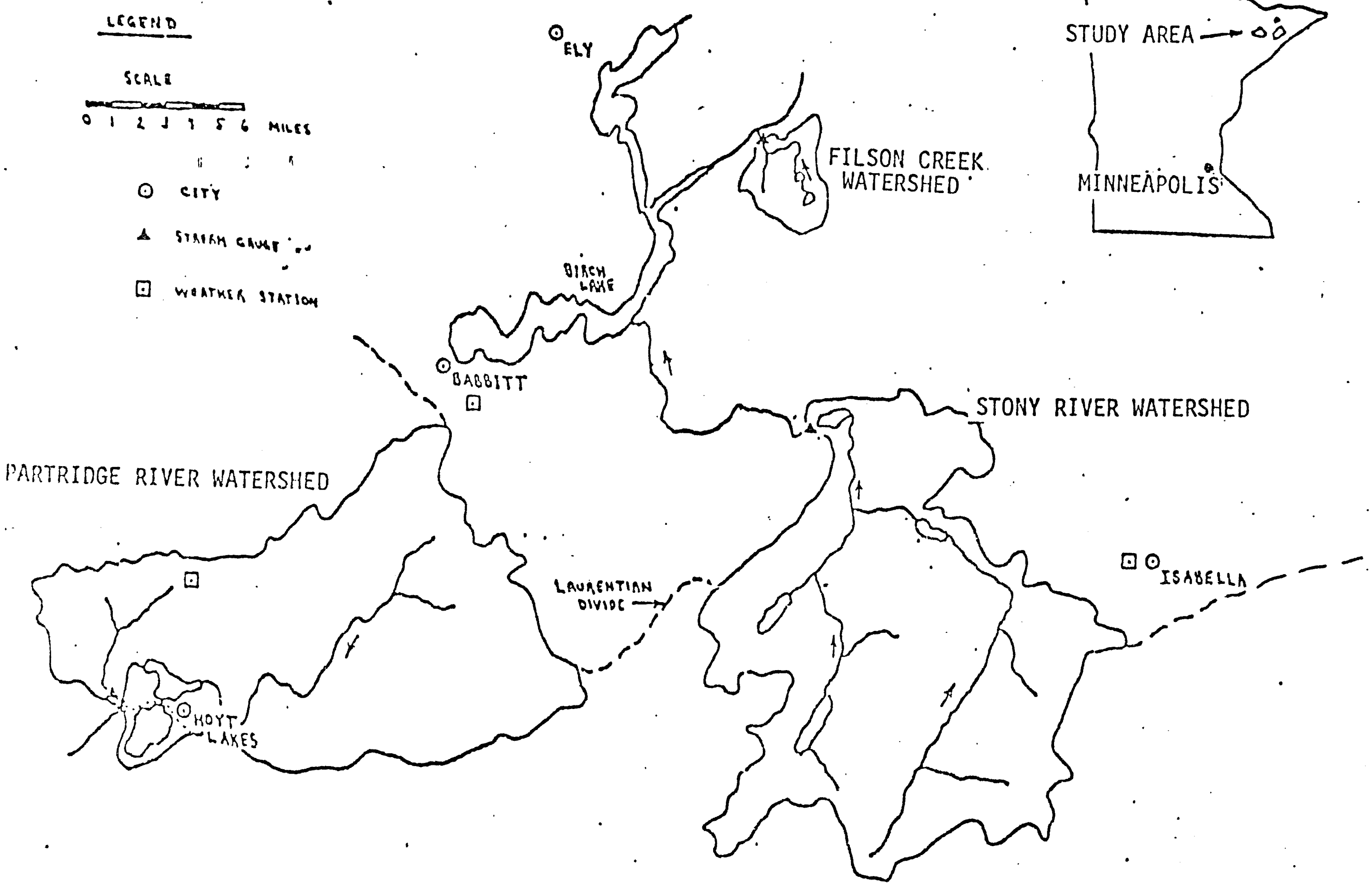

Fig. 1 - Watershed Location May.

in the extensive glacial deposits of the watersheds. Bouldery till and outwash deposits of sand and gravel are very important locally to the hydrologic response of small areas. The glacial deposits are generally thin, 0 - 50 feet, but many reach depths of more than 100 feet. They act as small storage reservoirs for interflow during wet periods. Thus, the interflow is released slowly after the precipitation event.

The region also has extensive peat and marsh-like areas. Along with the numerous lakes, these have a tendency to reduce peak flows and lengthen the time of concentration for single events in the watersheds.

SSARR MODEL

Description of the SSARR

The SSARR is a FORTRAN IV program designed to model the runoff process in a river system using mathematical abstractions of the physical world. It is a continuous synthesis model that is partially conceptually based and partially physically based. Determination of the runoff volume is physically based using such watershed parameters as the soil moisture index (SMI), the baseflow infiltration index (BII), and others. The timing of the runoff is conceptually based using reservoir routing theory. Surface, subsurface, and baseflow conceptual reservoirs accepted as inflow the runoff volume. An outflow hydrograph is then determined from the reservoir outflows and calibrated against observed discharges.

Other options in the SSARR not utilized in the present phase of the project include the 'river system model' section and the reservoir regulation model. Presently, plans are being made to extend the study and include these options in a hydrologic evaluation of the Copper-Nickel area.

As with any continuous computer model, time is broken down into finite steps. The length of computation period, the time step, is a function of the desired output detail, input detail, and desired error in the computation. For this study, daily time steps were used on the Stony and Partridge Rivers. On Filson Creek, hourly time steps were used. The major factor in determing the time step length was the time step used in measuring the actual river discharge.

In discussing the SSARR, input parameters can be divided into two groups, watershed parameters and time dependent parameters. The watershed parameters are optimized during calibration and should remain constant with time unless the watershed physically changes. The time dependent parameters, such as precipitation and temperature, continually change for different simulations.

The runoff process in the SSARR is flow charted in Figure 2 and will be discussed below. First, only runoff from a rain event will be explained. Then the snowmelt calculations will be added. These involve both snowmelt and rain inputs.

The precipitation input is calculated as the extrapolated amount over the entire watershed from point precipitation data. The runoff volume from the precipitation is calculated using the SMI (Soil Moisture Index) function. The SMI determines the runoff percentage of input. The SMI is a physical model of the soil system and the actual soil moisture an indicator of runoff. The SMI is depleted by the evapotranspiration index (ETI). The ETI reduces the SMI during each time step by a value specified by the user. The reduction represents the loss of soil water in the soil in the watershed. The soil moisture is replenished by rainfall. In the SSARR the amount of precipitation input that did not run off is added to the SMI. During periods of precipitation, the actual evapotranspiration should be reduced. The SSARR has a function called the KE function to reduce the ETI during precipitation. The ETI value is multiplied by a percentage which is a function of the precipitation intensity.

Once the volume of runoff is determined, the runoff is routed through the three conceptual reservoirs. The baseflow component is determined using the baseflow infiltration index (BII). The remaining volume is then split between surface and subsurface reservoirs using the surface-subsurface separation curve (S-SS).

Each of the three flow components is then routed through a series of conceptual reservoirs. The user specifies the number and time of concentration for each component flow system. An outflow from each reservoir system is computed for every time step. The outflow hydrograph of the basin is the sum of the three components.

The approach used in modeling snowmelt was the split basin method. The basis for the approach is that a watershed with snow cover behaves differently than a watershed without snow cover. An example of this behavior would be

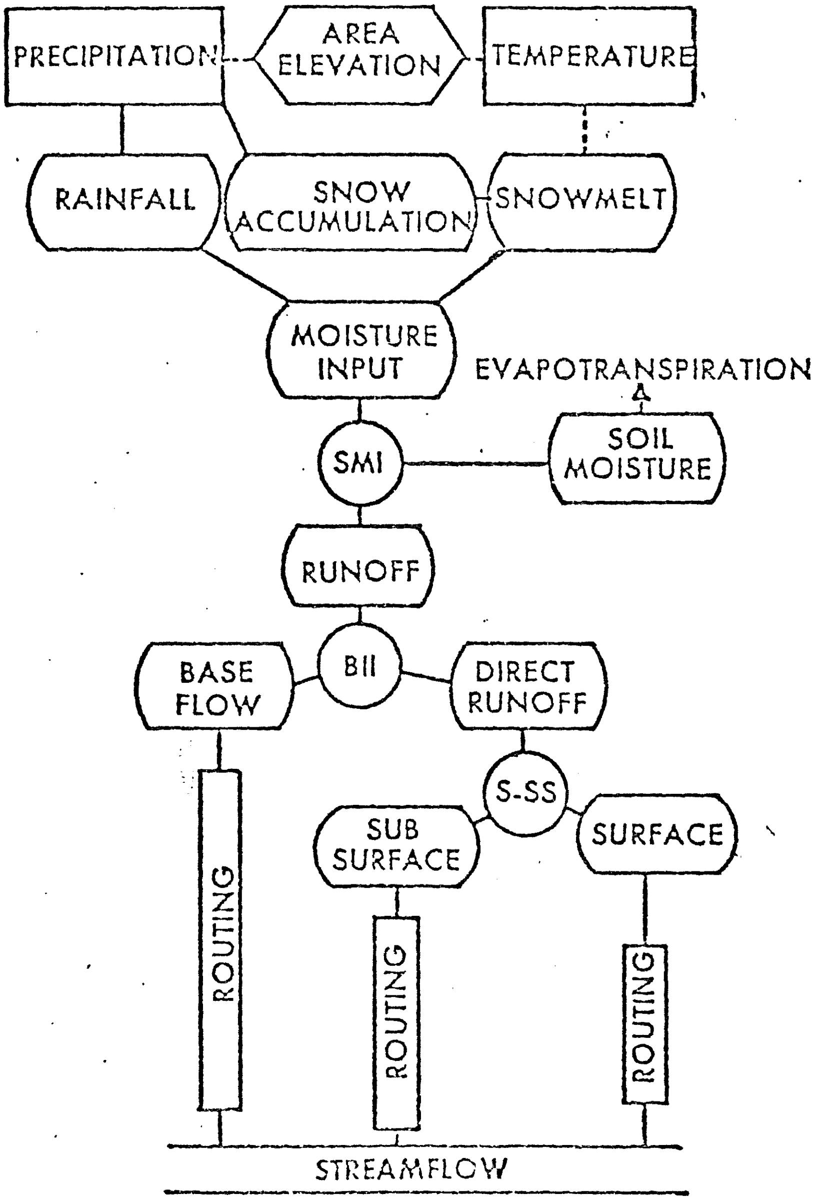

FIGURE 2 SSARR WATERSHED MODEL

frozen soil in a snow basin. High runoff rates would be expected. The SSARR uses two watershed basins, rain and snow, to model the physical basin. A simulation starts with the snow basin providing 100 percent of the runoff input. As the snowcover melts, the rain basin increases in runoff input until no snowcover remains. Then the snow basin no longer contributes to the runoff.

Several choices are available for snowmelt analysis, including 2 degree-day methods and an energy budget method. In this study a degree day, temperature index method was used. The amount of melt, the moisture input to the snow basin, is calculated from the equation

$$M = (T_A - T_B)R(PH/24)$$

where

M = moisture input
T_A = period temperature
T_B = base temperature
R = melt rate
PH = period length in hours.

The period temperature is taken from meteorological data; the base temperature used was 32°F. The melt rate is a functional value of the percentage of seasonal snowmelt runoff. Thus the snowpack can be ripened and melted faster late in the season.

Transfer of moisture input from snow to rain basin is controlled by a snowcover function. The snowcover area decreases as the accumulated water content of snow runoff reaches the estimated total seasonal runoff. When the accumulated amount reaches the seasonal total, snowcover becomes zero and the model transfers to the rain basin.

The SSARR has an elevation band option designed for melting snow in mountainous regions. Since there is no snow banding in northern Minnesota, the elevation change in a watershed was specified as only 20 feet. Thus, the lapse rate factors in the SSARR did not have any effect on the amount of melt.

Other snowmelt options available but not utilized were (1) General snowmelt equation including such factors as wind speed, solar radiation, and albedo, (2) Accumulated degree-day method, and (3) The snowcover depletion function to define the melt rate. The accumulated degree-day method has shown good results in southern Minnesota and possibly may be transferable to northern Minnesota.

The moisture inputs from the split basin are transferred into runoff volumes and routed through the conceptual reservoirs. The outflow hydrographs from both basins are combined to form the hydrograph of the real watershed. The simulation event can be started anywhere in time as the SSARR has initial condition options so parameters can be set to specified values and the simulation completed.

Calibration of the SSARR is accomplished by matching the models output to observed discharges. Each watershed was calibrated on the basis of the entire year. This means that low flows were just as important in the calibration as the large floods. Matching volumes and correct timing of both small and large events were used as the measure of calibration.

Ideally, several years of data should be used for calibration. Then the model's performance can be tested on a few more years of independent data and checked. The Stony and Partridge River watersheds had several years of data and were calibrated using 1961, 1962, 1963, and 1964 data. The check for the Partridge was made on 1975 data. The Stony was checked for 1976. However, a station downstream from the calibration gauge was used. The results for both watersheds were fairly good. In Filson Creek only late 1975, 1976, and early 1977 data were available. Thus, after calibration no data existed for checking.

To calibrate the model each of the watershed parameters must be optimized individually. The SSARR has no built-in optimization routines, therefore the user must optimize the parameters. Since the SSARR is a large computer program, turnaround time is slow during peak period usage. Thus the many individual runs necessary to optimize each parameter results in a very slow calibration process.

A punched card format was used to enter the input information. Other options in the SSARR allow for data to be handled from tape or disk storage. Some of the time dependent data used during a simulation are shown in Fig. 3. The meteorological data sets are shown across the top. The discharge measurements used in the calibration are shown along the bottom. The triangles represent the SSARR input deck for a simulation run.

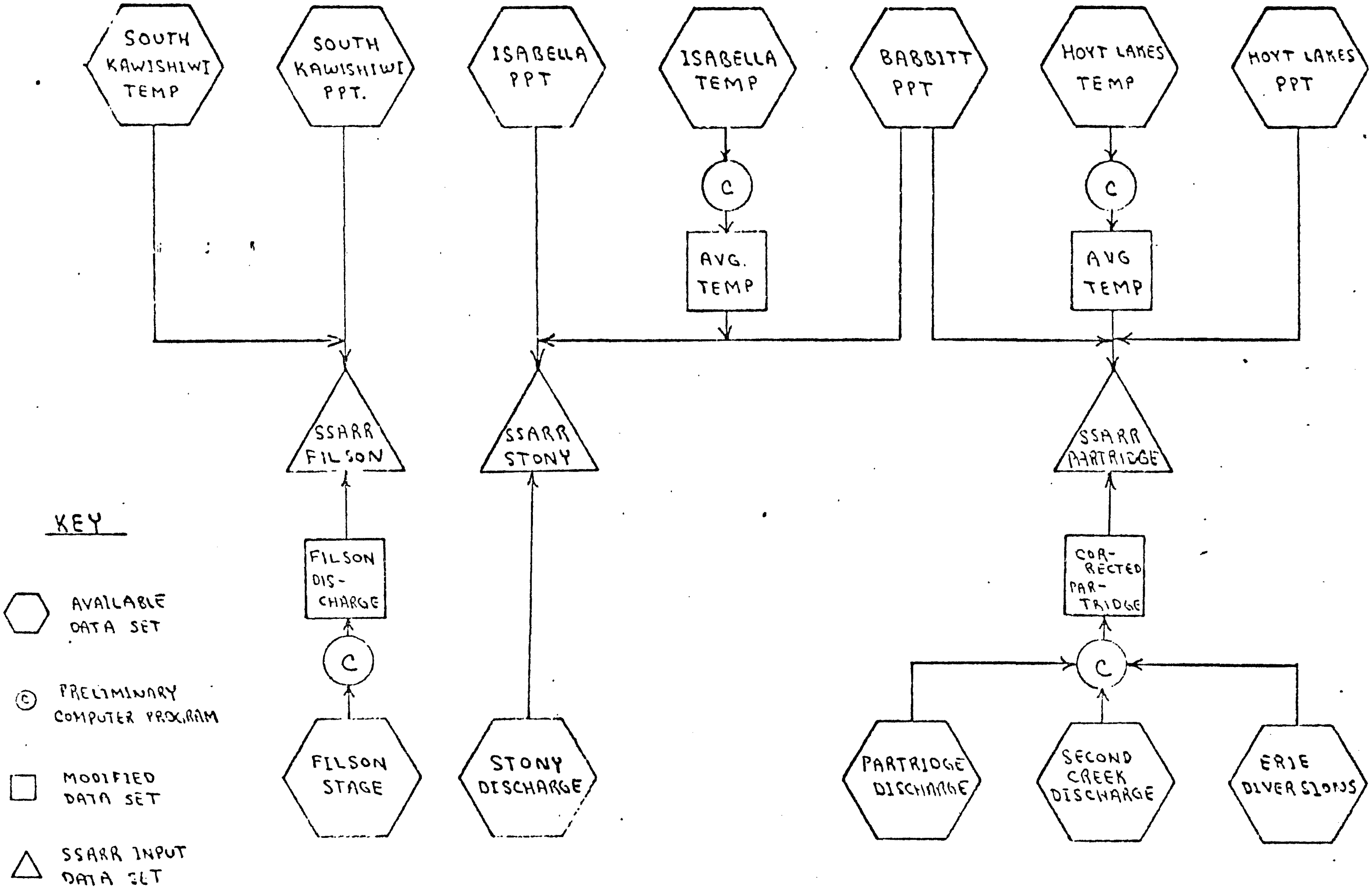

Fig. 3 - Time Dependent Information Flow For Use in the SSARR.

The output information for a simulation was on computer printout. The SSARR has other options, including storage of results on tape or disk and distribution of results throughout a teletype network. The output consists of detailed accounting of the parameters for each time step, along with the computed discharge. Also, the SSARR will print out a hydrograph along with the associated precipitation for visual inspection of the results.

Time Dependent Data

The precipitation input for the SSARR was determined using National Weather Service and U.S. Forest Service meteorlogical stations. For the Stony River watershed, two stations, Isabella 1 W and Babbitt 2 SE, were used. A Thiessen polygon weighting of 85 percent for Isabella and 15 percent for Babbitt were used. In the Partridge River watershed a Thiessen weighting of 66 percent for Hoyt Lakes SN and 34 percent for Babbitt was used. For Filson Creek, only the South Kawishiwi Lab station was used. The SSARR weighting factors are computed differently. The Thiessen weight is multiplied by the number of stations used. Thus, in the Stony River the percentages were 170 percent for Isabella and 30 percent for Babbitt.

For snowmelt computations, temperature data were needed for the temperature index method. Only one temperature station was used in each watershed to represent the temperature cycle for the whole watershed. For the Stony, Isabella was used. The Partridge used Hoyt Lakes while Filson Creek used the South Kawishiwi Lab. The hourly temperature readings from the Lab were used in the Filson computations.

For the Stony and Partridge Rivers a daily average was used. The daily average was the sum of the maximum and the minimum divided by two. The daily averages were only computed during the spring months when snowmelt runoff occurs.

The water content of the snowpack was needed for each year. The amount is used to compute the total amount of moisture to be inputed to the snow basin and also is used in the functions to determine the melt rate and snow covered percent of area. The data were taken from water content of snowpack maps prepared by the Corps of Engineers for specific years or snow course data taken by the Forest Service. The water content is an important parameter. It may be weak in that the whole watershed has to be lumped into one parameter. Therefore, the best estimate of the water content is extremely important for the SSARR to give good predictions of snowmelt events.

The potential evapotranspiration function (ETI) was partially determined from the pan evaporation data for Hoyt Lakes. The average daily values are indicated in Figure 4. During calibration of the SSARR, the ETI function was changed so that any departure from the average value during the calibration period would be represented in the simulation. The amount of change was calculated using the monthly departure from the average for the period of record. The departure was divided by thirty to get a daily departure then multiplied by a pan coefficient of 0.8 to get the amount of daily change. Thus, if the pan data for a month was greater than the average, this would indicate a higher potential evapotranspiration. The calibration improved when the ETI change was implimented.

For future application of the SSARR, the average ETI should closely approximate the potential evapotranspiration. If data are available indicating increased or decreased potential evapotranspiration for future simulation, then the ETI function should be changed accordingly. The sensitivity of the model to ETI varies. For single isolated events the ETI function is not that critical. But for precipitation events that follow one another quickly, the drying out of the soil (to give an accurate SMI) is important for determination of runoff volume.

The discharge measurements used for calibration were taken at gauging stations maintained by the U.S. Geological Survey and the Minnesota Department of Natural Resources. The average daily flow was used for the Stony and Partridge Rivers. For Filson Creek hourly stage measurements were available. These stages were converted to discharge using a preliminary USGS rating curve.

Discharge data for the lower Partridge River watershed (Fig. 5) required corrections for diversions due to iron ore processing. First, the Second Creek subwatershed was eliminated from the Partridge River watershed. The discharge in the creek is not representative of runoff since extensive dewatering operations of open pit mines for iron ore are emptied into Second

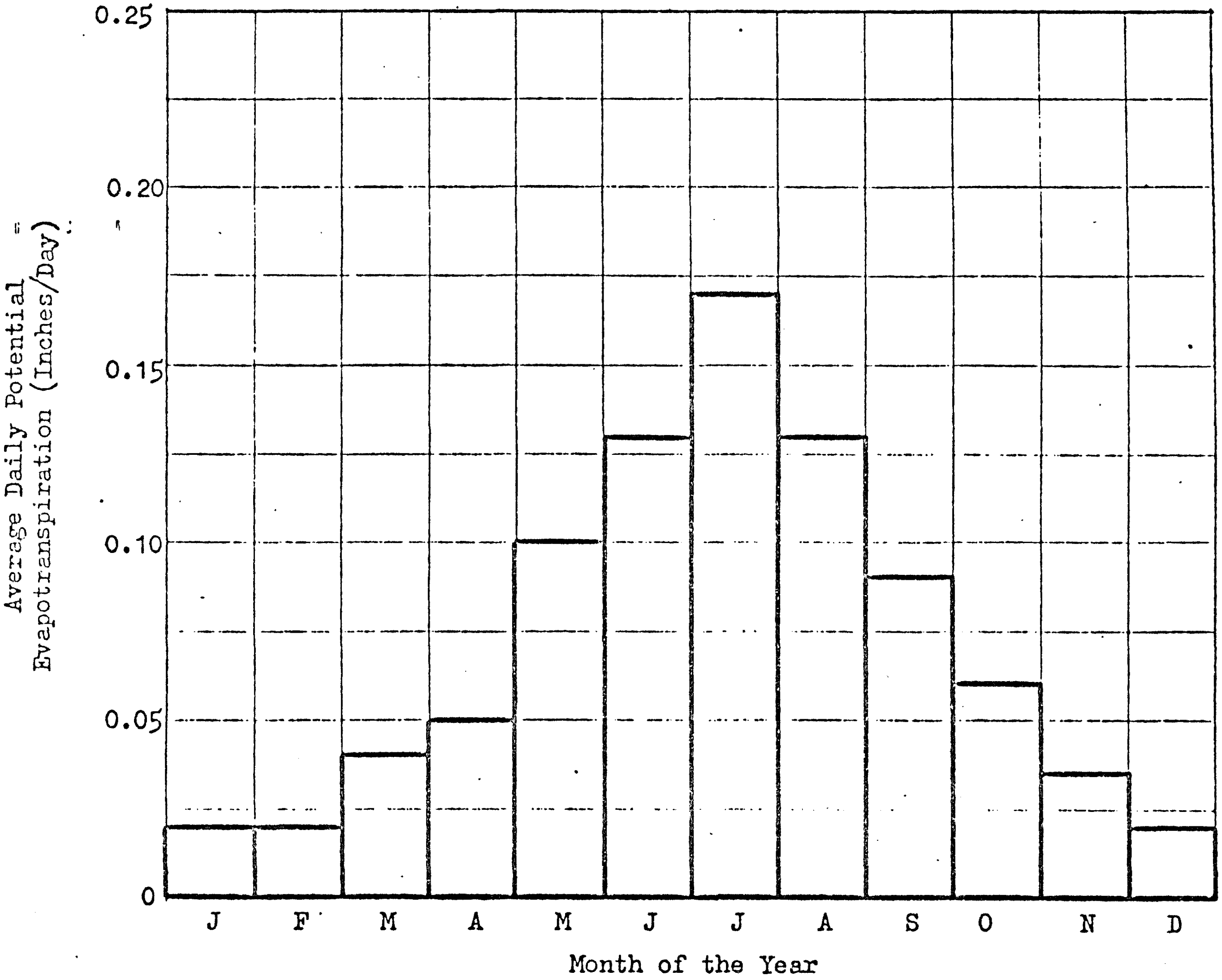

Fig. 4 - Average Evapotranspiration Index Table.

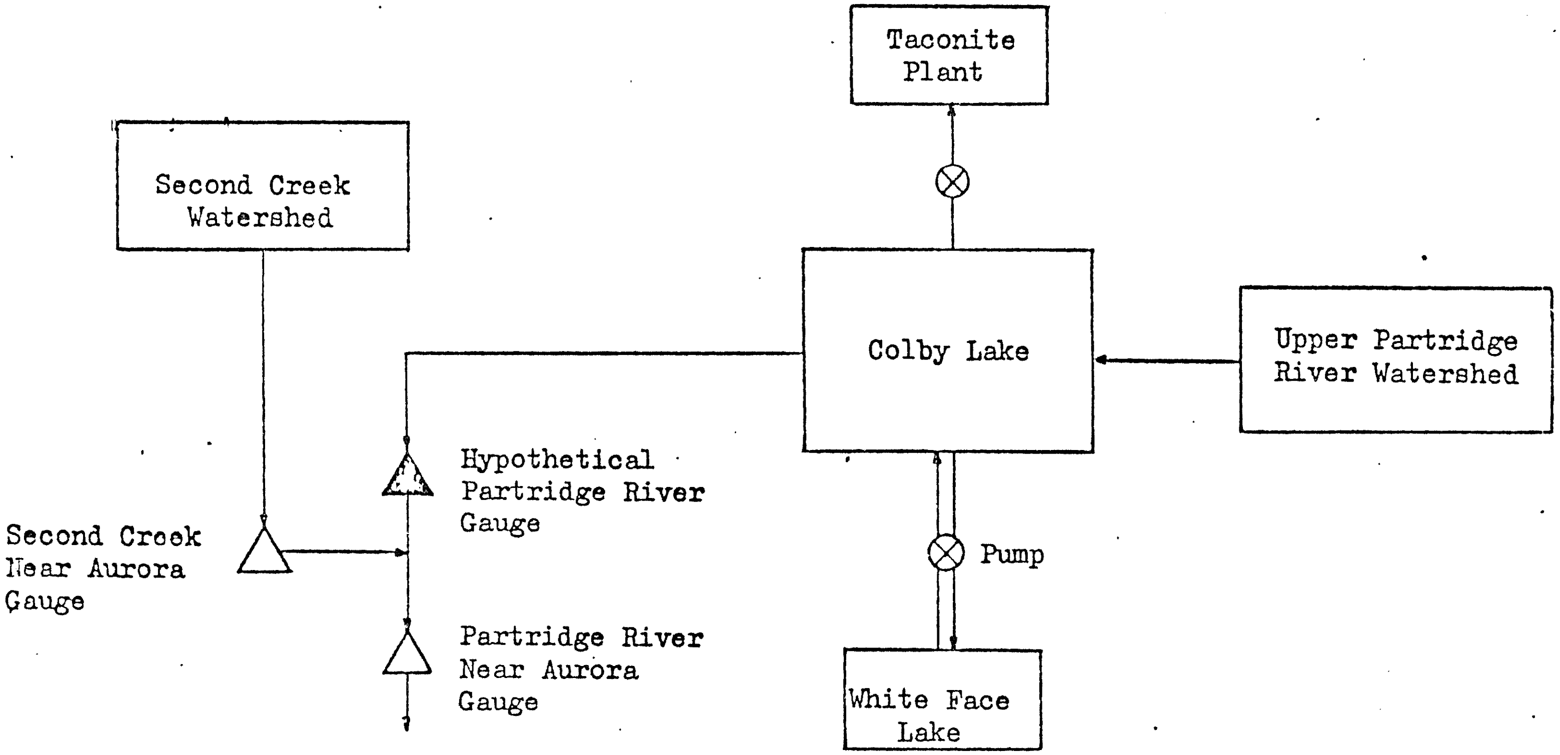

Fig. 5 - Schematic Map of Lower Partridge River Watershed Near Aurora, MN.

Creek. A hypothetical gauge was created by subtracting the Second Creek discharge from the Partridge discharge. With the two gauges only one third of a mile apart, the timing effect was ignored.

The hypothetical gauge then had to be corrected for diversions by the Erie Mining Company. The first diversion consisted of pumping water out of Colby Lake to a taconite processing plant. The amount pumped out was added back into the discharge measurement to get a flow that should have occured. The second diversion was the pumping of water into Whiteface Lake for storage and later released to Colby Lake. During high flows, Erie diverted water into Whiteface. During low stages, the water was released from storage to supplement the Partridge discharge. When flow was pumped out of Colby Lake, a correction was added to the gauge data. When flow was pumped back to Colby, a correction was subtracted to obtain a true Partridge River discharge.

Possible sources of error for a true Partridge River discharge would include the distance and timing of pumpage, leakage from Whiteface Lake into the Partridge River system, other pumpage in the lower watershed, natural storage in Colby Lake, and human error in data handling. Since all of the diversions and gauges are close enough together, the downstream propagation of flow changes will take place in less than a day. The corrections should be made the same day the diversion or flow happened. The leakage from Whiteface seems to be small enough to ignore at this time. Any other pumpage by itself should be small enough to be unimportant, but a combined effect of many small diversions may have to be investigated. The natural release of water from Colby storage should be incorporated within the model. The human error in data handling seems to be minimal.

Watershed Parameters

The watershed parameters were calibrated for each watershed with several years of data, except for Filson which only had two years of data. The results, to be discussed later, gave fairly good results. Since the hydrologic system is complex, the simple parameters possibly could be optimized several different ways to obtain good results. Calibration of parameters on the basis of several years of data, with similar results for these years, suggests that the parameter values are representative.

For each watershed, snow and rain basin soil moisture index (SMI) curves were prepared. The snow basin SMI relationships (Fig. 6) indicate a high percentage of runoff. A large portion of this runoff is routed through the base flow reservoirs and represents the spring recharge of the glacial aquifers. The high runoff may also be indicative of possible frozen ground or runoff of melt over the snowpack. A possible explanation for the difference of the runoff percentage at low SMI's for Filson Creek as opposed to the Stony or Partridge River is probably due to the physical nature of Filson.

The rain basin SMI relationships (Fig. 7) all show the same general trend with variance for each watershed. The differences between the snow and rain basin curves indicate a higher infiltration rate during the non-snow periods and a greater soil retention of water. A good optimization of the SMI curves is important because the volume of runoff is determined with this watershed parameter.

With the split basin approach there were two baseflow infiltration indexes (BII) for each watershed. The high percentage of runoff to baseflow in the snow basins (Fig. 8) represents spring recharge of the glacial aquifers, where some of the melt is percolating into the groundwater system to come out as runoff later. The BII is increased as the runoff rate increases. Thus, a higher percentage of flow will become surface or subsurface flow.

The three rain BII's (Fig. 9) are similar for each watershed. Again, as the BII increases, the baseflow percentage decreases. However, in the rain basin, higher percentages of runoff are routed through the surface and subsurface reservoirs.

It is important that the BII function be properly fitted. In between storm events the baseflow reservoirs release and control the low flow amounts to the greatest extent. To accurately model low flow conditions the BII functions must provide an adequate volume of runoff.

The time delay or time of storage parameter (TSBII) is used to calculate the BII. The TSBII was originally incorporated in the SSARR to account for changing baseflow characteristics between the rising and falling limbs of a hydrograph. The different values used for each basin can be seen in Table 1. The TSBII is a relatively unimportant parameter and does not exert a large effect on the hydrograph shape. A similar model calibration can be accomplished by

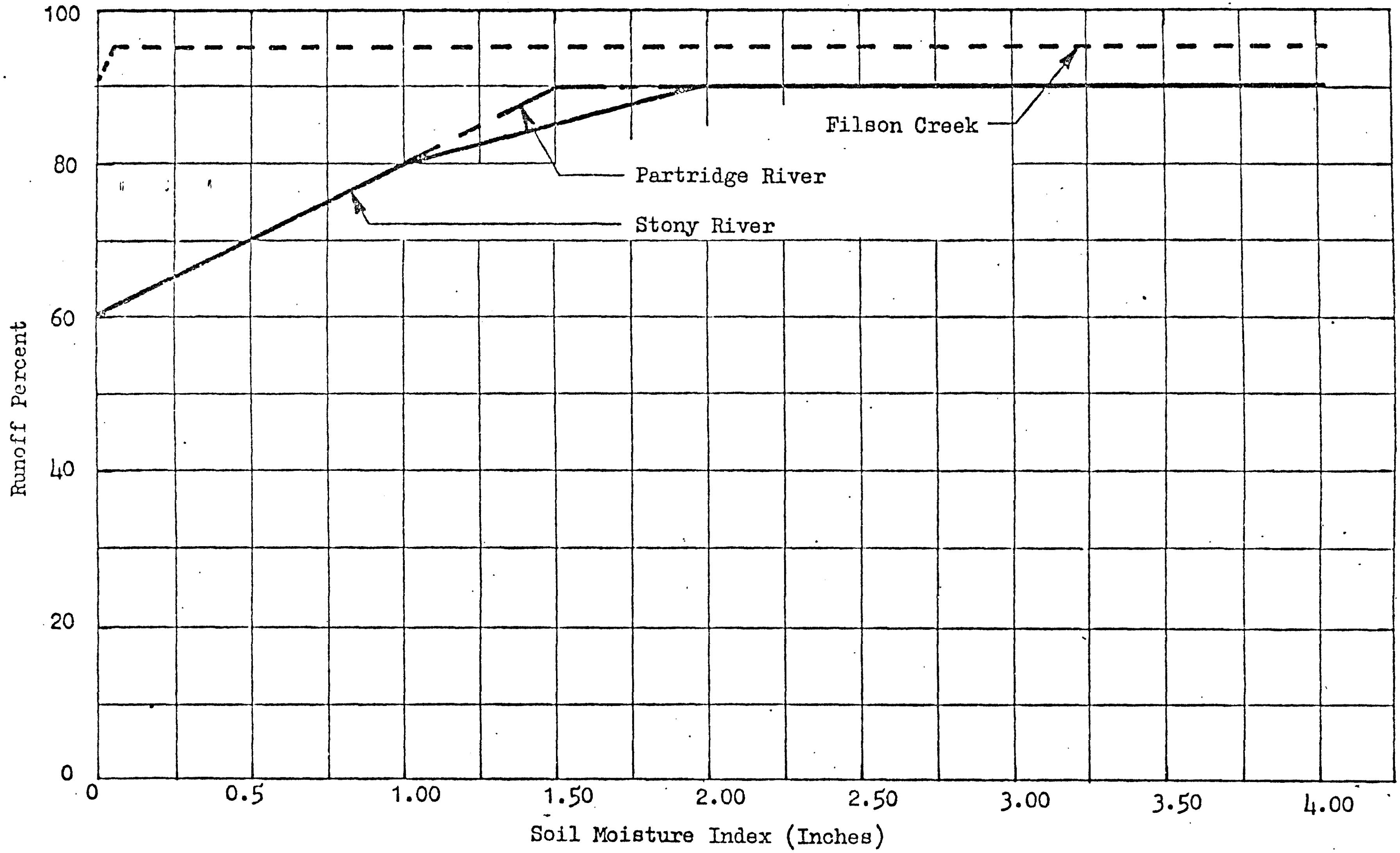

Fig. 6 - Snow Basin Soil Moisture Index-Runoff Relationships.

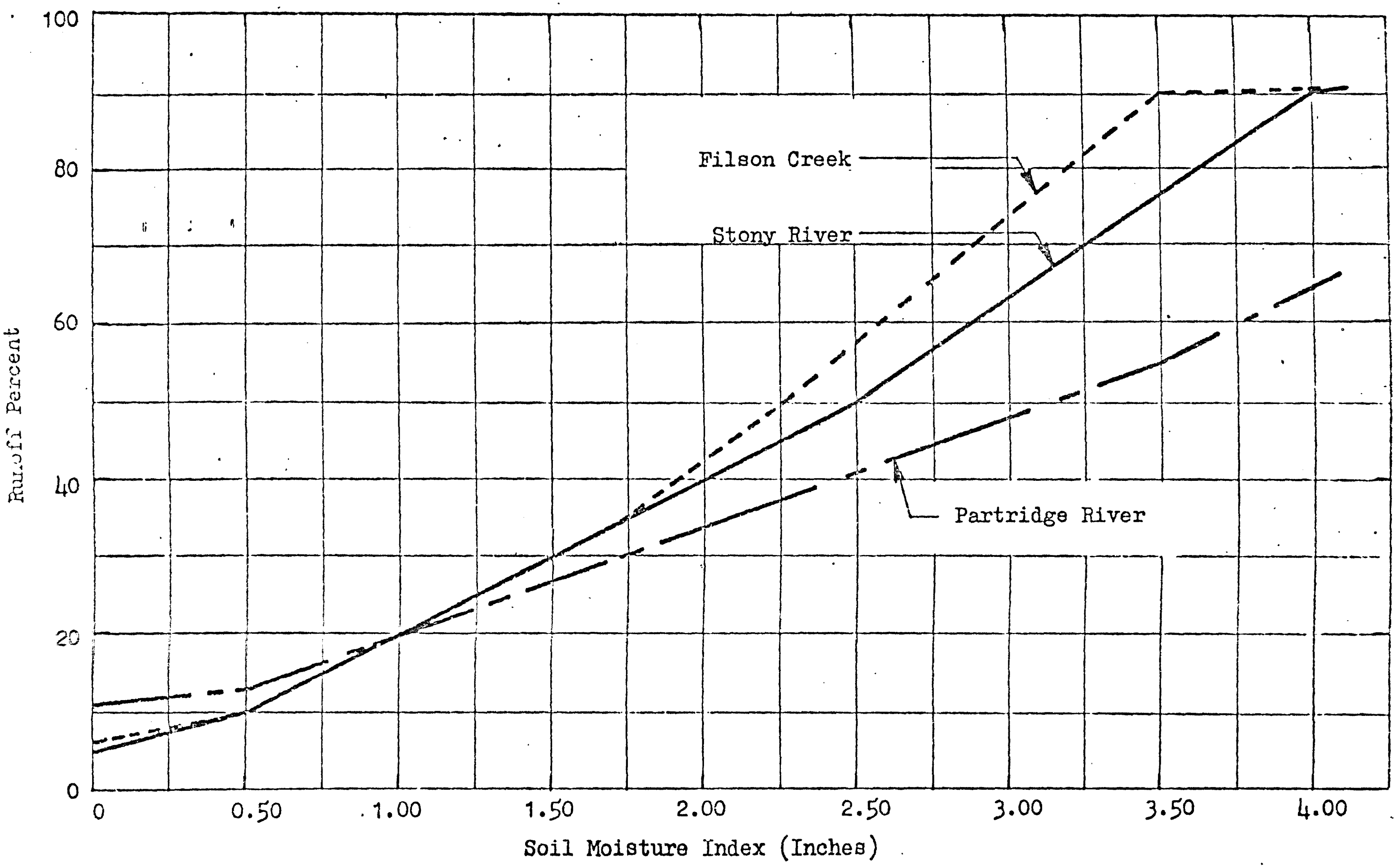

Fig. 7 - Rain Basin Soil Moisture Index-Runoff Relationships.

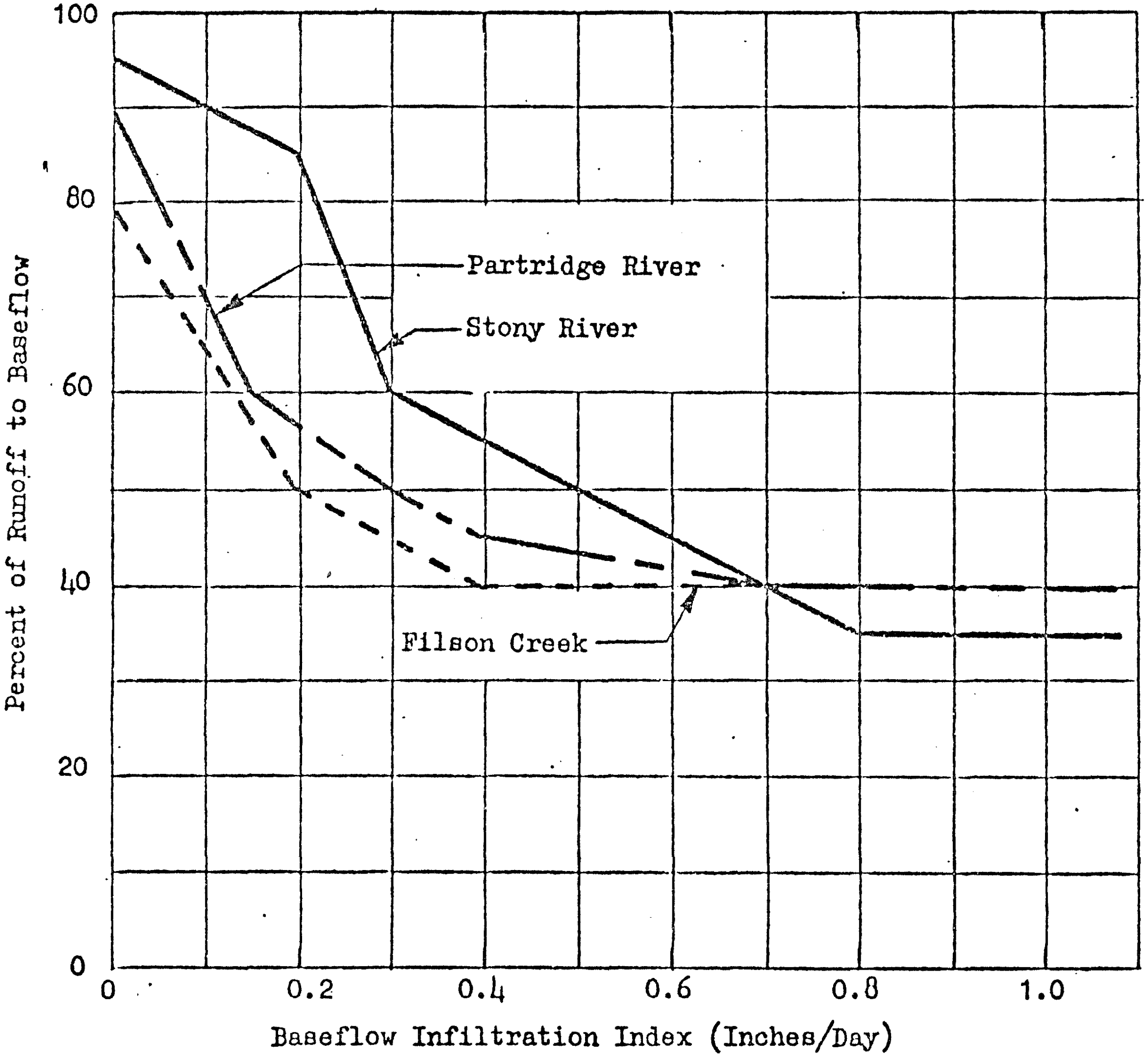

Fig. 8 - Snow Basin Baseflow Infiltration Index Function.

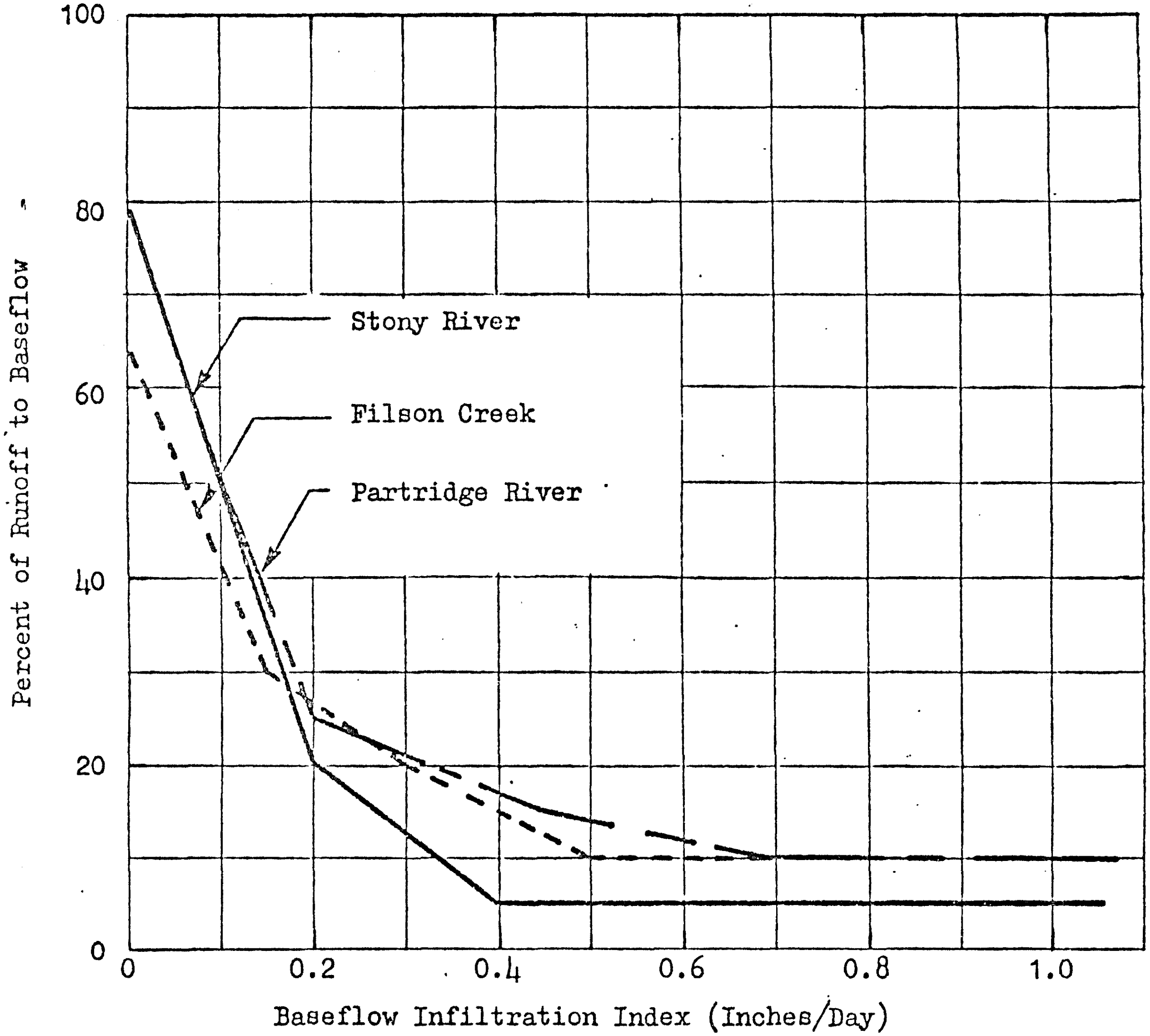

Fig. 9 - Rain Basin Baseflow Infiltration Index Function.

Table 1 - TSBII Parameter Values for the Watersheds

Watershed Basin	Rising Limb TSBII (Hours)	Falling Limb TSBII (Hours)
Stony River Snow	40	20
Stony River Rain	40	60
Partridge River Snow	40	60
Partridge River Rain	40	60
Filson Creek Snow	30	70
Filson Creek Rain	60	60

optimizing the parameters for the conceptual baseflow reservoirs. Very little optimization effort was used in determing the TSBII.

The remaining percentage of runoff after the baseflow has been determined is then split in surface and subsurface flows using the surface-subsurface separation curves (S-SS). The rain basin S-SS (Fig. 10) shows small amounts of runoff being routed to the surface component as compared to the total input rate. Physically, this is because very little overland runoff occurs in the forested watersheds, and large amounts of runoff become interflow. The interflow is caused by the porous forest soil and litter and is represented in the model by the subsurface reservoir. The S-SS curves are not well defined at the higher input rates, since during the calibration years very few events were in that region to optimize the curves. The curves do show an upward trend that as the input rate is increased, the surface component becomes more important and the subsurface component reaches an upper limit.

The snow basin S-SS curves (Fig. 11) all generally trend in the same pattern as the rain S-SS curves. A good optimization of the values is difficult since the snow conditions and the path of water during the snowmelt process is not well understood. More work could be done to refine the curves if better input information were available.

The melt rate functions (Fig. 12), using the percent of seasonal snowmelt runoff, were similar for all three watersheds. Starting at low melt rates and proceeding to higher rates indicate a ripening of the snowpack as the snowpack releases more moisture. Optimizing the melt rate was difficult. The guide to a correct melt rate would be the amount of moisture input to the system. The moisture input to the system is also a function of the number of degree-days during the time period. Thus the melt rate relationship could possibly be improved if the temperature cycle remained constant.

The snow covered area of the watershed is determined as a function of water equivalent in the snowpack (SCA). The function was nearly equal for all three watersheds (Fig. 13). The snow covered area in the snow basin was defined as 100 percent of basin area until a certain amount of water content was left in the snowpack. The snow covered area then decreased linearly to zero as the remaining water content of snow was melted. Very little optimizing was done on the SCA function. Since the melt rate is usually high when the break point in water content is reached, the snow covered area disappears quite rapidly, 1-5 days. Thus any difference in the SCA curves will not seriously affect the moisture input.

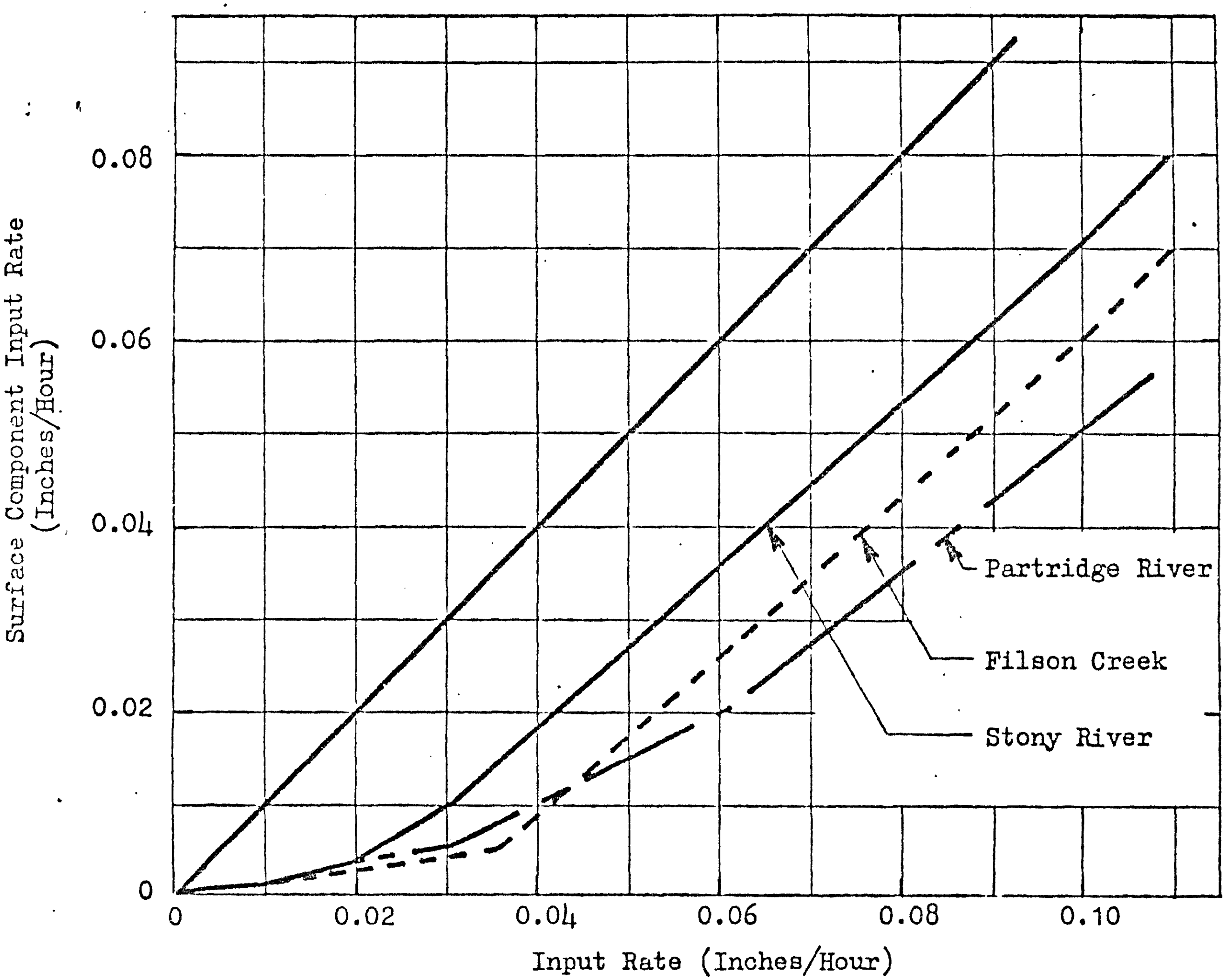

Fig. 10 - Rain Basin Surface-Subsurface Separation Curve.

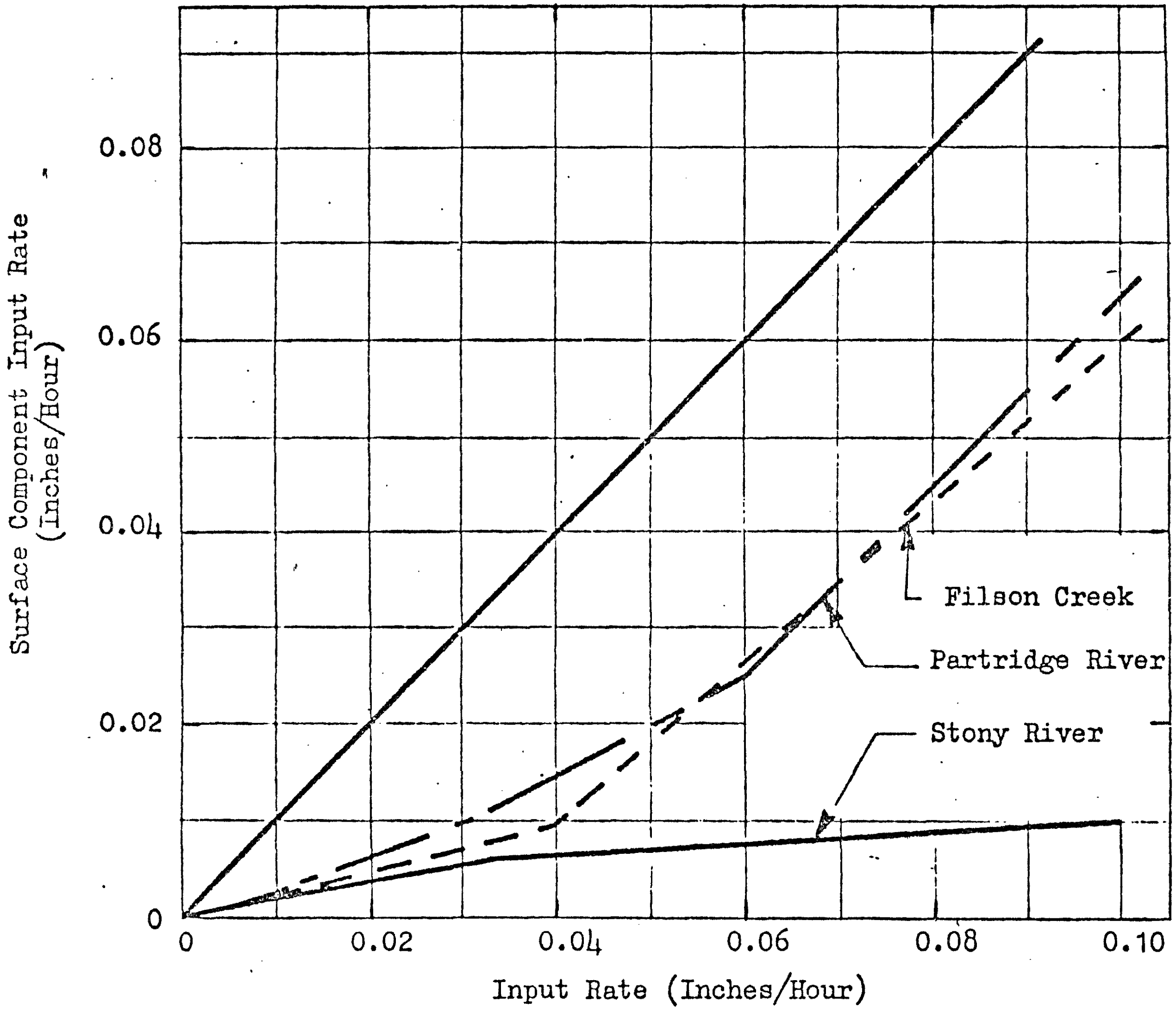

Fig. 11 - Snow Basin Surface-Subsurface Separation Curve.

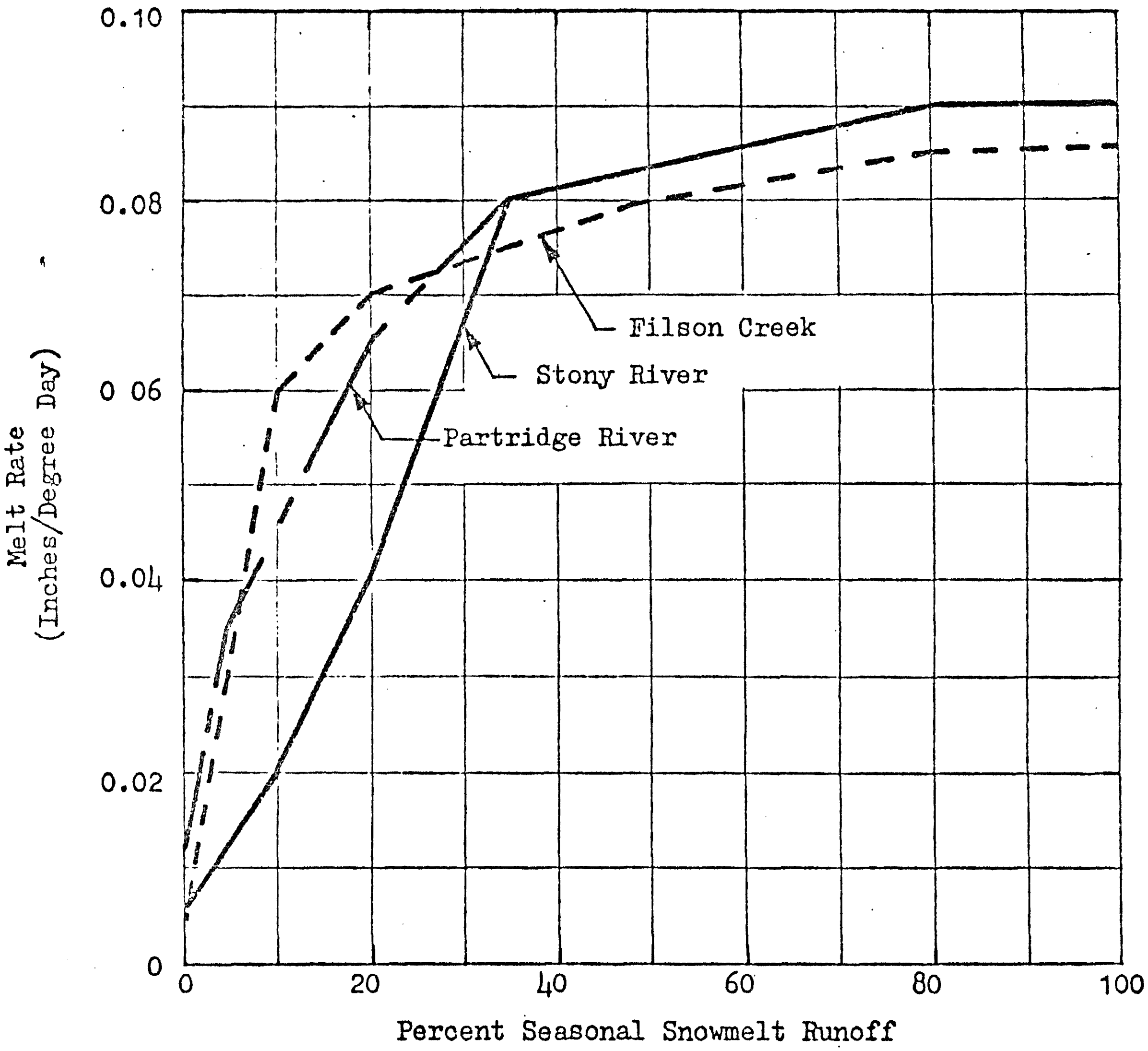

Fig. 12 - Melt Rate Function

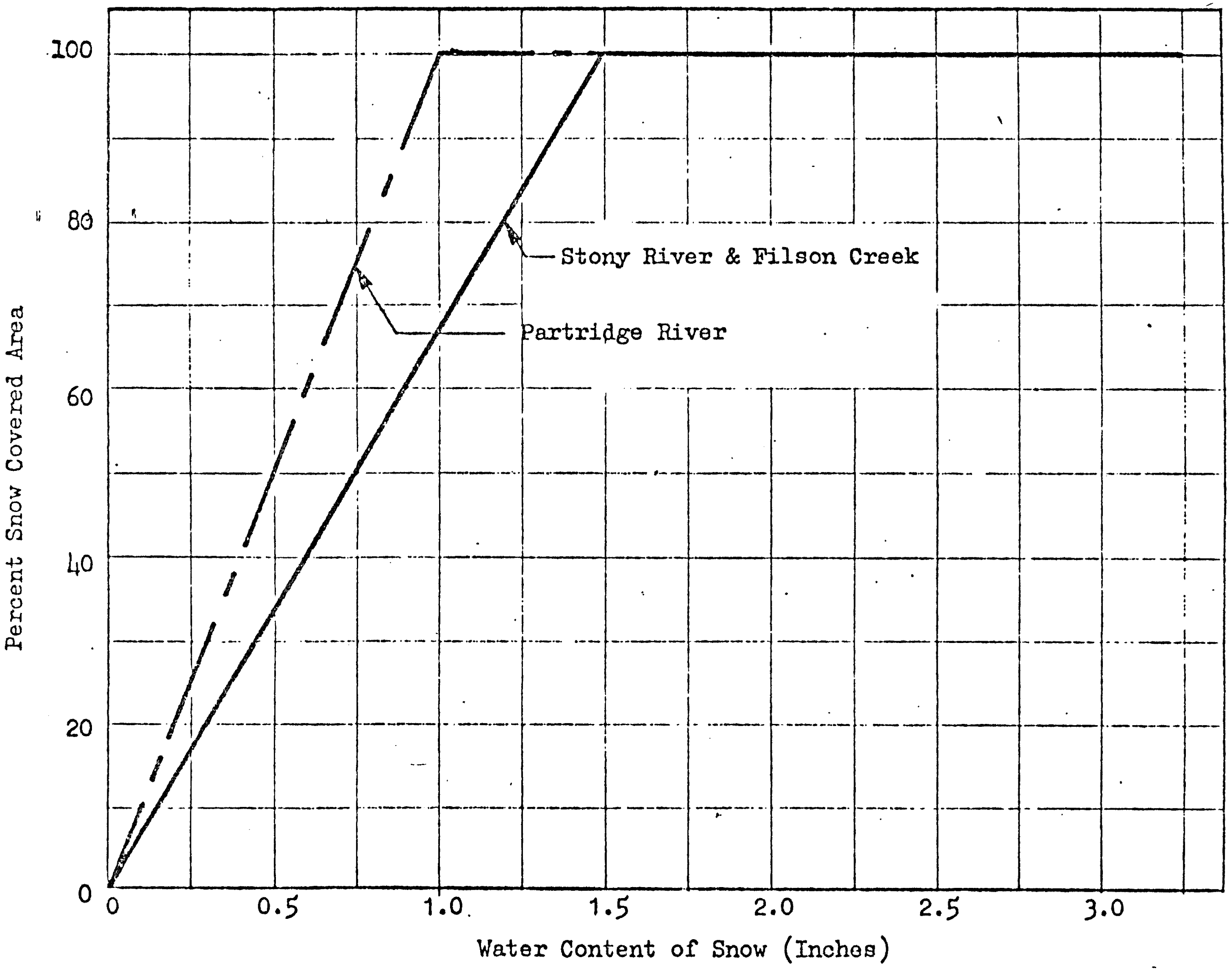

Fig. 13 - Snow Covered Area as a Function of Water Equivalent in the Snowpack.

The effectiveness of evapotranspiration index function is similar for all three watersheds (Fig. 14). Initially the values shown in the Corps of Engineers, SSARR documentation were used [2]. Since there are two major types of precipitation events in northern Minnesota, frontal and convective, optimization of the function was difficult. A frontal storm may last all day and result in low evapotranspiration, while a convective storm of the same volume may last only a short period, resulting in very little lost evapotranspiration potential. A better approach might be to make the effectiveness of ETI a function of duration of the rainfall. The SSARR does not currently have the capacity to do this, nor is the precipitation data usually fine enough to determine the distribution during the day.

The design, the number, and time of concentration for the baseflow, subsurface, and surface reservoirs determine the shape of the outflow hydrograph. Trial and error fitting of different designs resulted in the final designs as tabulated in Table 2. The output hydrographs are very sensitive to the design.

Discussion of Results

With the watershed parameters set as described in the previous section, calculated discharges represented the actual discharges with some degree of accuracy for all three watersheds. Improved performance could be obtained if additional meteorlogical data were available. Ideally, several more recording rain gauges and snow courses are described in each watershed.

Generally, the snowmelt can be modeled if good snowcover data are available. One problem encountered with the SSARR was modeling rain as the snowcover melted away. Using the two basin approach key parameters such as the SMI and BII are not transferred from the snow basin to the rain basin. In physical terms the wet soil of the snow basin is not transferred over to the rain basin. When early spring rain falls on the rain basin, a high percentage should run off.

Instead, the model uses the low SMI of the rain basin, and runoff is underpredicted. The 1964 simulation of the Stony River shows this very well in Figure 15. The watershed parameters could be changed to compensate for this, but then all the summer rain events would be overpredicted.

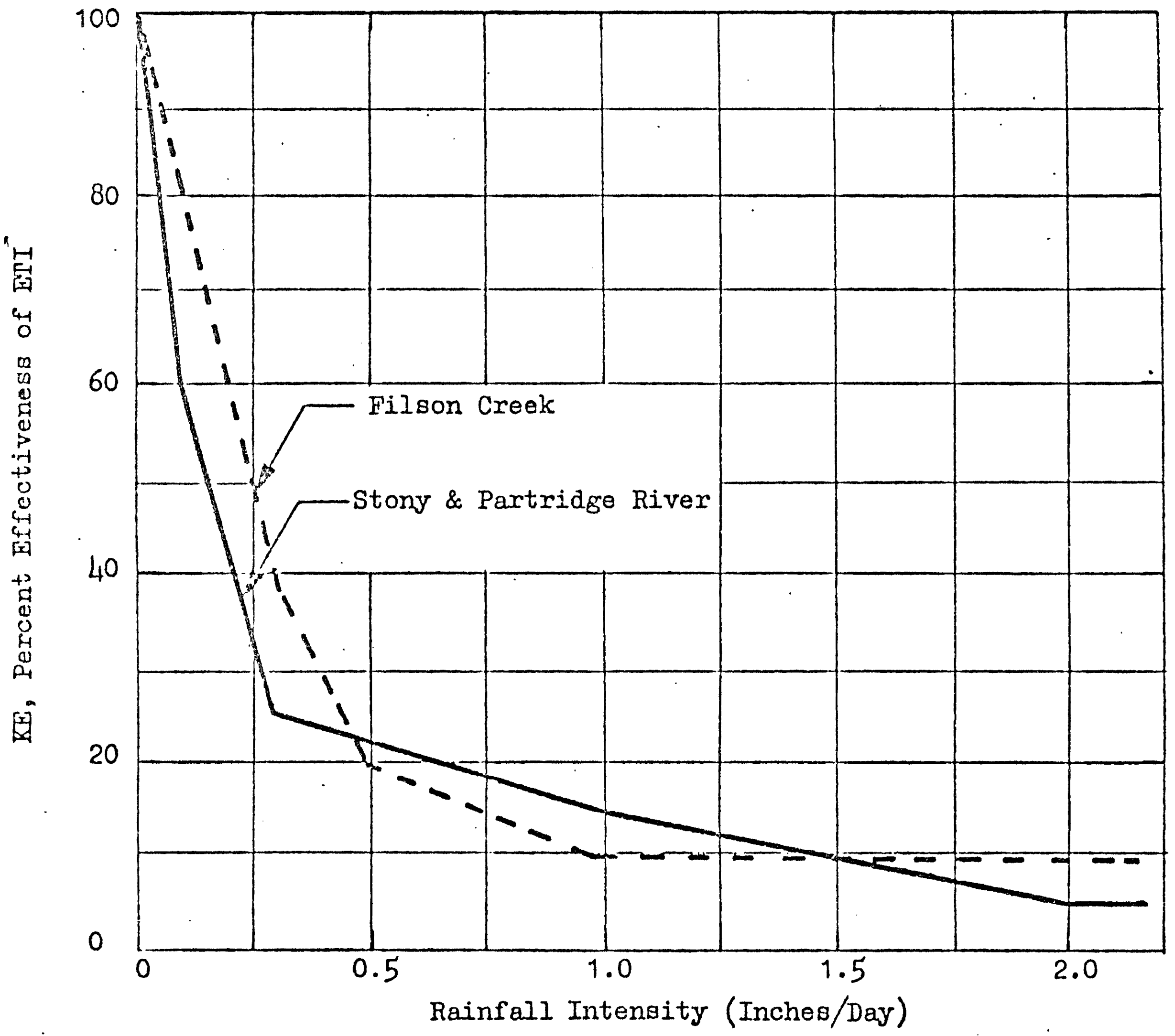

Fig. 14 - Effectiveness of Evapotranspiration Index During Rain.

Table 2 - Conceptual Reservoir Designs

Watershed Basin	Conceptual Reservoir System	Number of Reservoirs	Time of Concentration (Hours)
Stony River Snow	Surface	6	25
	Subsurface	6	70
	Baseflow	3	250
Stony River Rain	Surface	4	20
	Subsurface	4	45
	Baseflow	2	250
Partridge River Snow	Surface	5	25
	Subsurface	6	65
	Baseflow	3	250
Partridge River Rain	Surface	4	15
	Subsurface	3	45
	Baseflow	2	275
Filson Creek Snow	Surface	3	3.5
	Subsurface	4	12
	Baseflow	3	150
Filson Creek Rain	Surface	5	7
	Subsurface	4	20
	Baseflow	2	100

```
            180777      1 JAN 1964  1200          10STONY RIVER , BEGINNING RUNS                               N.P.D., CORPS OF ENGINEERS
                                      ETI =  .02 IN./DAY, MELT RATE = 0.000 IN./DEGREE-DAY, AREA =  180.0 SQ. MI.
  DAY HOUR  PCPN (RA RN-AR ML-AR (AR ELEV SCA D-DY (MA  MELT     MI    SMI ROP    RGP  BII BFP  BASEF  SUBSF     SURF   DISCH HOUR DAY

  DEC 1964                                                                                                               DEC 1964
    7 1200   .14  99  9.40  0.00    0     0   0  0.0   0  0.00   .14  1.34  27    .04  .02  79    34       8        0       43  1200  7
    8 1200  0.00  99  9.40  0.00    0     0   0  0.0   0  0.00  0.00  1.43  29   0.00  .01  74    34       7        0       43  1200  8
    9 1200  0.00  99  9.40  0.00    0     0   0  0.0   0  0.00  0.00  1.41  28   0.00  .01  77    34       7        1       43  1200  9
   10 1200   .00  99  9.41  0.00    0     0   0  0.0   0  0.00   .00  1.39  28    .00  .00  78    34       7        1       42  1200 10
   11 1200   .34  99  9.50  0.00    0     0   0  0.0   0  0.00   .34  1.37  27    .09  .04  79    35       7        1       44  1200 11
   12 1200  0.00  99  9.50  0.00    0     0   0  0.0   0  0.00  0.00  1.62  32   0.00  .02  67    36       8        1       47  1200 12
   13 1200   .00  99  9.50  0.00    0     0   0  0.0   0  0.00   .00  1.60  32    .00  .01  73    38      10        2       51  1200 13
   14 1200  0.00  99  9.50  0.00    0     0   0  0.0   0  0.00  0.00  1.58  32   0.00  .01  76    38      12        2       54  1200 14
   15 1200  0.00  99  9.50  0.00    0     0   0  0.0   0  0.00  0.00  1.56  31   0.00  .00  78    39      13        1       55  1200 15
   16 1200   .40  99  9.62  0.00    0     0   0  0.0   0  0.00   .39  1.54  31    .12  .06  79    41      14        1       57  1200 16
   17 1200  0.00  99  9.62  0.00    0     0   0  0.0   0  0.00  0.00  1.81  36   0.00  .03  62    44      15        2       62  1200 17
   18 1200  0.00  99  9.62  0.00    0     0   0  0.0   0  0.00  0.00  1.79  36   0.00  .02  71    46      17        3       67  1200 18
   19 1200   .08  99  9.65  0.00    0     0   0  0.0   0  0.00   .08  1.77  35    .03  .02  75    48      19        3       71  1200 19
   20 1200  0.00  99  9.65  0.00    0     0   0  0.0   0  0.00  0.00  1.80  36   0.00  .01  73    49      20        2       73  1200 20
   21 1200   .08  99  9.67  0.00    0     0   0  0.0   0  0.00   .08  1.78  36    .03  .02  76    51      20        1       74  1200 21
   22 1200   .08  99  9.70  0.00    0     0   0  0.0   0  0.00   .08  1.82  36    .03  .02  74    52      20        1       75  1200 22
   23 1200   .02  99  9.71  0.00    0     0   0  0.0   0  0.00   .02  1.86  37    .01  .02  73    53      20        2       77  1200 23
   24 1200   .27  99  9.81  0.00    0     0   0  0.0   0  0.00   .27  1.86  37    .10  .06  75    56      20        2       80  1200 24
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   27 1200  0.00  99  9.83  0.00    0     0   0  0.0   0  0.00  0.00  2.01  40   0.00  .01  73    62      26        3       93  1200 27
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   30 1200   .02  99  9.92  0.00    0     0   0  0.0   0  0.00   .02  2.09  42    .01  .02  68    66      26        2       96  1200 30

  * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

 FINAL FILE OF TIME RECORDS FOR OUTPUT AND PLOT IS ON UNIT 21

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                                             PLOT      STATION NAME                                    STATION
                                          CHARACTER                                                     NUMBER CONTROL

                                               X-CALCULATRD FLOW STONY RIVER                                 7.7    U
                                               S-SNOW BASIN,STONY RIVER                                     25.5    U
                                               R-RAIN BASIN,STONY RIVER                                    125.5    U
                                               *-OBSERVED FLOWS                                           5125.5    U
 FLOW CFS          0.        150.        300.        450.        600.        750.        900.      1050.      1200.       1350.       1500.
 PEC      66660                                                                      -10          10
                                               O-SYNTHETIC RESERVOIR                                      666.6    E
 ELEV FT.       -10.         -8.         -6.         -4.         -2.          0.          2.          4.          6.          8.         10.
 PRC 40683 100*                                                                      100          0
                                             *                                                -4068  3  100.
                10.00        9.00        8.00        7.00        6.00        5.00        4.00        3.00        2.00        1.00        0.00
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Fig. 15a - Stony River, 1964, SSARR Model.

430152

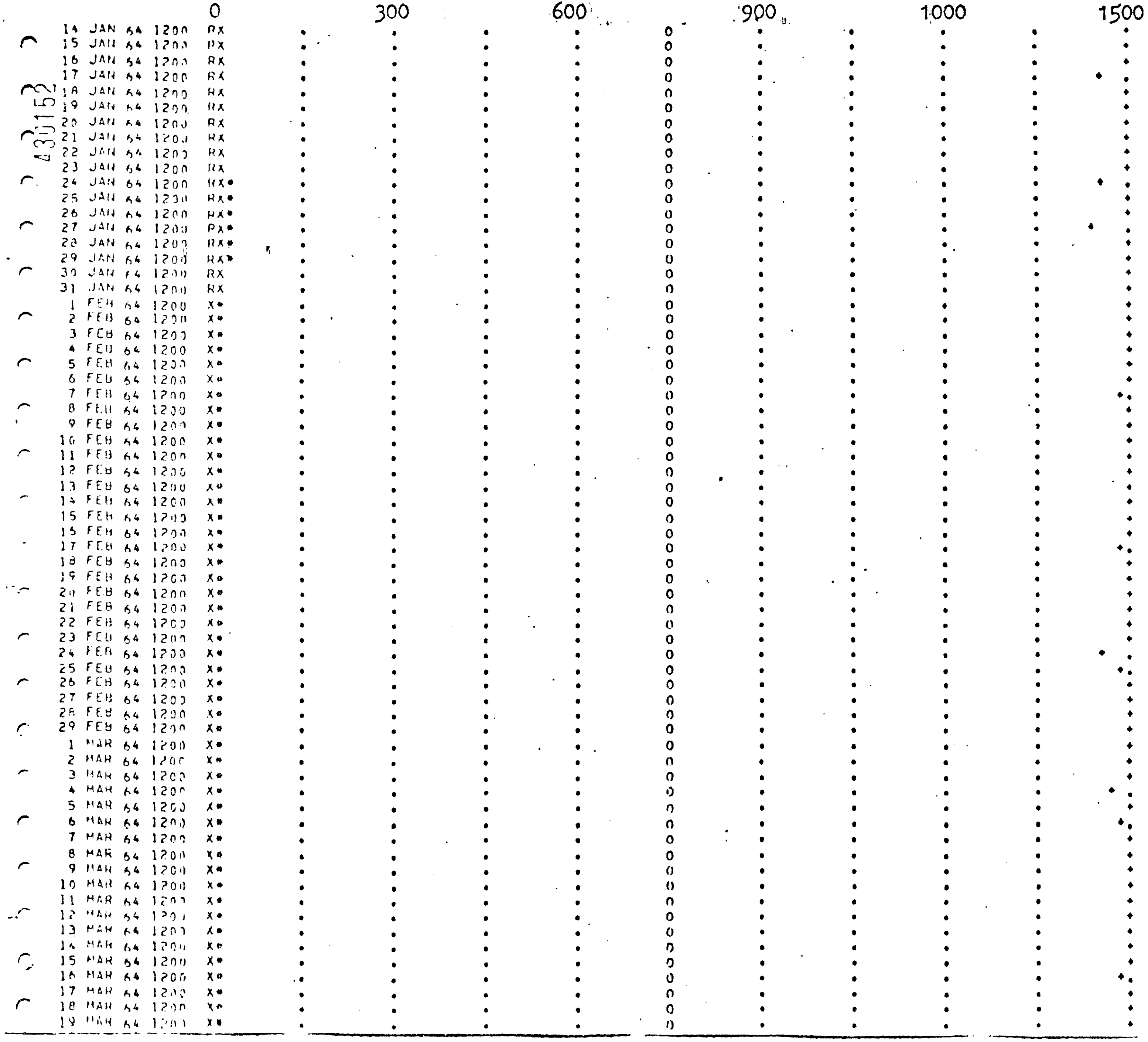
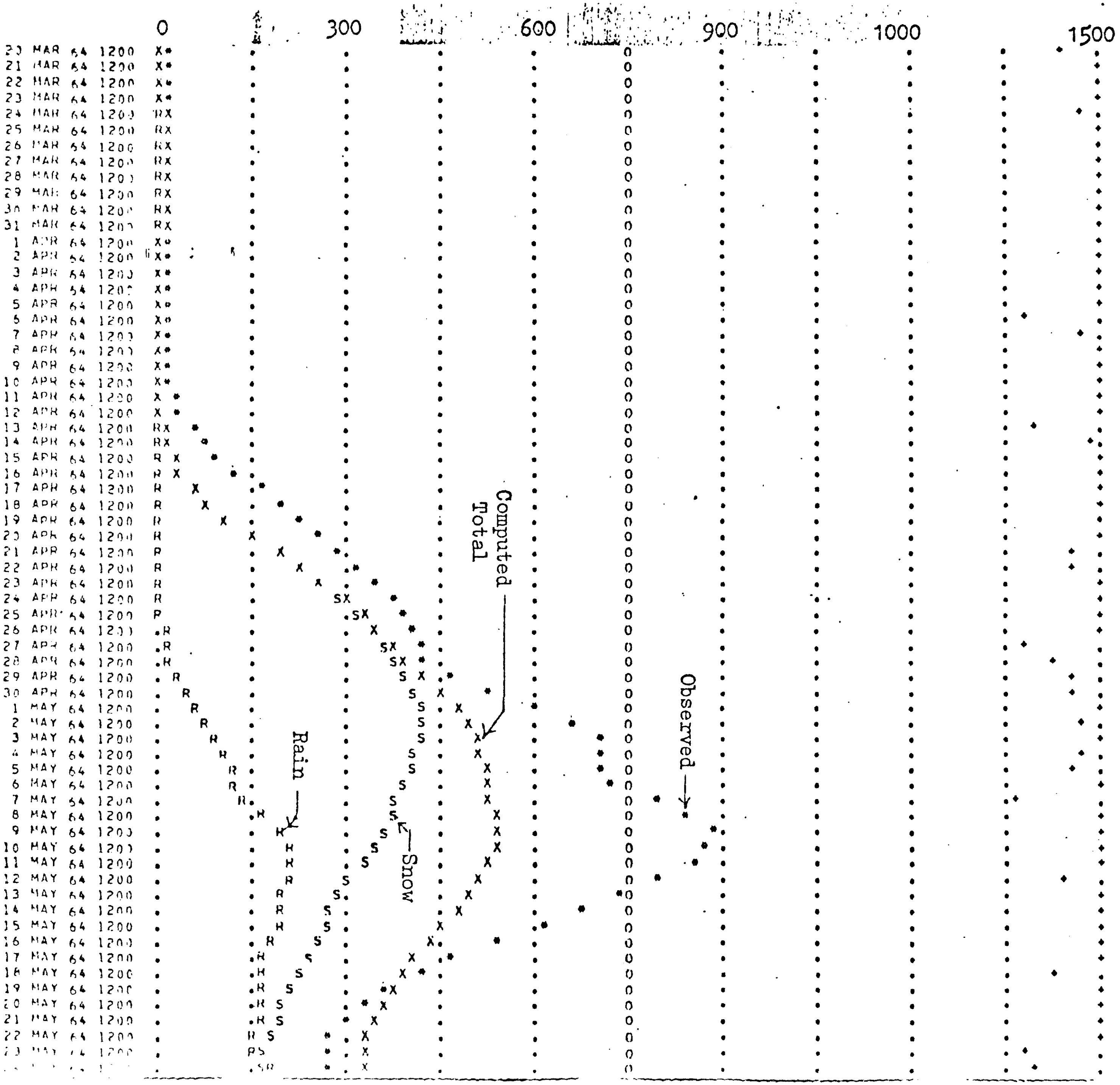


Fig. 15b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600
900
1000
1500
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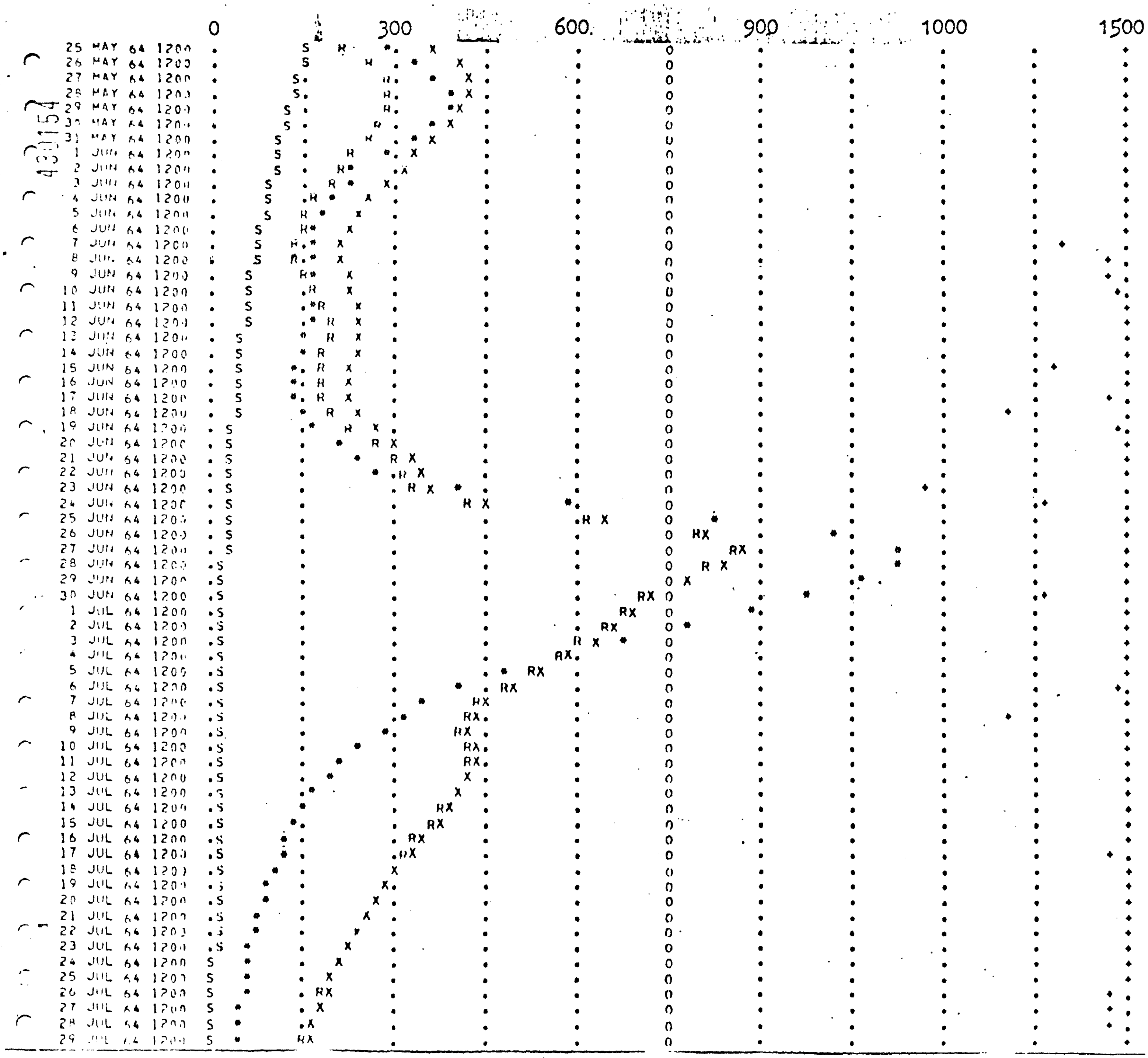
23 MAY 64 1200
Computed Total
Rain
Snow
Observed

Fig. 15c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X
RX
0

Fig. 15d

430155

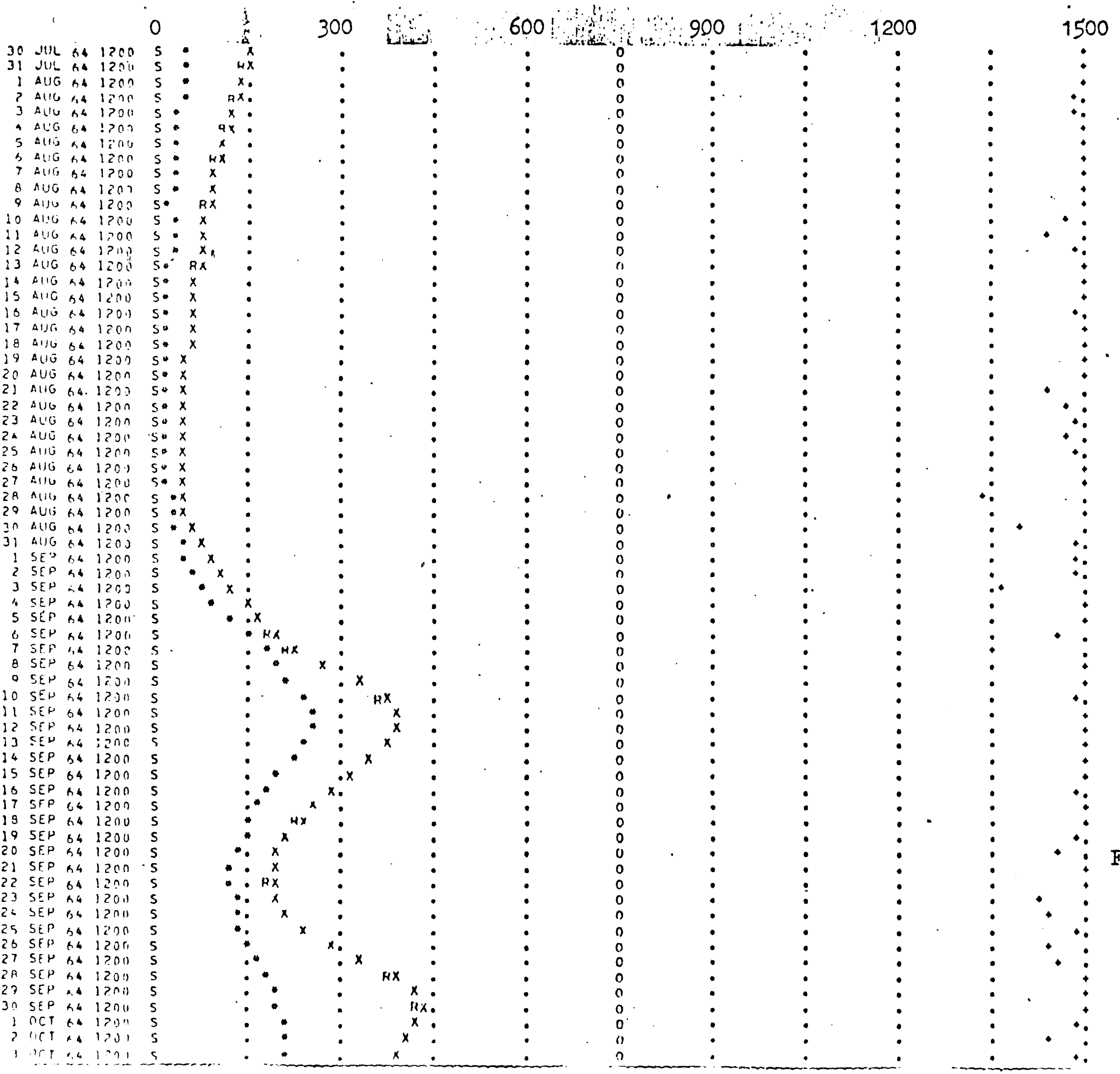
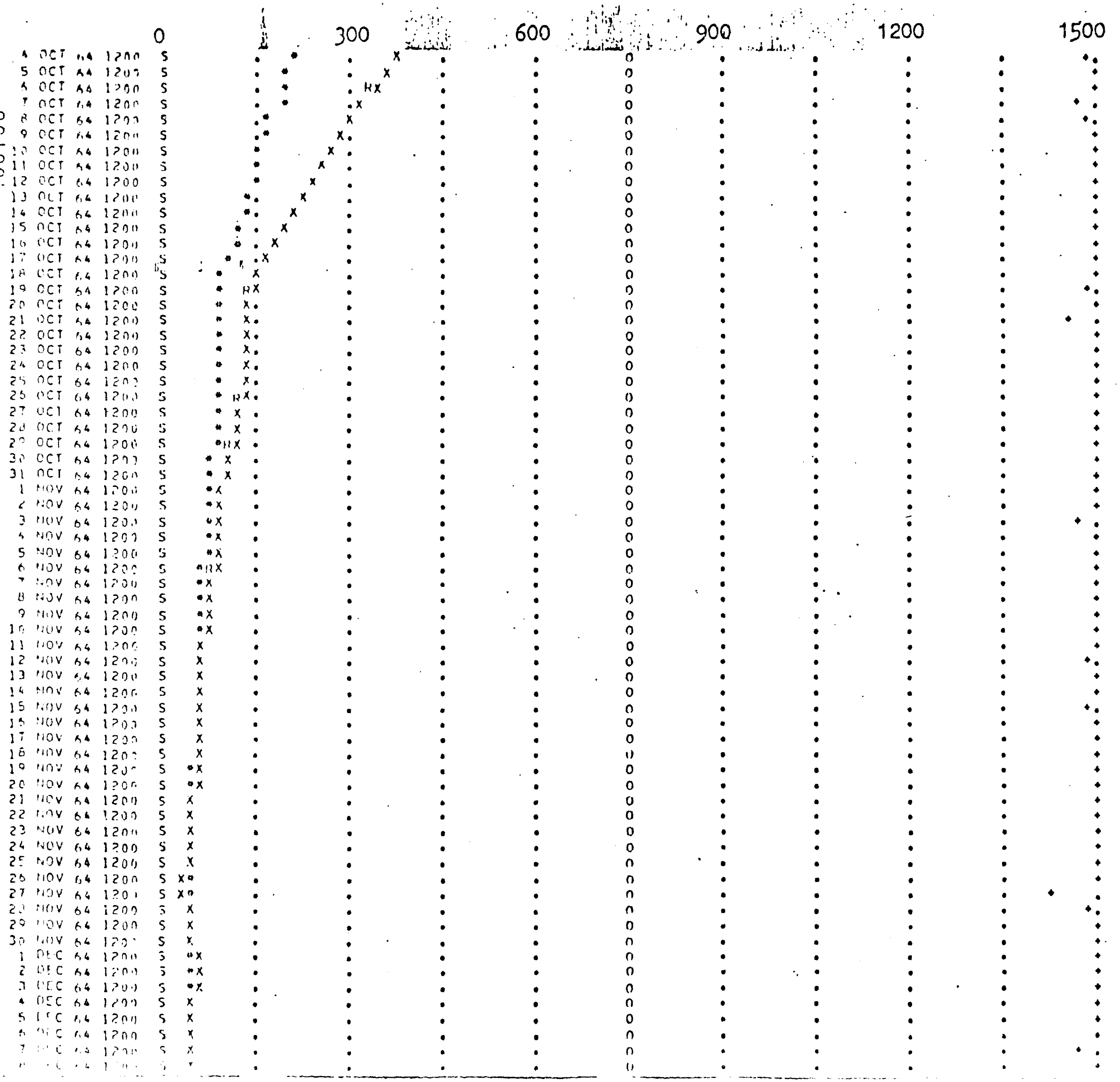


Fig. 15e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27 NOV 64 1200 S
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29 NOV 64 1200 S
30 NOV 64 1200 S
1 DEC 64 1200 S
2 DEC 64 1200 S
3 DEC 64 1200 S
4 DEC 64 1200 S
5 DEC 64 1200 S
6 DEC 64 1200 S
7 DEC 64 1200 S

Fig. 15f

Figure 16 again shows the underprediction of discharge (1962) when rain is falling during the period the snowcover is melted. The rest of the 1962 year results in a good fit for the Stony River, similar to 1964.

The Partridge River in 1975 (Fig. 17) shows fair fit for the entire year, with the exception of June. However, the simulation does show two problems continually encountered while trying to fit the parameters. For 1975 the snowcover is not really adequately defined for the watershed. Thus the calculated discharge is not as good as it should be. Associated with this may be the inability of the Degree-day method of the SSARR to model snow runoff in northern Minnesota. The snowpack may vary over the watershed a great deal, but the SSARR lumps the snowpack water equivalent into one number. The extrapolation of the water equivalent and other factors, such as the temperature, meltrate, and percentage of the watershed covered with snow may be inadequate for certain years.

The second problem is the problem of rain gauge density. Large storms can move through the watershed and not be picked up by the very sparse gauge system of northeastern Minnesota. Underprediction of events frequently results. An associated problem involves raingauge measurements of convective storms. These small storms do not affect the whole watershed, but the model extrapolates the rainfall and large overpredictions can occur.

The summer Filson Creek simulations gave fairly good results as illustrated in Figure 18 during 1975. Several of the summer events were underpredicted. Since the rain gauge data used in the simulation was outside the watershed by a few miles, a comparison was made with the nonrecording gauge in the watershed. Accumulated volumes for approximately two week periods were compared. When the watershed received more rain than recording gauge, the calculated outflow shoud be underpredicted. It did this during the time periods May 17, 1976 to June 17, 1976 and June 1, 1977 to June 20, 1977. When the recording gauge receives more than the watershed, the model should overpredict. The model did this during the time period June 15, 1976 to July 1, 1976. During the period May 16, 1977 to June 1, 1977, the two gauges agreed fairly closely. The computed outflow was fairly close to the observed discharges.

```
 17 1200  0.00 100  5.81  0.00   0    0   0  0.0   0  0.00  0.00  0.00  5  0.00  .00  80     1     0     0     1  1200 17
 18 1200  0.00 100  5.81  0.00   0    0   0  0.0   0  0.00  0.00  0.00  5  0.00  .00  80     0     0     0     1  1200 18
 19 1200  0.00 100  5.81  0.00   0    0   0  0.0   0  0.00  0.00  0.00  5  0.00  .00  80     0     0     0     1  1200 19
 20 1200  0.00 100  5.81  0.00   0    0   0  0.0   0  0.00  0.00  0.00  5  0.00  .00  80     0     0     0     1  1200 20
 21 1200  0.00 100  5.81  0.00   0    0   0  0.0   0  0.00  0.00  0.00  5  0.00  .00  80     0     0     0     1  1200 21
 22 1200   .03 100  5.82  0.00   0    0   0  0.0   0  0.00   .03  0.00  5   .00  .00  80     0     0     0     1  1200 22
 23 1200   .01 100  5.82  0.00   0    0   0  0.0   0  0.00   .01   .01  5   .00  .00  80     0     0     0     1  1200 23
 24 1200  0.00 100  5.82  0.00   0    0   0  0.0   0  0.00  0.00   .00  5  0.00  .00  80     0     0     0     1  1200 24
 25 1200  0.00 100  5.82  0.00   0    0   0  0.0   0  0.00  0.00  0.00  5  0.00  .00  80     0     0     0     1  1200 25
 26 1200  0.00 100  5.82  0.00   0    0   0  0.0   0  0.00  0.00  0.00  5  0.00  .00  80     0     0     0     1  1200 26
 27 1200   .01 100  5.82  0.00   0    0   0  0.0   0  0.00   .01  0.00  5   .00  .00  80     0     0     0     1  1200 27
 28 1200  0.01 100  5.82  0.00   0    0   0  0.0   0  0.00  0.00  0.00  5  0.00  .00  80     0     0     0     1  1200 28
 29 1200  0.00 100  5.82  0.00   0    0   0  0.0   0  0.00  0.00  0.00  5  0.00  .00  80     0     0     0     1  1200 29
 30 1200  0.00 100  5.82  0.00   0    0   0  0.0   0  0.00  0.00  0.00  5  0.00  .00  80     0     0     0     1  1200 30

 * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

FINAL FILE OF TIME RECORDS FOR OUTPUT AND PLOT IS ON UNIT 21

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                                             PLOT      STATION NAME                                  STATION
                                           CHARACTER                                                  NUMBER CONTROL

                                                X-CALCULATRD FLOW STONY RIVER                              7.7   Q
                                                S-SNOW BASIN,STONY RIVER                                  25.5   Q
                                                R-RAIN BASIN,STONY RIVER                                 125.5   Q
                                                *-OBSERVED FLOWS                                        5125.5   Q
FLOW CFS         0.       150.      300.      450.      600.      750.      900.     1050.     1200.     1350.     1500.
PHC 40683 100+                                                         100        0
                                       +                                                -4068  3  100.
              10.00      9.00      8.00      7.00      6.00      5.00      4.00      3.00      2.00      1.00      0.00
END
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 26 JAN 62 1200  R* X      .         .         .         .         .         .         .         .         .         +
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 31 JAN 62 1200  R* X      .         .         .         .         .         .         .         .         .         +
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Fig. 16a - Stony River, 1962, Area = 180 Sq. Mi., SSARR Model.

431455

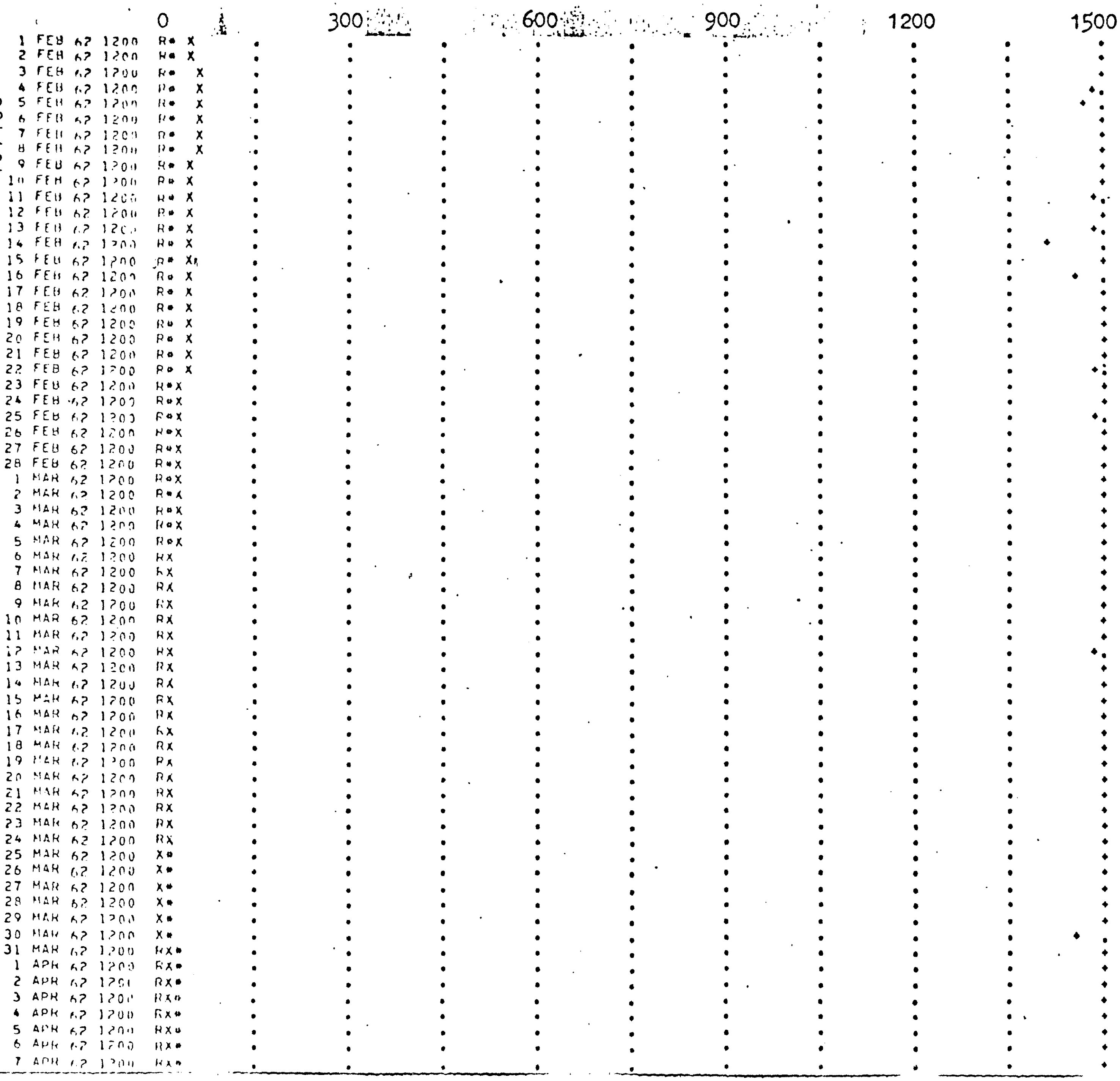


Fig. 16b

431456

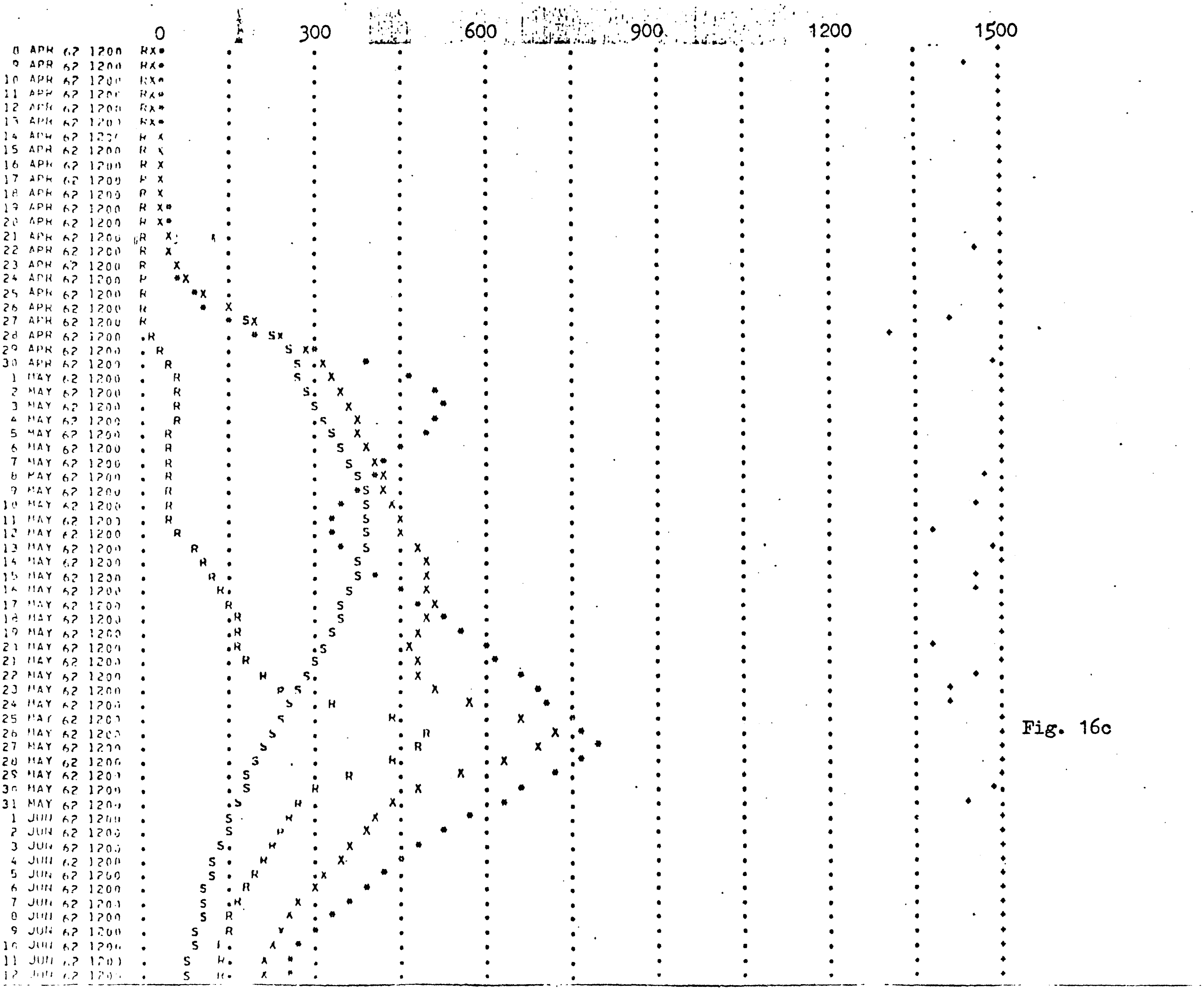
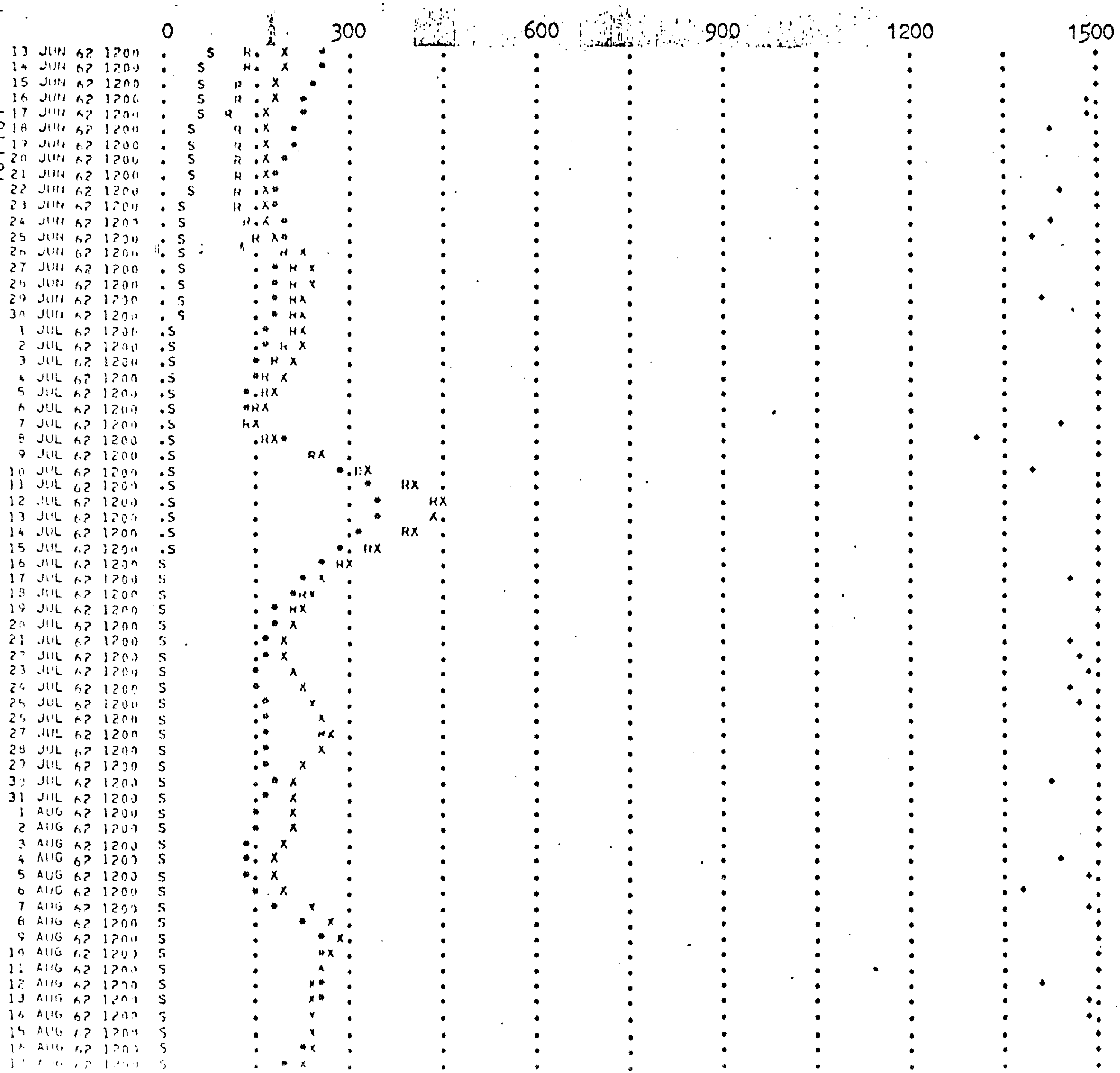


Fig. 16c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S
R
X

Fig. 16d

431458

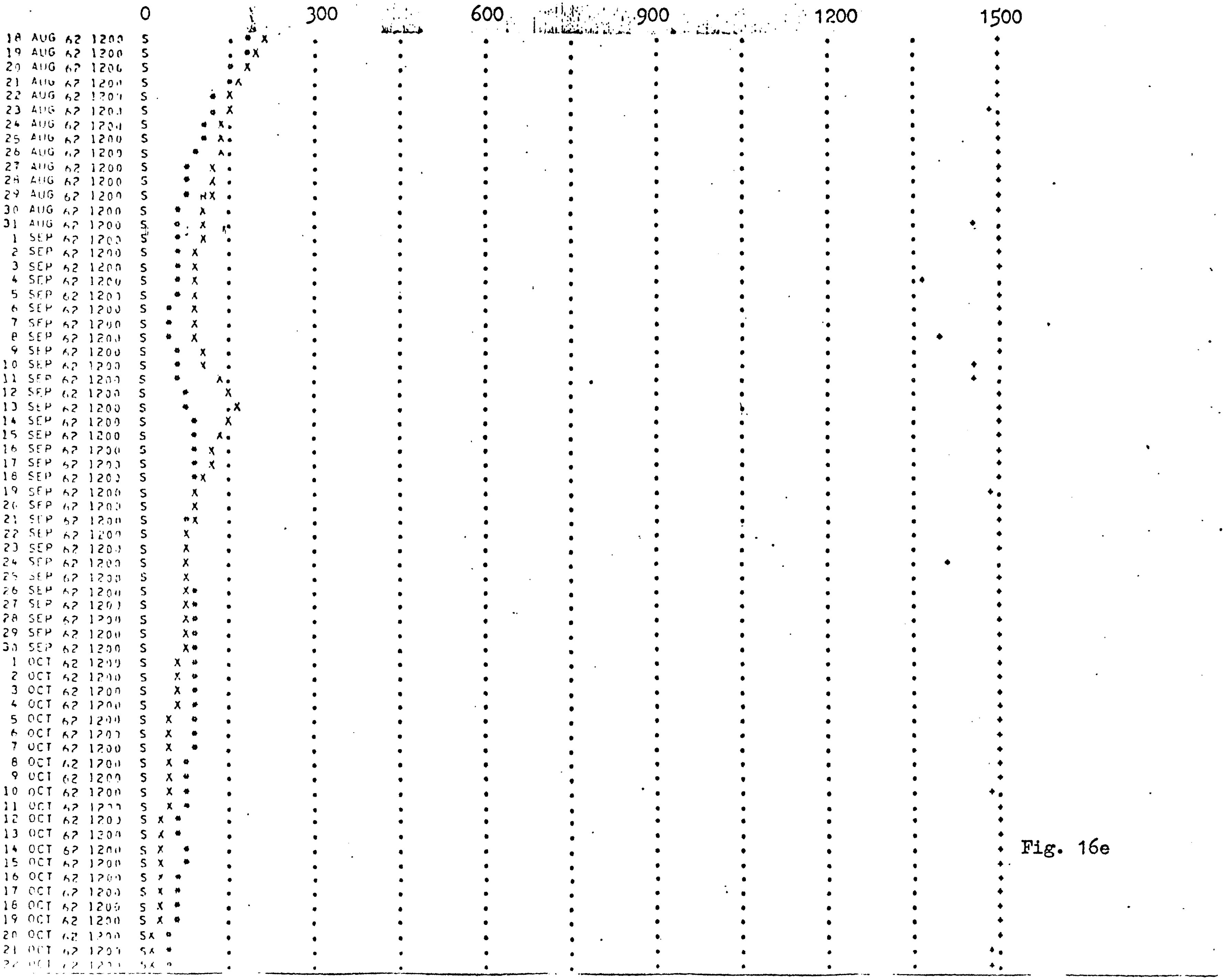


Fig. 16e

431459

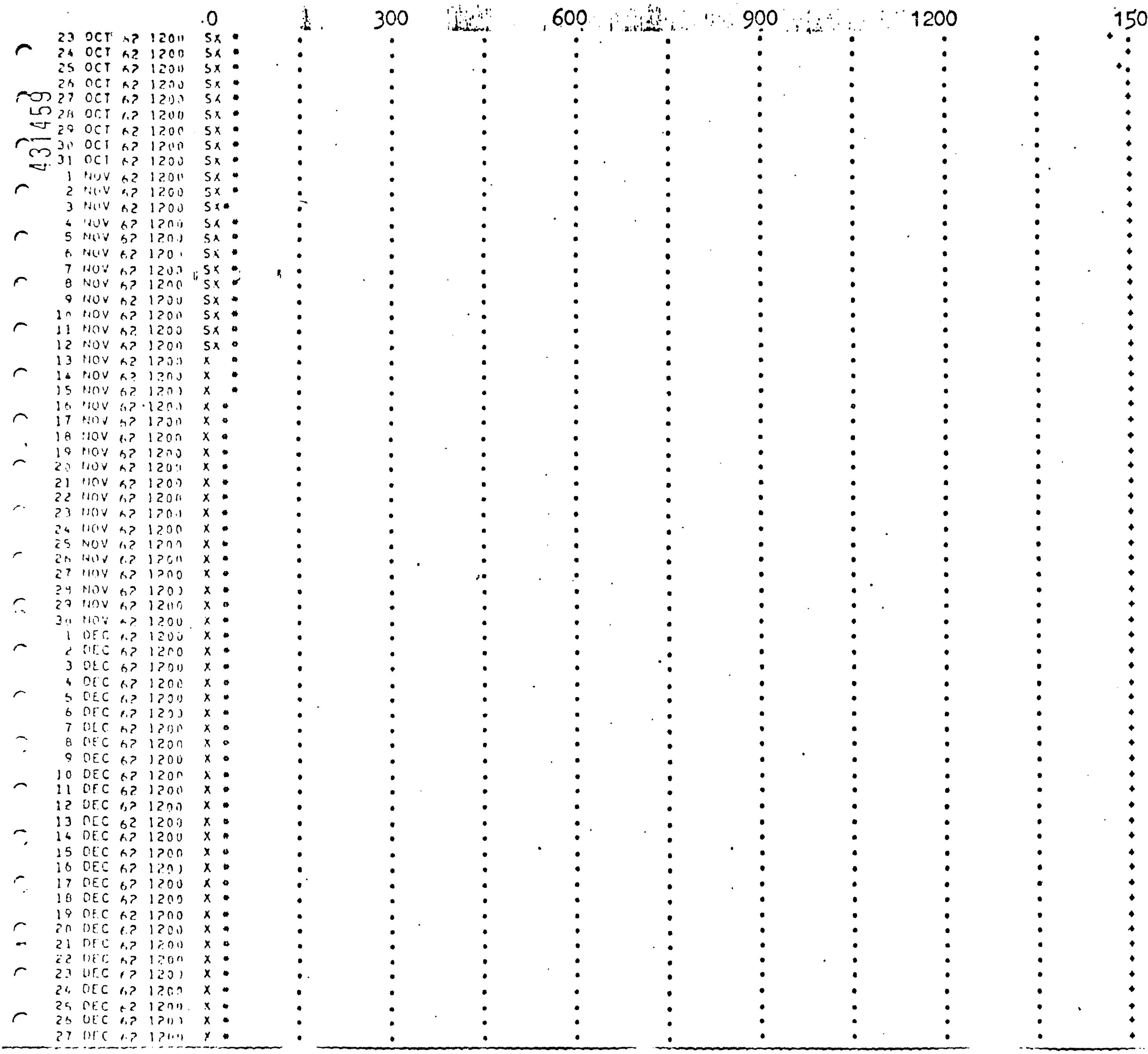


Fig. 16f

```
25 1200   .04 100  5.52  0.00    0     0    0  0.0    0  0.00   .04  1.98  33   .01  .01  77     34       2       2       40  1200 25

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                         BASIN RESULTS - STATION        116.0 RAIN BASIN,PARTRIDGE RIVER
 RUN DATE   RUN NO.   INITIAL DATE, HOUR           JOB DESCRIPTION
                    0      1 MAR 1975  1200   666666666CORRECTED PARTRIDGE RIVER                          N.P.D., CORPS OF ENGINEERS
                                ETI =  .02 IN./DAY, MELT RATE = 0.000 IN./DEGREE-DAY, AREA =  130.0 SQ. MI.
DAY HOUR  PCPN  (RA RN-AR ML-AR (AR ELEV SCA D-DY (MA  MELT      MI   SMI ROP    RGP  BII BFP  BASEF  SUBSF   SURF   DISCH HOUR DAY

DEC 1975                                                                                                            DEC 1975
 26 1200  0.00 100  5.52  0.00    0     0    0  0.0    0  0.00  0.00  1.99  33  0.00  .01  77     34       2       4      41  1200 26
 27 1200  0.00 100  5.52  0.00    0     0    0  0.0    0  0.00  0.00  1.97  33  0.00  .00  78     33       2       3      40  1200 27
 28 1200  0.00 100  5.52  0.00    0     0    0  0.0    0  0.00  0.00  1.95  33  0.00  .00  79     32       2       1      37  1200 28
 29 1200  0.00 100  5.52  0.00    0     0    0  0.0    0  0.00  0.00  1.93  33  0.00  .00  79     31       1       0      34  1200 29
 30 1200  0.00 100  5.52  0.00    0     0    0  0.0    0  0.00  0.00  1.91  32  0.00  .00  80     30       1       0      32  1200 30

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

FINAL FILF OF TIME RECORDS FOR OUTPUT AND PLOT IS ON UNIT 21

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

                                               PLOT      STATION NAME                                STATION
                                             CHARACTER                                               NUMBER CONTROL

                                                  X-CALCULATED FLOW,PARTRIDGE ABOVE SECOND                   6.0   0
                                                  *-OBSERVED FLOW ABOVE SECOND                            4016.0   0
                                                  S-SNOW BASIN,PARTRIDGE RIVER                              16.0   0
                                                  R-RAIN BASIN,PARTRIDGE RIVER                             116.0   0
FLOW CFS          0.       150.      300.      450.      600.      750.      900.     1050.     1200.     1350.     1500.
PHC 39213 100+                                                           100       0
                                                                                -3921  3  100.
                 10.00     9.00      8.00      7.00      6.00      5.00      4.00      3.00      2.00      1.00      0.00
END
    END OF FILE ON INPUT DECK

 1 MAR 75 1200   X*        .         .         .         .         .         .         .         .         .         +
 2 MAR 75 1200   X*        .         .         .         .         .         .         .         .         .         +
 3 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .         +
 4 MAR 75 1200   X*        .         .         .         .         .         .         .         .         .         +
 5 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .         +
 6 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .         +
 7 MAR 75 1200   X*        .         .         .         .         .         .         .         .         .         +
 8 MAR 75 1200   X         .         .         .         .         .         .         .         .         .         +
 9 MAR 75 1200   X*        .         .         .         .         .         .         .         .         .         +
10 MAR 75 1200   X*        .         .         .         .         .         .         .         .         .         +
11 MAR 75 1200   X*        .         .         .         .         .         .         .         .         .         +
12 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .        +.
13 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .         +
14 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .         +
15 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .         +
16 MAR 75 1200   X*        .         .         .         .         .         .         .         .         .         +
17 MAR 75 1200   X*        .         .         .         .         .         .         .         .         .         +
18 MAR 75 1200   X*        .         .         .         .         .         .         .         .         .         +
19 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .        +.
20 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .        +.
21 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .         +
22 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .         +
23 MAR 75 1200   X *       .         .         .         .         .         .         .         .         .         +
24 MAR 75 1200   X*        .         .         .         .         .         .         .         .         .       + .
25 MAR 75 1200   RX        .         .         .         .         .         .         .         .         .         +
26 MAR 75 1200   RX        .         .         .         .         .         .         .         .         .       + .
27 MAR 75 1200   *X        .         .         .         .         .         .         .         .         .        +.
28 MAR 75 1200   *X        .         .         .         .         .         .         .         .         .       + .
29 MAR 75 1200   *X        .         .         .         .         .         .         .         .         .         +
30 MAR 75 1200   *X        .         .         .         .         .         .         .         .         .         +
```

Fig. 17a - Partridge River, 1975, SSARR Model.

826958

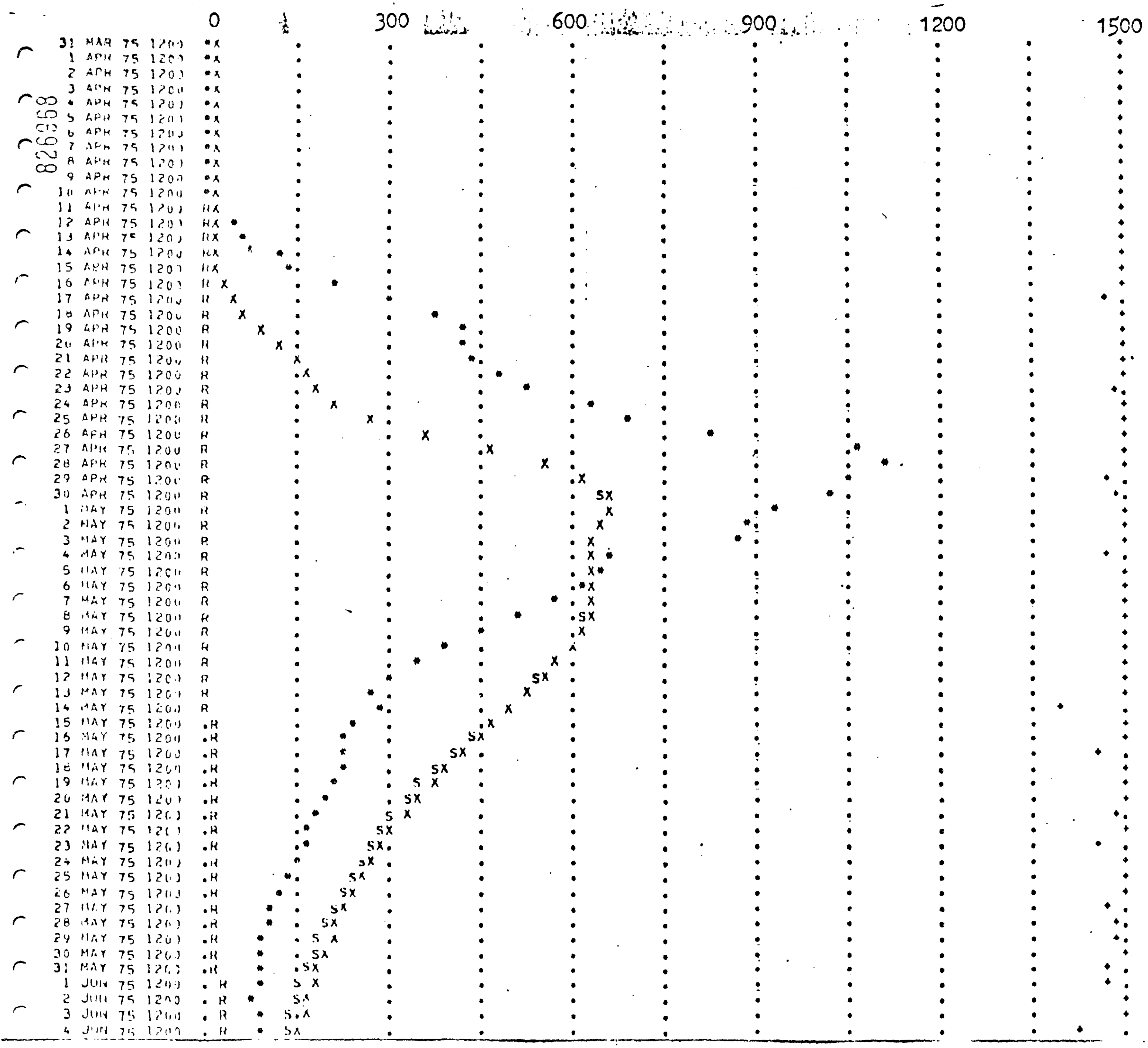
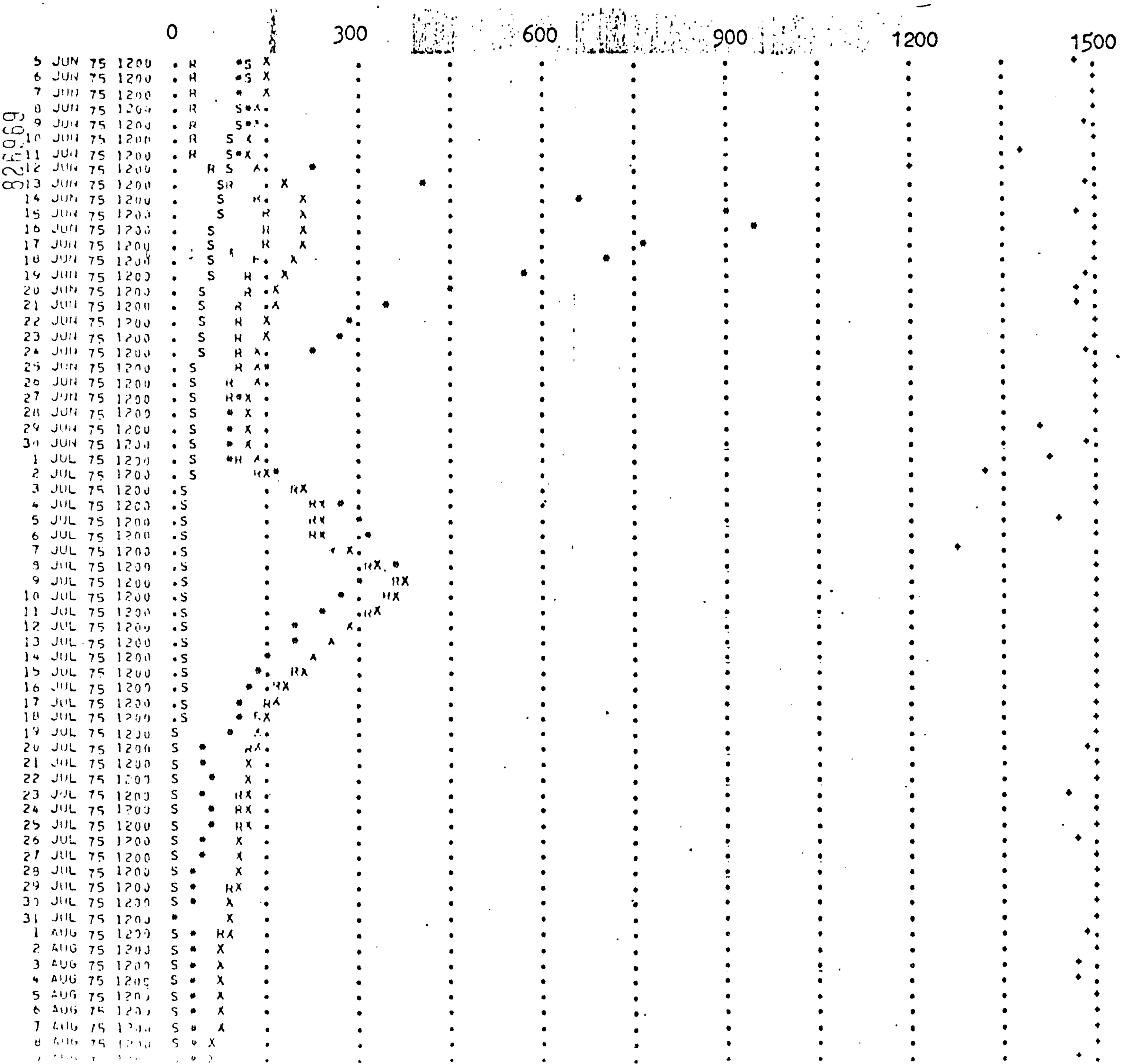


Fig. 17b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1 AUG 75 1200
2 AUG 75 1200
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8 AUG 75 1200
S
R
X

Fig. 17c

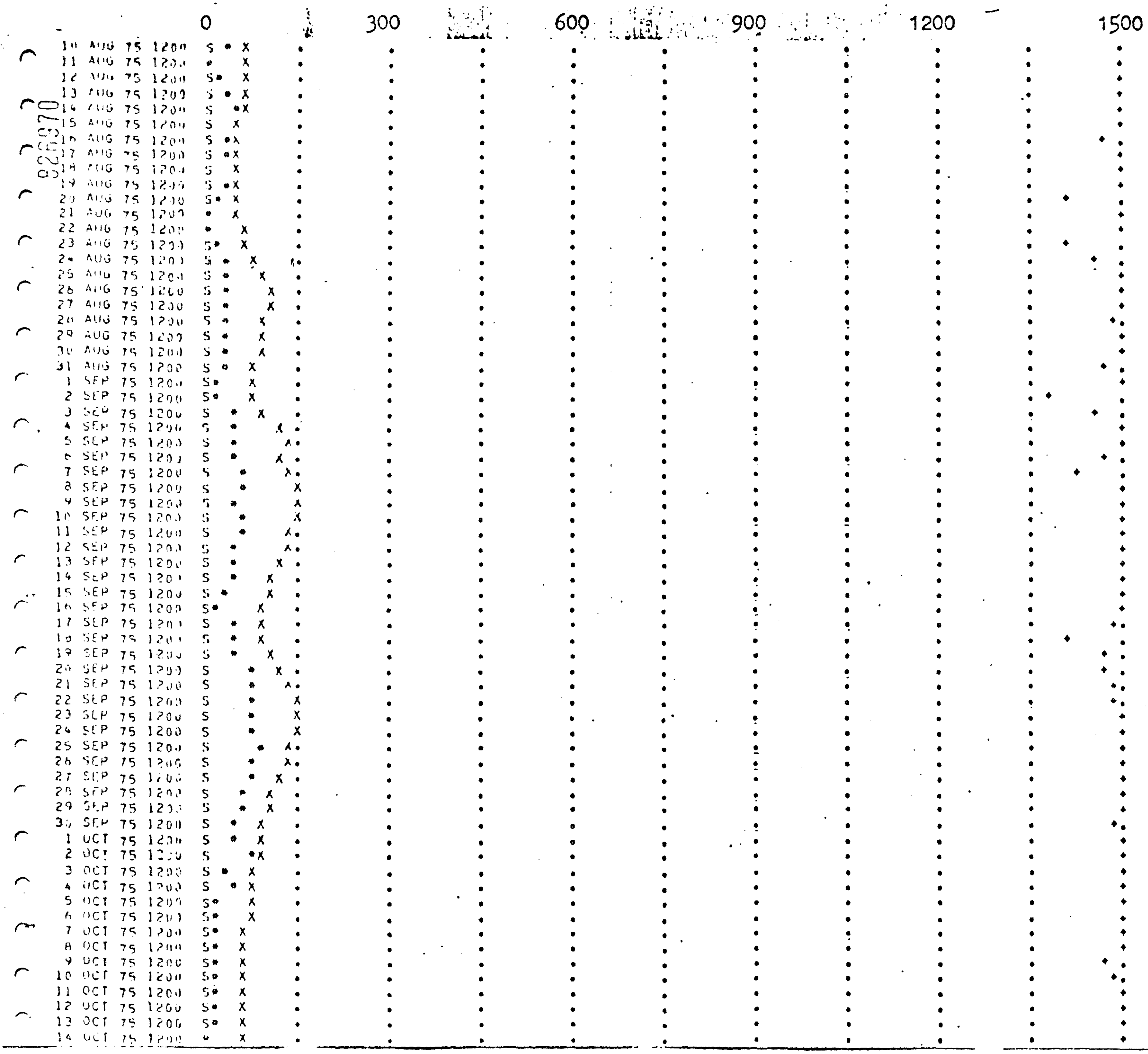
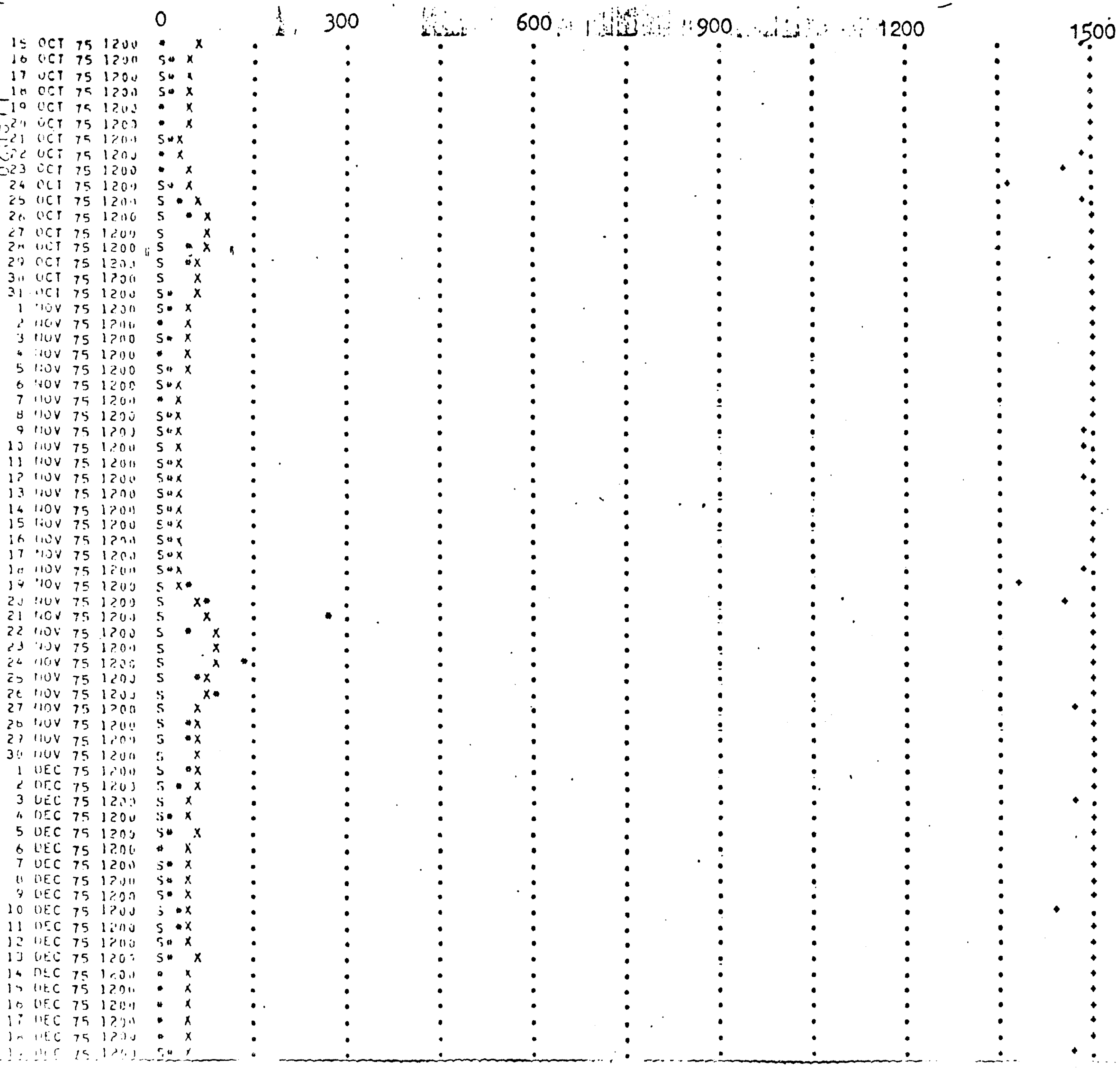


Fig. 17d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1200
1500
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11 DEC 75 1200
12 DEC 75 1200
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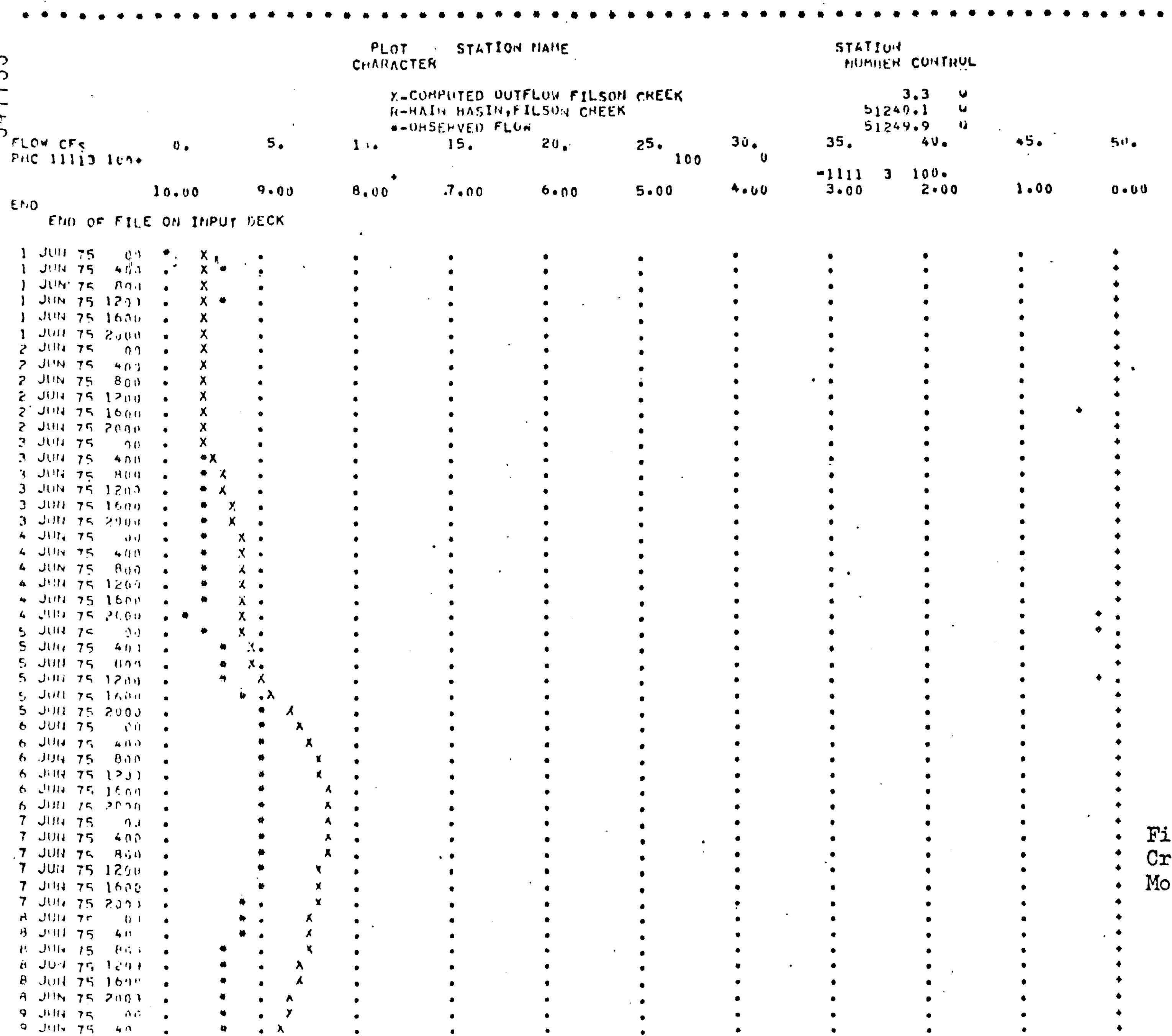
18 DEC 75 1200
19 DEC 75 1200
S
X

Fig. 17e

947793



```
PLOT    STATION NAME                          STATION
CHARACTER                                      NUMBER CONTROL

X-COMPUTED OUTFLOW FILSON CREEK                   3.3    0
R-RAIN BASIN,FILSON CREEK                     51240.1    0
*-OBSERVED FLOW                               51249.9    0
FLOW CFS    0.      5.     10.     15.     20.     25.     30.     35.     40.     45.     50.
PHC 11113 100.                                 100      0
                                                        -1111  3  100.
          10.00    9.00    8.00    7.00    6.00    5.00    4.00    3.00    2.00    1.00    0.00
END
    END OF FILE ON INPUT DECK

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1 JUN 75  400
1 JUN 75  800
1 JUN 75 1200
1 JUN 75 1600
1 JUN 75 2000
2 JUN 75   00
2 JUN 75  400
2 JUN 75  800
2 JUN 75 1200
2 JUN 75 1600
2 JUN 75 2000
3 JUN 75   00
3 JUN 75  400
3 JUN 75  800
3 JUN 75 1200
3 JUN 75 1600
3 JUN 75 2000
4 JUN 75   00
4 JUN 75  400
4 JUN 75  800
4 JUN 75 1200
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5 JUN 75   00
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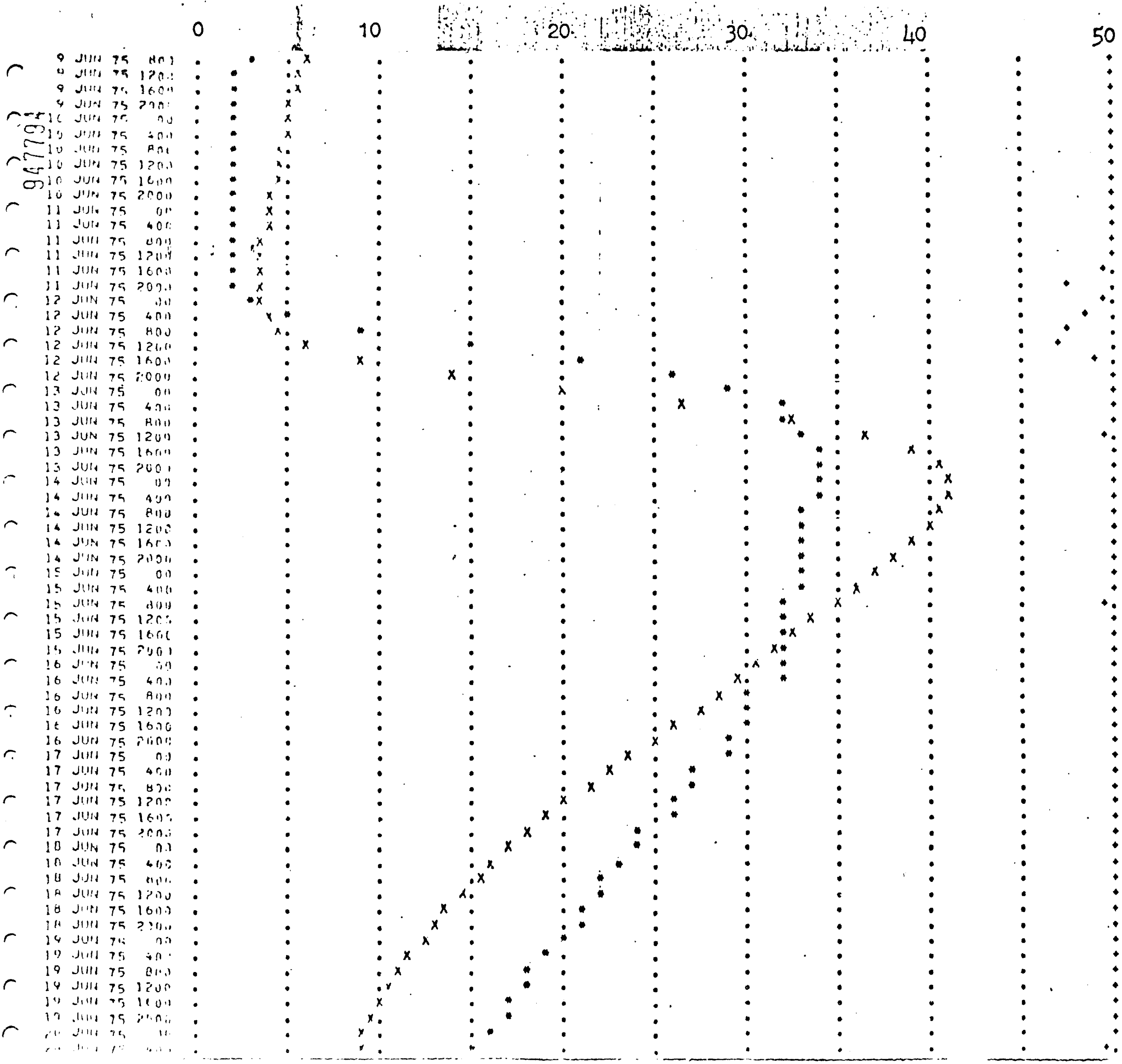
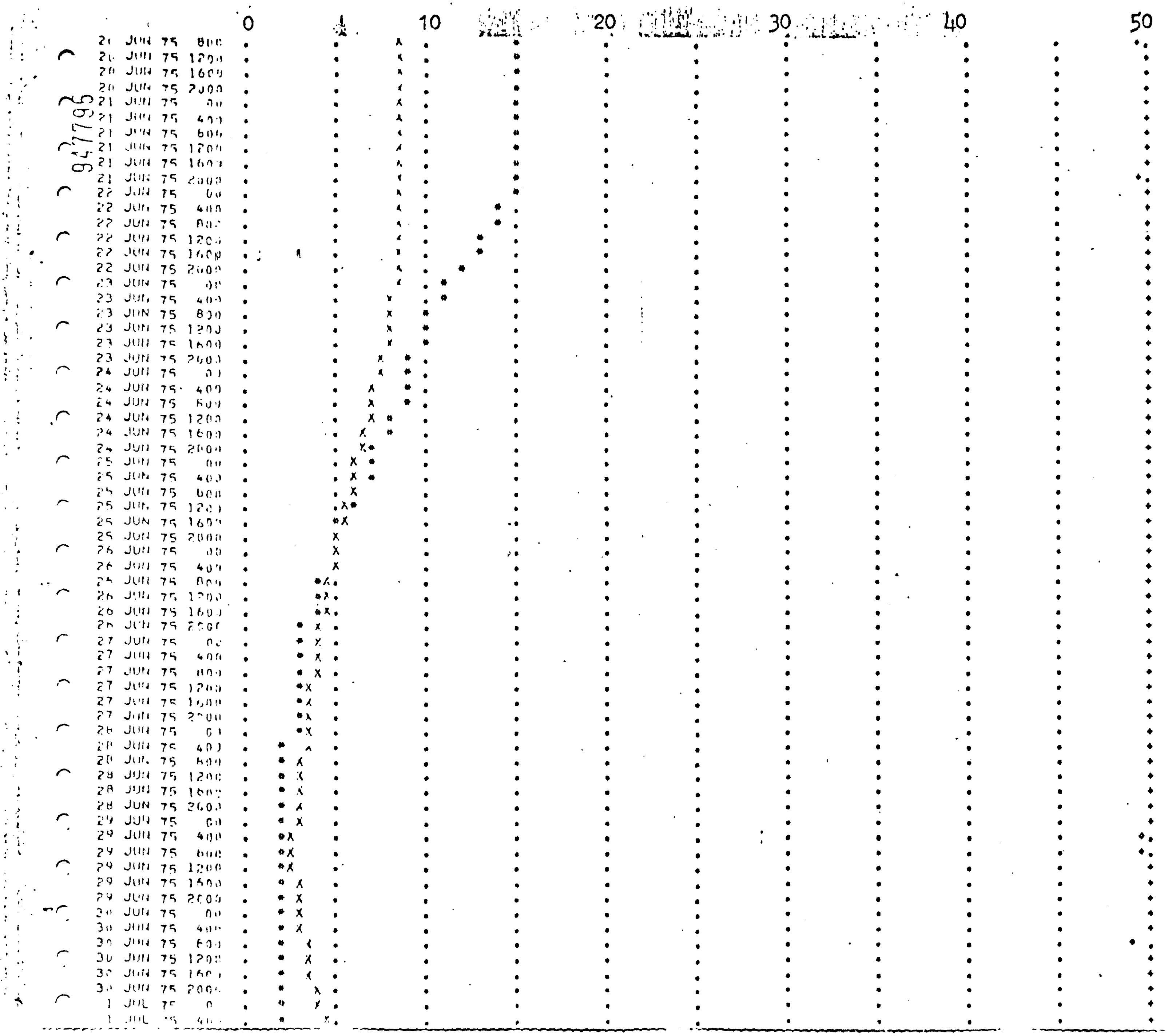
6 JUN 75 1600
6 JUN 75 2000
7 JUN 75   00
7 JUN 75  400
7 JUN 75  800
7 JUN 75 1200
7 JUN 75 1600
7 JUN 75 2000
8 JUN 75   00
8 JUN 75  400
8 JUN 75  800
8 JUN 75 1200
8 JUN 75 1600
8 JUN 75 2000
9 JUN 75   00
9 JUN 75  400
```

Fig. 18a - Filson Creek, 1975, SSARR Model.



947793

Fig. 18b


947795
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23 JUN 75 00
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23 JUN 75 2000
24 JUN 75 00
24 JUN 75 400
24 JUN 75 800
24 JUN 75 1200
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29 JUN 75 800
29 JUN 75 1200
29 JUN 75 1600
29 JUN 75 2000
30 JUN 75 00
30 JUN 75 400
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30 JUN 75 1200
30 JUN 75 1600
30 JUN 75 2000
1 JUL 75 0
1 JUL 75 400

Fig. 18c

947796

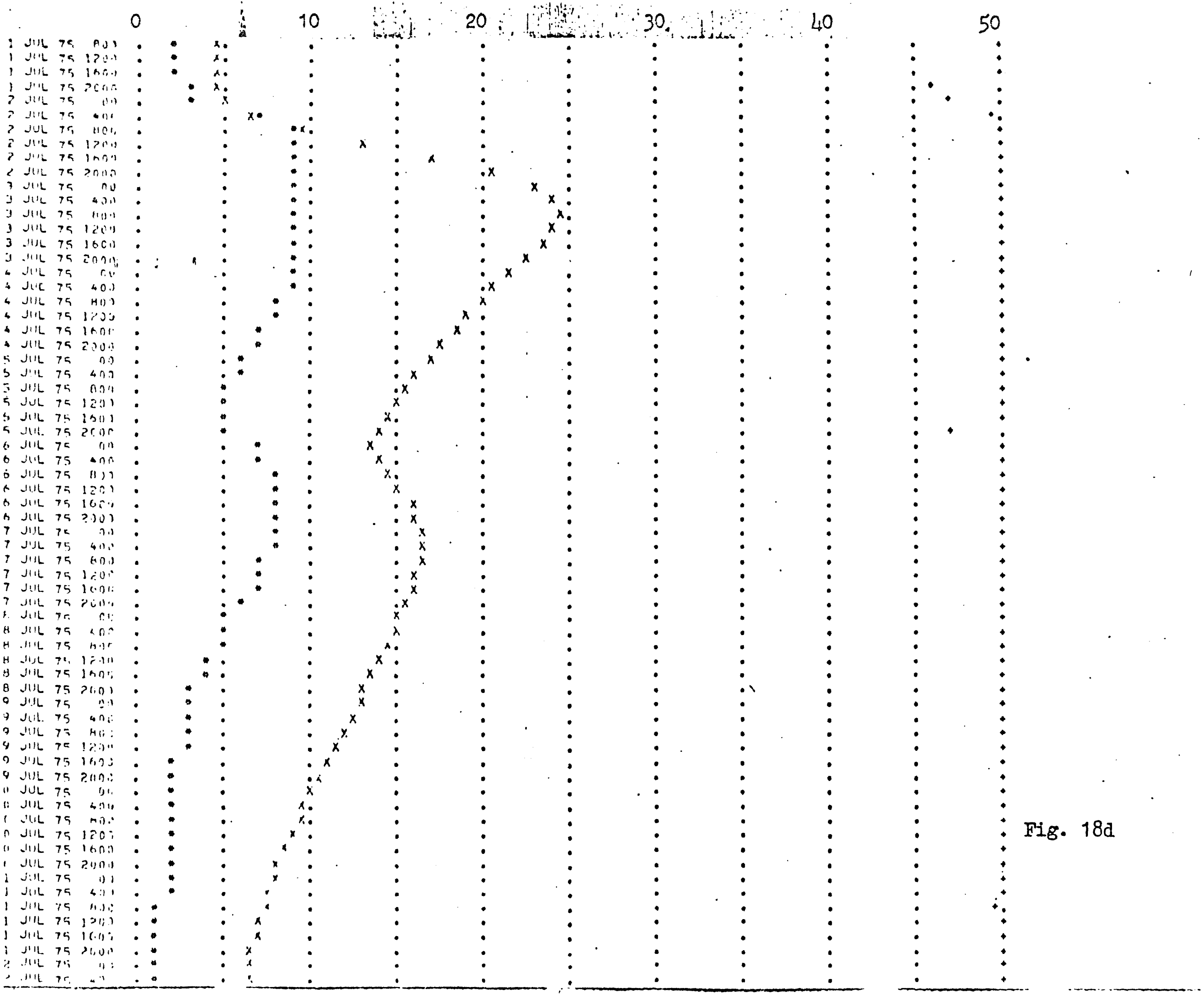


Fig. 18d

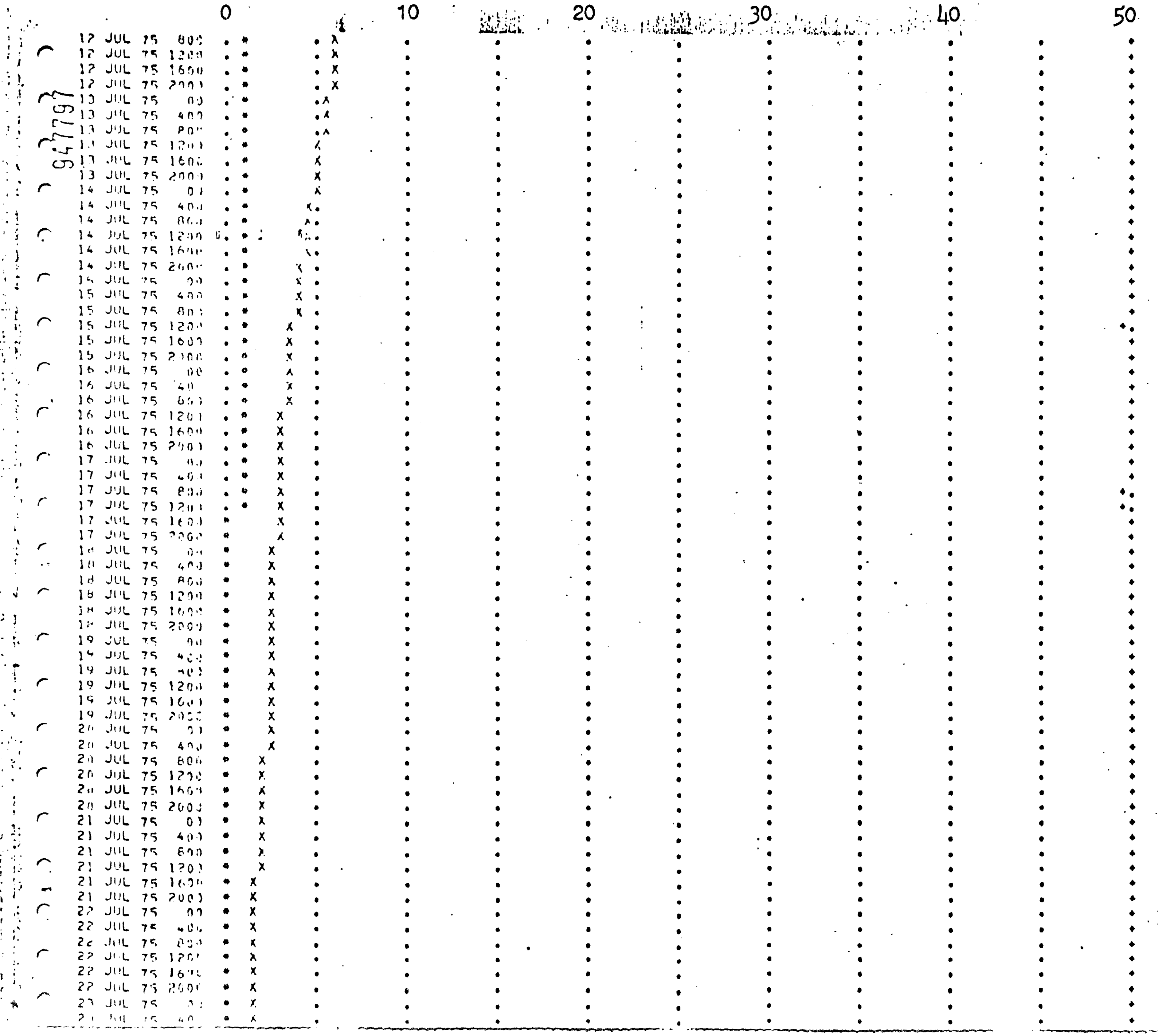


Fig. 18e

947798

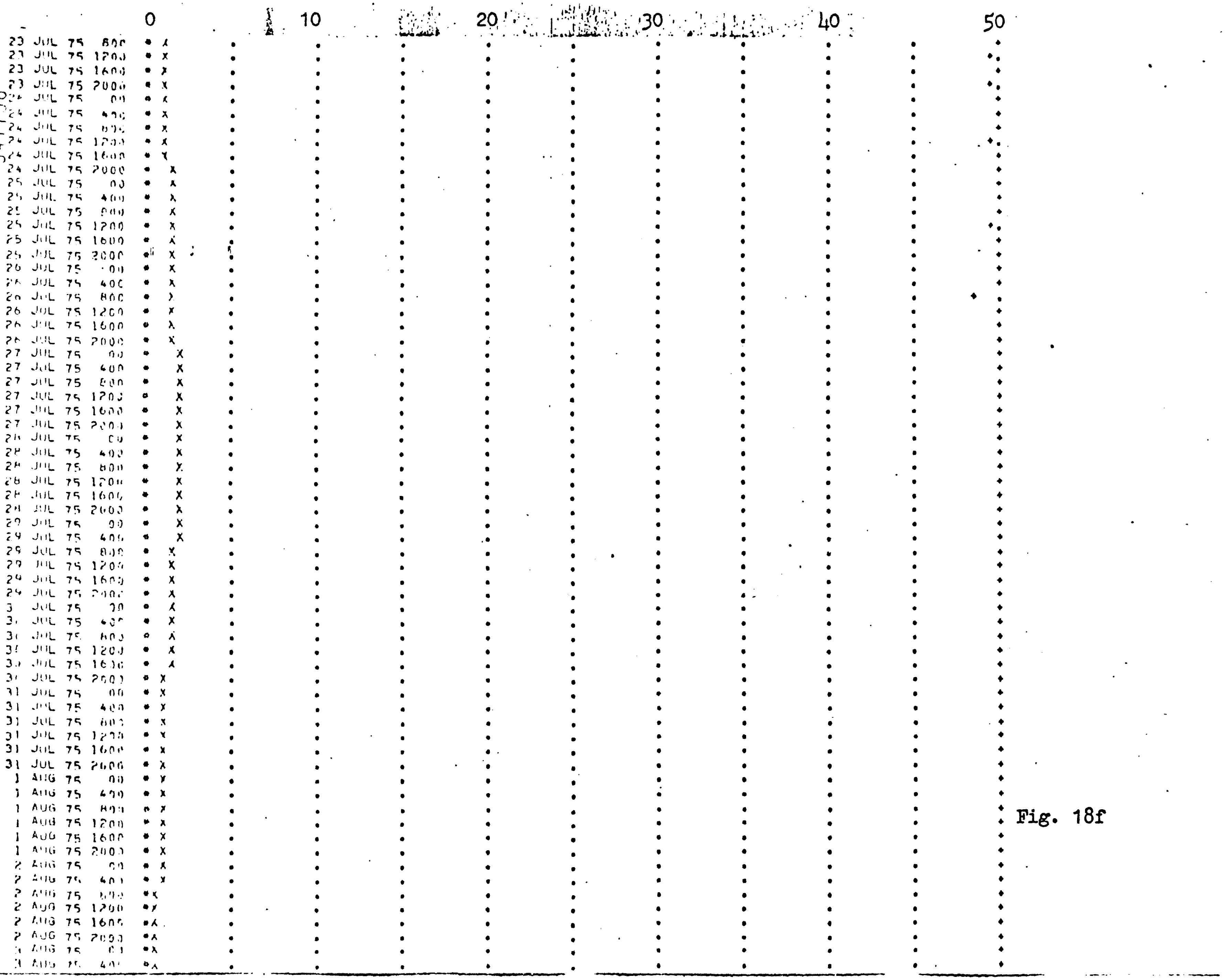
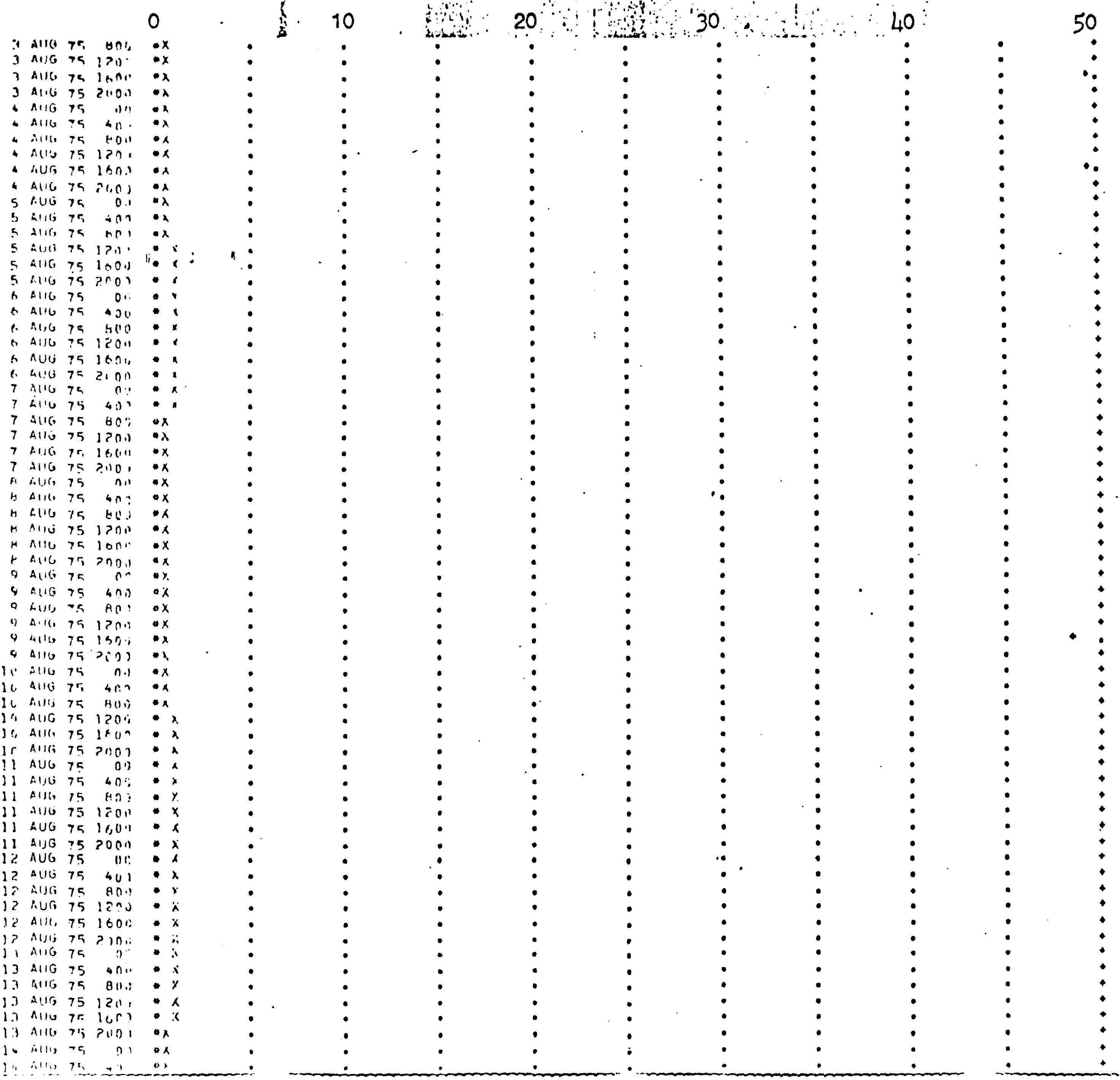


Fig. 18f



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3 AUG 75 800
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3 AUG 75 2000
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Fig. 18g

947800

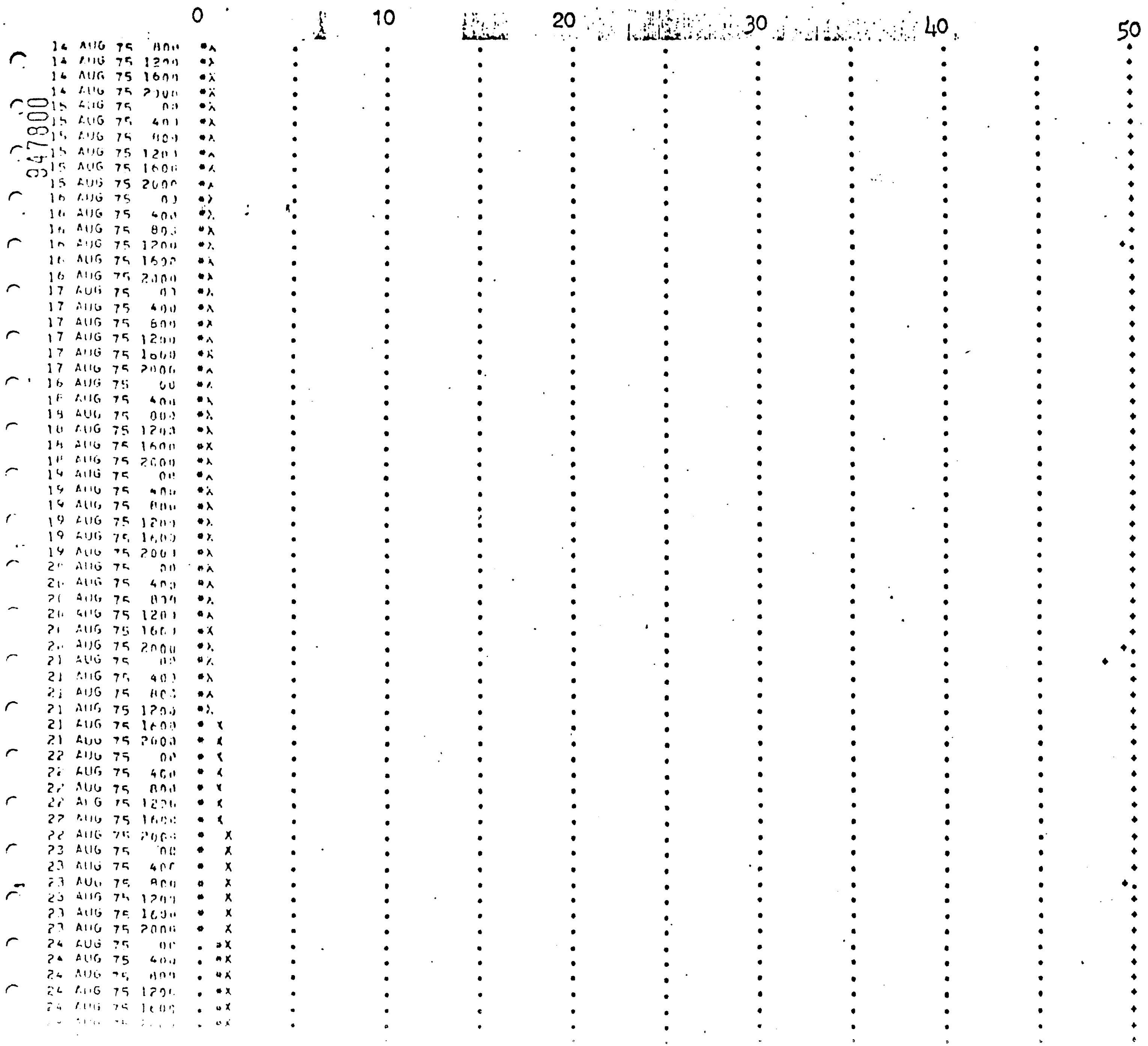

Fig. 18h

Calibration for snowmelt events on Filson Creek was not very good since only one snowmelt event could be simulated. The poor agreement, as shown in Figure 19, may be due to several factors: (1) inaccurate input data for precipitation, initial snowpack conditions, temperature, or observed discharges, (2) failure of the SSARR model to determine runoff rates from snowmelt and rain, and (3) improper use of the model.

In fitting simulation models of this type the tendency is to assume that the computed discharge is wrong whenever differences exist. However, in this case consideration must be given to the fact that ice can cause serious errors in measured discharge and stage due to (1) increased friction losses, (2) ice jams and backwater influences, and (3) frozen riverbeds during severe winters with water from the spring melt flowing over ice. The sharp rise and fall of the discharge on March 29-31, 1976, April 4, 1976, and April 7, 1976 may be sharp increases in stages due to ice problems, with a much lower discharge than the values shown. In an attempt to improve the fit for the data of Figure 18, numerous changes were made in the parameters and in the assumed initial snowpack. It appeared very difficult to improve significantly on the values shown. It is possible that the computed discharge for the simulation is superior to the "observed" values.

In general, the SSARR appears to be able to predict fairly well and should provide useful simulation data for the hydrologic study of the Copper-Nickel area. Further optimization of the parameters is always desirable along with more detailed meteorological data to provide a better predictive tool.

Also, different snowmelt methods, available in the SSARR, should be investigated.

Frequency Analysis

One objective of this study was the determination of the 2, 10, 25, and 100 year floods for the three watersheds. To determine the floods, frequency-events, such as the 100 year-rainstorm or the 100-year-snowcover (March 1-15) were used as input to the SSARR. The computed floods were then synthesized using the input data.

```
15 1000  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  1000 15
15 1100  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  1100 15
15 1200  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  1200 15
15 1300  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  1300 15
15 1400  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  1400 15
15 1500  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  1500 15
15 1600  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  1600 15
15 1700  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  1700 15
15 1800  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  1800 15
15 1900  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  1900 15
15 2000  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  2000 15
15 2100  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  2100 15
15 2200  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  2200 15
15 2300  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0  2300 15
16   00  [illegible]  99  .15  0.00  0  0  0  0.0  0  0.00  0.00  0.00  10  0.00  .00  65     0     0     0     0    00 16

 * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

FINAL FILE OF TIME RECORDS FOR OUTPUT AND PLOT IS ON UNIT 21

 * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

                                     PLOT     STATION NAME                                 STATION
                                   CHARACTER                                                NUMBER CONTROL

                                       X-COMPUTED OUTFLOW FILSON CREEK                           3.3    0
                                       S-SNOW BASIN,FILSON CREEK                             51240.0    0
                                       U-RAIN BASIN,FILSON CREEK                             51240.1    0
                                       *-OBSERVED FLOW                                       51247.9    0
FLOW CFS          0.        15.       30.       45.       60.       75.       90.      105.      120.      135.      150.
PPC 11113 105.                                                       100      0
                                                                                      -1111  3  100.
                 10.00      9.00      8.00      7.00      6.00      5.00      4.00      3.00      2.00      1.00      0.00
E N.
   END OF FILE ON INPUT DECK

15 MAR 76    0   X*        .         .         .         .         .         .         .         .         .         .
15 MAR 76  400   X*        .         .         .         .         .         .         .         .         .         .
15 MAR 76  800   X*        .         .         .         .         .         .         .         .         .         .
15 MAR 76 1200   X*        .         .         .         .         .         .         .         .         .         .
15 MAR 76 1600   X*        .         .         .         .         .         .         .         .         .         .
15 MAR 76 2000   X*        .         .         .         .         .         .         .         .         .         .
16 MAR 76    0   X*        .         .         .         .         .         .         .         .         .         .
16 MAR 76  400   X*        .         .         .         .         .         .         .         .         .         .
16 MAR 76  800   X*        .         .         .         .         .         .         .         .         .         .
16 MAR 76 1200   X*        .         .         .         .         .         .         .         .         .         .
16 MAR 76 1600   X*        .         .         .         .         .         .         .         .         .         .
16 MAR 76 2000   X*        .         .         .         .         .         .         .         .         .         .
17 MAR 76    0   X*        .         .         .         .         .         .         .         .         .         .
17 MAR 76  400   X*        .         .         .         .         .         .         .         .         .         .
17 MAR 76  800   X*        .         .         .         .         .         .         .         .         .         .
17 MAR 76 1200   X*        .         .         .         .         .         .         .         .         .         .
17 MAR 76 1600   X*        .         .         .         .         .         .         .         .         .         .
17 MAR 76 2000   X*        .         .         .         .         .         .         .         .         .         .
18 MAR 76    0   X*        .         .         .         .         .         .         .         .         .         .
18 MAR 76  400   X*        .         .         .         .         .         .         .         .         .         .
18 MAR 76  800   X*        .         .         .         .         .         .         .         .         .         .
18 MAR 76 1200   X*        .         .         .         .         .         .         .         .         .         .
18 MAR 76 1600   X*        .         .         .         .         .         .         .         .         .         .
18 MAR 76 2000   X*        .         .         .         .         .         .         .         .         .         .
19 MAR 76    0   X*        .         .         .         .         .         .         .         .         .         .
19 MAR 76  400   X*        .         .         .         .         .         .         .         .         .         .
19 MAR 76  800   X*        .         .         .         .         .         .         .         .         .         .
19 MAR 76 1200   X*        .         .         .         .         .         .         .         .         .         .
19 MAR 76 1600   X*        .         .         .         .         .         .         .         .         .         .
19 MAR 76 2000   X*        .         .         .         .         .         .         .         .         .         .
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Fig. 19a - Filson Creek, 1976, SSARR Model.

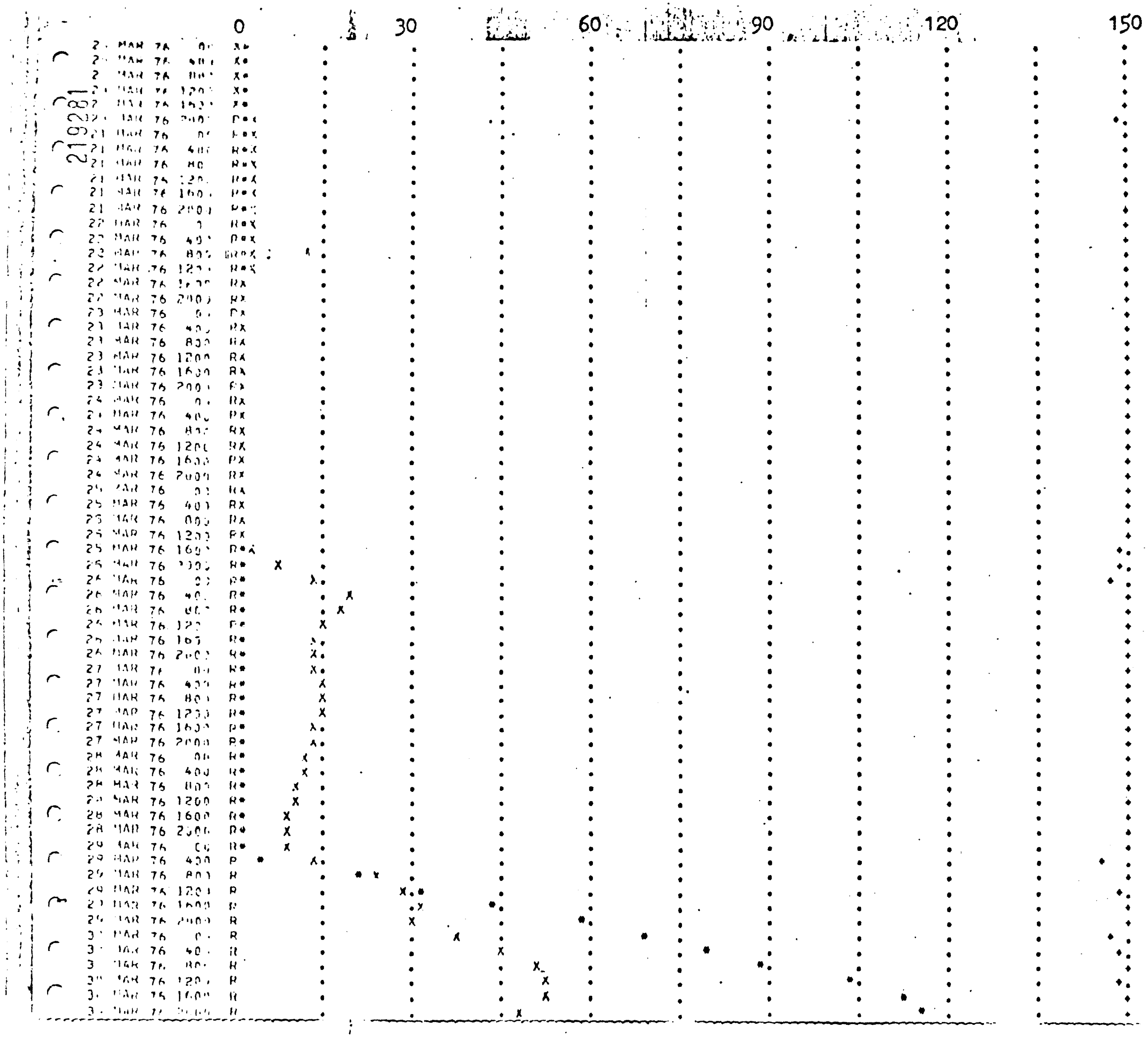
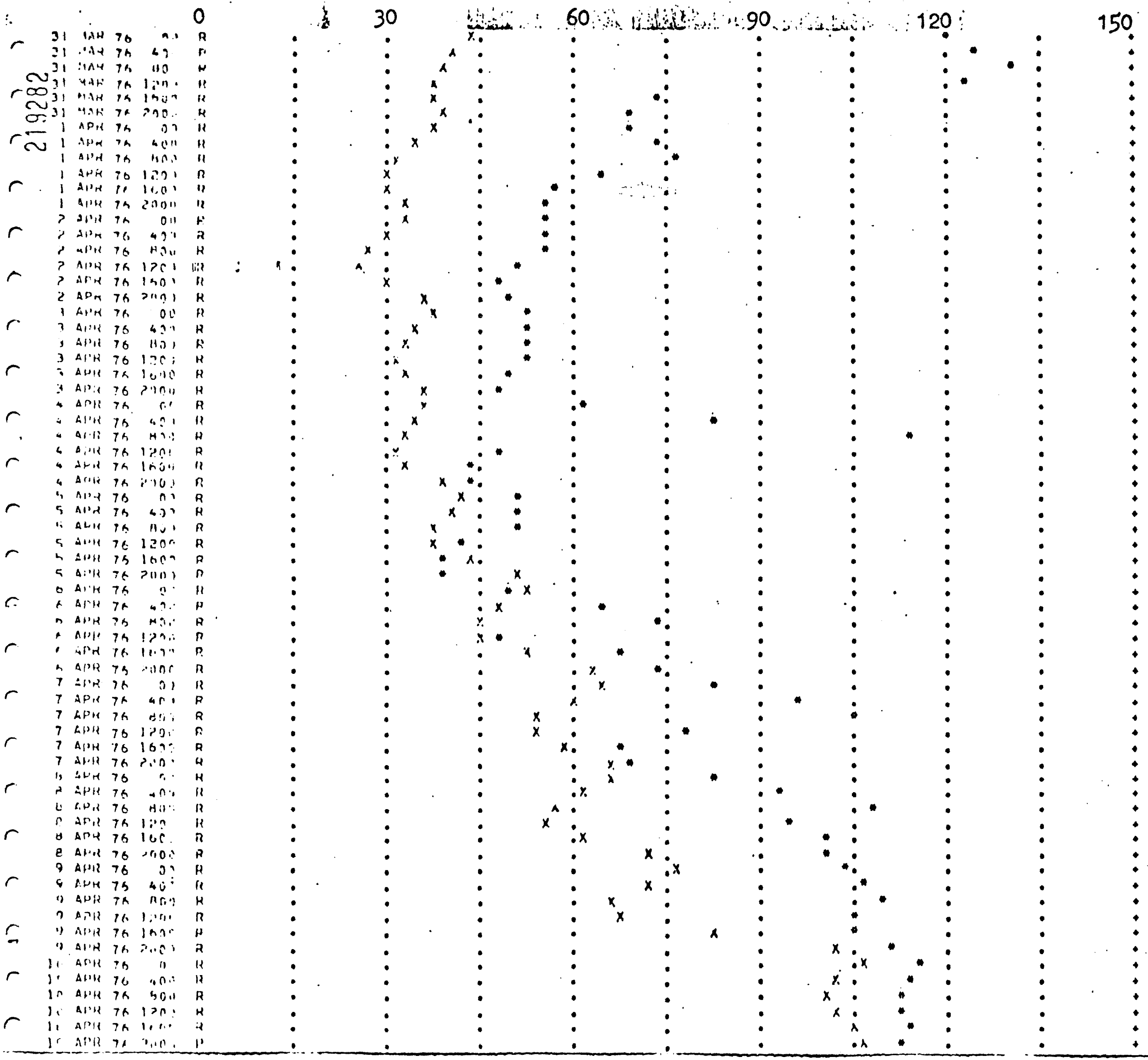


Fig. 19b


0
30
60
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31 MAR 76 00 R
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31 MAR 76 1600 R
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1 APR 76 800 R
1 APR 76 1200 R
1 APR 76 1600 R
1 APR 76 2000 R
2 APR 76 00 R
2 APR 76 400 R
2 APR 76 800 R
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2 APR 76 1600 R
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9 APR 76 1600 R
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10 APR 76 2000 R
219282

Fig. 19c

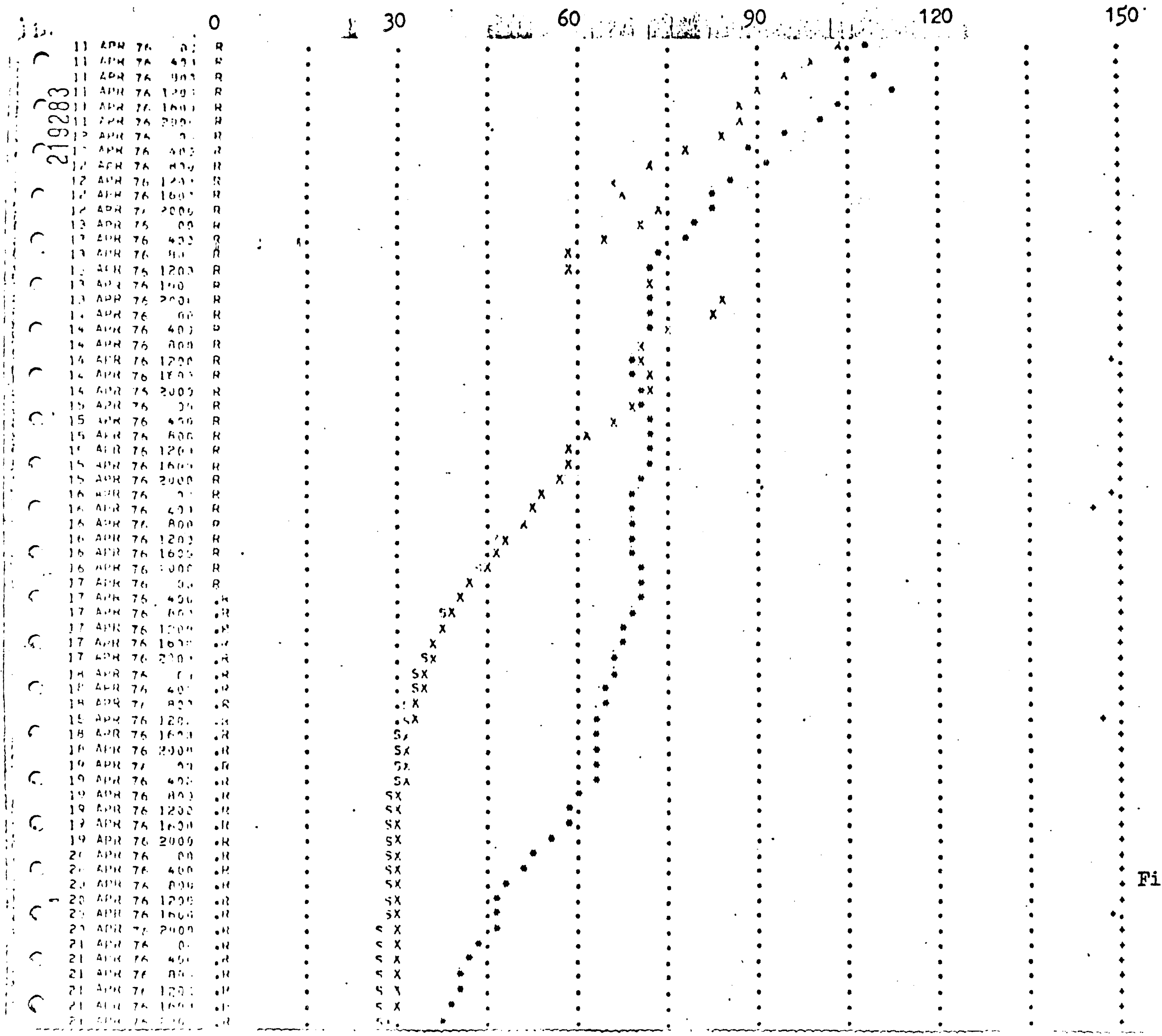
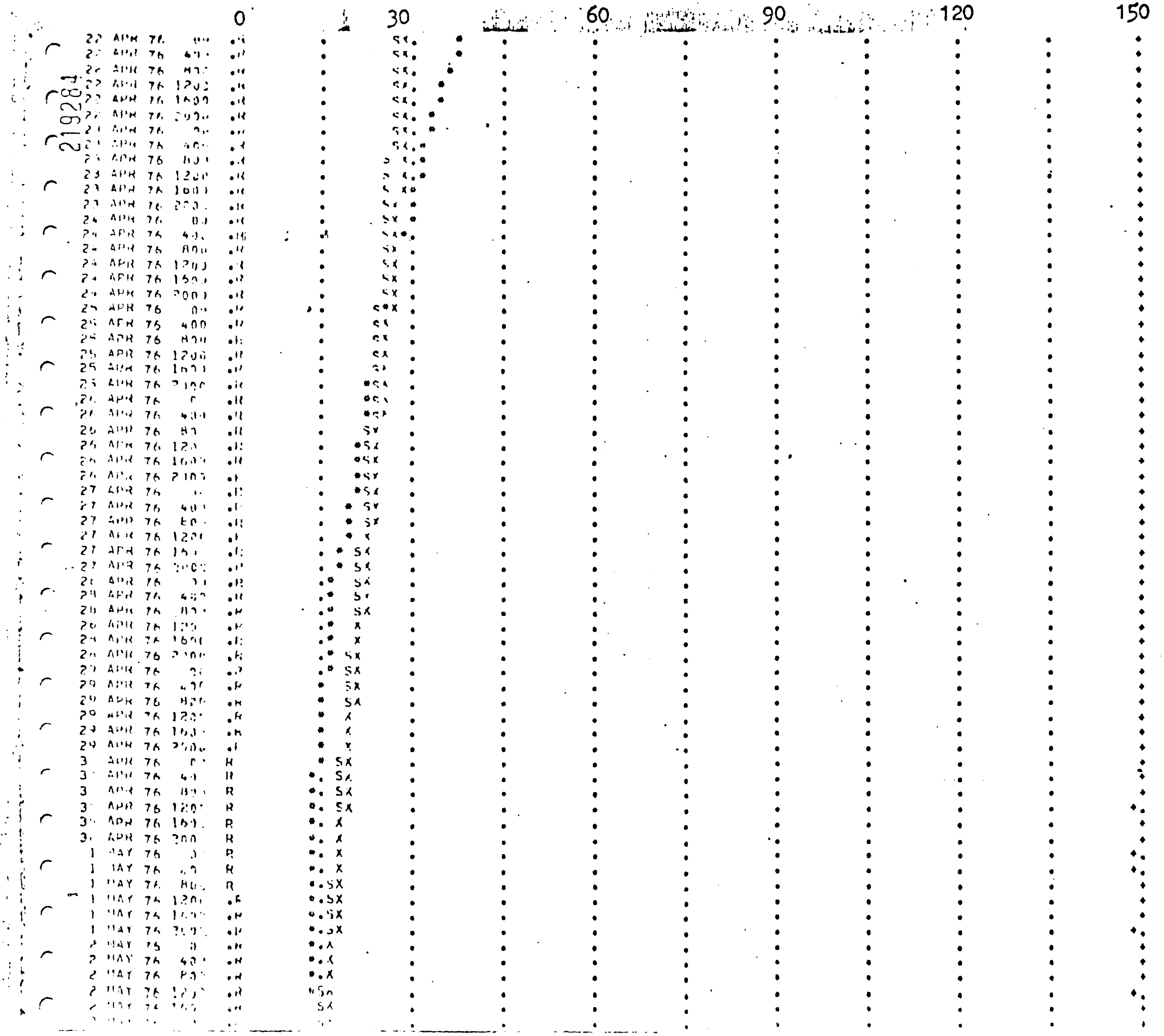


Fig. 19d


0
30
60
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120
150
22 APR 76
23 APR 76
24 APR 76
25 APR 76
26 APR 76
27 APR 76
29 APR 76
1 MAY 76
2 MAY 76
SX
219284

Fig. 19e

219285

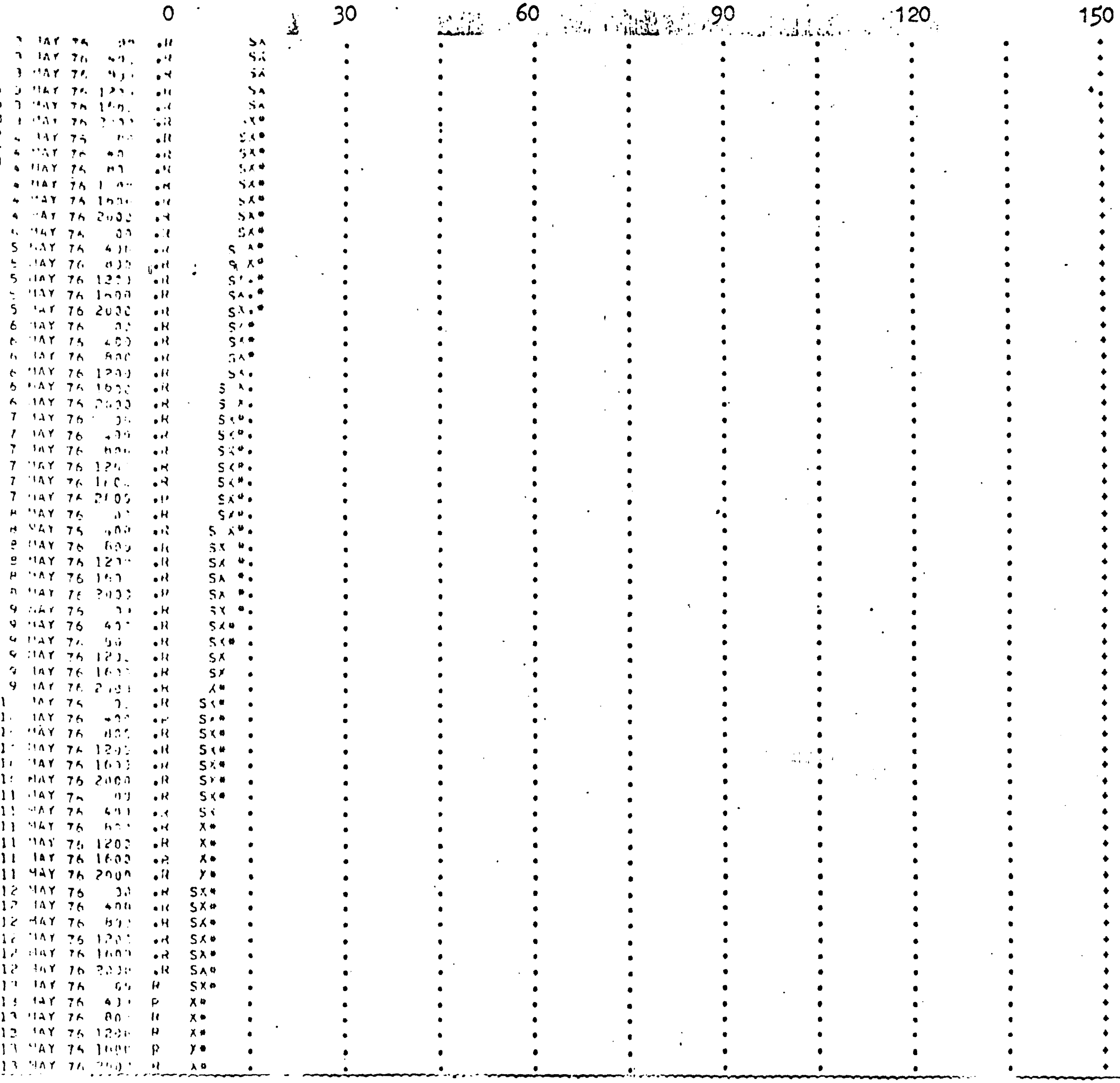


Fig. 19f

For the Stony and Partridge River watersheds the 2, 10, 25, and 100 year 10 day precipitation events were used as input. For Filson Creek only the one day events of the same frequency were used. The precipitation amounts were determined from TP 40 and TP 49 of the National Weather Service. Incremental values were determined within the time period and the storm rearranged around the middle of either the 10 day or 1 day event, as shown in Figure 20. Depth-area corrections were applied to translate the point rainfall data across the watershed.

The snowmelt floods used the 2, 10, 25, and 100 year snowcover equivalents as of March 1-15, determined from Corps of Engineers maps. The temperature cycle was fixed for all snowmelt events as the 1964 record of Isabella. Also, the rainfall record from Isabella for the same year was chosen and fixed as the rainfall pattern to determine flood frequencies. A stochastic analysis might provide for better data input, but time and funds did not permit a full evaluation of temperature cycles and rainfall events in association with snowmelt. Since Filson Creek needed hourly temperature readings, and Isabella had only daily minimum and maximum temperatures, a temperature cycle was synthesised from them. Using the daily minimum temperature at 0300 hours and the daily maximum at 1500 hours, a sine curve approximation was used to determine the other hourly readings.

Shown in Table 3 are the resulting peak discharges for each calculated event. Frequency graphs for each watershed were prepared (Figs. 21, 22, and 23). The curves derived from the data seem to be a good approximation for the desired events.

Possible errors in the frequency analysis could be (1) Improper calibration of the SSARR for infrequent events, (2) Over or under estimation of meteorological events leading to the discharge events, and (3) Over or under estimation of watershed initial conditions.

In general, the results appear feasible. It was anticipated that curves for summer rain floods would be below the spring snowmelt "combined" floods because many of the annual floods in this region are snowmelt-rain combined floods. However, for Filson Creek they differ by a factor of 3. This may be realistic due to a higher percentage of "high infiltration soils" in the watershed. The hills or raised portions of this area appeared to contain considerable

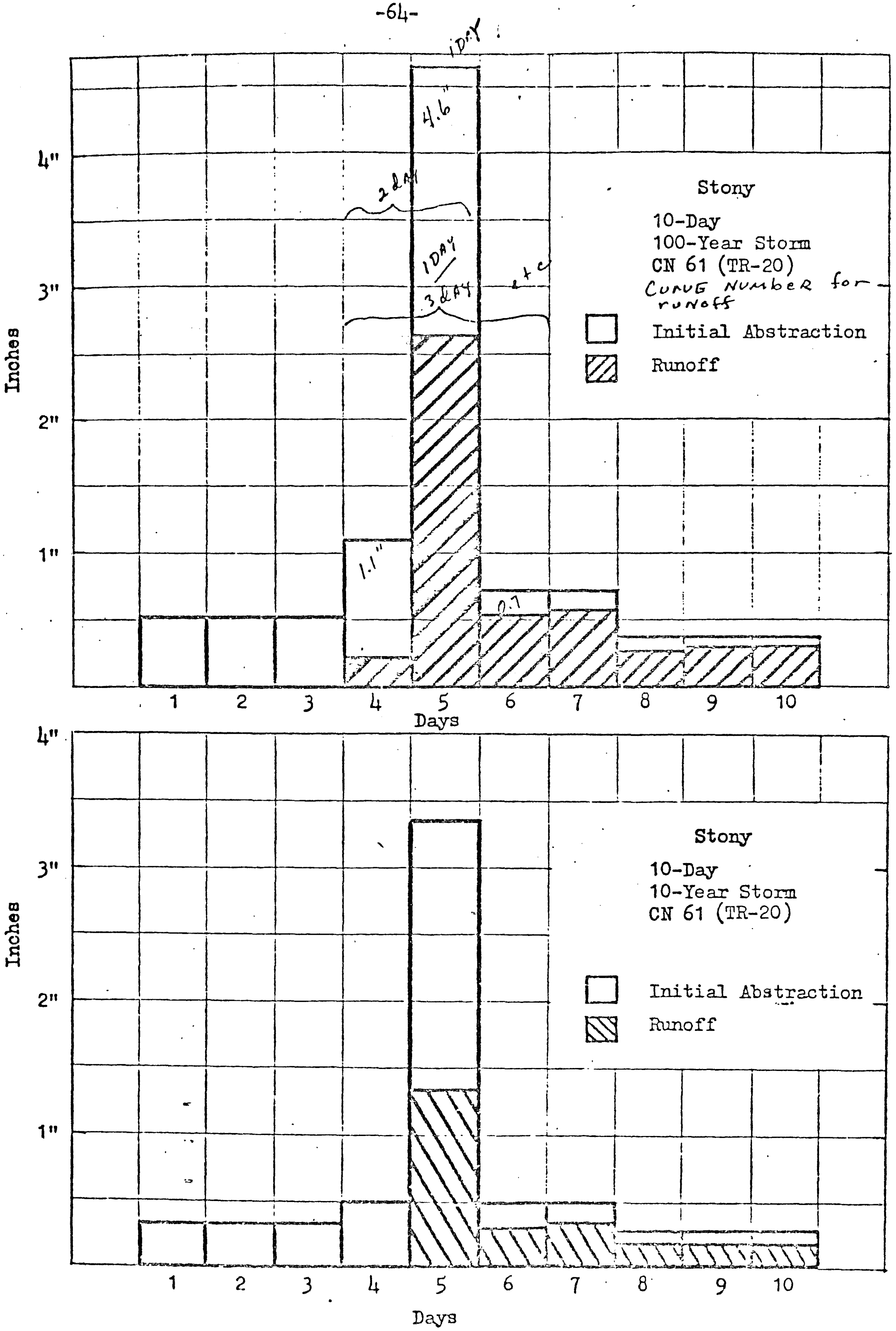


Fig. 20 - Rainstrom Distribution.

Table 3 - Peak Discharge Table - CU-NI Watershed Events, SSARR

Watershed Event	Q_{P_2}	$Q_{P_{10}}$	$Q_{P_{25}}$	$Q_{P_{100}}$	Q_{100}/A ✓
Stony/Rain	355	1041	1386	2295	12.75
Stony/Snow	619 ✓	1300	1940	3169	17.61
Stony/USGS	835	1670	2130	2820	15.67
Partridge/Rain	280	700	1001	1584	12.18
Partridge/Snow	308 ✓	740	1306	2121	16.32
Filson/Rain	32	94	128	204	20.4
Filson/Snow	113 ✓	292	422	533	53.3

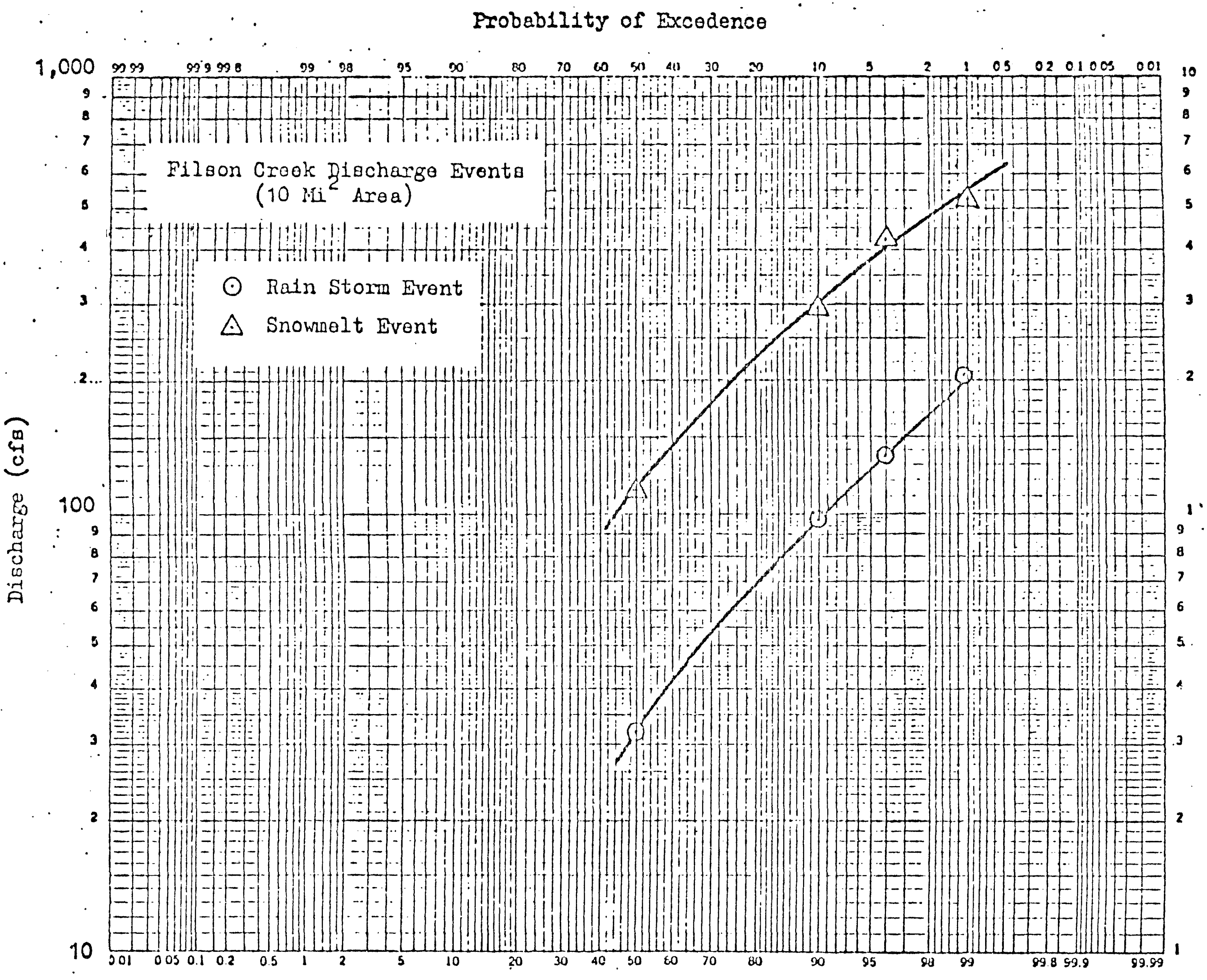


Fig. 21 - Rain and Snowmelt Floods, Determined by SSARR, for Filson Creek.

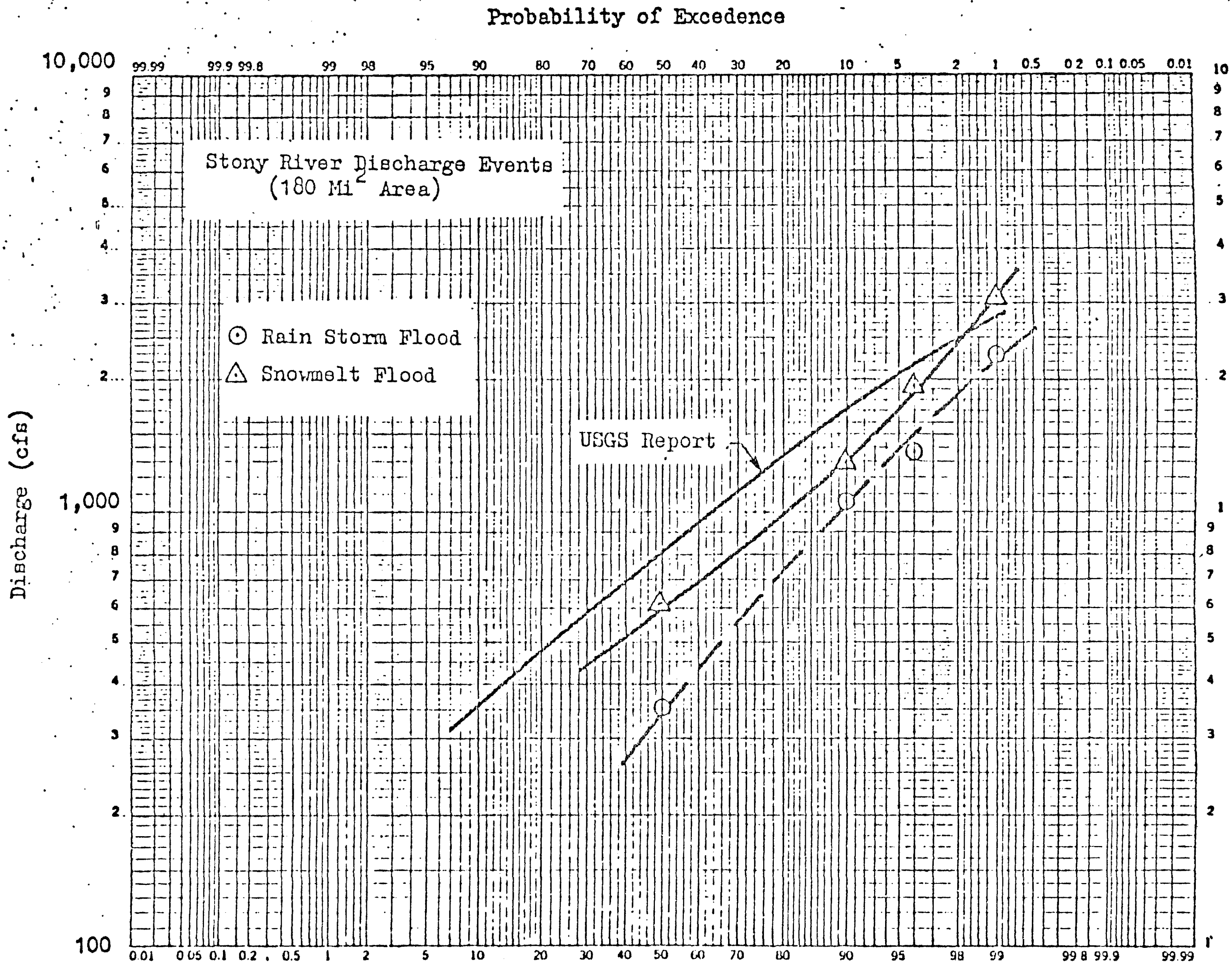


Fig. 22 - Rain and Snowmelt Floods, Determined by SSARR, for Stony River.

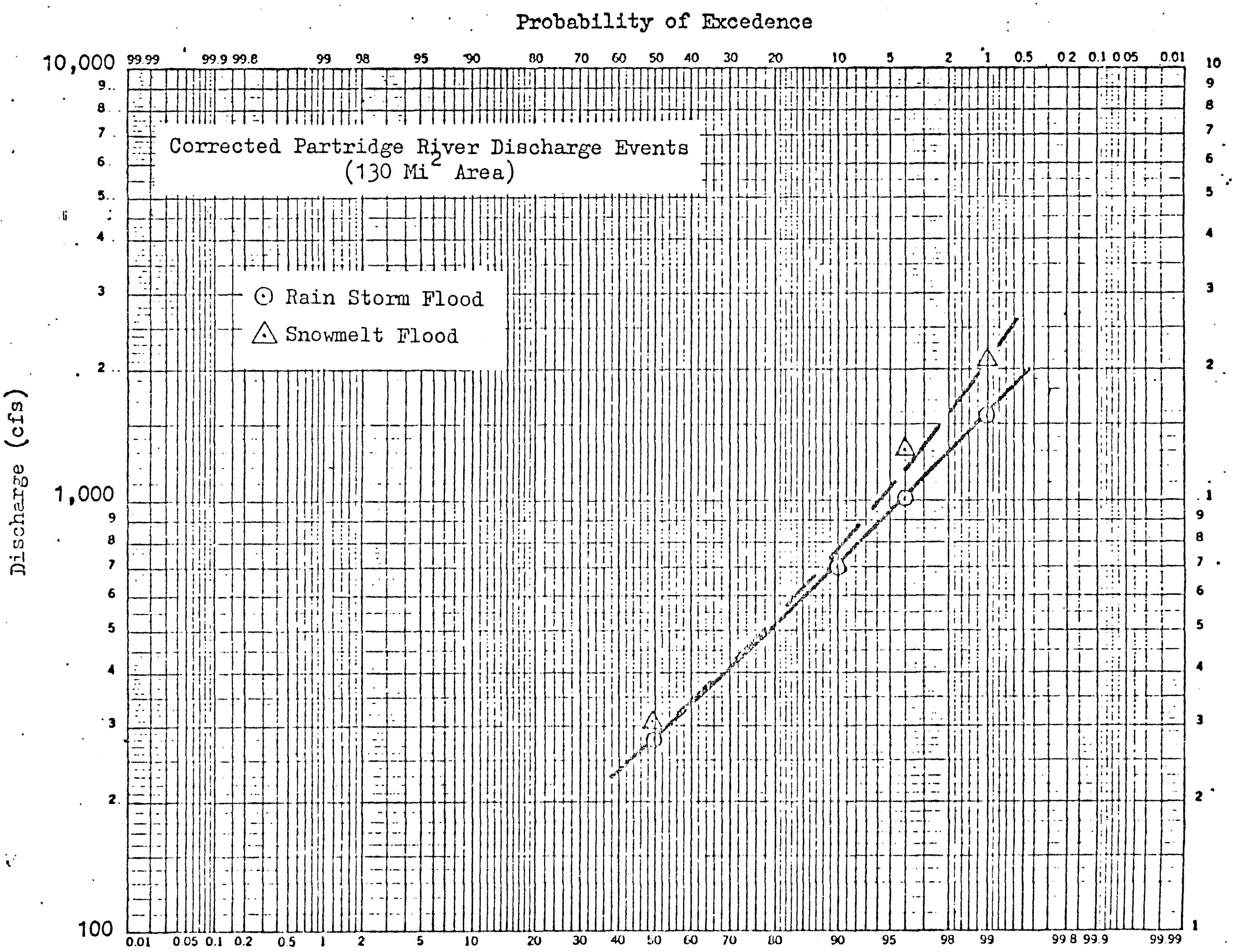


Fig. 23 - Rain and Snowmelt Floods, Determined by SSARR, for Partridge River.

sand and gravel. It is possible that these areas may have a high infiltration rate in summer and a lesser rate in the spring when the ground is frozen. Also, as only about 2 years of data were available to calibrate the Filson Creek watershed, the summer events may have been too small to produce an acceptable calibration.

A curve based on a U.S.G.S. frequency analysis of annual floods for the Stony River is also shown in Figure 22. This curve is based on all annual floods, including snowmelt, and should be compared with the computed snowmelt floods. It may be noted that agreement is excellent for recurrence intervals of 25 to 100 years (probability of occurrence of 4 percent to 1 percent) and good for lower recurrence intervals. This provides considerable support for the SSARR. However, due to the short record on the Stony, both the computed and frequency curve may be a bit low.

TR-20 MODEL

Description of Model

The TR-20 Model was developed by the Hydrology Branch of the Soil Conservation Service. Its primary purpose is for the determination of flood hydrographs with specified recurrance intervals for design purposes. Because these are large events of short duration, the model is designed to be used for single events only. Thus, there is no provision for drying of the soil over time and the representation of baseflow is rudimentary.

The program uses the SCS hydrologic procedures to estimate the runoff pattern. Precipitation input is reduced to a runoff volume according to

$$Q = \frac{(P - 0.2\ S)^2}{P + 0.8\ S}$$

P = Precipitation

Q = Runoff

S = Loss parameter for initial abstraction, storage, infiltration

The equation is reduced to a series of curves (Fig. 24) numbered 1 to 100 through the relationship

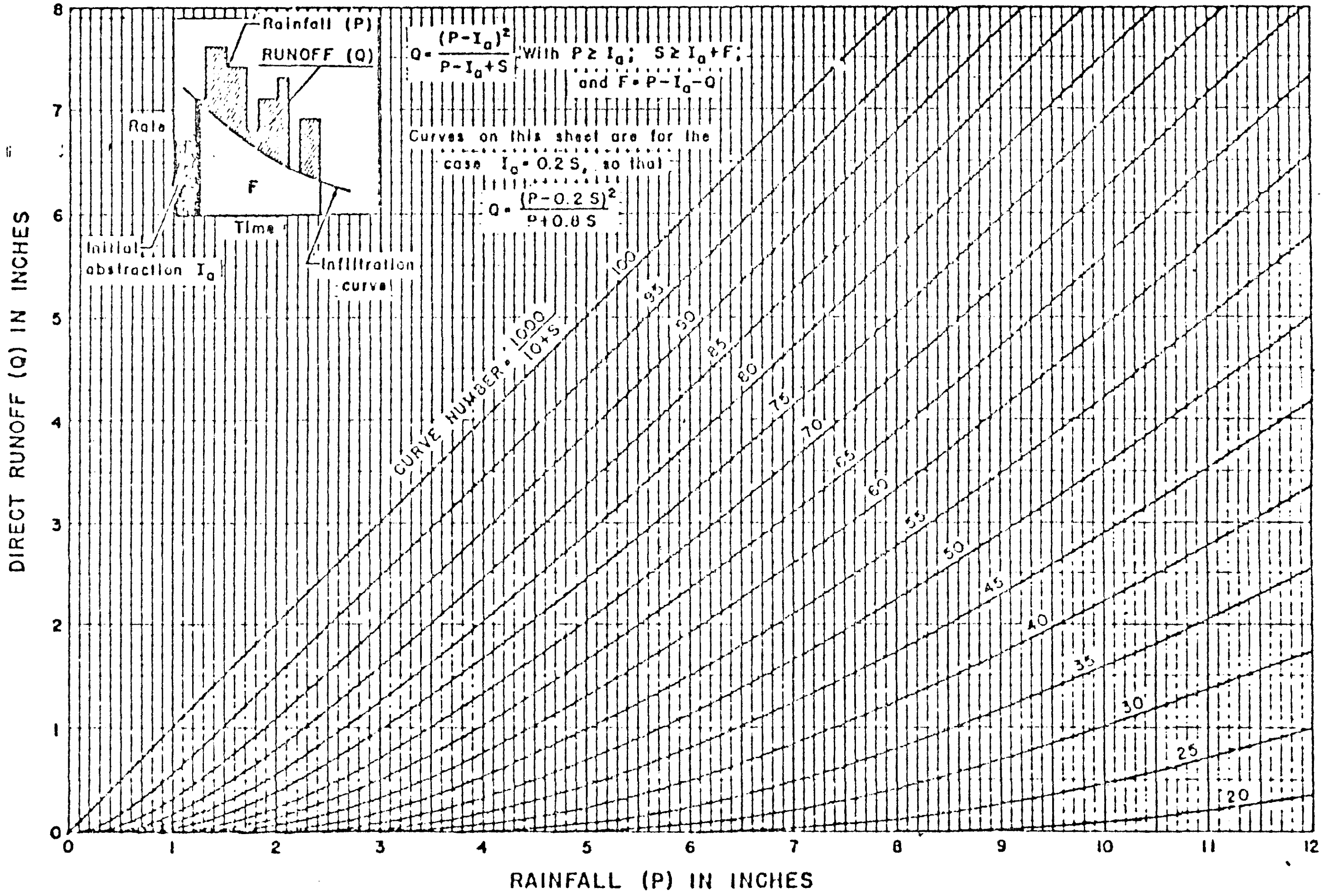
$$S = \frac{1000}{CN} - 10$$

It is important to realize that as rainfall accumulates, the ratio $\frac{Q}{P}$ approaches 1 regardless of the precipitation pattern. For a given storm, only one curve number can be used. The SCS has guidelines for curve selection based upon soil type, vegetation, and antecedent soil moisture of the watershed.

From the runoff pattern a hydrograph is developed by scaling the SCS dimensionless hydrograph using the peak flow and time of concentration for the watershed. The equations used are $Q_p = \frac{484\ A}{t_p}$ and $t_p = D/2 + t_1$, $D = .133\ t_c$

HYDROLOGY: SOLUTION OF RUNOFF EQUATION $Q = \frac{(P-0.2S)^2}{P+0.8S}$

P = 0 to 12 inches
Q = 0 to 8 inches



$Q = \frac{(P-I_a)^2}{P-I_a+S}$ With $P \geq I_a$; $S \geq I_a + F$; and $F = P - I_a - Q$

Curves on this sheet are for the case $I_a = 0.2S$, so that

$Q = \frac{(P-0.2S)^2}{P+0.8S}$

REFERENCE
Mockus, Victor; Estimating direct runoff amounts from storm rainfall:
Central Technical Unit, October 1955

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
ENGINEERING DIVISION - HYDROLOGY BRANCH

STANDARD DWG. NO.
ES- 1001
SHEET 1 OF 2
DATE 5-71-34

Fig. 24 - SCS Runoff Curves.

Q_p = Peak Discharge

A = Area

t_p = Time to Peak

D = Duration of Rainfall

t_c = Time of Concentration

t_1 = Lag time from Centroid of Rainfall to Q_p.

The resulting runoff hydrographs can then be routed and added by the machine. Routing in reservoirs is controlled by parameters of discharge and storage as a function of stage. Routing in channels is controlled by discharge and end area as a function of stage and by a routing coefficient. If no routing coefficient is chosen, the machine will compute the velocity $\left(\frac{\text{Disch}}{\text{End Area}}\right)$ and select a routing coefficient automatically.

In the watersheds of the study, storage was a significant factor in determining runoff patterns while channel routing had a minor effect on the overall hydrograph. The overall response of the watersheds is quite slow.

Filson Creek

The first runs with the Filson Creek watershed used four sub-watersheds and two reservoirs (Fig. 25). The reservoirs corresponded to Bogberry and Omaday Lakes. The storage characteristics of these lakes were estimated from USGS quadrangle maps by planimetering the contour intervals. The discharge characteristics were derived from an estimate of friction control in a small channel. Curve number and time of concentration were estimated from SCS guidelines (Figs. 26 and 27).

Results obtained from these parameters (Fig. 28) were unsatisfactory. This is due probably equal to two factors. First, the guidelines are intended for use in agricultural areas and may contain assumptions not valid in northern Minnesota and second, the guidelines require experience in judgement of the limited soil and land use information, which may have been lacking in this study.

In an effort to match the hydrograph of the June 1975 storm, the time of concentration and curve numbers were increased greatly. When a reasonable fit was obtained (Figs. 29 and 30), these two parameters had exceeded any reasonable value for the watershed, ($CN = 90$ $TC \simeq 130$). The problem was more evident when a second storm, that of August 25, 1977, was used. The multiwatershed model greatly over-predicted both peak and volume for the larger storm (Fig. 31-Model B).

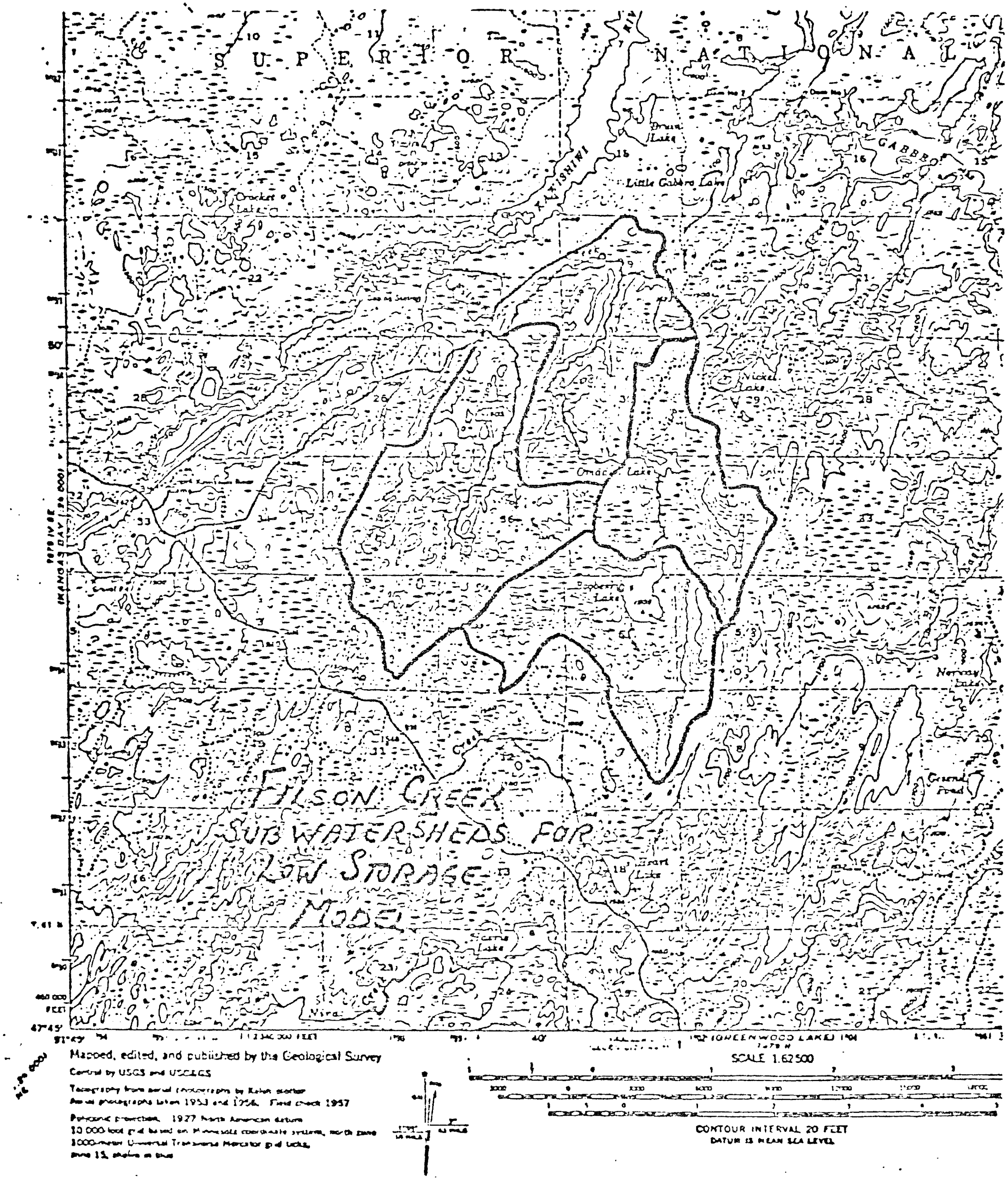


Fig. 25 - Filson Creek Subwatersheds for Low Storage Model.

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(File Code ENG-13)

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

HYDROLOGIC CURVE NUMBER COMPUTATION SHEET

______ LAND USE FOR RURAL AREAS
Present or Future

Watershed Filson Site ______ D.A. ______ Acres ______

Computed by NPN Date ______ Checked by ______ Date ______

Cover	Practice	Condition or Rotation	Mi^2 Per Practice	Curve Numbers Moisture Condition II A Soils	B Soils	C Soils	D Soils	Product
Fallow	Straight Row			77	86	91	94	
Row Crops	Straight Row	Poor		72	81	88	91	
	Straight Row	Good		67	78	85	89	
	Straight Row	Mulch till		61	76	84	87	
	Contoured 2/	Poor		70	79	84	88	
	Contoured 2/	Good		65	75	82	86	
	Contoured 2/	Mulch till		62	73	80	85	
	C and T 1/	Poor		66	74	80	82	
	C and T 1/	Good		62	71	78	81	
	C and T 1/	Mulch till		61	70	77	80	
Sm. Grain	Straight Row	Poor		65	76	84	88	
	Straight Row	Good		63	75	83	87	
	Straight Row	Mulch till		58	74	82	86	
	Contoured 2/	Poor		63	74	82	85	
	Contoured 2/	Good		61	73	81	84	
	Contoured 2/	Mulch till		59	72	80	83	
	C and T 1/	Poor		61	72	79	82	
	C and T 1/	Good		59	70	78	81	
	C and T 1/	Mulch till		55	69	77	80	
Legumes or Rotation Meadow	Straight Row	Poor		66	77	85	89	
	Straight Row	Good		58	72	81	85	
	Contoured 2/	Poor		64	75	83	85	
	Contoured 2/	Good		55	69	78	83	
	C and T 1/	Poor		63	73	80	83	
	C and T 1/	Good		51	67	76	80	
Pasture		Poor		68	79	86	89	
		Fair		49	69	79	84	
		Good		39	61	74	80	
Meadow (Permanent)		Good		30	58	71	78	
Wood or Forest Land		Poor		45	66	77	83	
		Fair	1.65	36	60	73	79	99
		Good		25	55	70	77	
Farmsteads		--		59	74	82	86	
Roads (Inc.R.O.W.)	Dirt Surface	--		72	82	87	89	
	Hard Surface	--		74	84	90	92	
Impervious Surfaces		--		100	100	100	100	
Water Surfaces(lakes,ponds)		--	.130	100	100	100	100	13
Swamp (open water) 3/		--		85	85	85	85	
Swamp (vegetated) 4/		--	.52	78	78	78	78	41.6
Low Density Residential		--		47	65	76	82	
Medium Density Residential		--		54	70	79	84	
High Density Residential		--		70	81	87	90	
Commercial and Industrial		--		86	91	93	94	

Total Acres 2.30 Product Total = 153.6

Weighted Runoff Curve No. $\frac{\text{Product Total}}{\text{Total Acres}}$ = 66.8 ≈ = 67

1/ Contoured and graded terraces or land with less than 2% slope.

2/ Includes level terraced areas. (runoff corrected by volume)

3/ 1/3 of swamp surface is open water.

4/ Swamp has no open water and the design is a 25-year frequency or less.

Fig. 26 - SCS Hydrologic Curve Number Computation Sheet.

Distance from Watershed Rim =

$(1.37 + 1.42 + 1.50 + 1.56 + 1.40) \div 5 = 1.47$ Map Wheel Units

$1.47 \div 1.022 = 1.44$ Miles

Δ Elevation - 1600 - 1508 = 92 Ft.

Slope = 1.2%

$$\left.\begin{array}{l}\text{Velocity (Forest)} = .28 \text{ fps}\\ \text{Velocity (Swamp)} = .60 \text{ fps}\end{array}\right\} \quad \text{Average} = .45 \text{ fps}$$

$$\frac{\text{Distance}}{\text{Velocity}} = \text{Time of Concentration} = \frac{(1.44(5280)}{.45}$$

$$= 16896 \text{ Seconds}$$

$$= 4.70 \text{ Hours}$$ ✓

Fig. 27 - Watershed #1 - Bogberry Lake Watershed
Calculation of Time of Concentration.

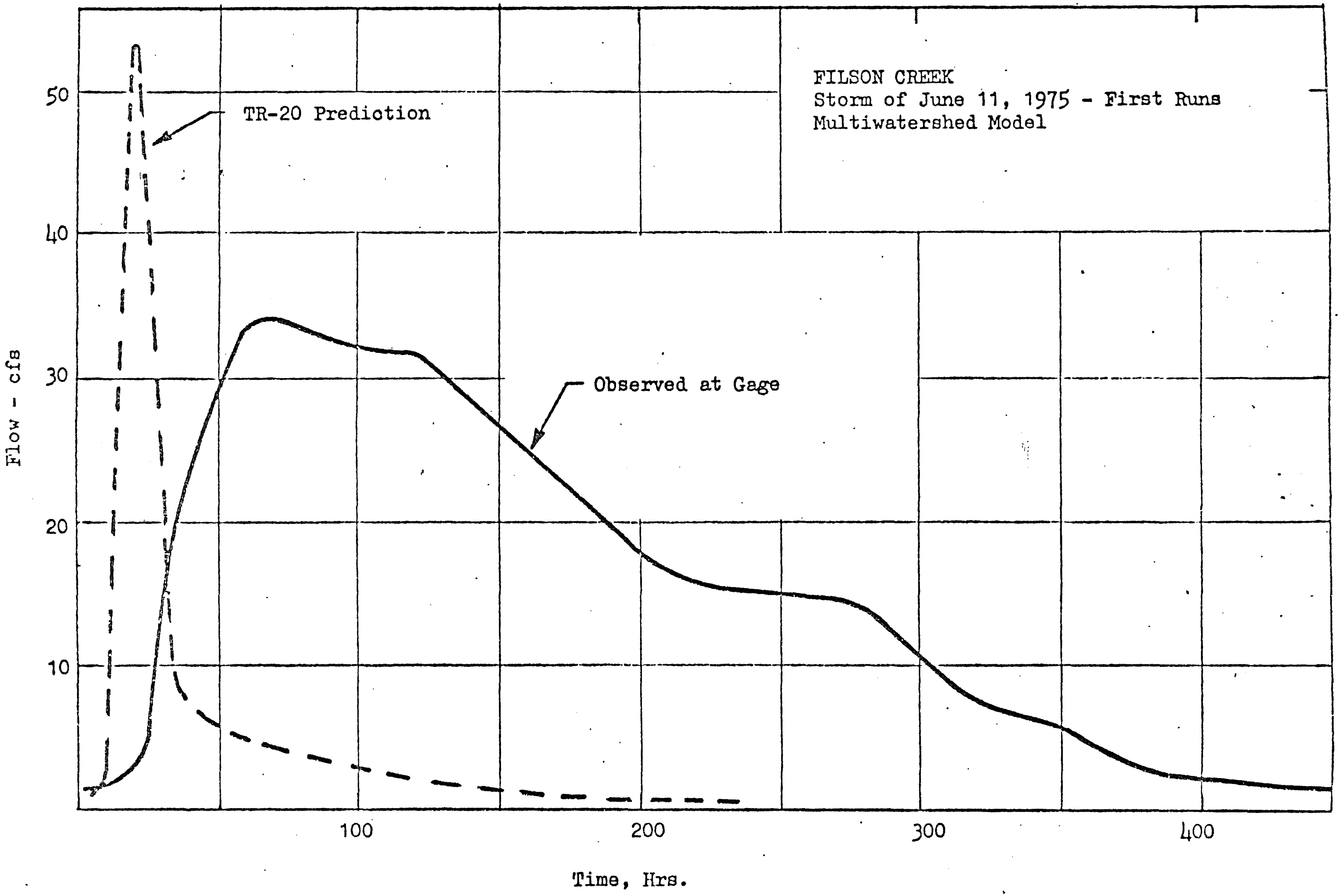


Fig. 28 - Filson Creek, Initial Run With TR-20 Model.

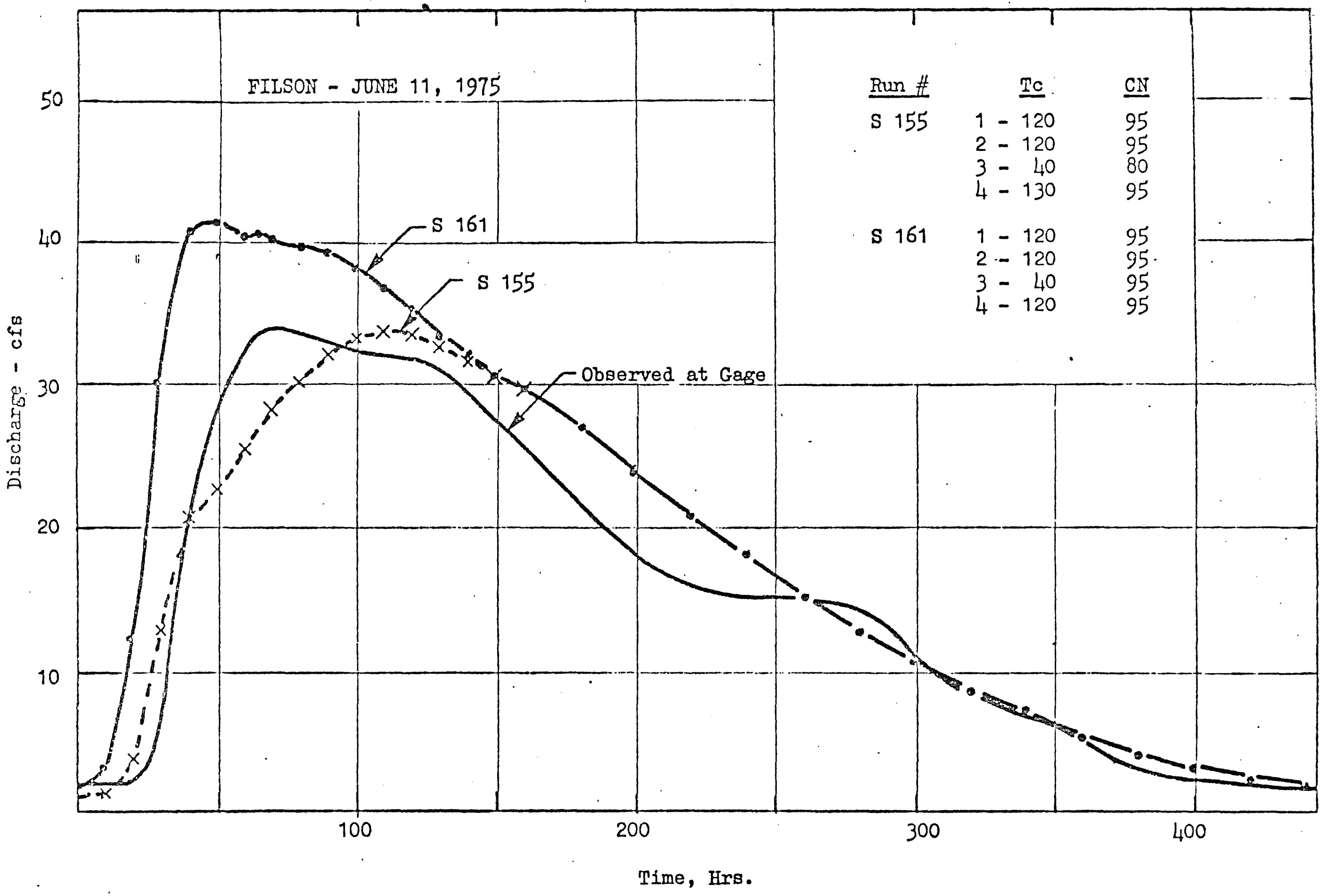


Fig. 29 - Filson Creek, TR-20 Runs With 4 Subwatersheds, Large Curve Numbers, and Large Tc.

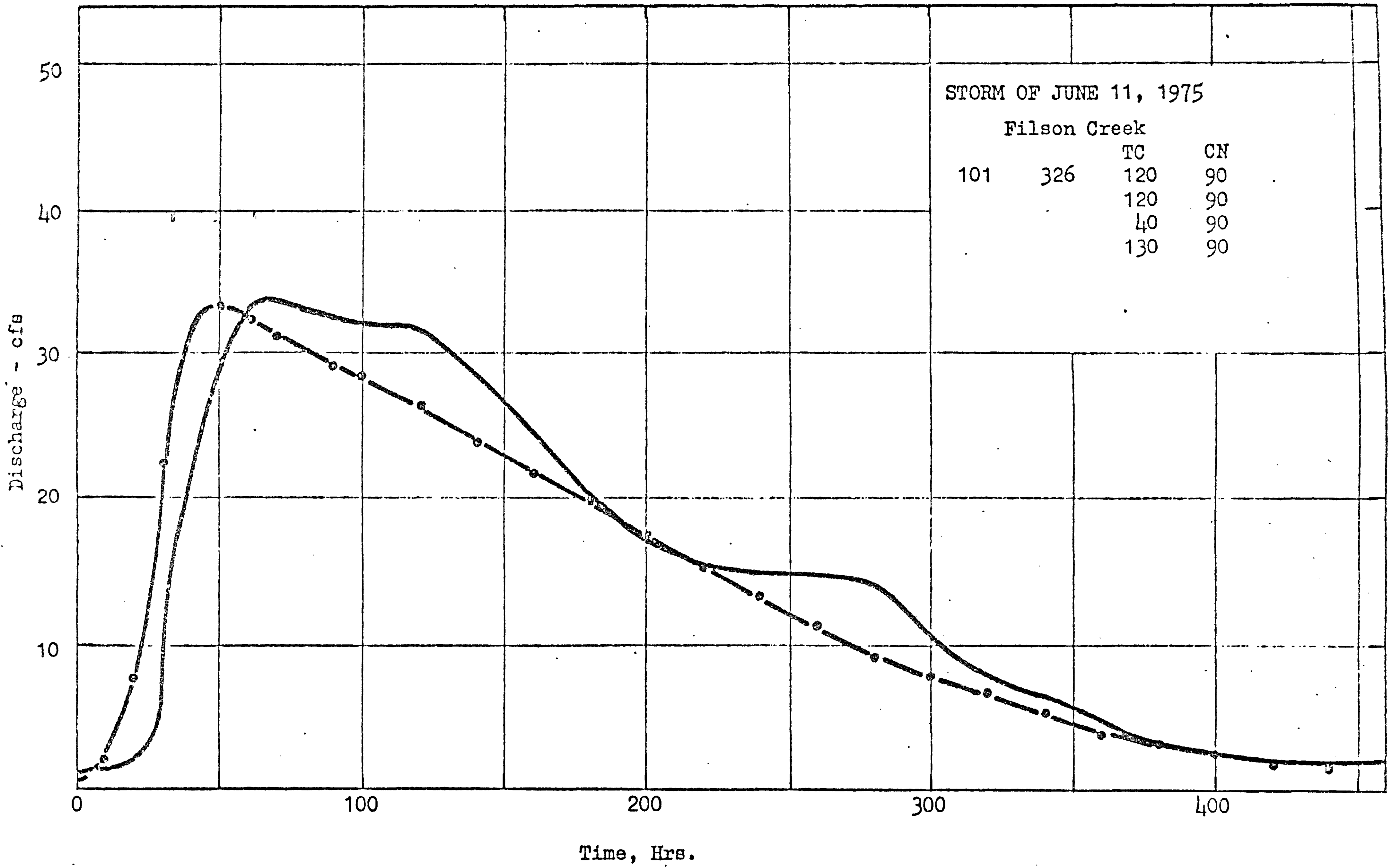


Fig. 30 - Filson Creek, TR-20 Runs With 4 Subwatersheds, CN = 90 and Tc = 40 to 130.

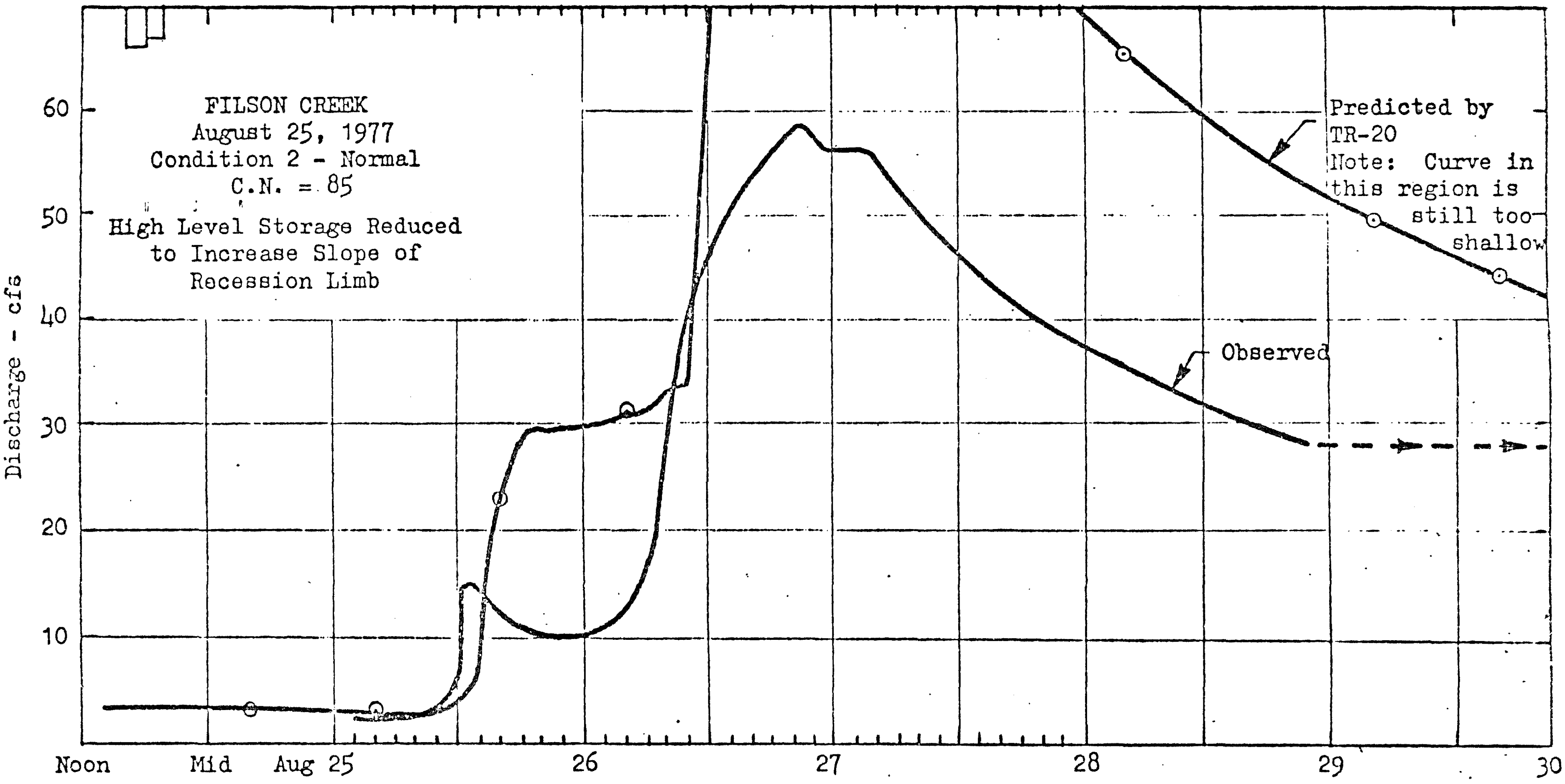


Fig. 31 - Filson Creek, TR-20 Run With CN = 85.

In order to reconcile these two events, a simple one-watershed model was tried with a large hypothetical reservoir regulating the flow (Fig. 31, Fig. 32) While this reservoir storage slowed the runoff from the larger storm and reduced the slope of the recession curve from the smaller storm, it also depended on parameters which could not be easily estimated, e.g. reservoir level at T = 0 as a function of watershed moisture condition.

At this time, DNR aerial photo information became available which indicated that the true area of bog and swamps in the watershed was higher than had been assumed. The data were bog surface areas only but it was possible to incorporate these into the model by lumping the bog areas by subwatershed and assuming them to be conical basins with maximum depth of 3 ft. This required a new reservoir on the west branch of the creek and an increased storage capacity in the other two reservoirs (Fig. 33).

The new high storage model allowed the use of more reasonable curve numbers and times of concentration. It was still found to be impossible to fit both large and small storms. By fitting three storms individually, it was found that the larger storm had a good fit with curve number 78 and Tc of 26 hours (max.), while the smaller storm required a higher curve number (85) and much longer time of concentration (45 to 60 hrs.). The parameters, which fit one storm, produce a poor fit for the others. Figures 34 to 42 show a set of 3 storms using three sets of parameters. The first set (Figs. 34, 35, and 36) uses parameters which fit storm 1. The second set (Figs. 37, 38, and 39) fits storm 2 (August 25, 1975) and the third set fits storm 3 (Figs. 40, 41, and 42).

An important factor is that the storms used to fit the watershed are not large events--the largest - 3.1" in 60 hours appears to be about the 2-year frequency storm. The hydrographs of storms 2 and 3 contain a large baseflow component which is not easily modelled by the TR-20 since it is designed for such major events as the 50-and 100-year storms and uses a hydrograph which simulates surface runoff. The program was modified by SCS to input a baseflow but the baseflow volume, base time, and time to peak must be specified and no method of predicting these baseflow parameters is given by the SCS.

A possibility which holds some promise was that of dividing the precipitation itself into two components - one for baseflow, and one for surface runoff and running these through the watershed separately using baseflow-type parameters

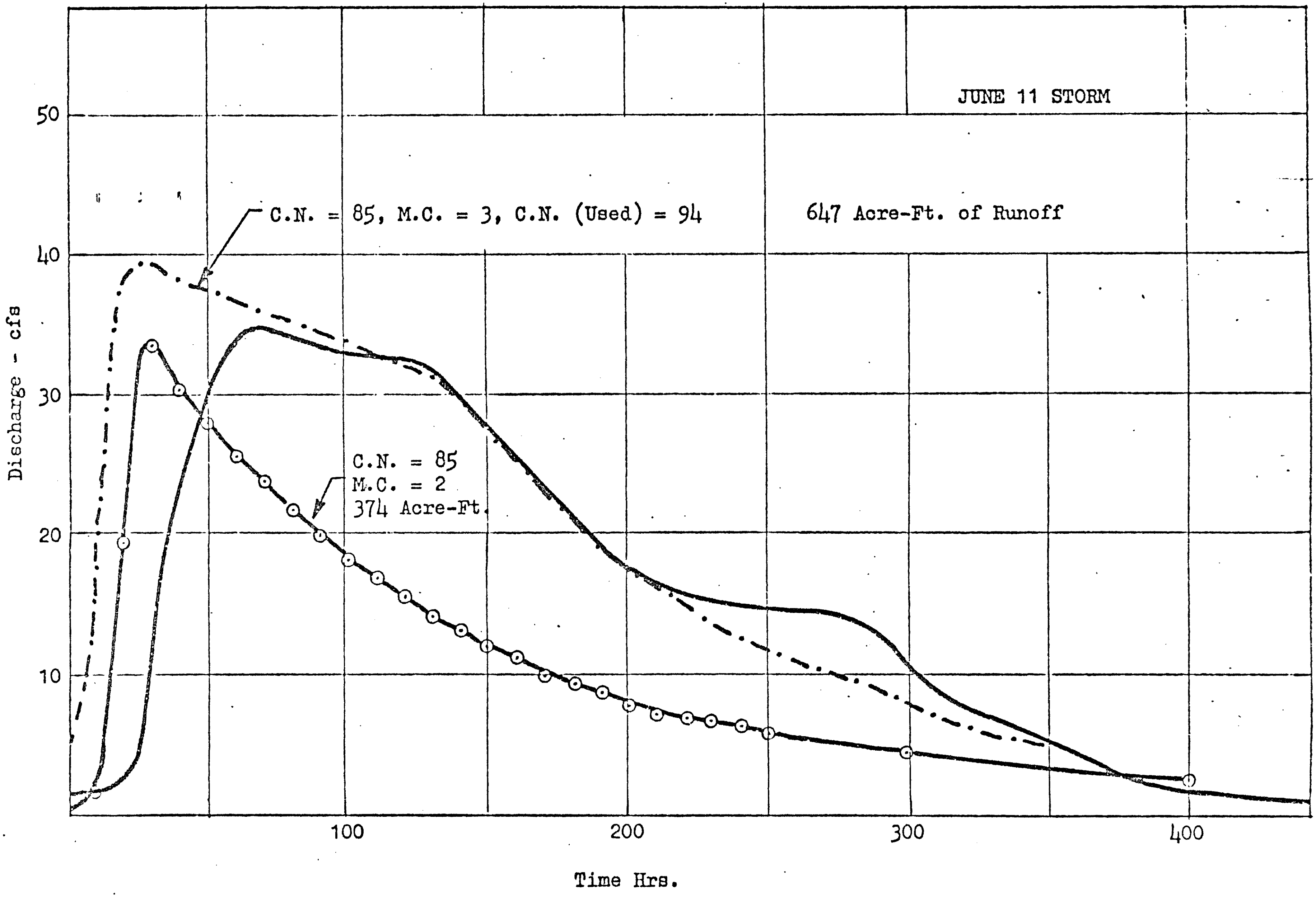


Fig. 32 - Filson Creek, TR-20 Run With One Watershed and Large Hypothetical Reservoir.

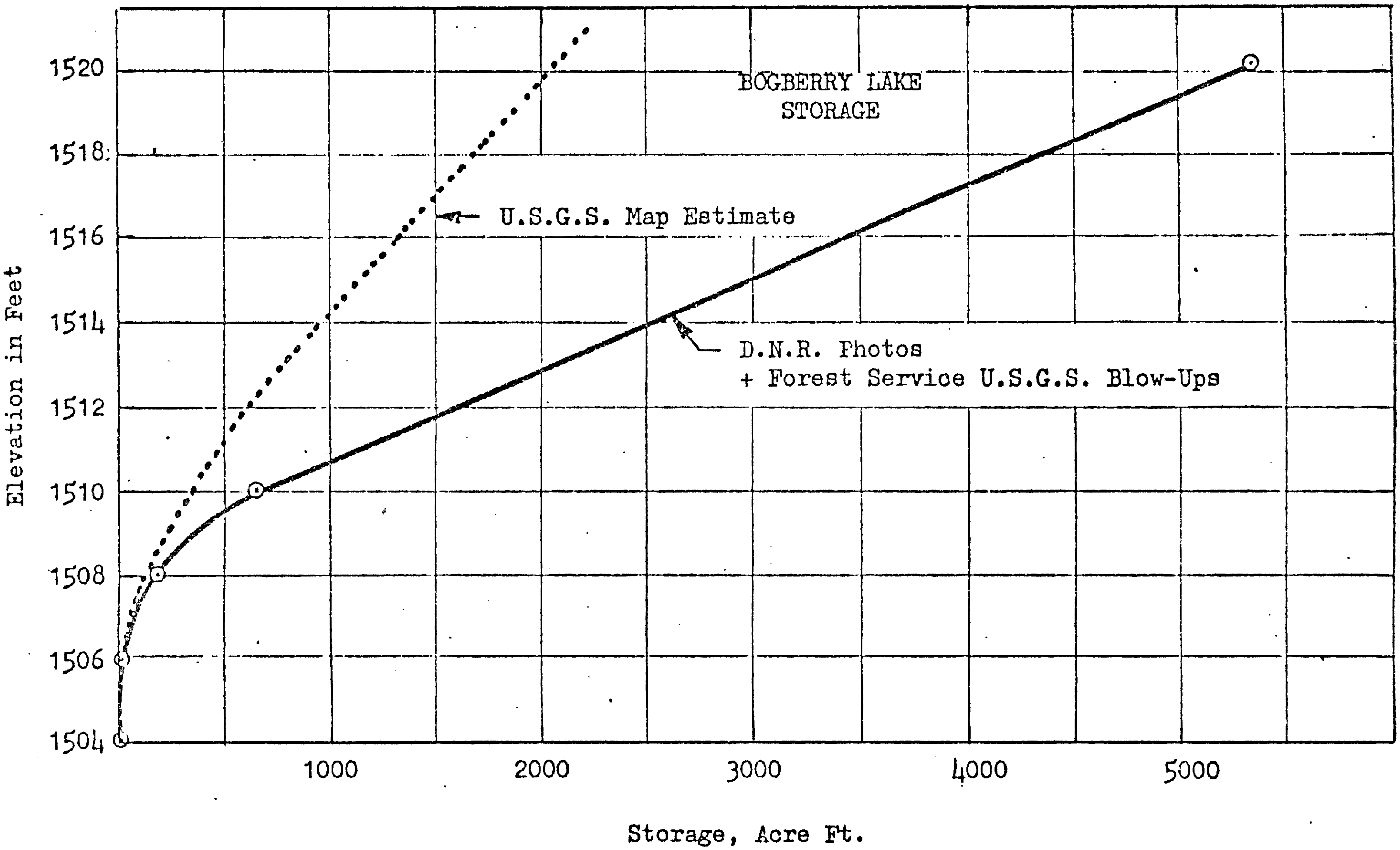


Fig. 33 - Initial and Revised Storage for Bogberry Lake, Based on D.N.R. Photos, Plus Forest Service - USGS Maps.

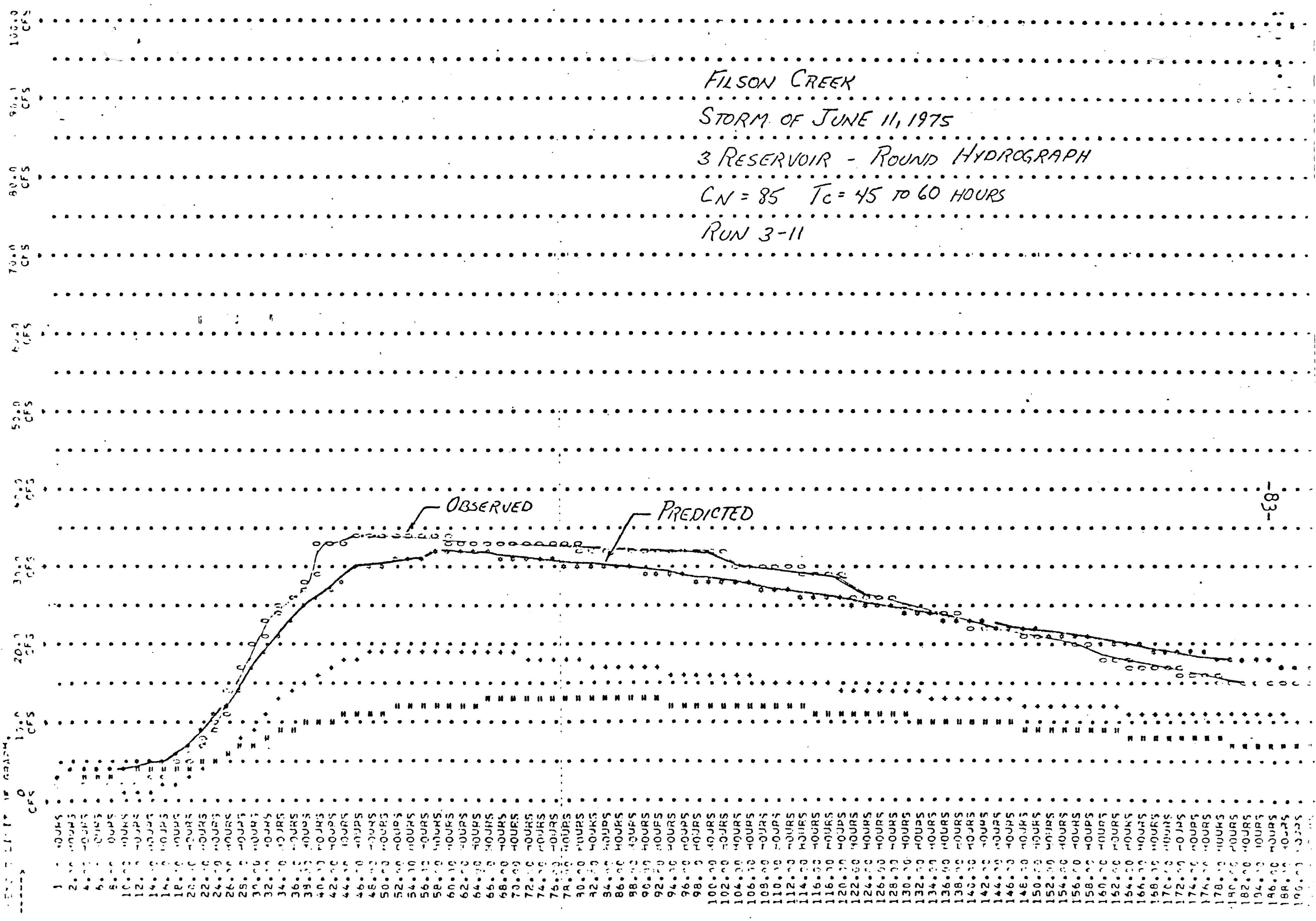


Fig. 34 - Filson Creek, TR-20 Run With High Storage Model and Parameters Fitted to Storm 1.

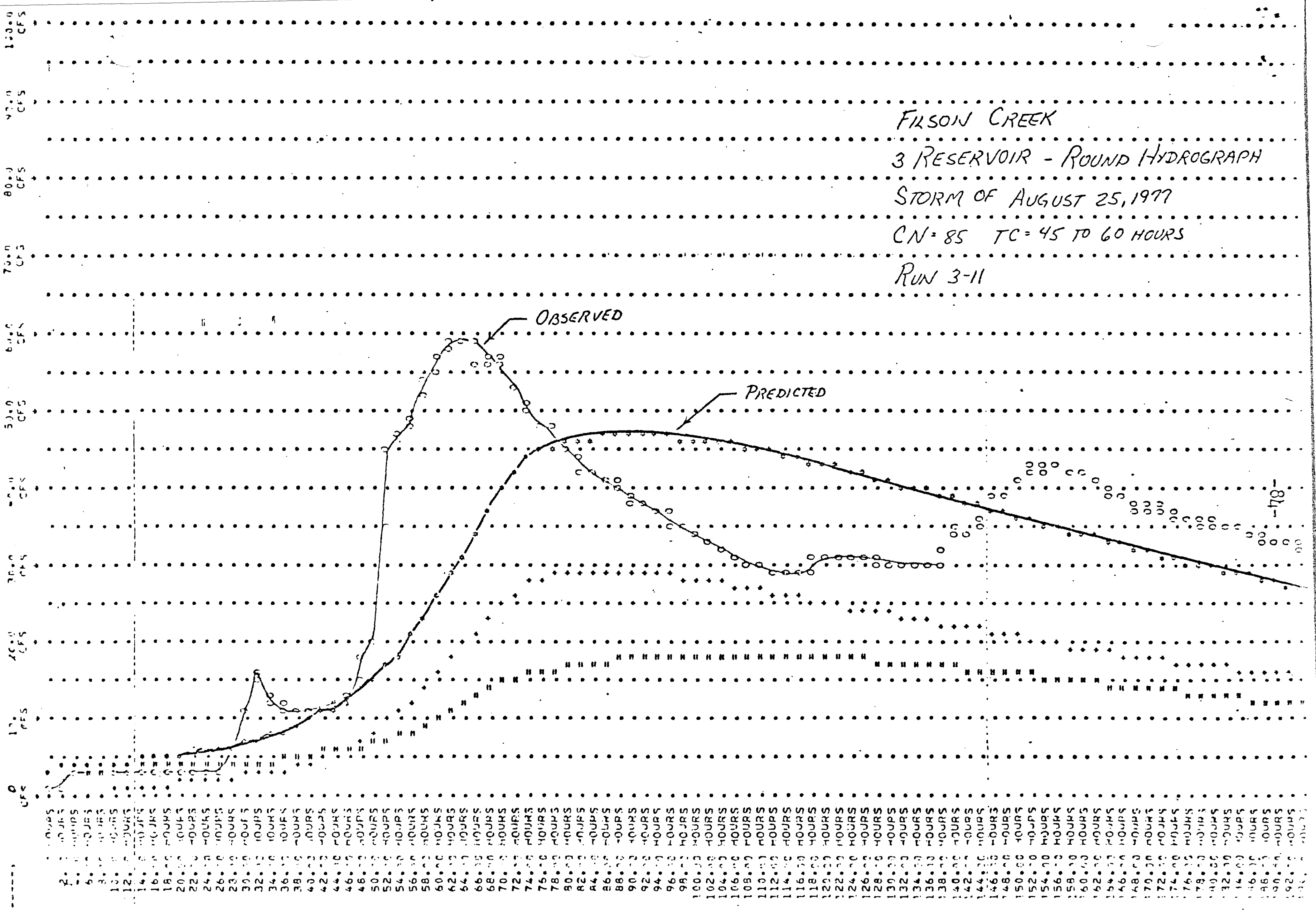


Fig. 35 - Filson Creek, TR-20 Run of Storm 2, With Parameters Fitted to Storm 1.

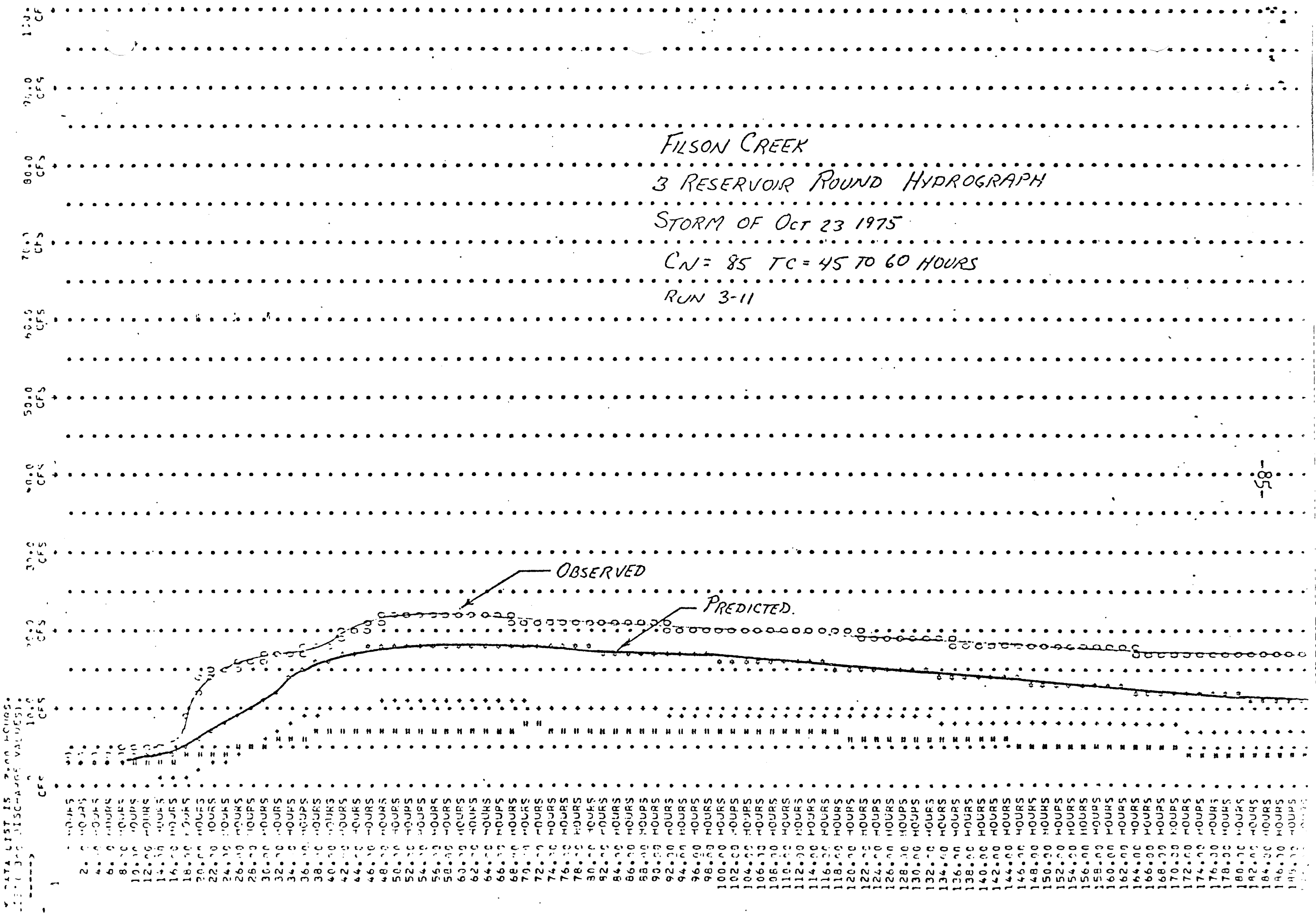


Fig. 36 - Filson Creek, TR-20 Run With Storm 3 and Parameters Based on Storm 1.

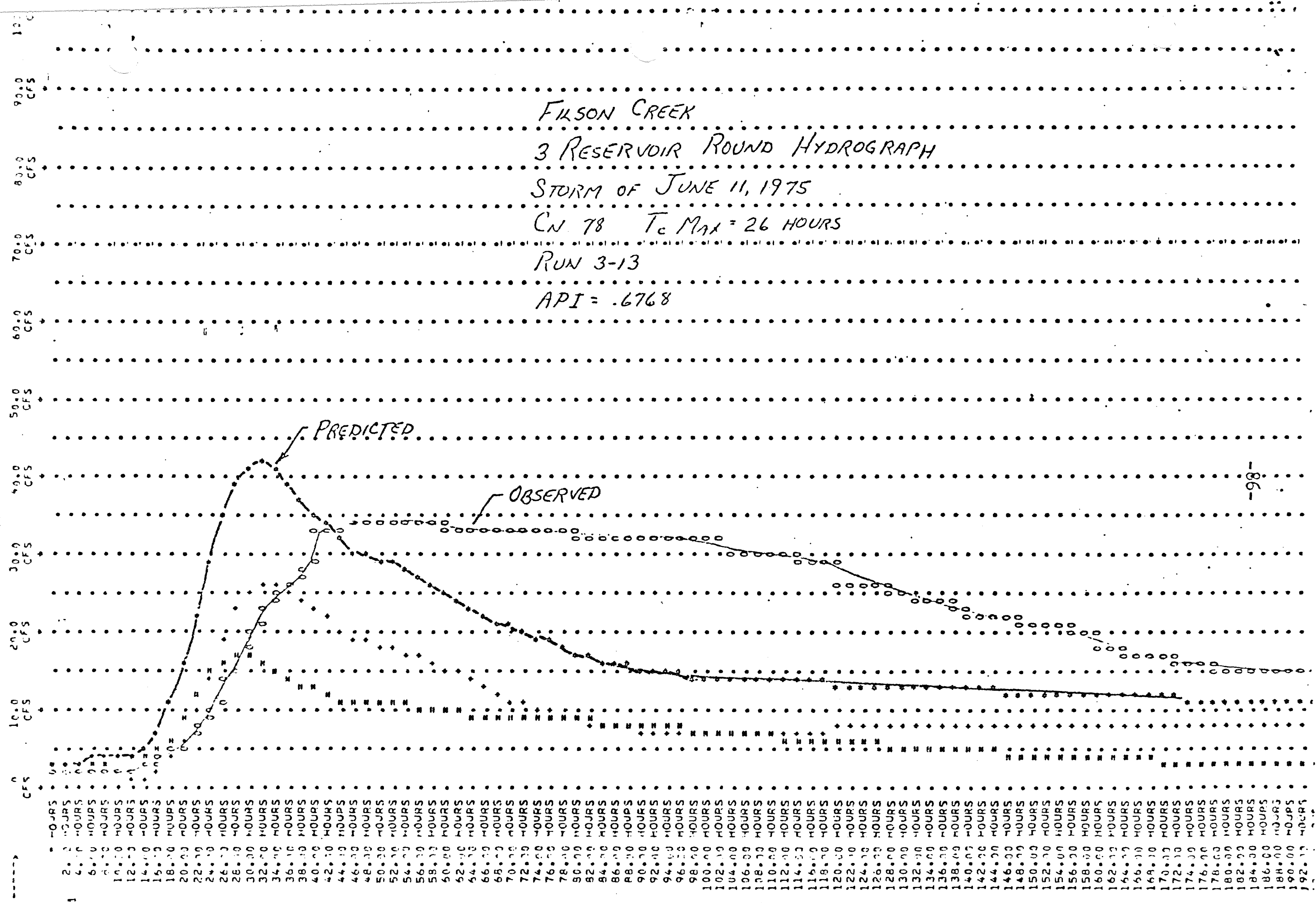


Fig. 37 - Filson Creek, TR-20, Storm 1 With Parameters Based on Storm 2.

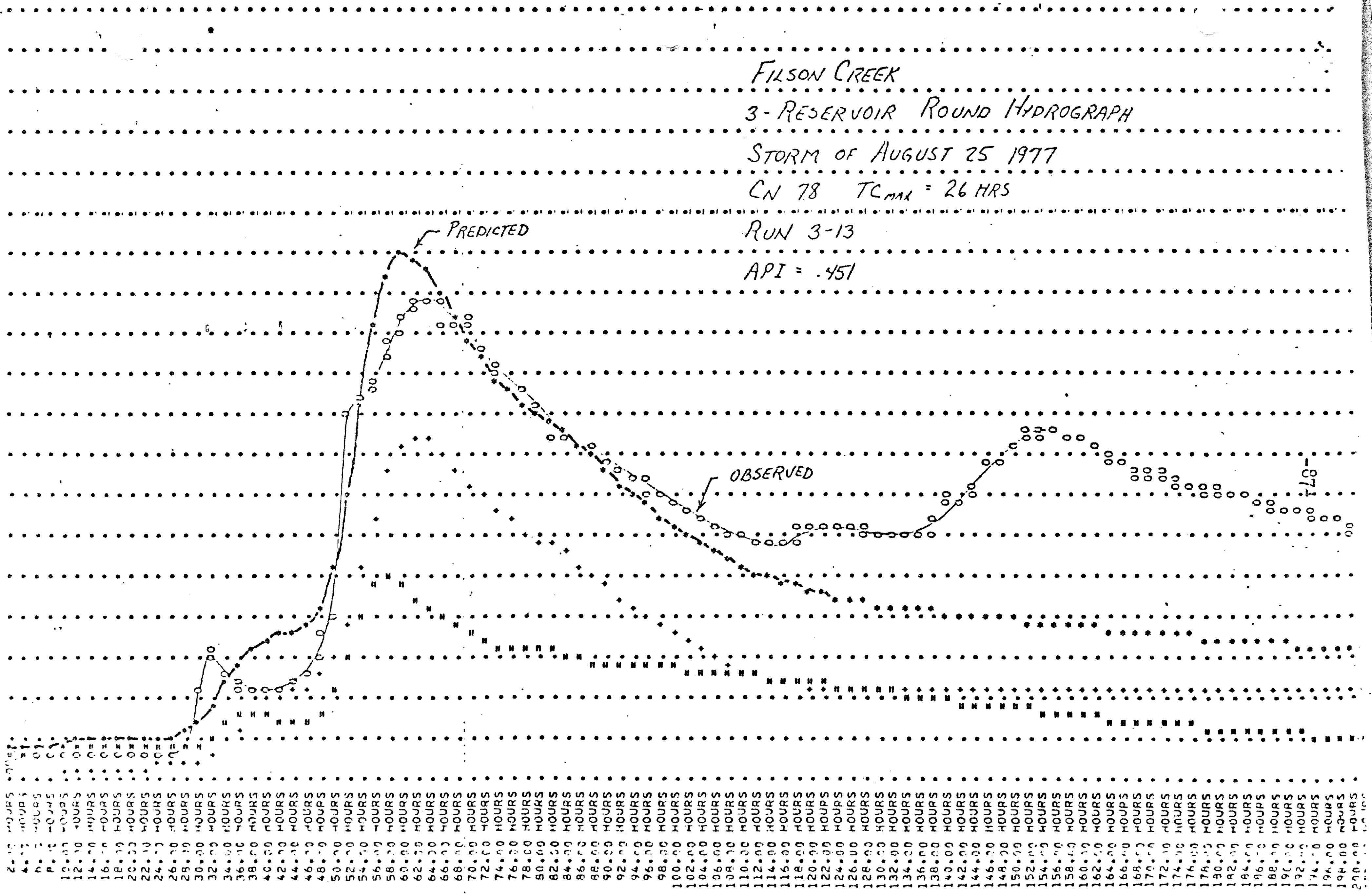


Fig. 38 - Filson Creek, TR-20, Storm 2 With Parameters Based on Storm 2.

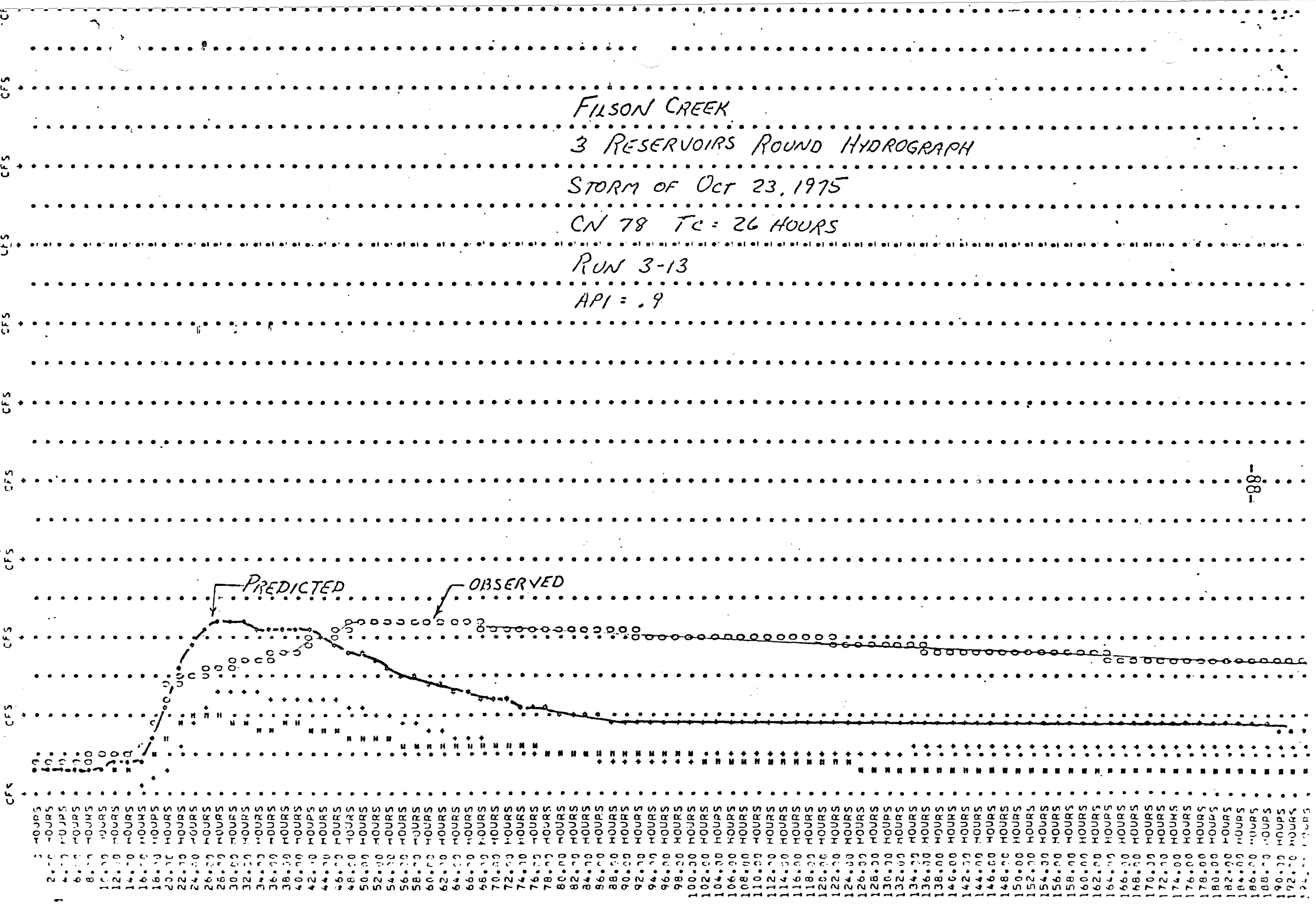


Fig. 39 - Filson Creek, TR-20, Storm 3 With Parameters Based on Storm 2.

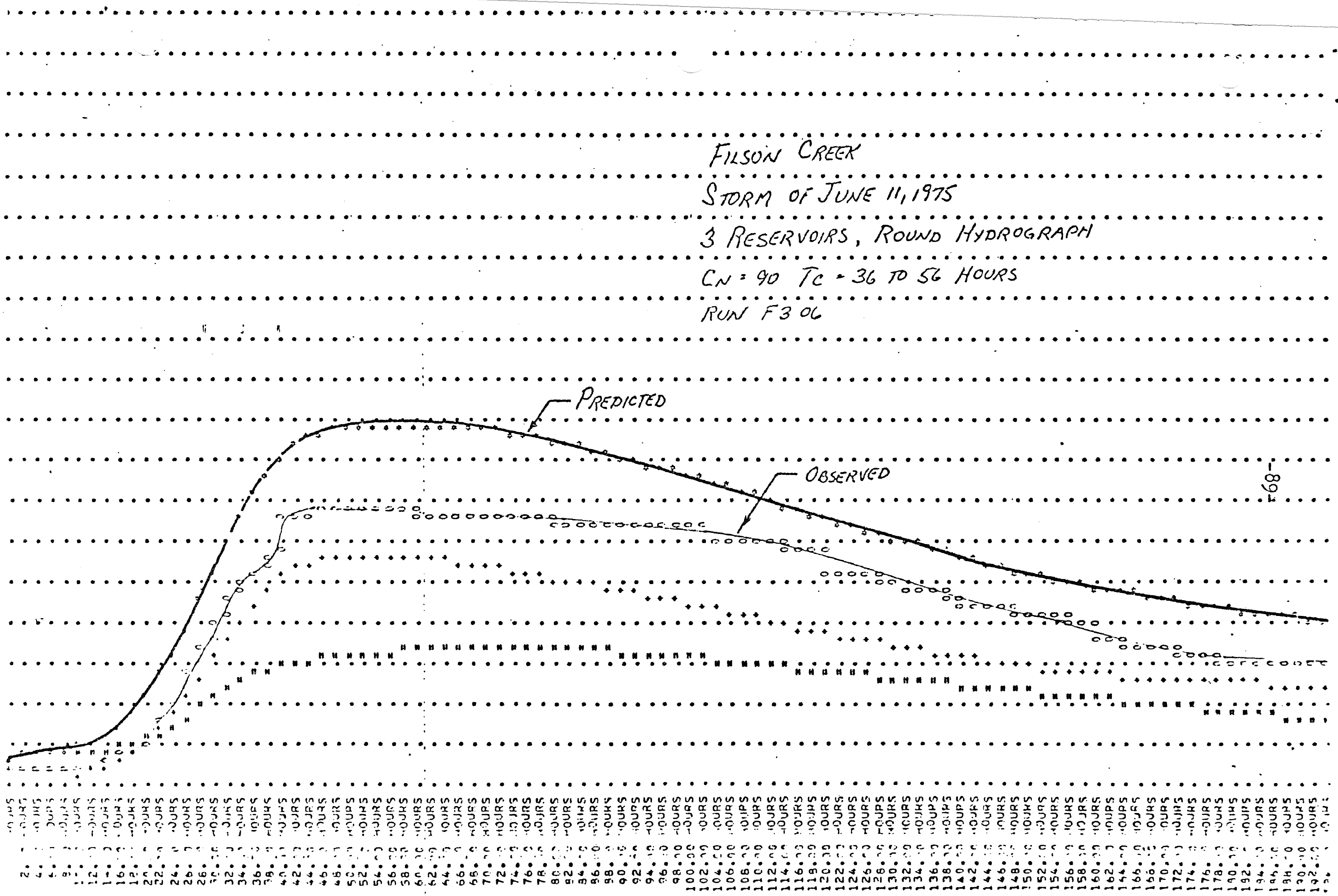


Fig. 40 - Filson Creek, TR-20, Storm 1 With Parameters Based on Storm 3.

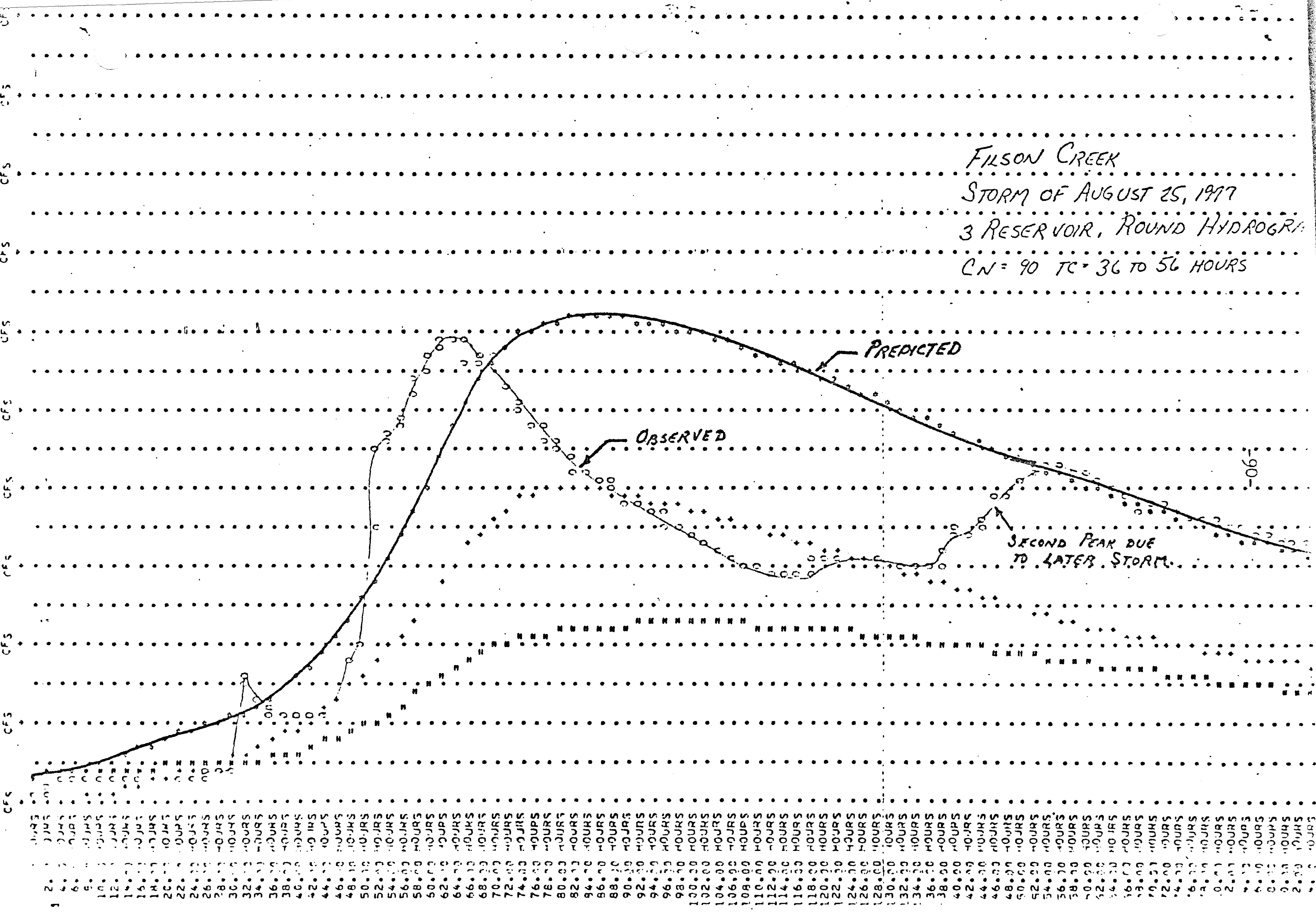


Fig. 41 - Filson Creek, TR-20, Storm 2 With Parameters Based on Storm 3.

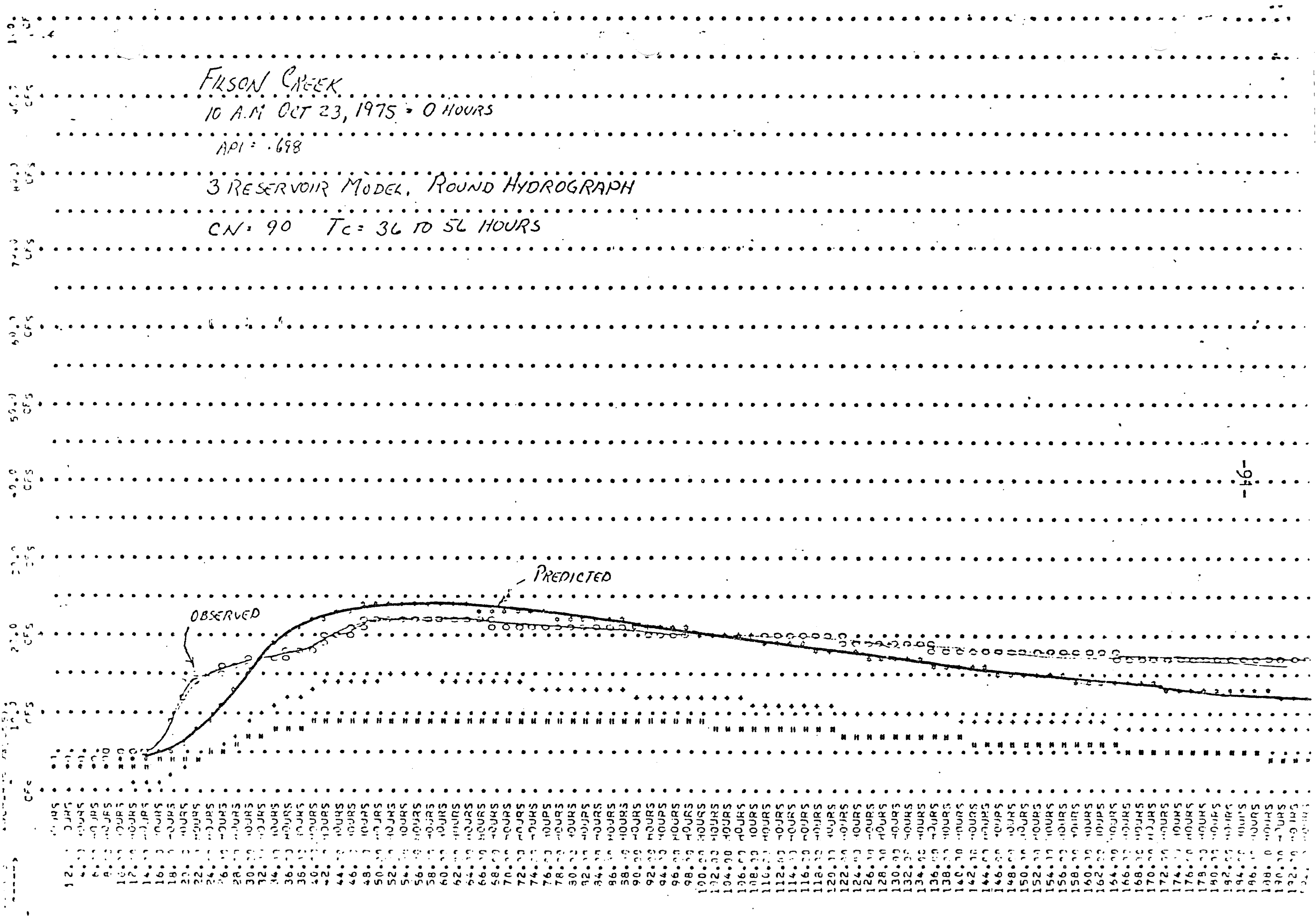


Fig. 42 - Filson Creek, TR-20, Storm 3 With Parameters Based on Storm 3.

for the baseflow component and runoff parameters for the runoff component. This actually requires using two identical watersheds and adding the hydrographs obtained from each. Figures 43, 44, and 45 show the results of a run with this model. These results may be compared with Figures 37-39 and an improvement in overall fit noted. Lack of time precluded further exploration of this idea, but it appears very promising. It was based on the observation that for smaller storms, under about 1.5", all flow had a very slow response. This suggests either interflow or base flow. For storms in excess of 1.5" a quicker response peak was present, suggesting surface runoff or fast response interflow.

A final attempt at making the model as exact as possible was the inclusion of 15 reservoirs (Fig. 46). These were beaver dams shown on a tracing of DNR aerial photographs. The stage storage curves were estimated by assuming the reservoirs to be half-cones 3 feet deep. Overflow from the dams was regulated by the equation for a broad crested weir. The model was quite large and did not produce any visible improvement (Figs. 47, 48, and 49) over the 3 reservoir model.

A slight modification of the SCS unit hydrograph was also attempted by moving the peak forward and lengthening the tail, but this merely reduced the time of concentration required for fitting any storm without allowing a single fit of all three storms. Figures 50 and 51 give a summary of the parameters which fit the three storms, using the two types of hydrograph.

The round hydrograph in this study was similar to the SCS hydrograph with the recession curve increased slightly. The "sharp" hydrograph had the peak moved forward and the recession curve raised even higher.

Figure 52 is a graph of the computed 100-, 25-, 10-, and 2-year computed floods for Filson Creek. Tabulated values are as follows:

T_r	Precipitation (inches)	Peak Flow cfs
2 Year	4.30	55
10 Year	6.85	134
25 Year	8.15	177
100 Year	10.15	259

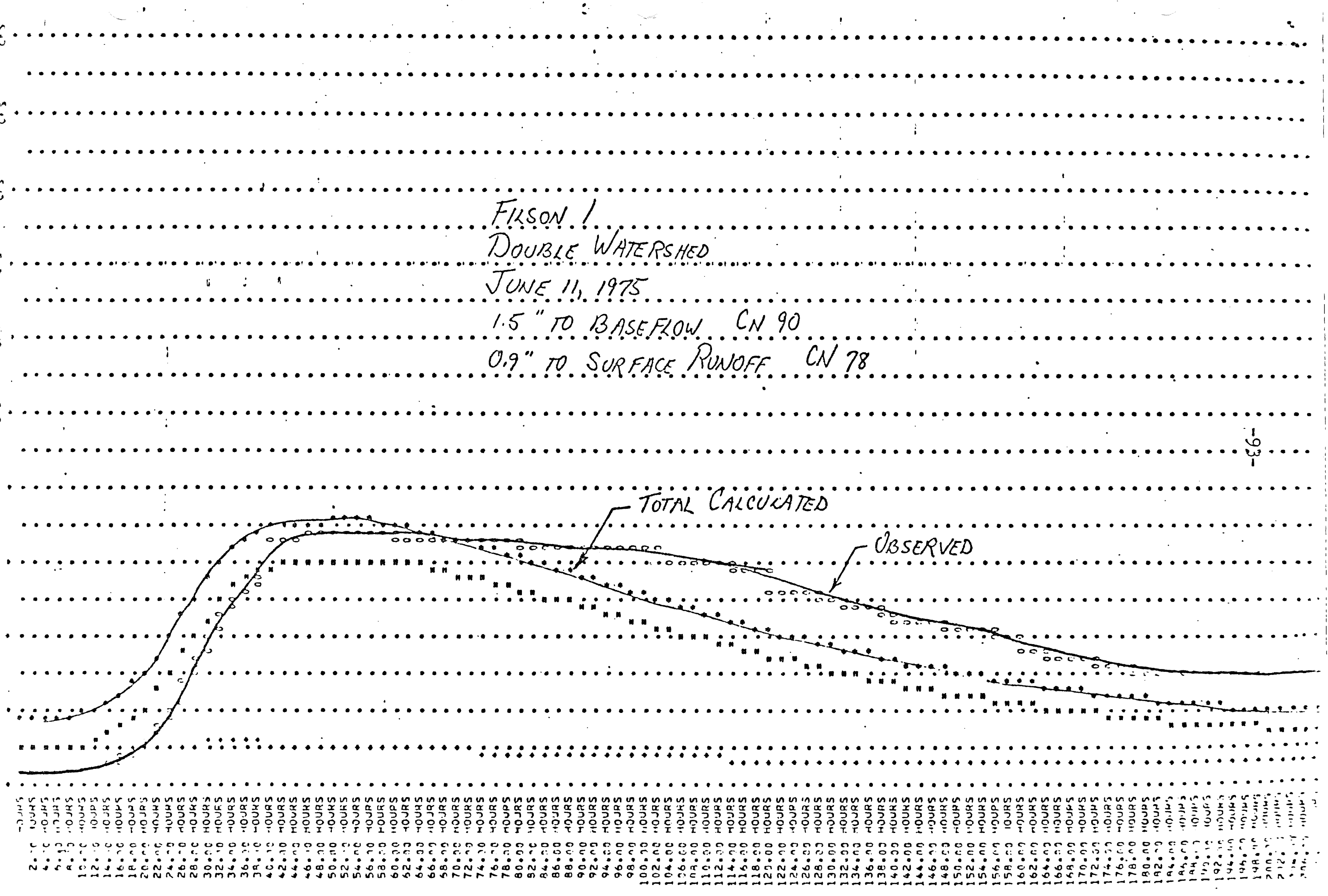


Fig. 43 - Filson Creek, TR-20, Baseflow Plus Surface Runoff Model, June 1975.

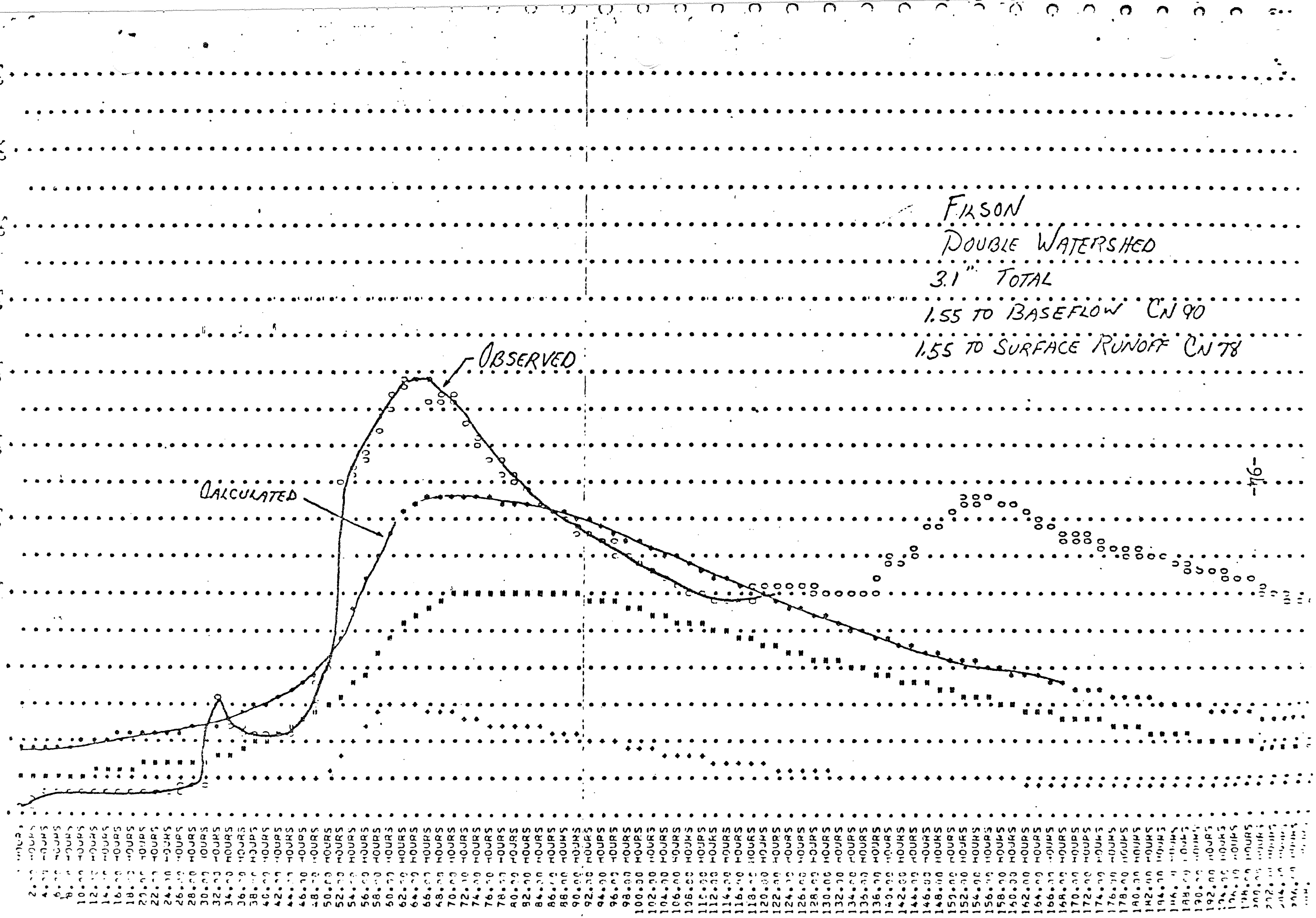


Fig. 44 - Filson Creek, TR-20, Baseflow Plus Surface Runoff Model, August 1977.

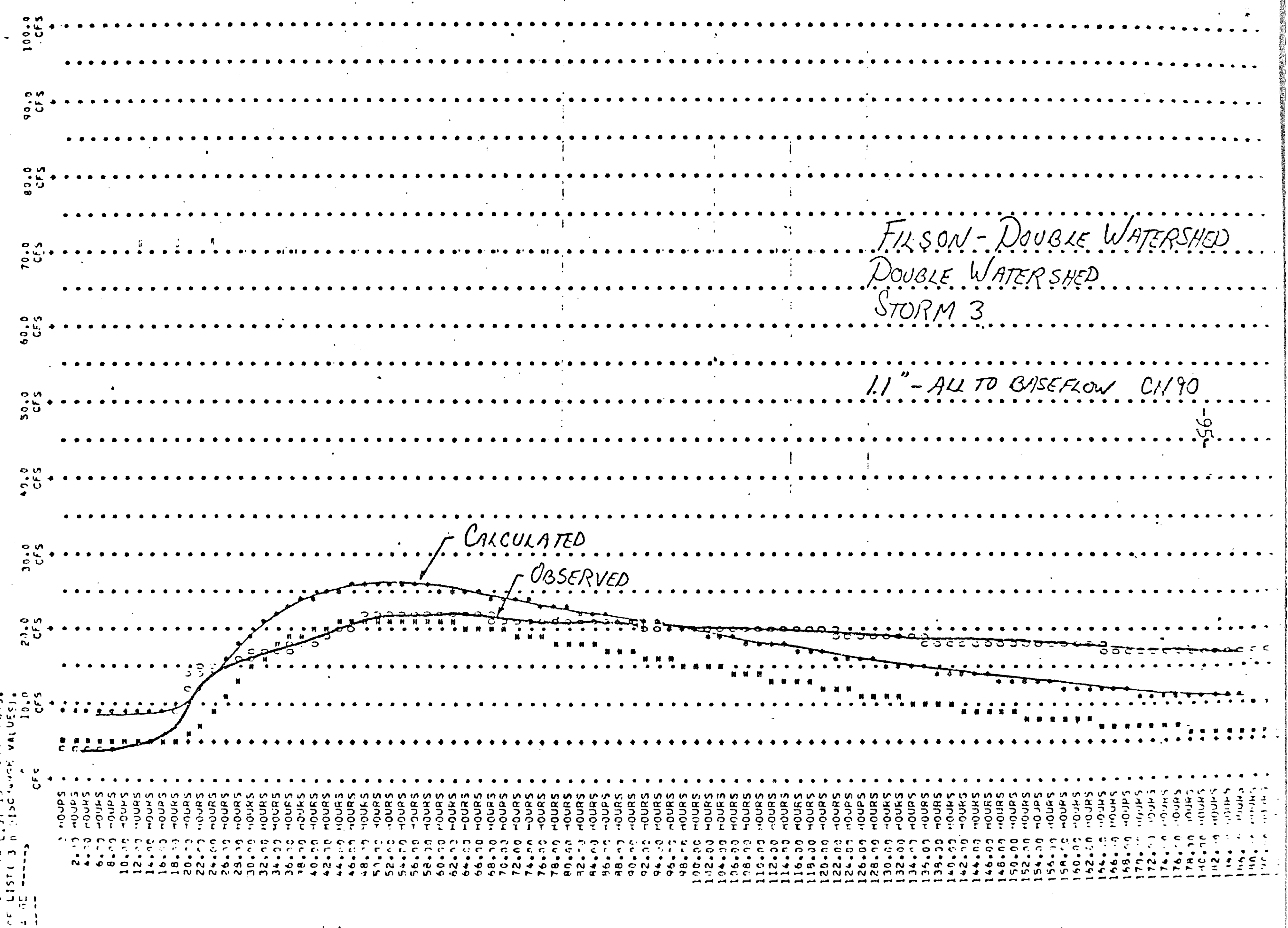
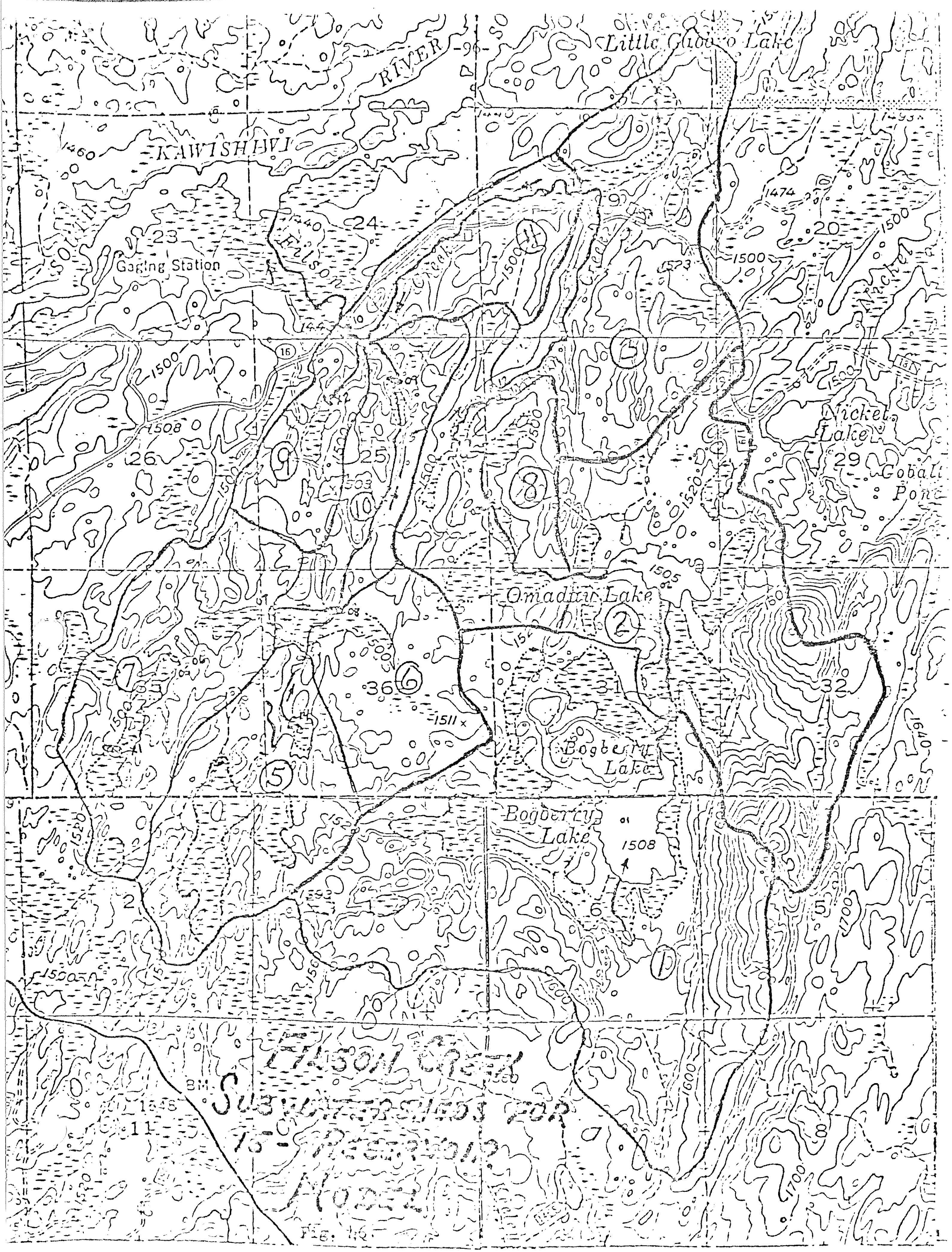


Fig. 45 - Filson Creek, TR-20, Baseflow Plus Surface Runoff Model, Oct. 1975.



Filson Creek Subwatersheds for 15-Reservoir Model

Fig. 16

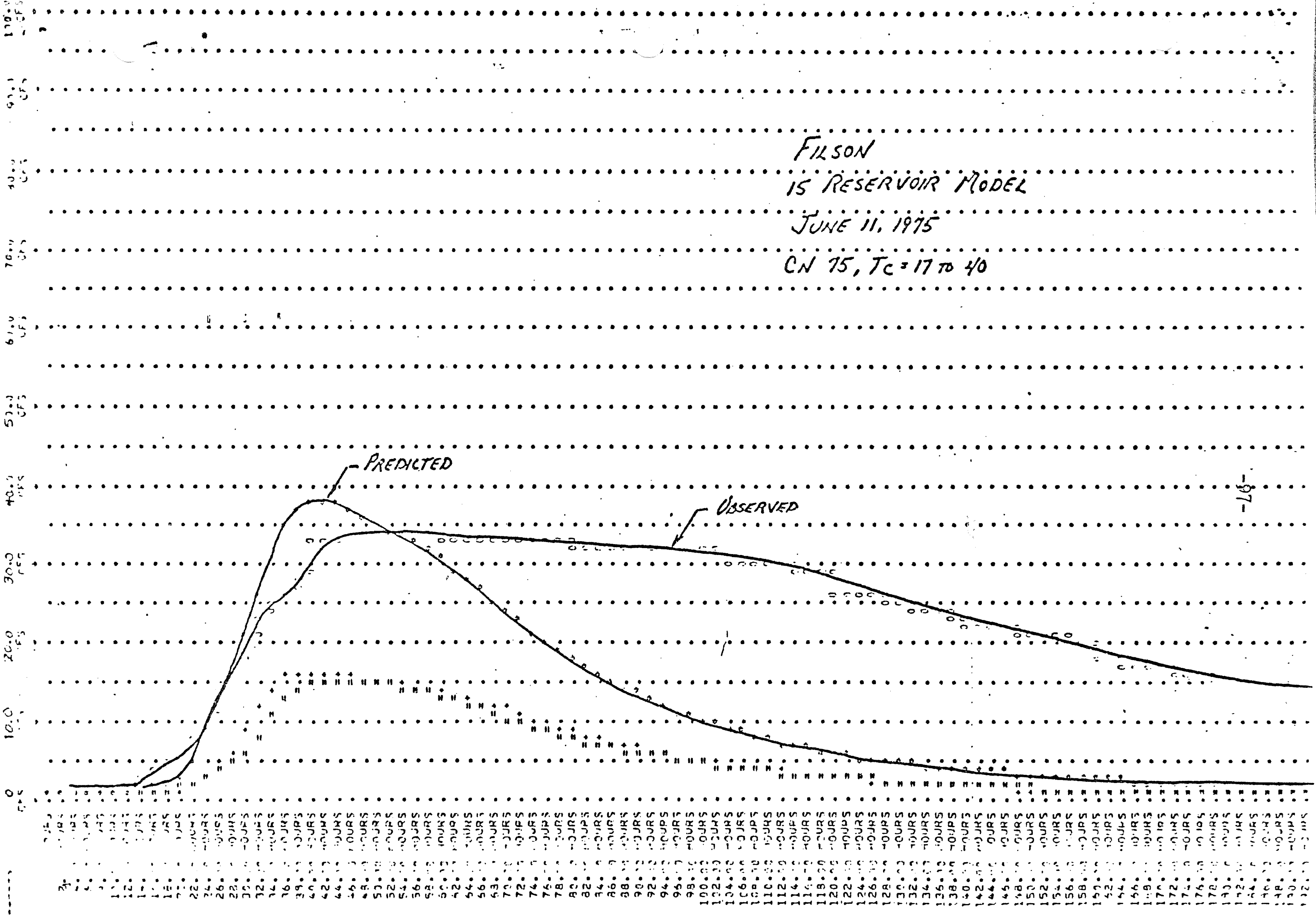


Fig. 47 - Filson Creek, TR-20, is Reservoir Model, June 1975.

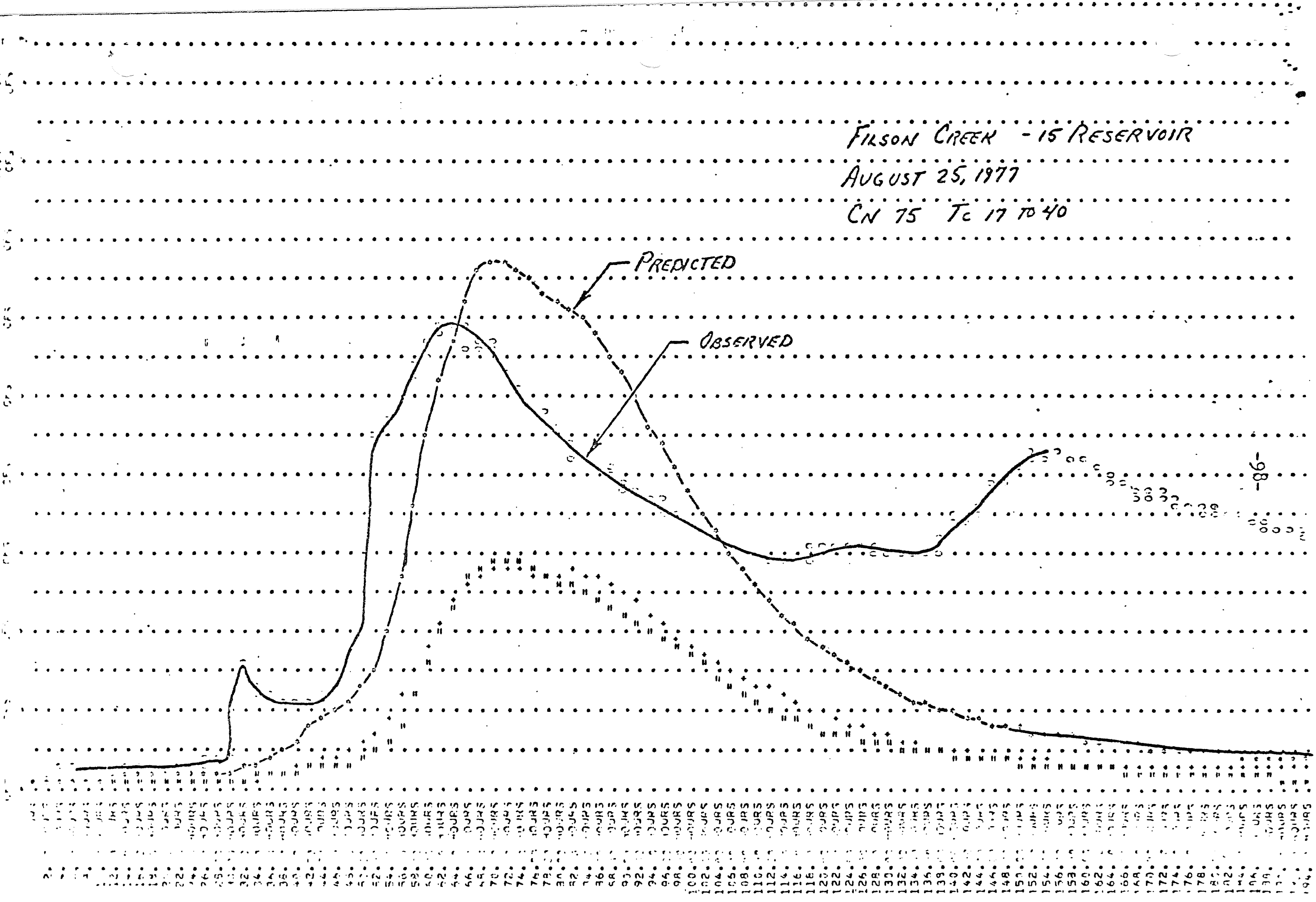


Fig. 48 - Filson Creek, TR-20, is Reservoir Model, Aug. 1977.

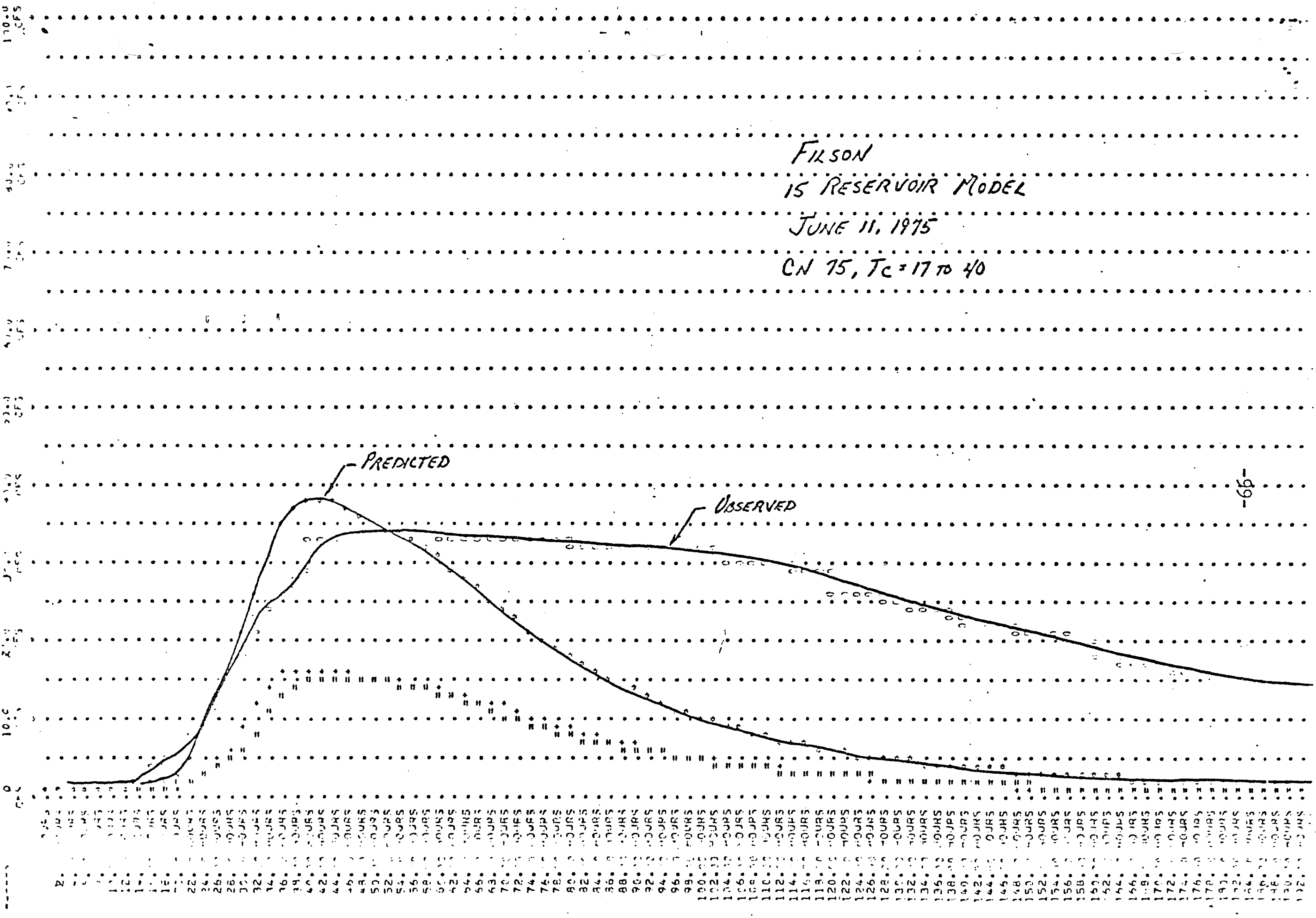
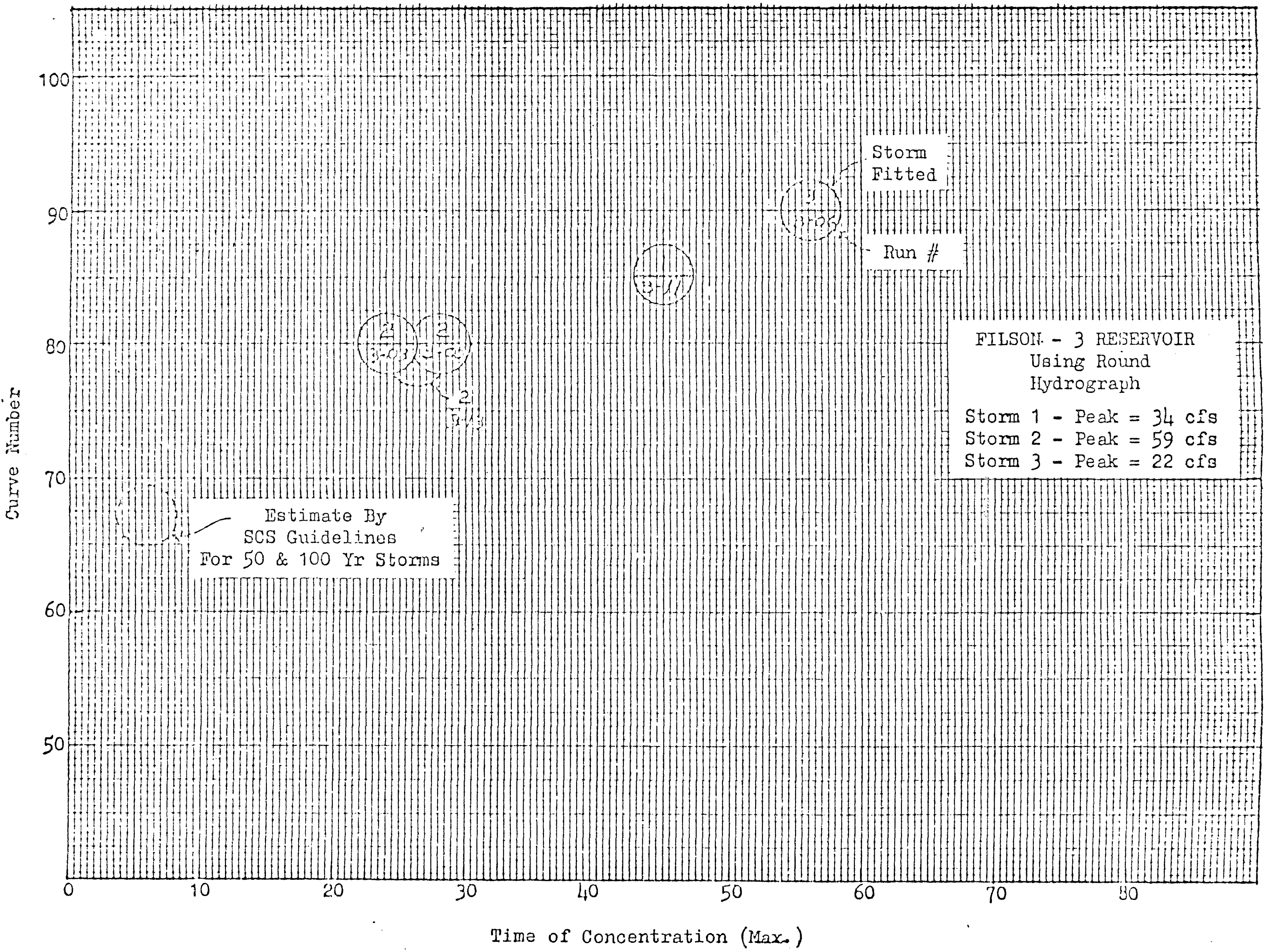


Fig. 49 - Filson Creek, TR-20, is Reservoir Model, October 1975.



FILSON - 3 RESERVOIR
Using Round
Hydrograph

Storm 1 - Peak = 34 cfs
Storm 2 - Peak = 59 cfs
Storm 3 - Peak = 22 cfs

Estimate By
SCS Guidelines
For 50 & 100 Yr Storms

Fig. 50 - Tc and CN, Round Hydrograph.

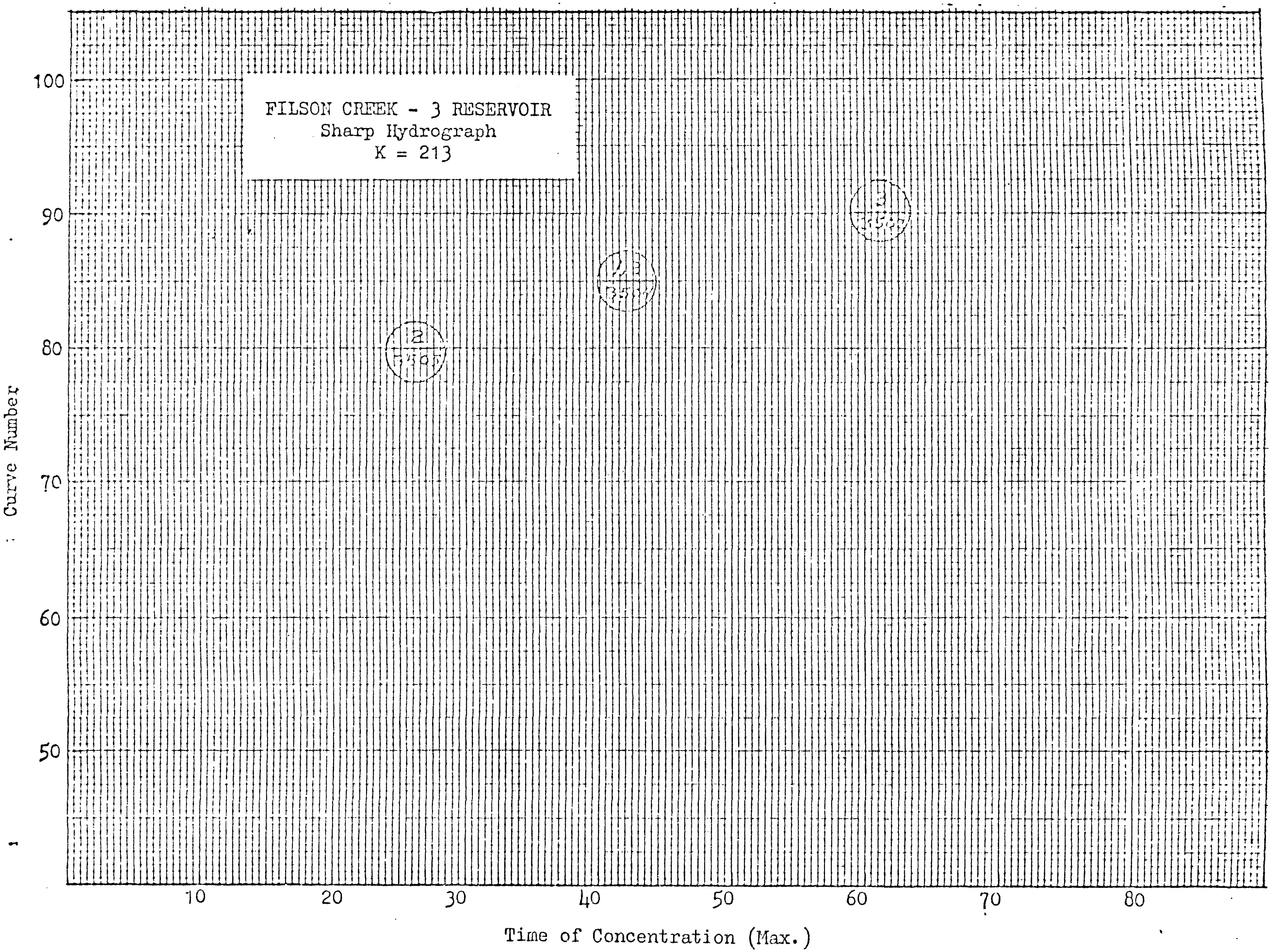


Fig. 51 - Tc and CN, Sharp Hydrograph.

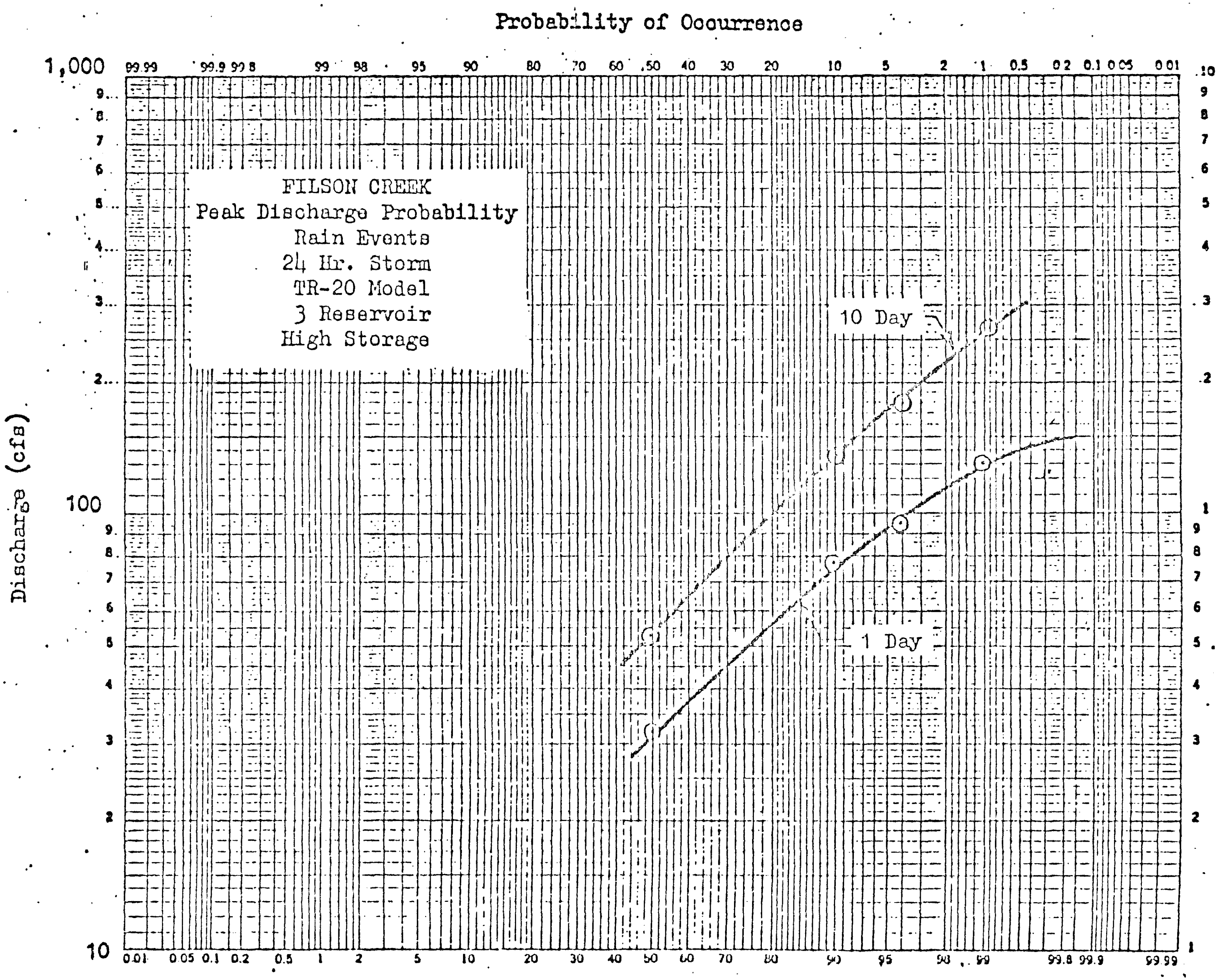


Fig. 52 - Filson Creek, One-Day and 10-Day Rain Floods by TR-20.

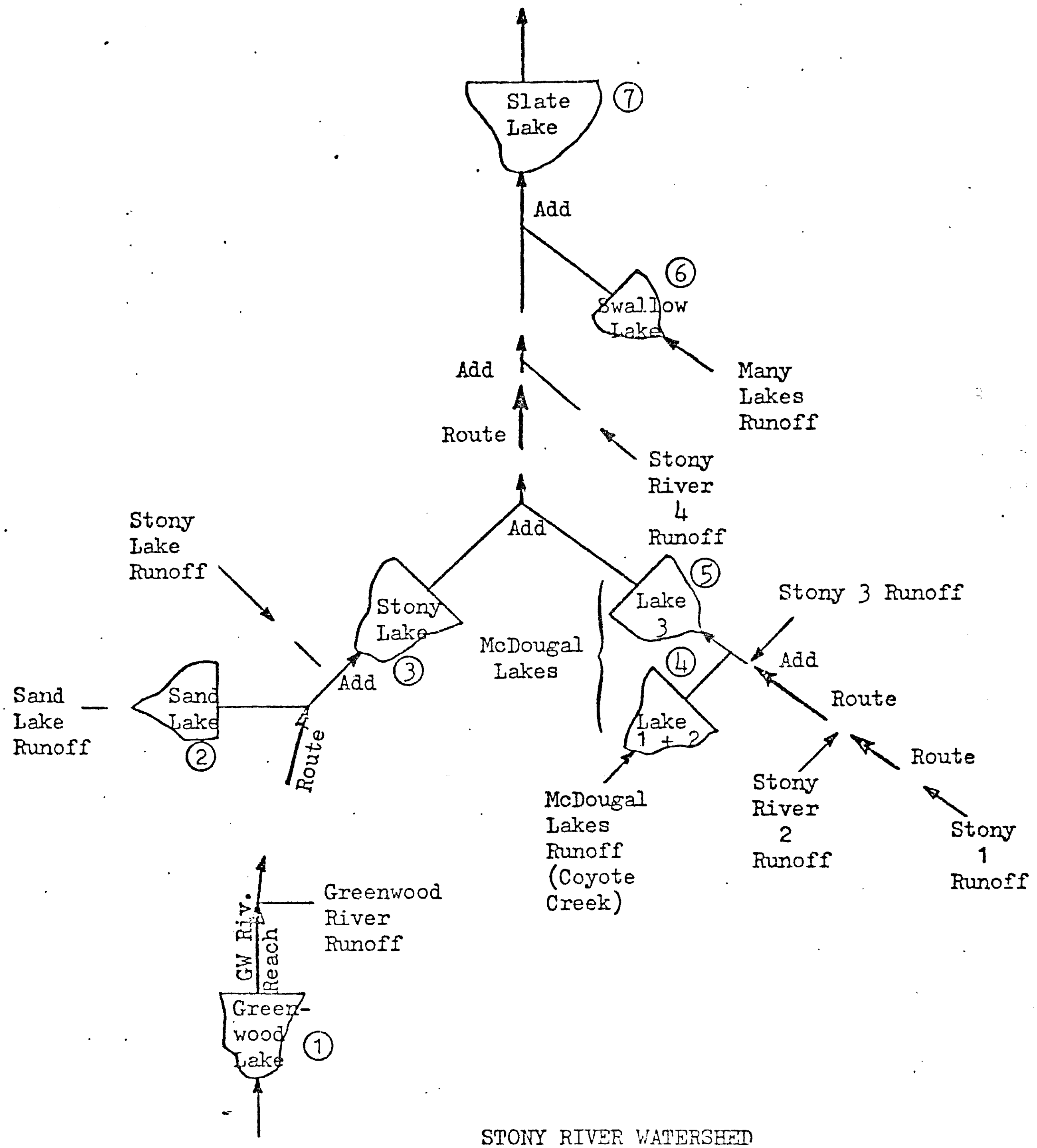
Stony River Near Isabella (180 Sq. Mi)

The Stony River model was begun after fitting of the Filson Creek watershed had started. Realizing that the SCS parameters were unlikely to lead to a fit, no attempt was made to estimate these from the guidelines. Since a few cross sections of the river were available, the lakes were assumed to be regulated by friction control in these sections except at Slate Lake, above the gaging station, where a broad-crested weir was used to simulate an old logging dam at Highway 1. At first, capacity of the reservoirs was determined from planimetry of the contour intervals giving a low estimate of storage. Figure 53 shows the schematic arrangement of watersheds and reservoirs for the Stony River, while Figure 54 shows the actual subwatershed boundaries.

Because a longer period of precipitation was available, larger storms were used on the Stony than on Filson Creek. The largest event was the storm of June 22, 1964, which had a peak of 1100 cfs. As fitting of the model to this storm progressed, a double peak became evident in the computed hydrograph. This was caused by a second burst of rain at about 264 hours (Figs. 55 and 56).

It was hoped that this double peak could be smoothed by increasing the storage to account for additional bogs and swamps within the watershed. The "high storage model", Figure 57, added five new reservoirs and increased the storage of most existing reservoirs using storage estimates derived from DNR aerial photos, as was done for the Filson Creek model. The increased storage required that the time of concentration be lowered but did not reduce the double peaks of the June 22 storm (Fig. 58).

The solution to the problem was to treat the storm not as a single event, but as two events, with a drying-out period between them. This had to be done by hand because the TR-20 can only handle a single event. For the June 22 storm, the last burst, from 4.53 to 5.45 inches, produces .836" of runoff in the model. The model works on the assumption that the watershed is very wet from the previous 4.53 inches of rain, when it has actually been dried by 5 days of rainless summer weather. (The antecedent moisture condition is 1.97", which is wet but not unusual.) If treated as a separate storm with MC III, the curve number would be increased to 88 and a 1.02" storm will produce only .262" of runoff at CN 88.

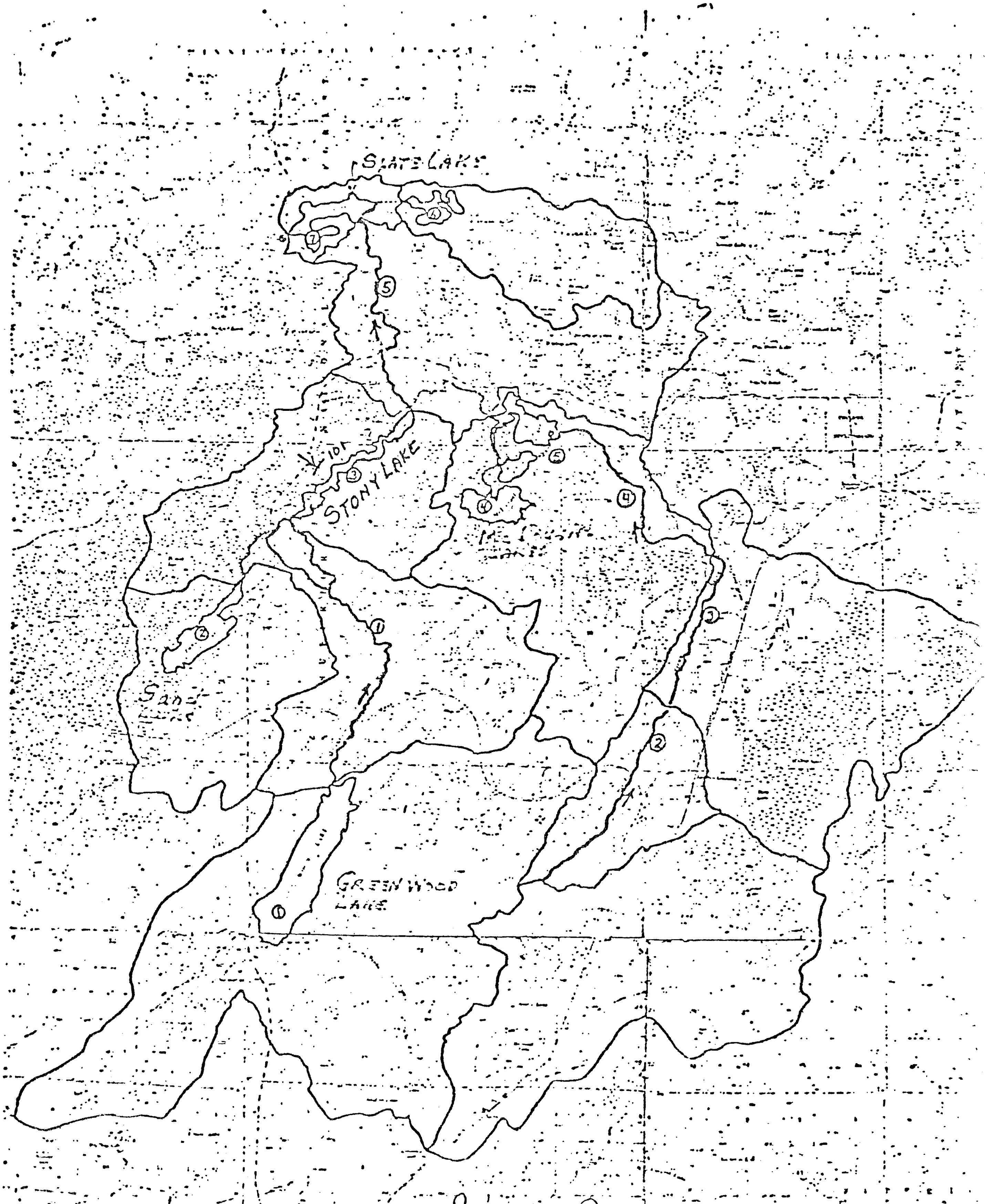


STONY RIVER WATERSHED

Small Storage

-Lakes Only
-No Account of Bog & Swamp Area
-Circled Numbers are Structure Numbers

Fig. 53



STONY RIVER SUBWATERSHEDS

Fig. 54

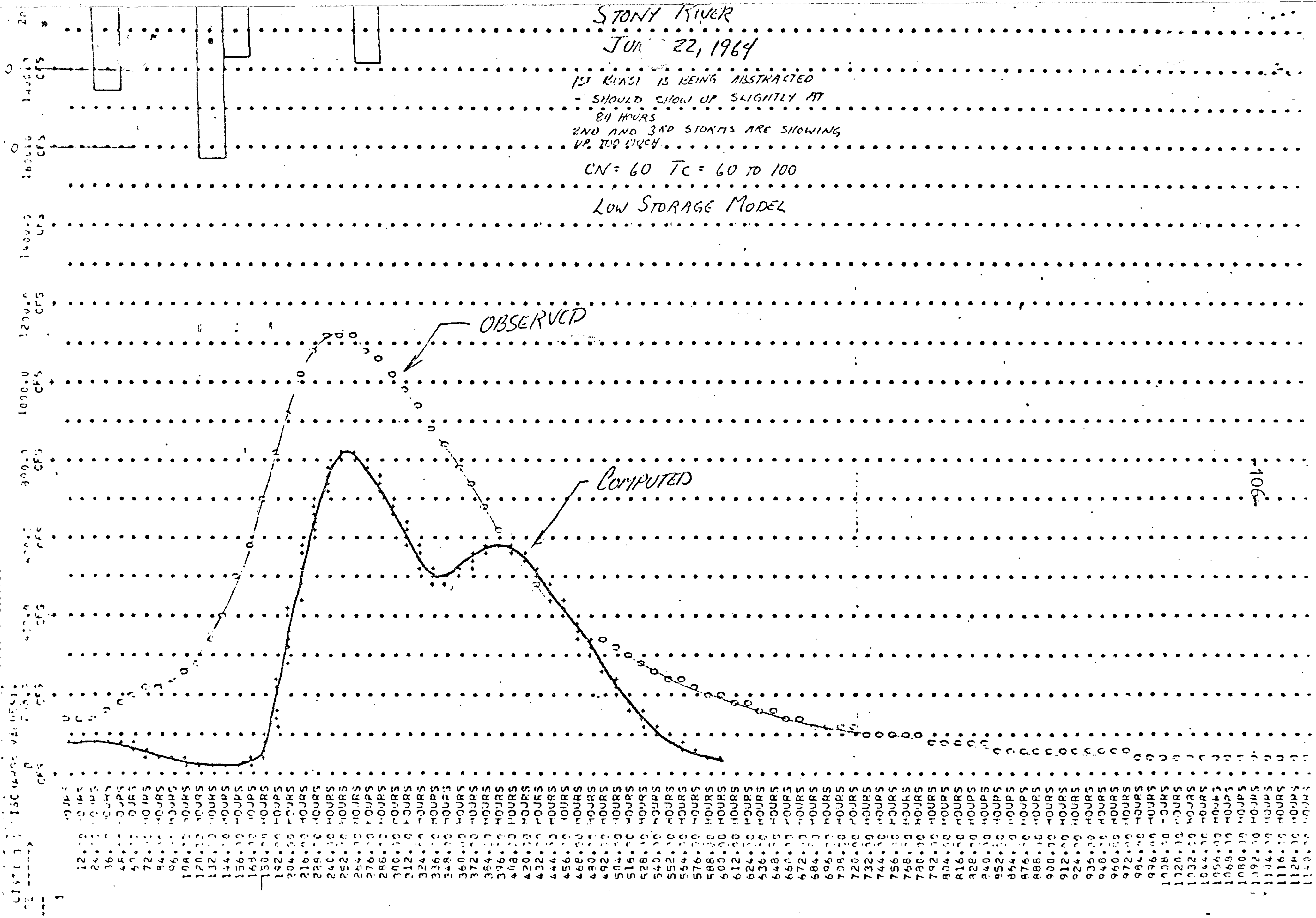


Fig. 55 - Stony River, TR-20, Low Storage Model, June 1964, CN = 60.

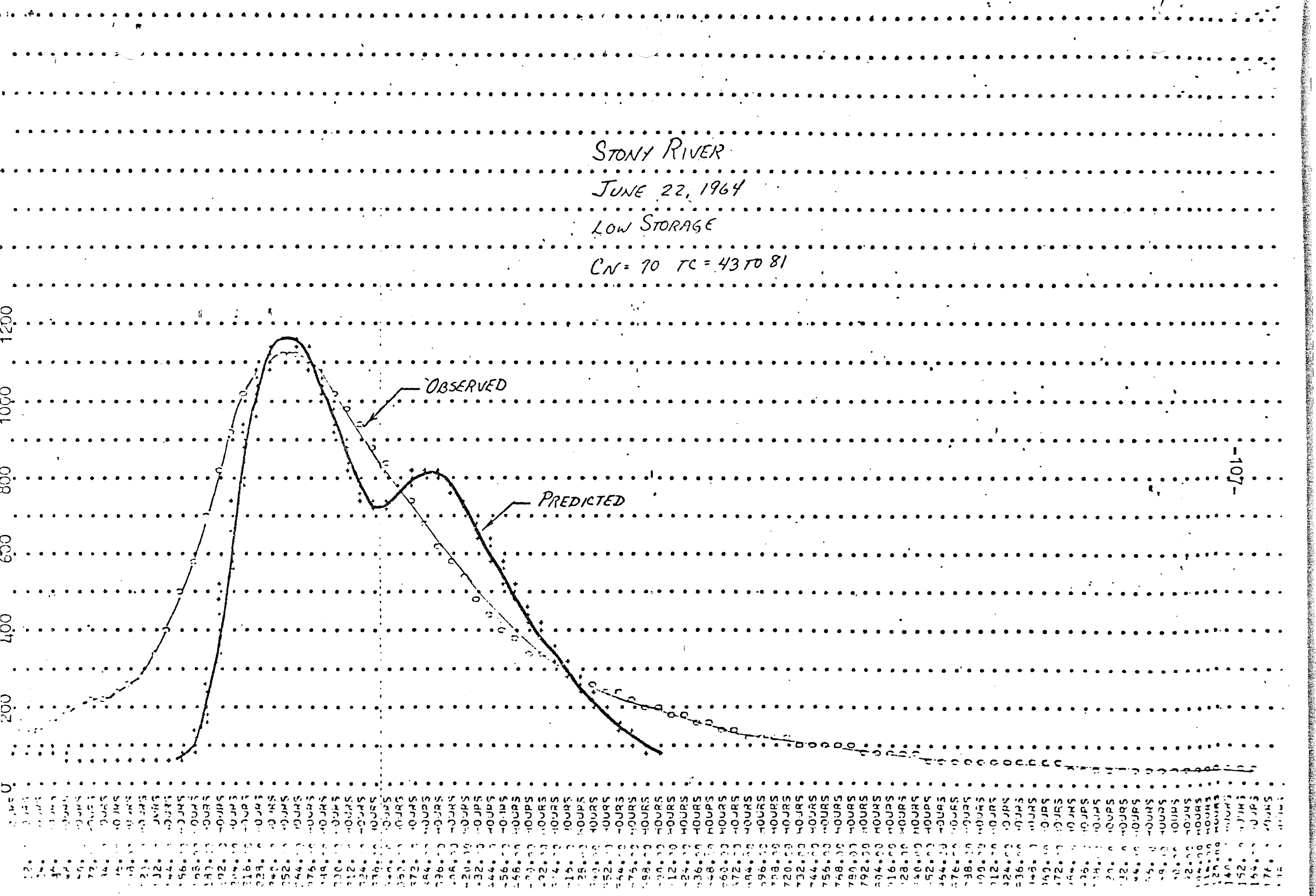


Fig. 56 - Stony River, TR-20, Low Storage Model, June 1964, CN=70.

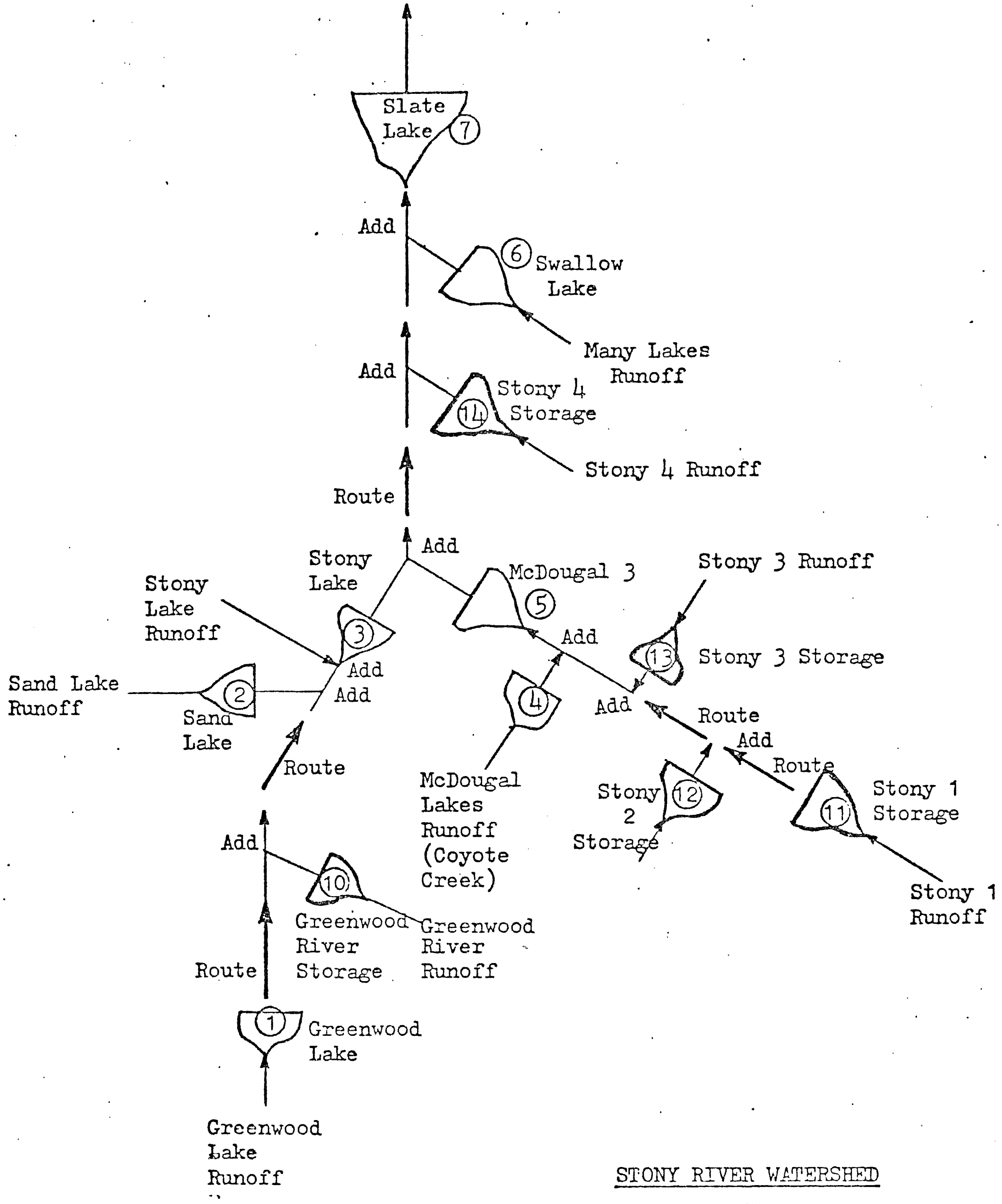


Fig. 57 - Stony River, Large Storage Model.

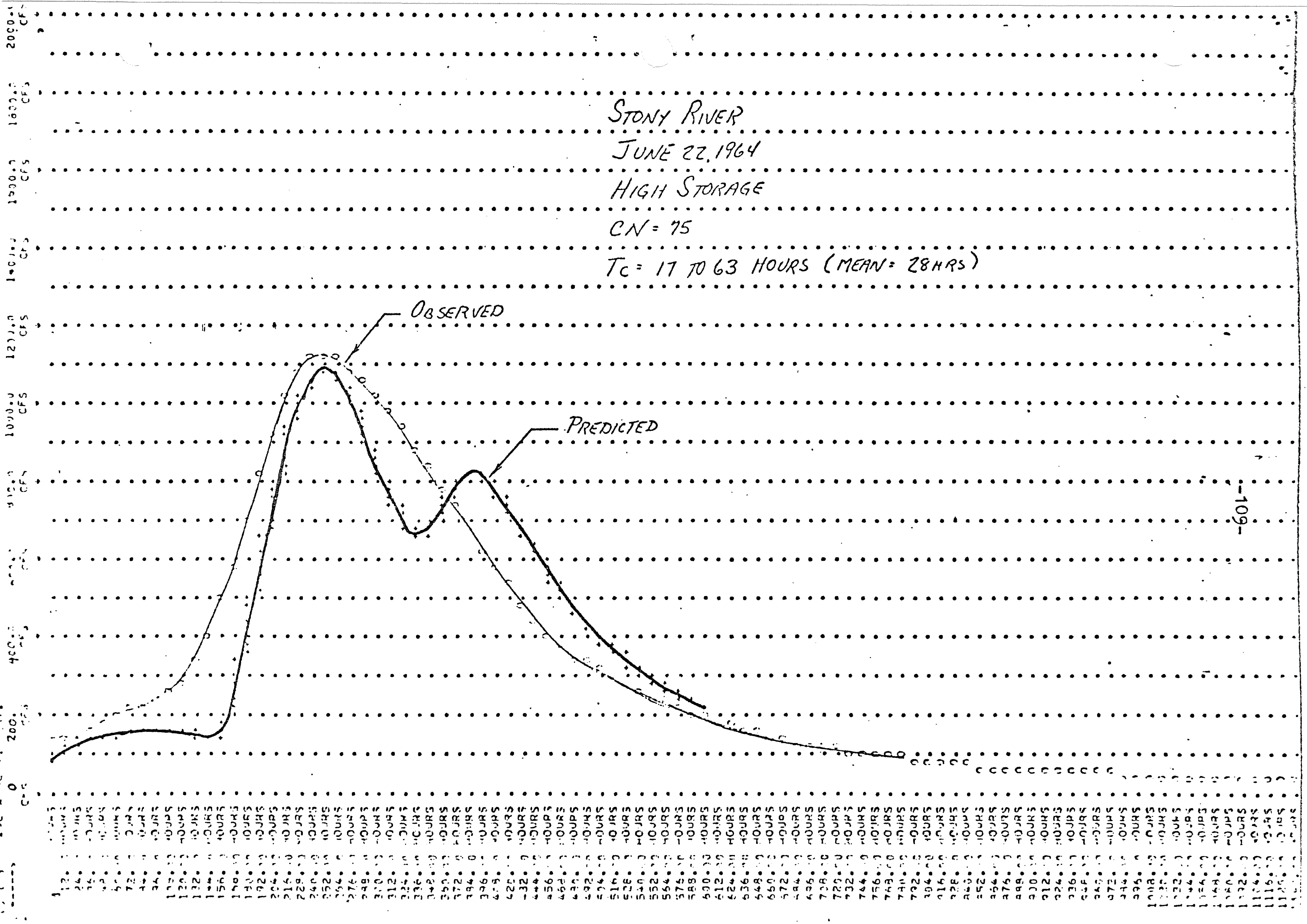


Fig. 58 - Stony River, TR-20, High Storage, June 1964.

To make the single event model give .262" of runoff instead of .836", the precipitation input must be lowered. Using CN 75 (Fig. 59). The precipitation should increase from 4.53" to 4.69" instead of to 5.45". A fairly good fit resulted.

If the entire set of rainfall events for a run are altered in this way by hand, then one can stop when the runoff has been calculated from the precipitation and use this as input to the model (curve number 100 is used). (All "precipitation" is converted to runoff by the model.) This eliminates the need to construct a hypothetical raintable which the program would convert back to runoff.

When adjusted in this way, the Stony storms gave generally good results (Figs. 60, 61, and 62). The exception was the storm of September 1-15, 1961, as shown in Figures 63 and 64. This storm followed two exceptionally dry months (API = .12 at Babbitt on August 28). Over an inch of rain fell August 28 and 29 but the river discharge increased only from 6.8 to 9.3 cfs. In the following two weeks 5.4 inches of precipitation produced a peak flow of only 187 cfs and .5" of runoff for the month of September. The observed hydrograph indicates that some runoff was produced by the rain of the 10th and 11th of September, which indicates a fairly wet watershed condition. Yet the 1.36 inches on the 13-15 of September will cause the model to over predict unless a very dry watershed is assumed. It amy be that although some runoff was being produced, large losses to the soil were still occuring.

The 10-day storms for 2, 10, 25, and 100 year recurrance intervals were run using CN 61 as suggested by the SCS (Minnesota Hyd. Guide 3-10). The peak flows were:

	Precip.	Peak
2 Yr	4.14"	398 cfs
10 Yr	6.61"	1132 cfs
25 Yr	7.80"	1615 cfs
100 Yr	9.75"	2684 cfs

The 1-day storms for 2, 10, 25, and 100 year recurrance intervals were run using CN 75. The peak flows were:

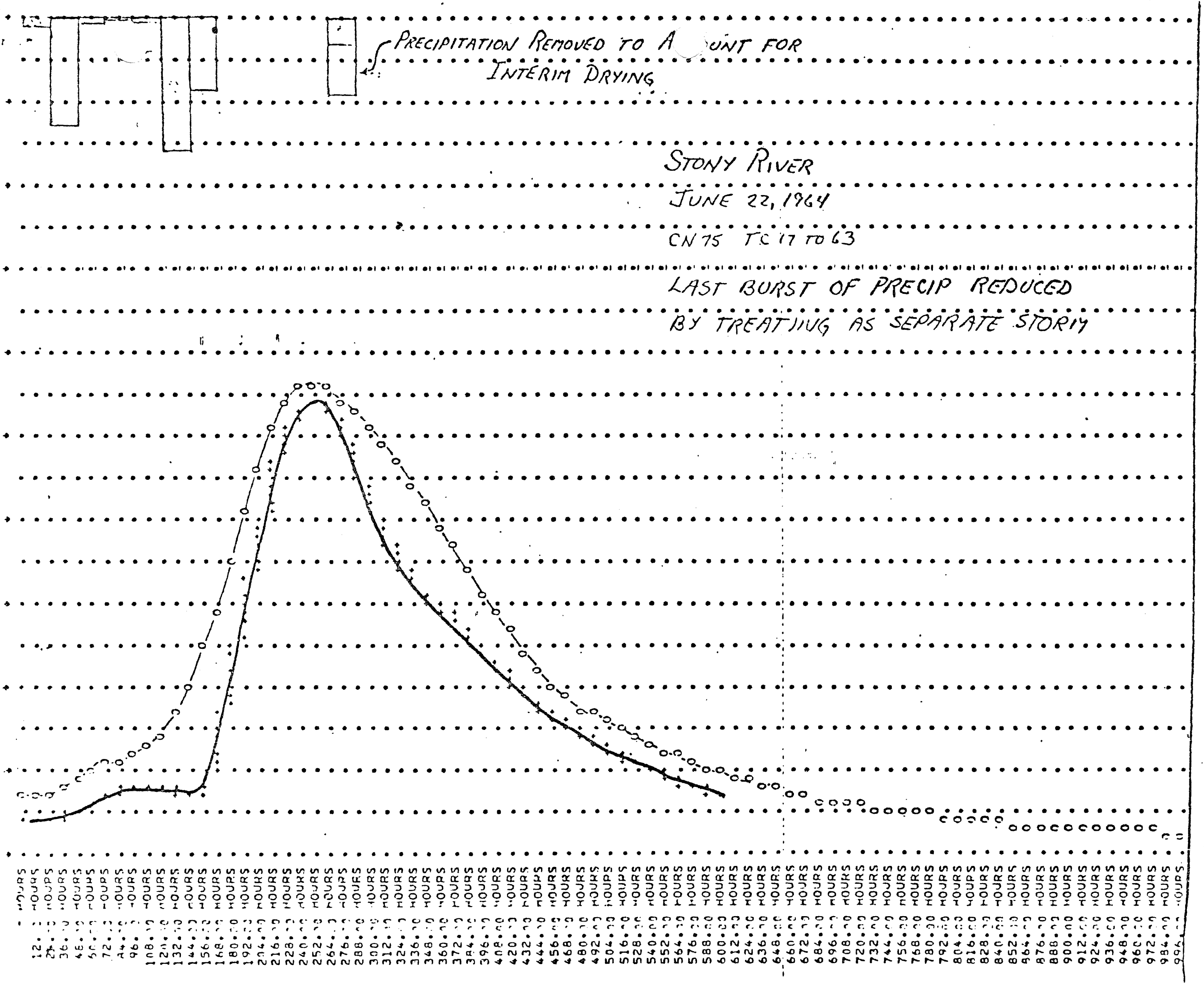


Fig. 59 - Stony River, TR-20, High Storage Model, June 1964, Modified Precipitation.

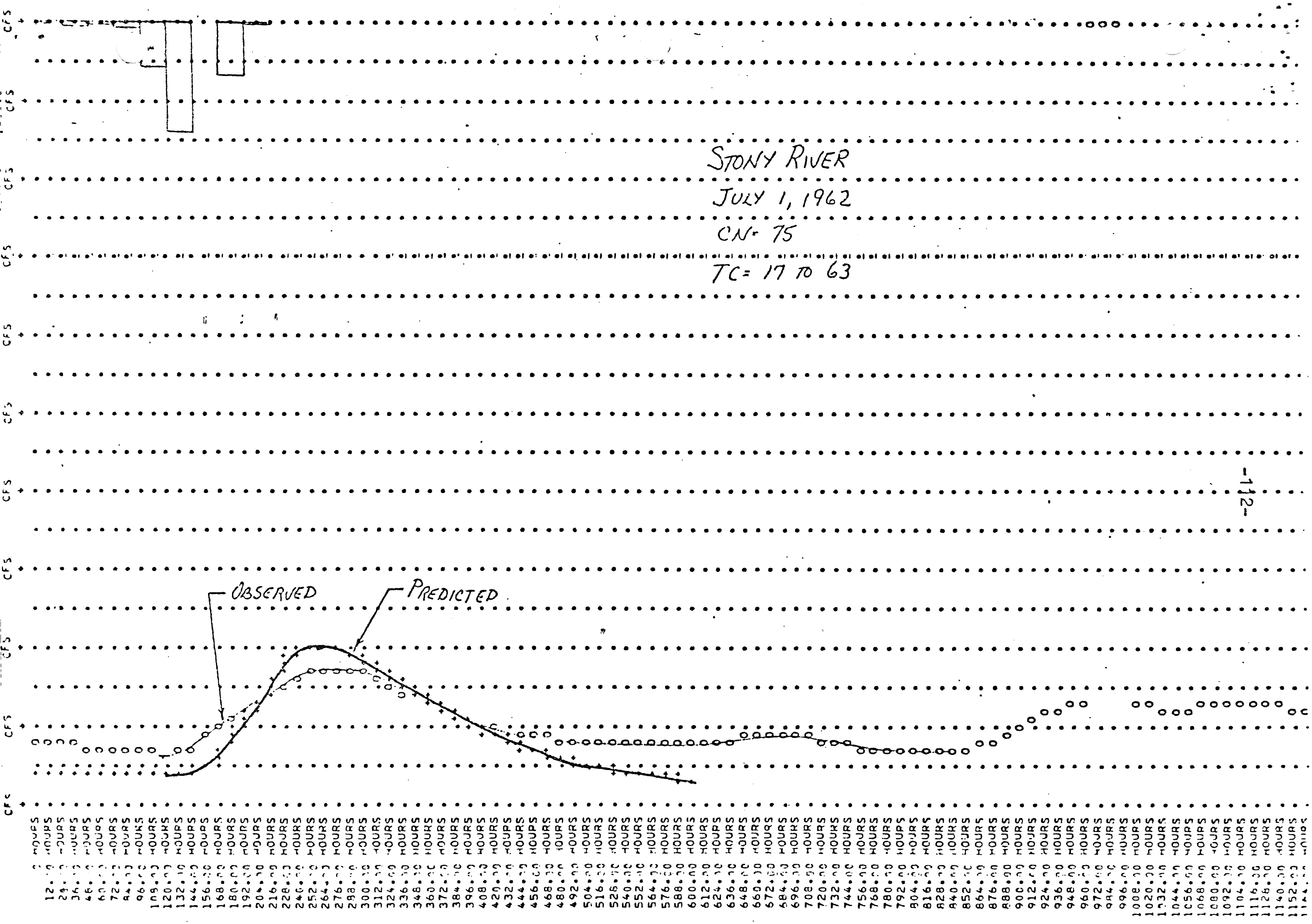


Fig. 60 - Stony River, TR-20, High Storage Model, Modified Precipitation.

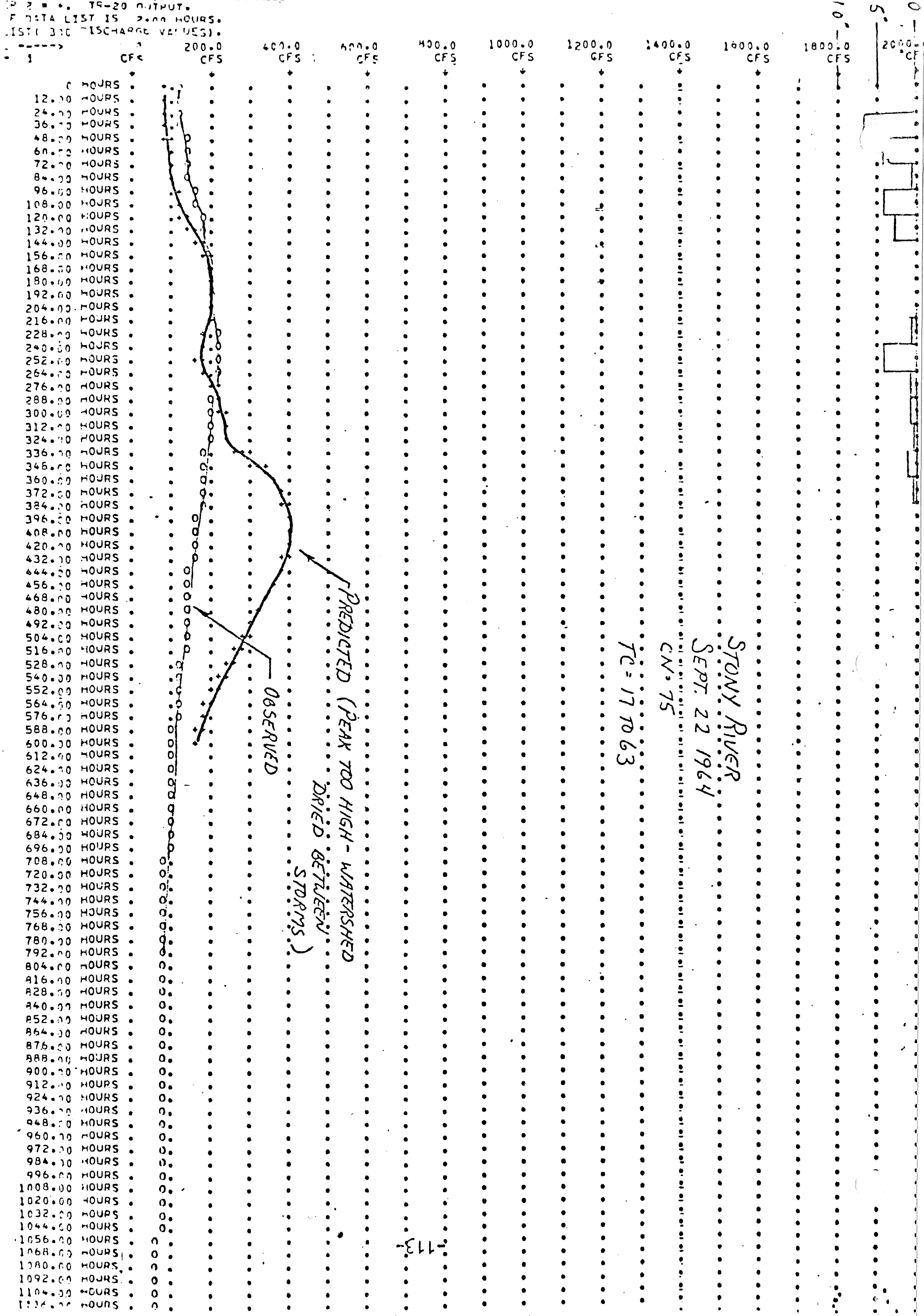


Fig. 61 - Stony River, TR-20, High Storage Model, Modified Precipitation.

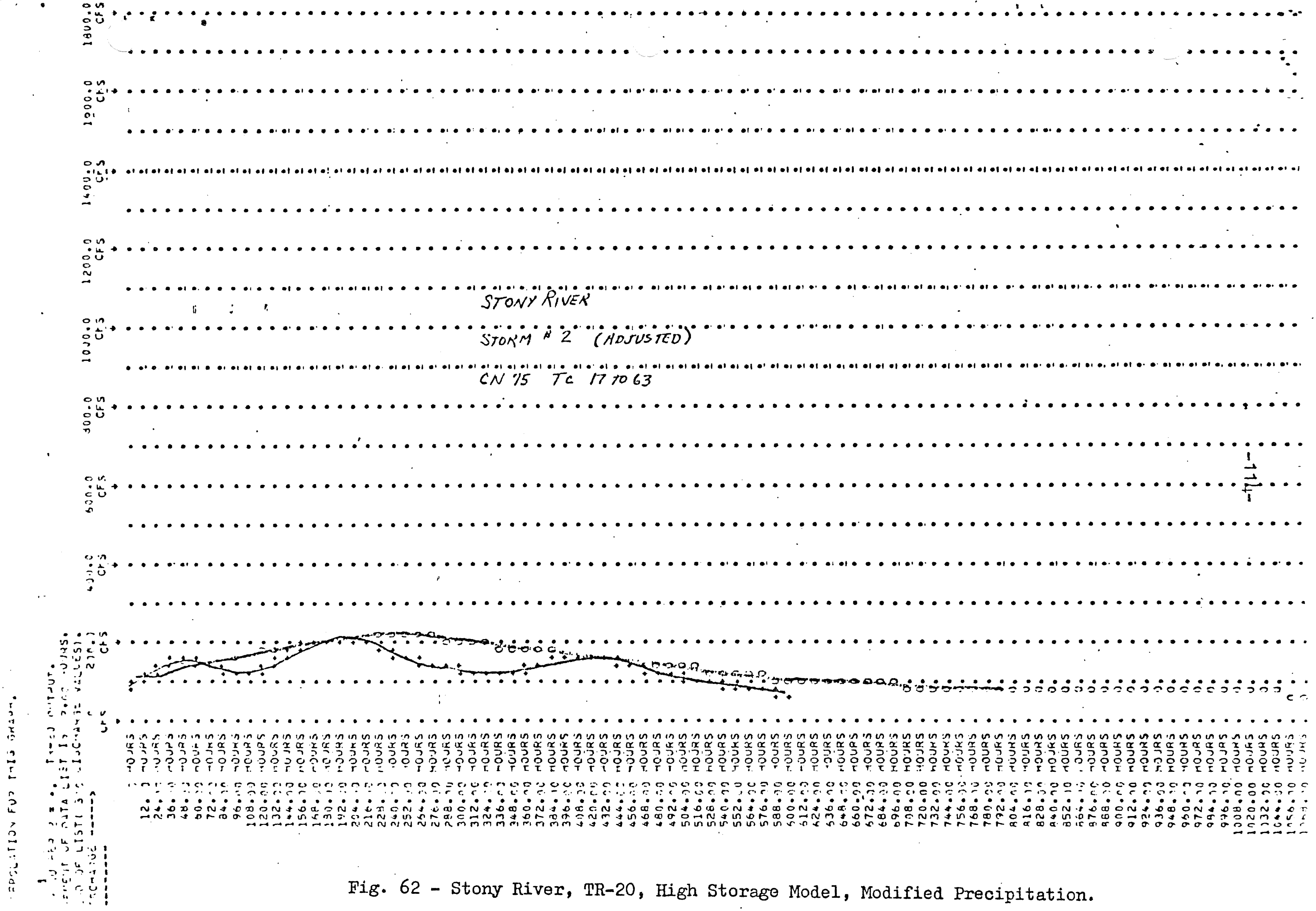


Fig. 62 - Stony River, TR-20, High Storage Model, Modified Precipitation.

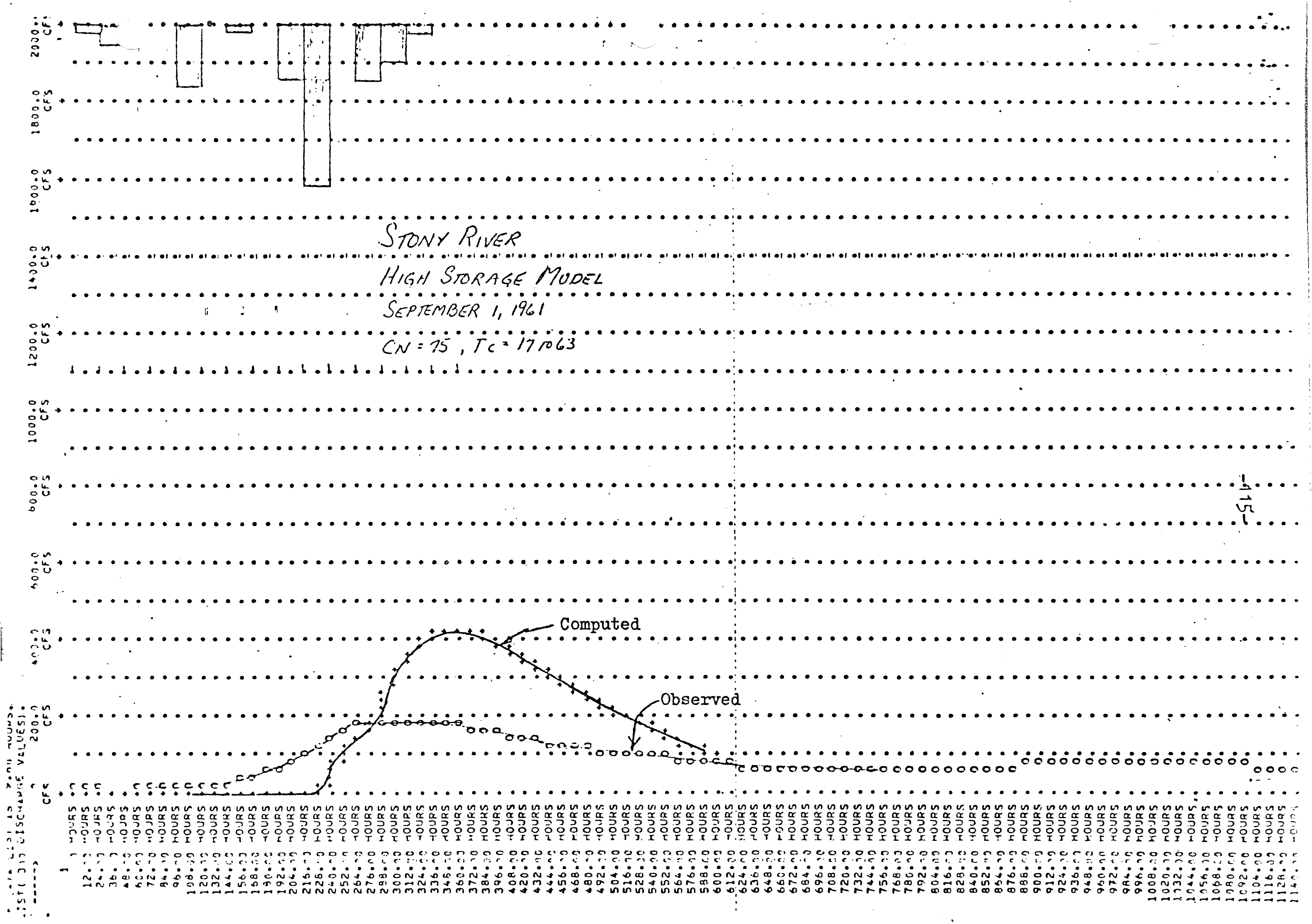


Fig. 63 - Stony River, TR-20, High Storage Model, September 1-15, 1961.

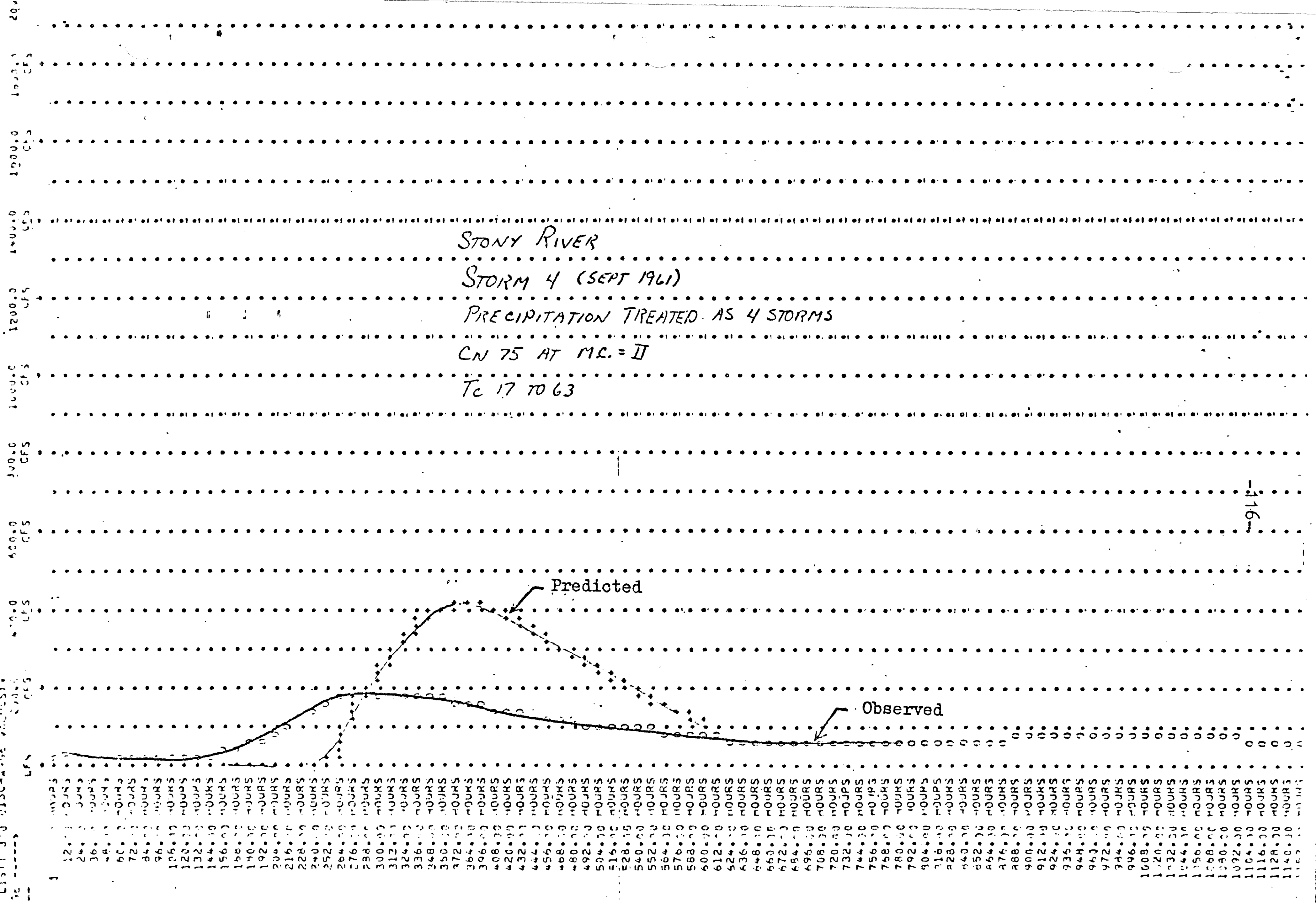


Fig. 64 - Stony River, TR-20, High Storage Model, Modified Precipitation.

	Precip.	Peak
2 Yr	2.20"	319 cfs
10 Yr	3.35"	661 cfs
25 Yr	3.76"	841 cfs
100 Yr	4.64"	1275 cfs

The data for both the 10-day and 1-day storms are plotted in Figure 65.

See Appendix A for further discussion of curve numbers.

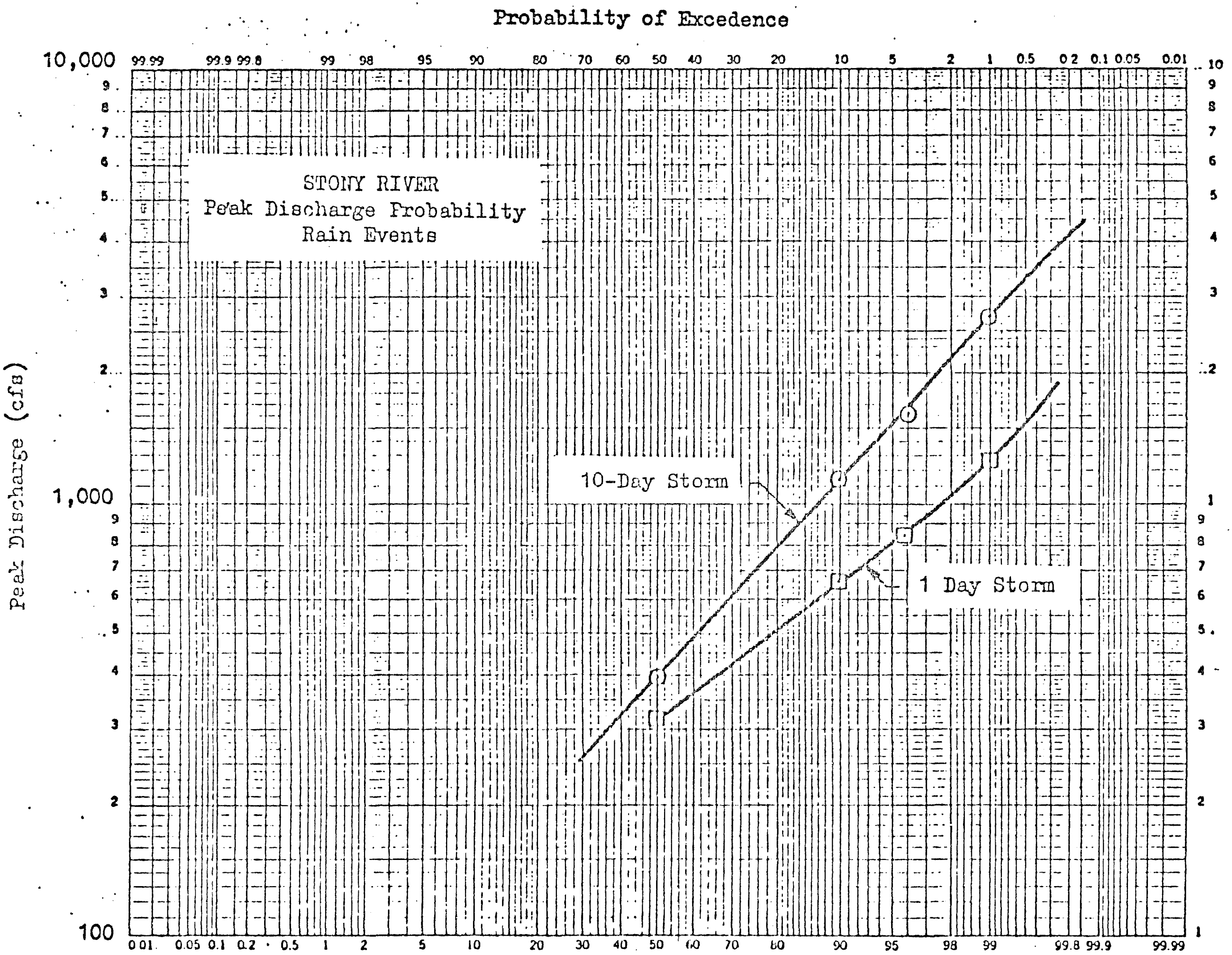


Fig. 65 - Stony River, TR-20, Flood Frequency (CN61 for 10 days, CN75 for 1 day)

Partridge River

The Partridge River model was a high storage model, i.e. every watershed contains a reservoir with capacity suggested by DNR aerial photodata, as was the case with Stony and Filson. Figure 66 illustrates the sub-watersheds. The curve number was begun at 80 and time of concentration at about 40 hours. From the experience with Filson Creek and the Stony River, it seemed fairly certain that a curve number around 80 would be correct. Since the model underestimated the peaks (Fig. 67), the time of concentration was halved to 20 hours maximum. A shorter T_c seemed unlikely for such large subwatersheds ($\simeq$ 40 square miles each), so storage was adjusted next. By reducing storage to 1/8 of the original estimate, a fit was finally obtained for the highest peak, but here, as on Filson Creek, the parameters used for one storm would not give a fit for the others. Unlike Filson Creek, there was no tendency for smaller storms to produce flatter, longer hydrographs. In fact, no simple relationship can be observed in the four storms under consideration. The table summarizes the storms used:

Table 4

Date	API (in)	Precip. (in)	Avg. Daily (in)	Max. Daily (in)	Observed Peak Flow (cfs)	Computed Peak Flow (cfs)
Sept '61	.94	4.89	.326	2.36	370	365
July '62	.86	3.55	.97	2.31	636	765
June '64	.50	4.46	.30	2.24	1217	1120
Sept '64	1.76	3.46	.17	1.01	250	230

(See Figs. 68, 69, 70, 71, respectively)

As on the Stony, the storm of September 1961 is a problem and, as on the Stony, hand calculation of runoff from the individual substorms was tried but here no great improvement was noted. The final storage estimates seem very low considering the flat swampy character of the watershed. They are far smaller than the storage used on the Stony River. The relationship of T_c and storage used to fit the storms are:

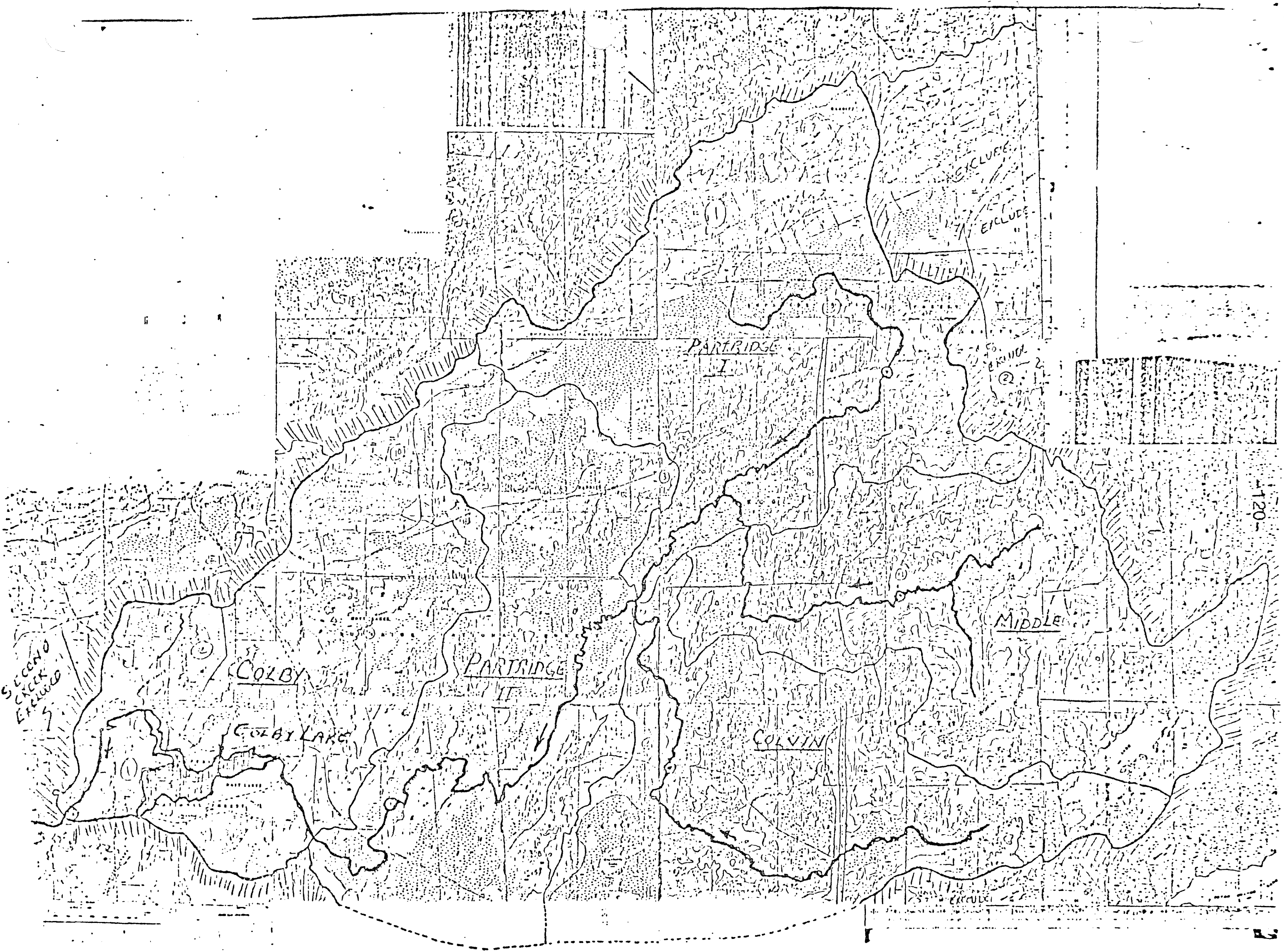


Fig. 66 - Partridge Subwatersheds.

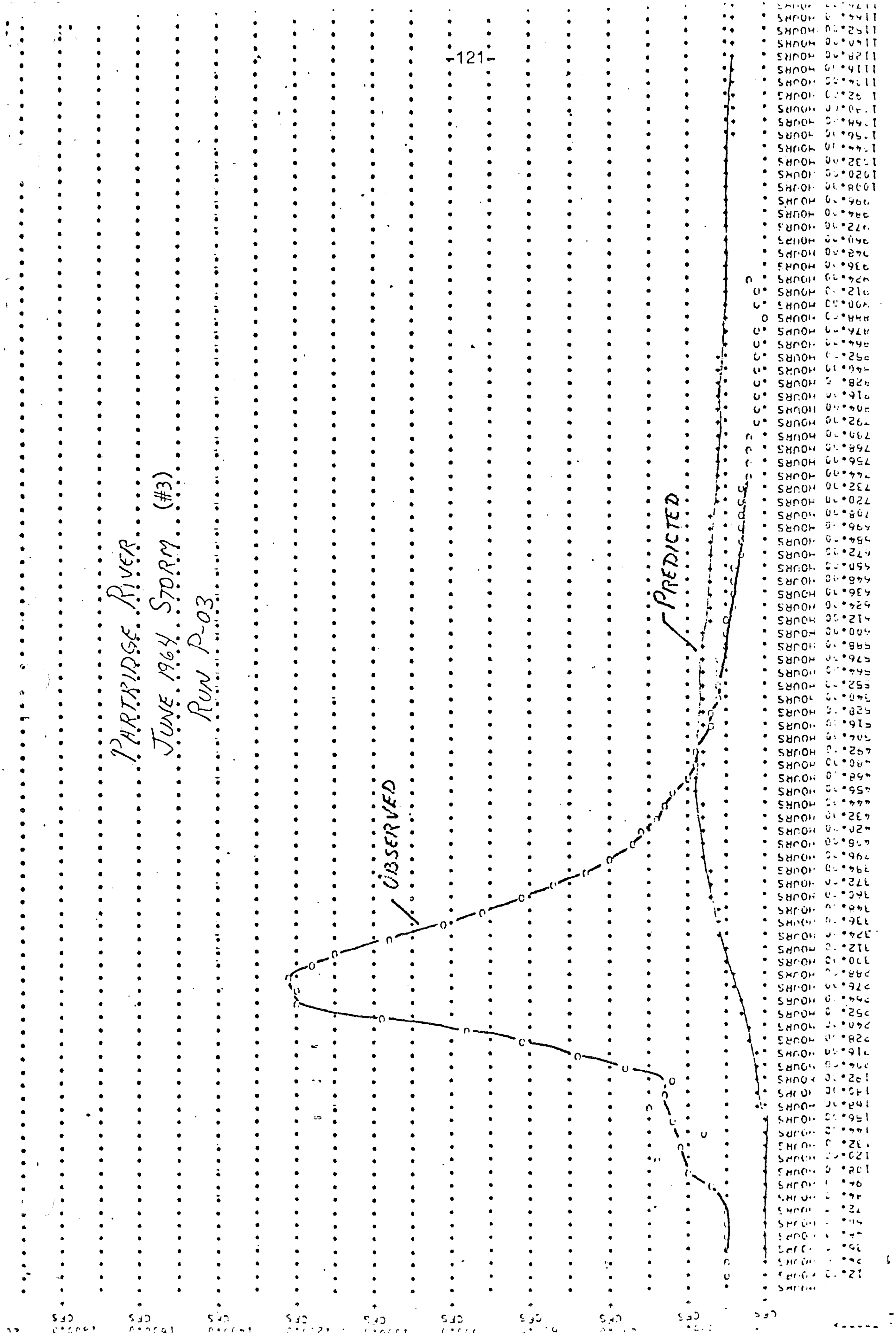


Fig. 67 - Partridge River, TR-20, Initial Run, June 1964.

Storm	Run #	CN	Tc	Storage
Sept 1961	P 03	80	40	16 - Original Estimate
June 1962	P 09	80	20	2
June 1964	P 10	80	20	1
Sept 1964	P 07	80	20	4

Figures 68, 69, 70, and 71

Using the parameters for the largest of these storms, the 1- and 10-day storms for 2, 10, 25, and 100-year recurrance intervals were run. The peak flows were:

10-Day Storms

	Precipitation	Peak Flow
2 Yr	4.16"	382 cfs
10 Yr	6.61"	1297 cfs
25 Yr	7.85"	1883 cfs
100 Yr	9.79"	2854 cfs

1-Day Storms

	Precipitation	Peak Flow
2 Yr	2.22"	265 cfs
10 Yr	3.38"	915 cfs
25 Yr	3.79"	1235 cfs
100 Yr	4.67"	1874 cfs

The peak flows are plotted in Figure 72.

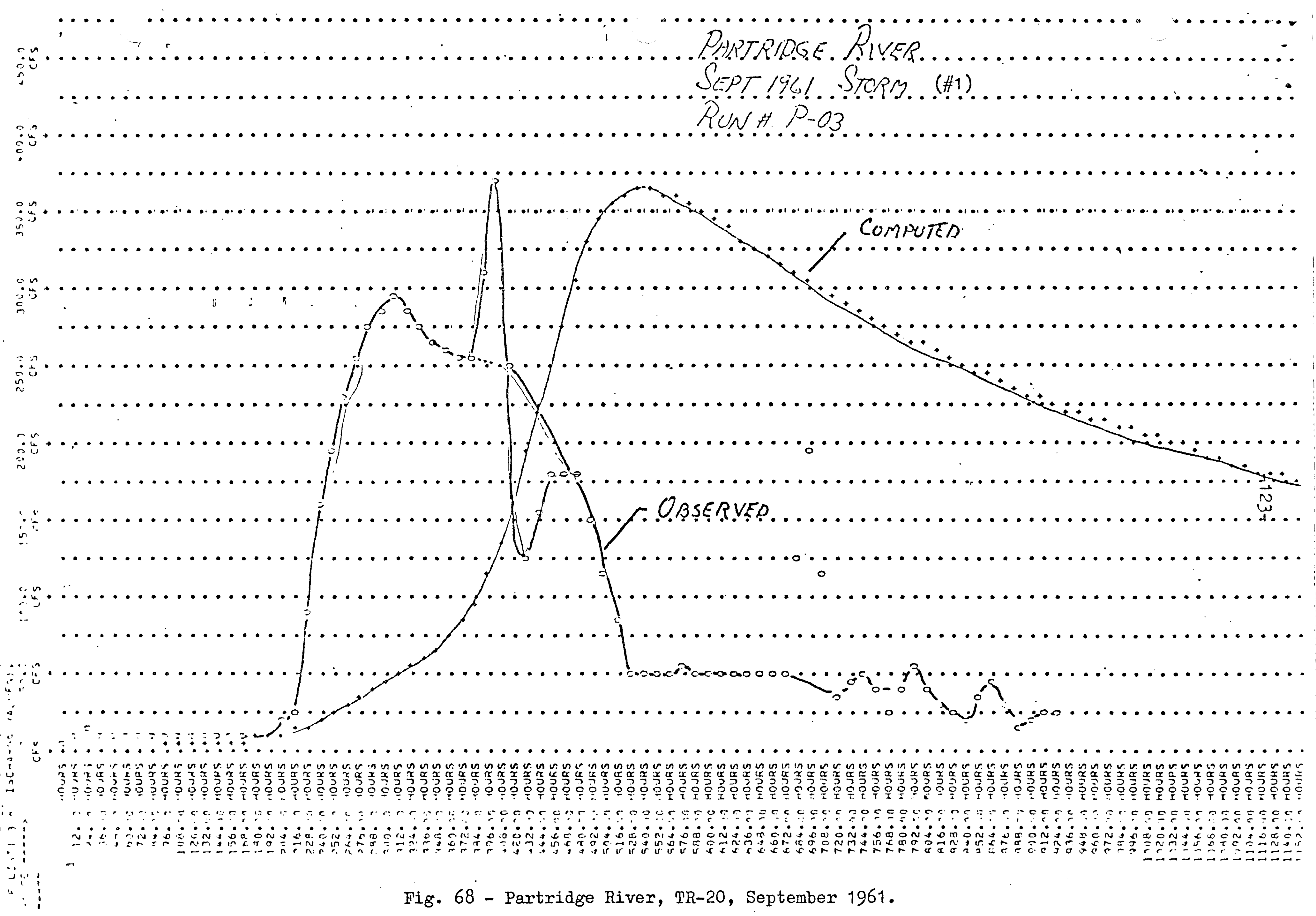


Fig. 68 - Partridge River, TR-20, September 1961.

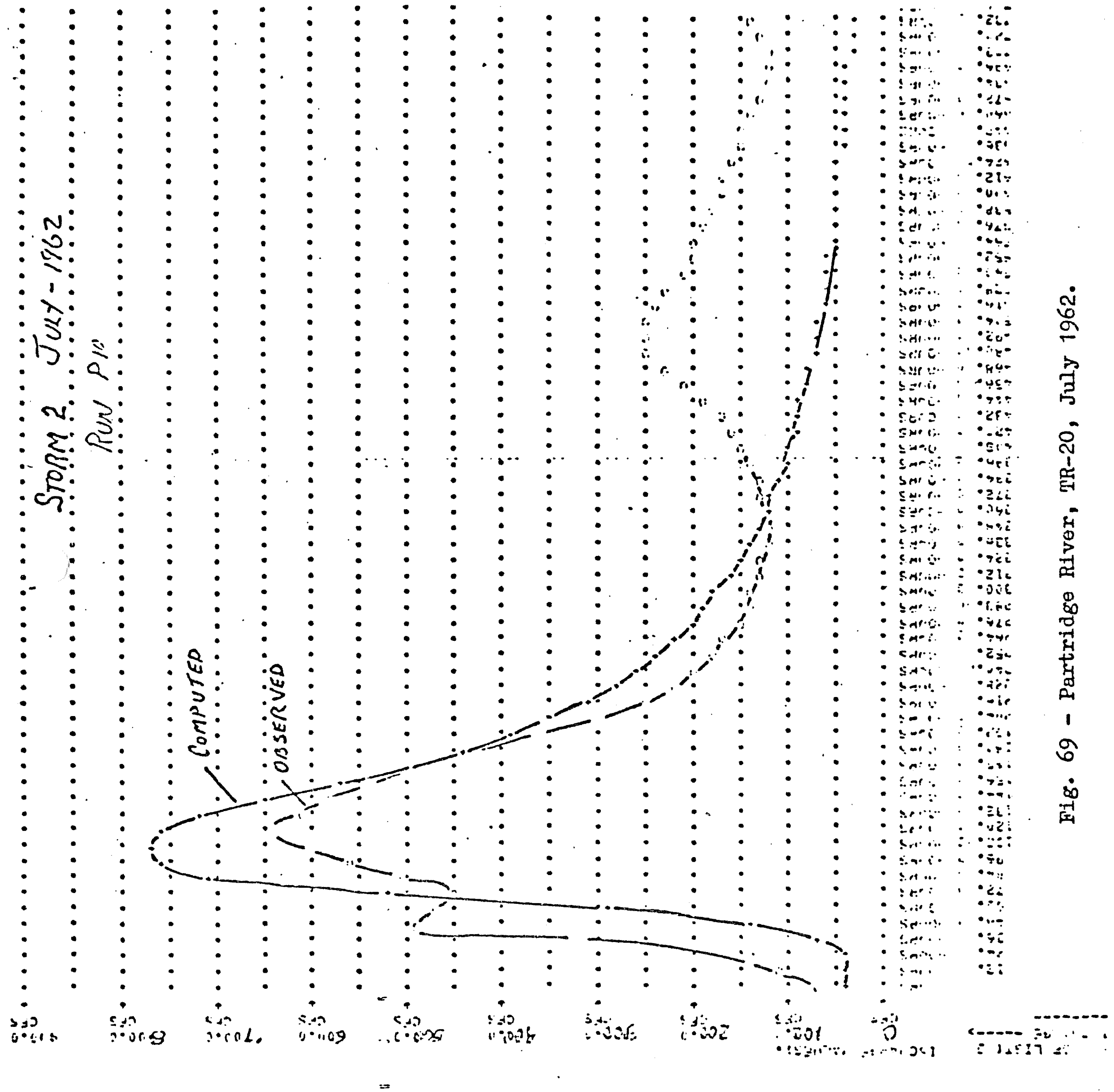


Fig. 69 - Partridge River, TR-20, July 1962.

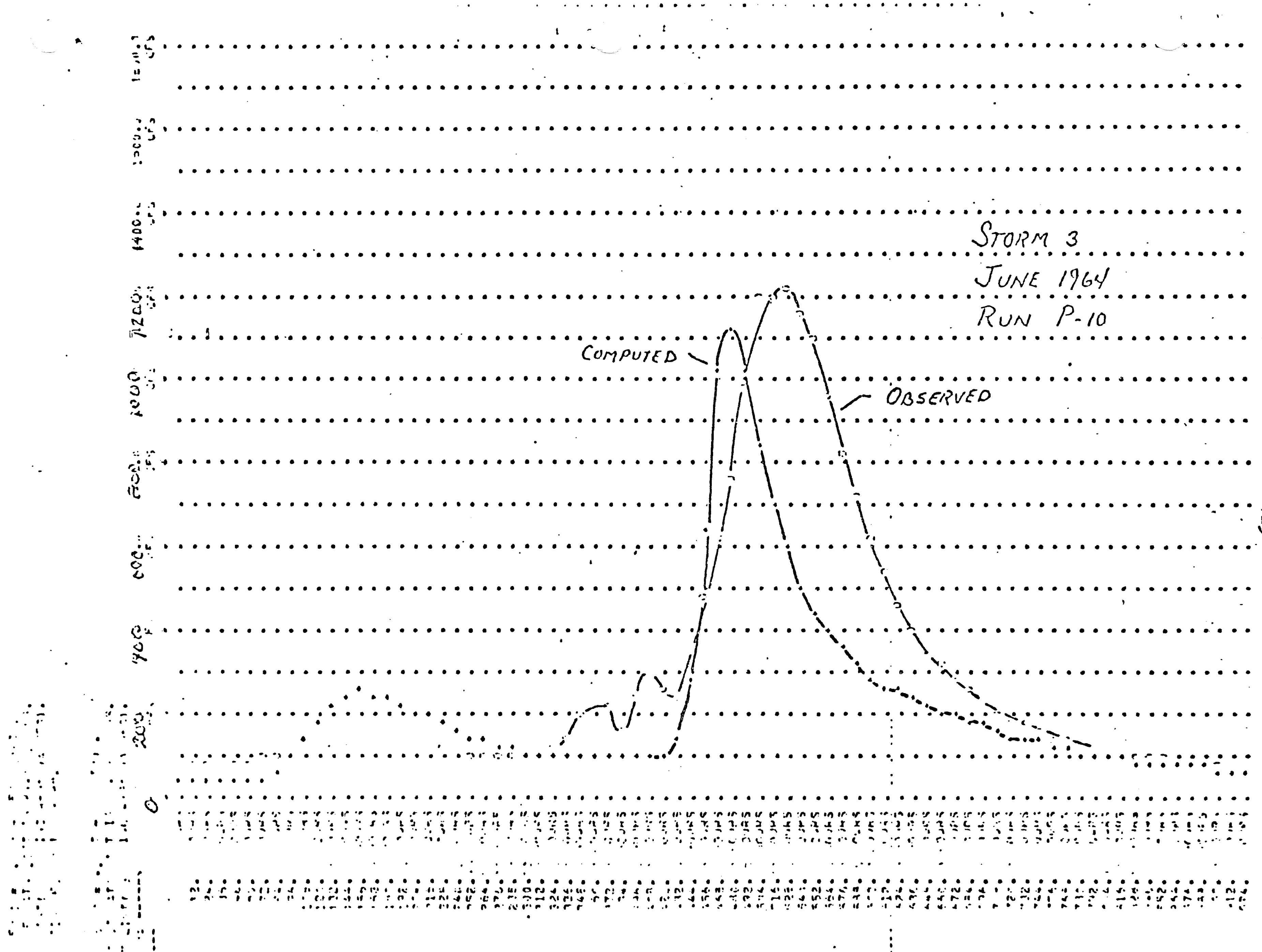


Fig. 70 - Partridge River, TR-20, June 1964.

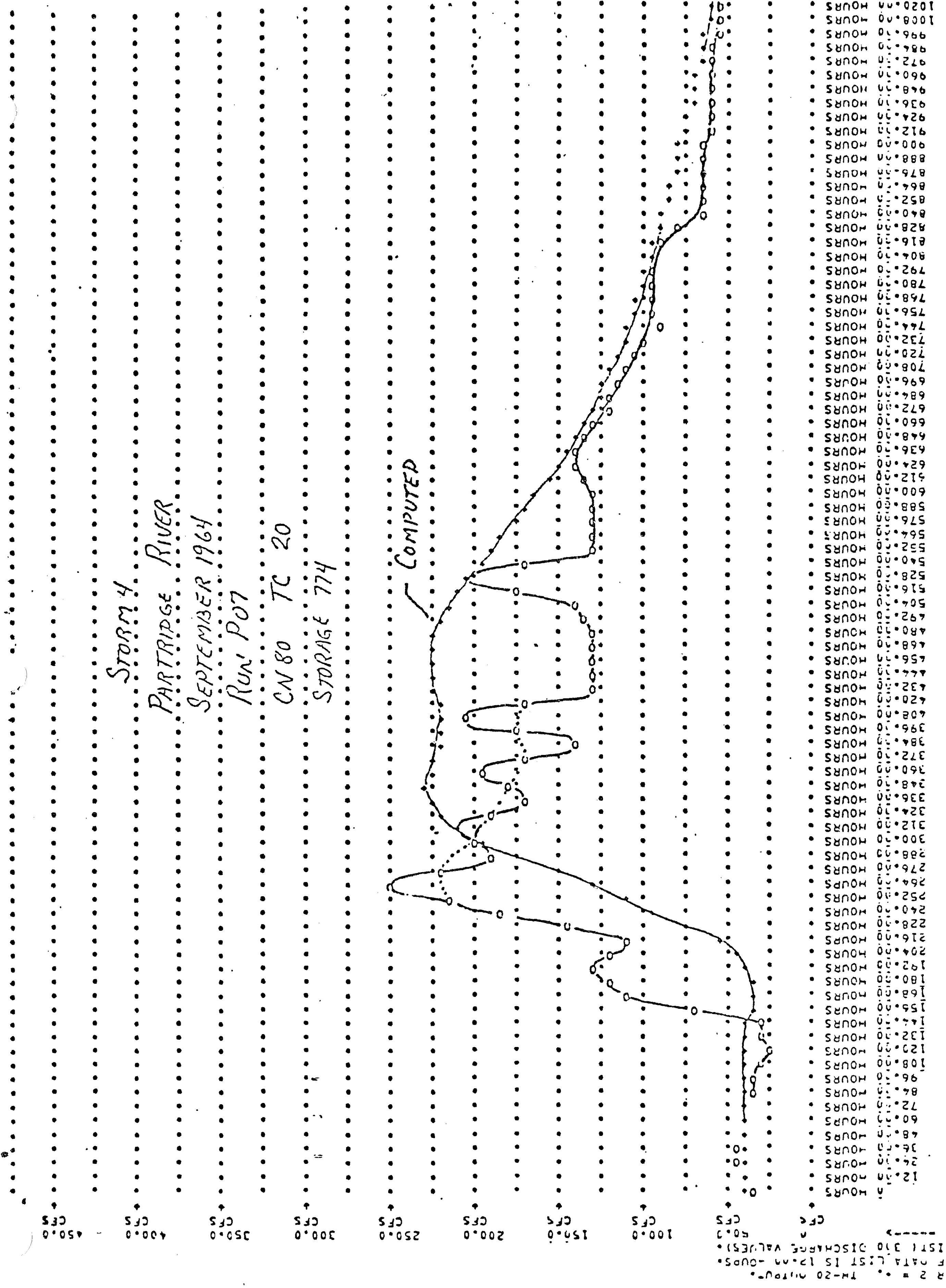


Fig. 71 - Partridge River, TR-20, September 1964.

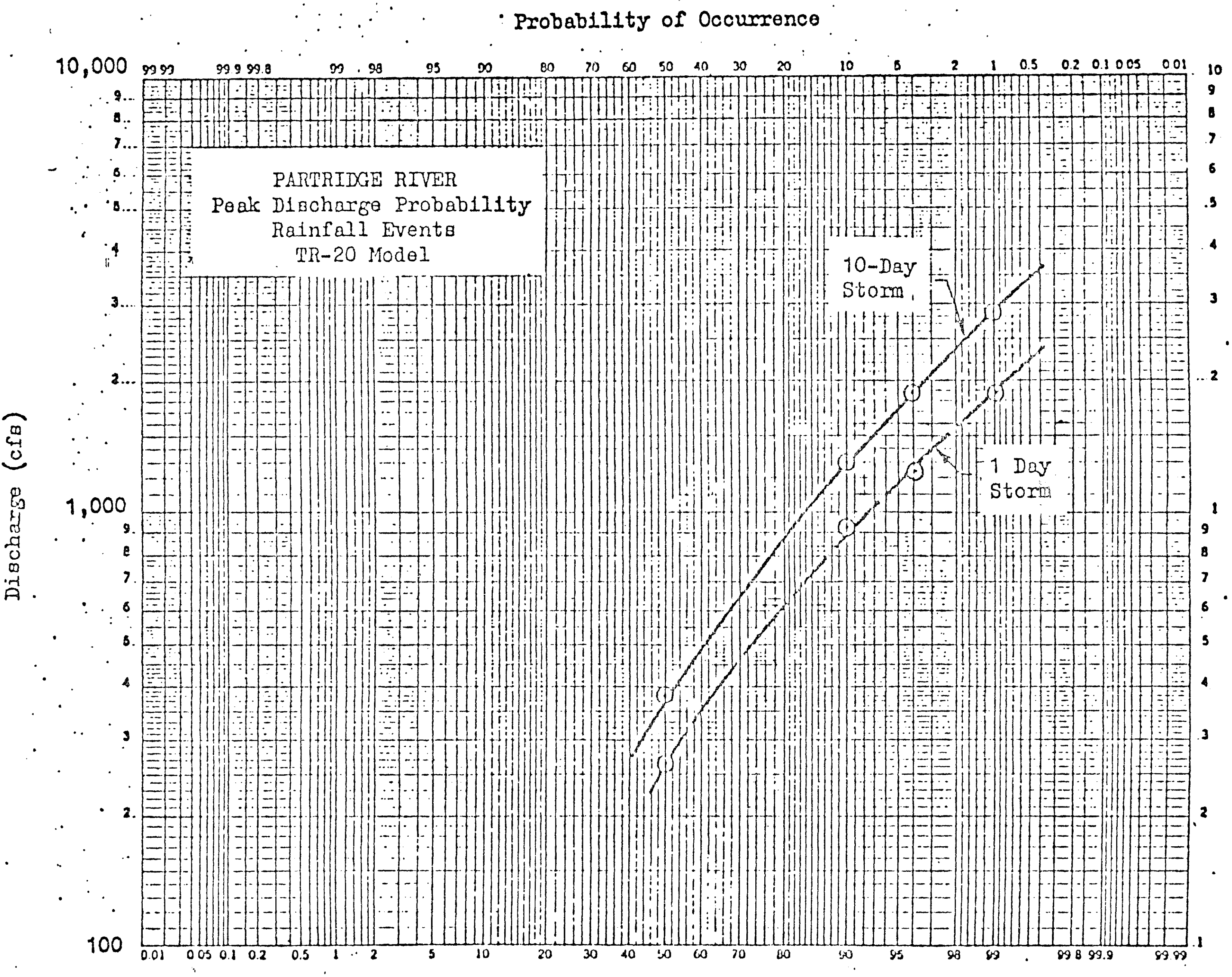


Fig. 72 - Partridge River, TR-20, Frequency of Floods.

SUMMARY

SSARR

The SSARR model was used to simulate runoff response in the Stony River, Partridge River, and Filson Creek. Calibrating the model with several years of data for each watershed, a predictive tool exists for hydrologic response. The larger watersheds are calibrated best because the averaging out of watershed parameters, lumping over large areas, gives a good representation of the actual watershed conditions. In small watersheds the average response is less likely to match with actual watershed runoff. Local variations play a more important part in the runoff process.

Extrapolation of meteorological events leads to some variation of the computed runoff and the actual runoff. Calibration of the SSARR to certain meteorological conditions and then extrapolating them to large events may induce some error and is risky.

Good runoff volumes for entire years have been achieved with the SSARR on Stony and Partridge Rivers. Variations occur in localized events for both the large and small, Filson Creek, watersheds. Overall, the model seems to be a good predictive tool for runoff. (CM = 110000 words.)

TR-20

The TR-20 was conceived as a measured-parameter model for large scale concentrated rainfall events. Because detailed watershed data were not available in this study, it was converted to use as a fitted parameter model for smaller, long-term events.

The advantages of using the TR-20 in this way are:

1. The parameters are directly related to physical phenomena and can-be easily handled.
2. The parameters are few in number for simple storms - curve number, Tc and storage.
3. The program runs quickly and is relatively cheap.

4. The model gives estimates of flow and reservoir elevation at many points within a basin and can easily represent changes in a subregion of a basin.

Disadvantages are:

1. The model has only a rudimentary base flow provision. Whether the double watershed model tried on Filson Creek can overcome this problem is uncertain.
2. Natural storms are not usually well suited to handling by SCS rainfall - runoff curves. For longer intermittant storms the precipitation must be prepared by hand and the three moisture conditions (dry-normal-wet) give only a rough estimate of watershed condition.
3. The model has no snowmelt capability.
4. The TR-20 is a very large program and turnaround is slow. (CM = 155000 words.)

An alternative would be to use the TR-20 as a measured-parameter model, collect a great deal more data, and refine the watershed description in each model. This seems to be a poor alternative because: 1) Some data would be difficult and expensive to acquire - i.e., soil type, vegetation, and topography of the "Partridge 100-mile swamp watershed"; 2) In the case of the Filson model, increasing detail did not lead to appreciably better results.

The effort expended on the TR-20 in this study appears to be reaching a point of diminishing returns. It might be worthwhile to investigate the Partridge River a bit further to understand the unusual results there and to run more storms for the Filson and Stony models to verify the results. Extended work on the snowmelt would be working with the weakest part of the model and probably not be very rewarding.

Comparisons

Figure 73 is a typical printout of the 100-year snowmelt flood on the Stony River. The initial water content of snow was 17 inches. Figures 74-77 illustrate comparisons of the 100-year and other floods as determined by the SSARR and the TR-20. Both snowmelt and rain floods are shown for the SSARR. The one day rain

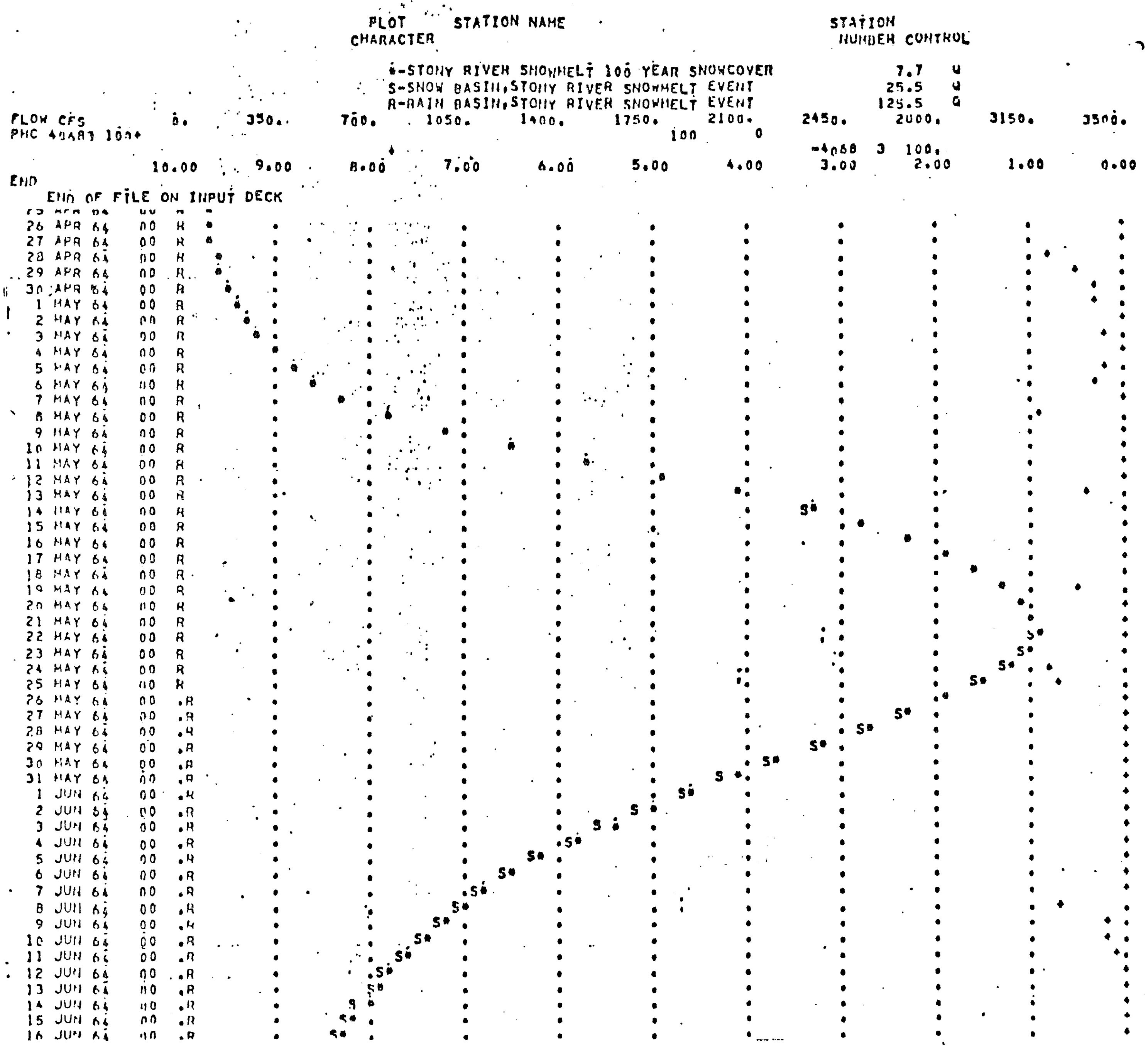


Fig. 73 - Stony River 100-Year Snowmelt Flood (SSARR).

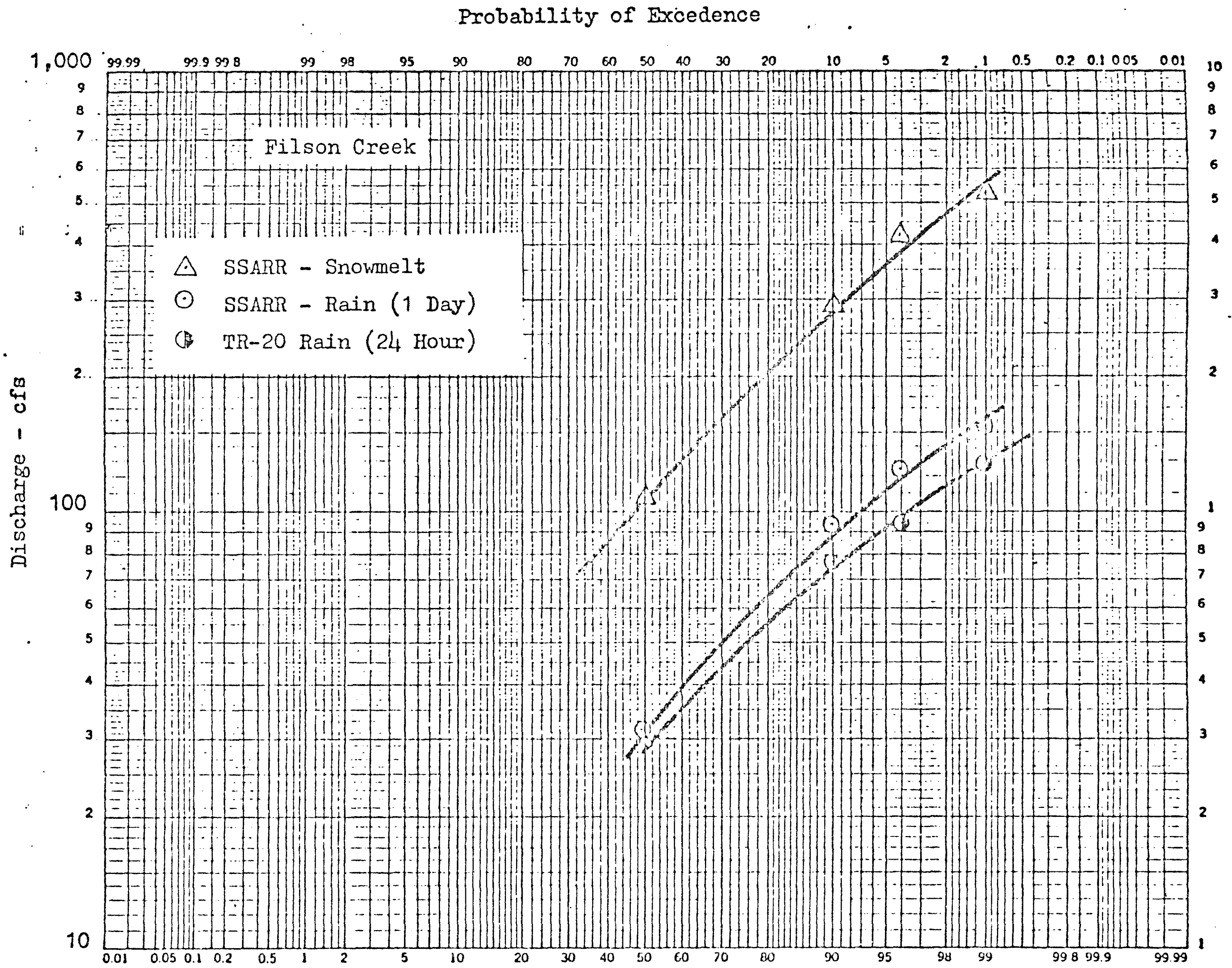


Fig. 74 - Comparison of SSARR and TR-20 for Filson Creek.

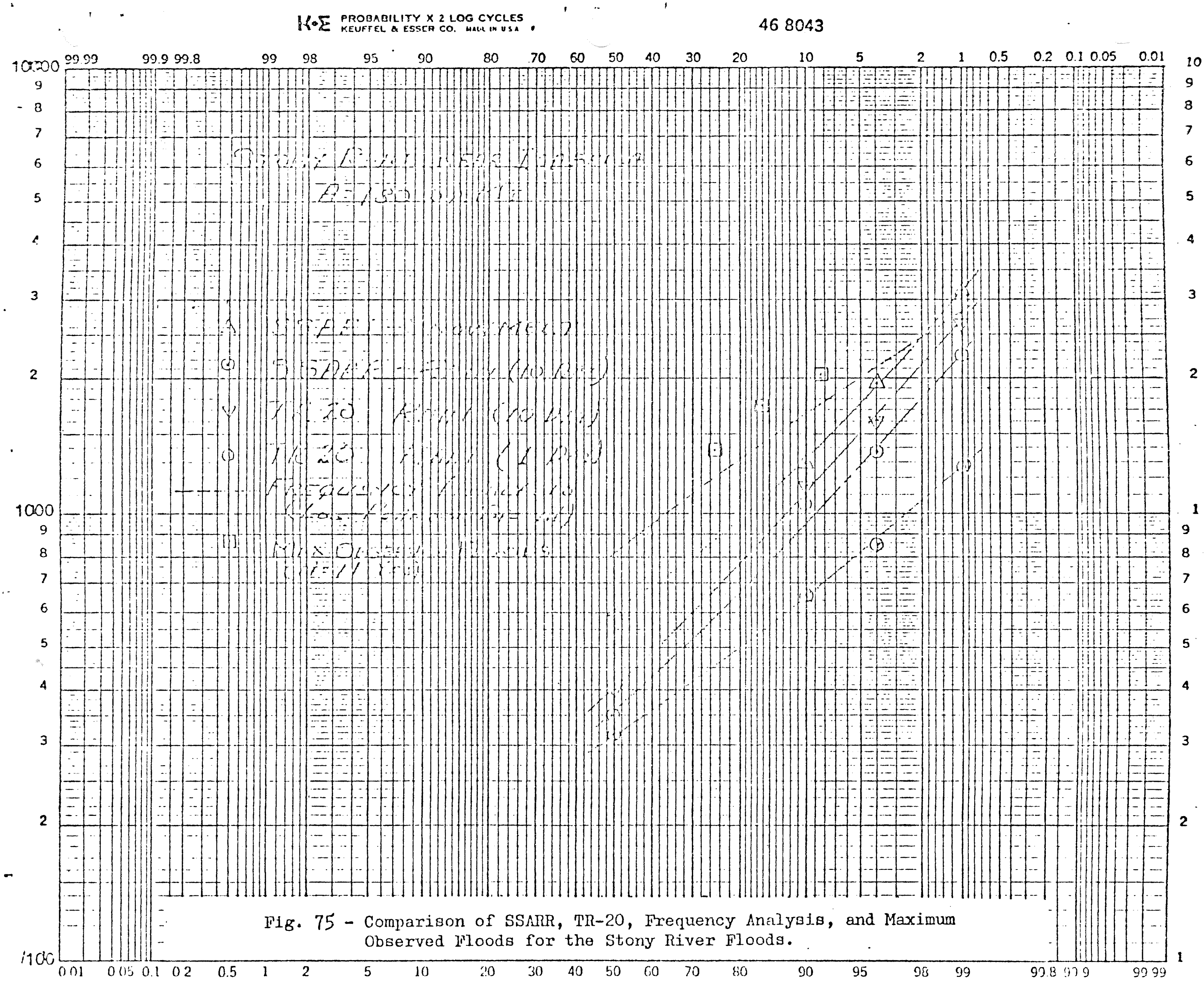


Fig. 75 - Comparison of SSARR, TR-20, Frequency Analysis, and Maximum Observed Floods for the Stony River Floods.

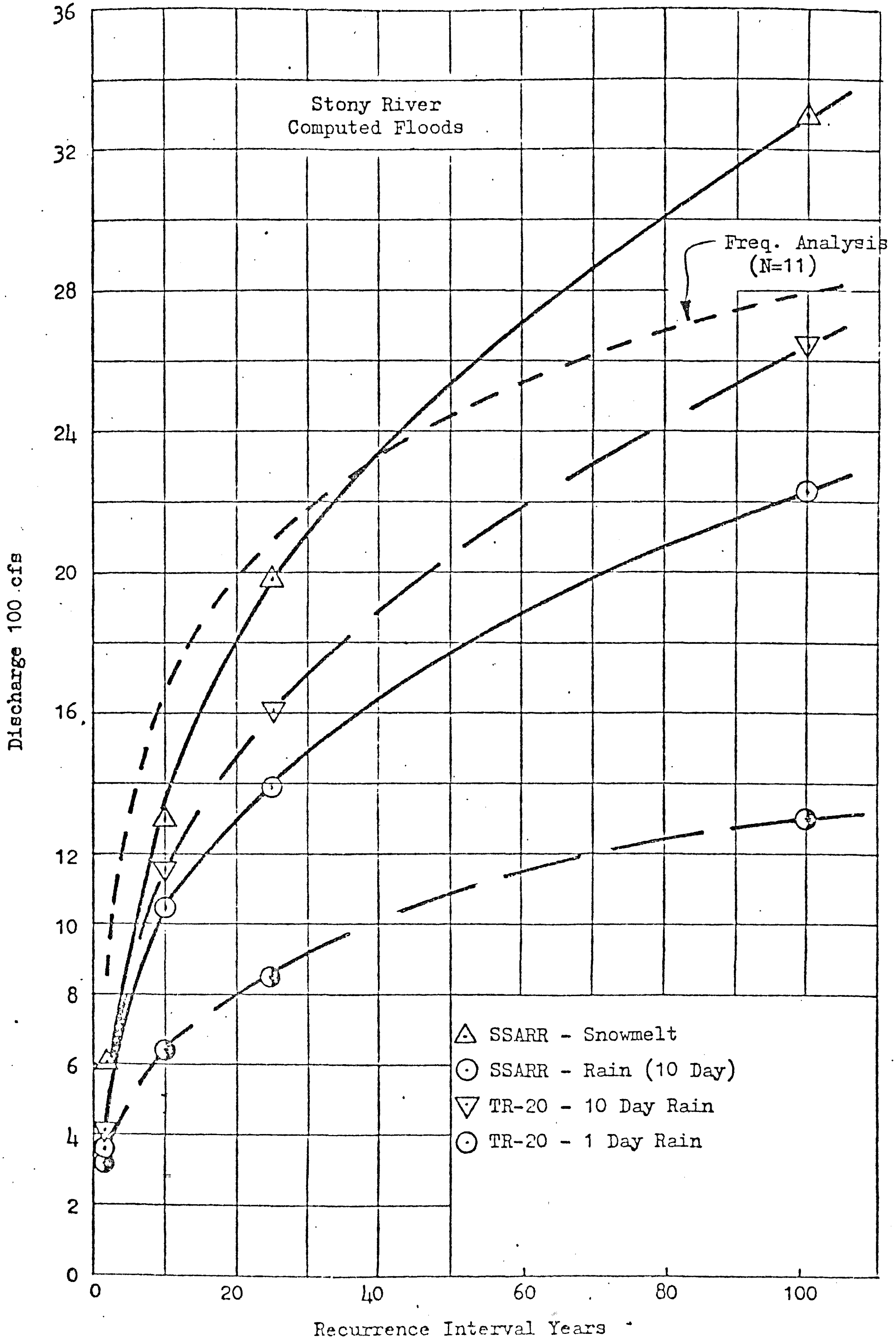


Fig. 76 - Computed Floods for the Stony River on Linear Graph.

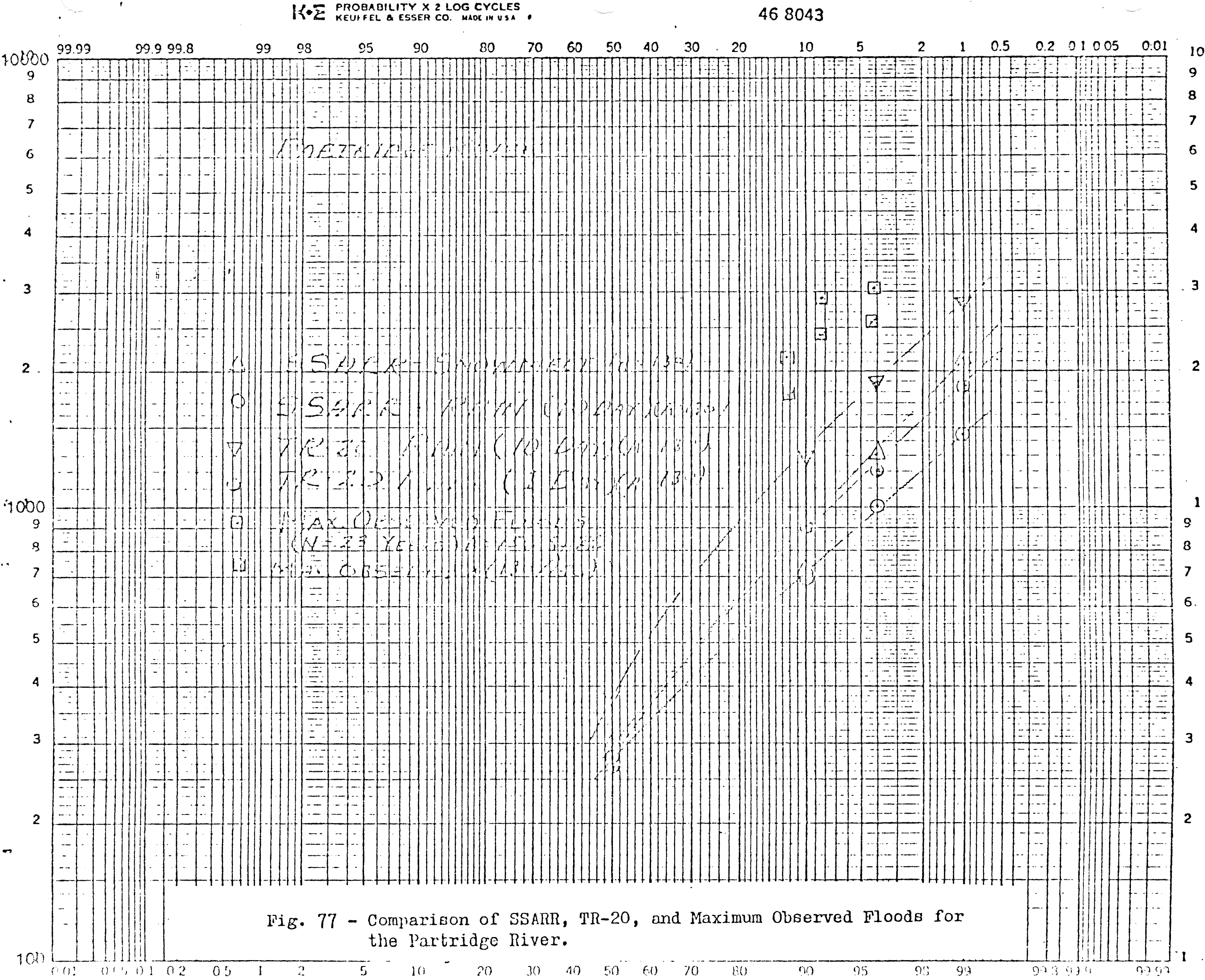


Fig. 77 - Comparison of SSARR, TR-20, and Maximum Observed Floods for the Partridge River.

floods as determined by the TR-20 are shown for Filson Creek. For the Stony and Partridge Rivers both 1 day and 10-day floods are shown for the TR-20. For Filson Creek the 1 day rain floods determined by the SSARR and TR-20 are in good agreement. However, both are well below the SSARR snowmelt floods.

The fact that the summer floods for Filson Creek are well below the computed snowmelt floods may indicate that the short two-year record did not provide a summer flood of sufficient magnitude to properly extrapolate to 100-year values. Of interest is the fact that the TR-20 summer floods for Filson Creek are very close to the SSARR summer floods.

Figures 75 and 76 show a comparison of the SSARR and TR-20 data for Stony Creek, plus a curve based on a Log-Pearson Type III analysis of the annual floods for the Stony River (N = 11 years of data). In the vicinity of 5% to 1% probabilities, (20- to 100-year recurrence intervals), the frequency analysis, the SSARR snowmelt floods and the TR-20 10-day summer floods are in close agreement. These indicate a 100-year (or 1% probability) flood of 2600 to 3100 cfs. The SSARR 100-year rainstorm flood is 2200 and the TR-20 1-day flood is 1300 cfs (quite low). The TR-20 1-day and 10-day rain floods are in close agreement with the SSARR rainstorm floods in the region of 50% probability or 2-year floods.

Figure 76 is a linear graph of the above data, which is helpful to obtain a picture of the relative magnitudes of the data. The conservative approach is to favor the method that gives the highest discharges, the SSARR snowmelt floods. Also the computed snowmelt floods are closest to the frequency analysis of measured floods; it should be noted that there are only 11 years of record for the Stony River frequency analysis. The three largest floods of the 11-year record are shown in Figure 75. They were plotted using the equation $P_{oc} = m/(N+1)$.

For the Stony River the results might be summarized by saying that the SSARR snowmelt floods and the TR-20 10-day rain floods are in good agreement with the frequency analysis of observed floods.

Figure 77 shows a comparison of the TR-20 and SSARR data for the 130-square-mile Partridge River above Second Creek. Three of the largest floods in the 23-year record (A = 156 sq. miles) are also shown. The latter include Second Creek. As the observed floods were for 156 square miles and the computed curves were for 130 square miles, the observed data were multiplied by (130/156) and plotted as a second set of 3 points. They are still somewhat high.

In this case, the SSARR snowmelt and the TR-20 1-day floods are in close agreement, but well below the TR-20 10-day floods and the 3 observed floods. Guetzkow [5] did not include the Partridge River in his report, probably because of the extensive pumping in the watershed. In the current study consideration was also given to this problem. An adjacent watershed, the Embarrass, was considered to be a simpler problem, but the Partridge was selected because the extensive mining operations indicated that it was worthy of special study.

The TR-20 10-day-rain, flood curve was the largest of the computed curves (Fig. 77) and closest to the 3 largest observed floods.

An overall assessment of Figure 77, with reference to the 3 largest observed floods, suggests that either they are plotted with the wrong probability, or the computed curves were based on fitting events that were too small.

Table 5 lists all of the observed floods for the 3 watersheds. The Partridge and Stony Rivers were fitted primarily on the data of 1960-64. It appears that in Phase II of this study the Partridge River floods of 1944 (2930 cfs), 1950 (3070 cfs), and 1954 (2150 cfs), with suitable corrections for area, should be used for fitting.

Figure 78 is a graph of drainage intensity (Q/A) as a function of area for the computed 100-year floods and the single largest observed flood of the 3 watersheds. It also includes the 100-year floods, for 6 watersheds in the immediate area, as determined by Gutzekow [5]. While some scatter of data occurs, the graph is very interesting. A nominal line was drawn thru the 100-year floods determined by frequency analysis (diamond symbol). Another line was drawn thru the SSARR snowmelt data (triangle). This was parallel to the preceding line. A third line was drawn parallel to the preceding two, thru the SSARR 100-year rain floods (the Filson Creek data were ignored in drawing this line). The TR-20 data for the Stony River and Partridge River are close to these 3 lines except for the 1-day floods for the Stony River and Filson Creek.

The SSARR and TR-20 rainstorm floods for Filson Creek and the largest observed flood for the same site are well below the curves. This suggests that the short 2-year record did not produce a major summer flood. The 100-year SSARR snowmelt flood for Filson Creek appears reasonable. Considering the Partridge River in Figure 78, the computed 100-year floods are well below the largest

Table 5 - Observed Floods in the Filson Creek, Stony River and Partridge River

FILSON CREEK

Year	Peak, cfs	Rain Peak, cfs
1975	118	33
1976	114	24
1977	103	103

STONY RIVER

Year	Peak, cfs	Rain Peak, cfs
1952-1953	786	786
1954	1750	553
1955	553	454
1956	1390	384
1957	2040	776
1958	449	449
1959	472	453
1960	980	297
1961	665	518
1962	800	340
1963	330	297
	17415	5307

PARTRIDGE RIVER (156 sq. miles)

Year	Peak, cfs	Rain Peak, cfs
1942-1943	680	680
1944	2930 ✓	738
1945	1560	660
1946	764	495
1947	1980	910
1948	-	-
1949	950	950
1950	3070	284
1951	-	-
1952	711	711
1953	711	711
1954	2150 ✓	1460
1955	-	-
1955-1956	784	-
1960-1961	694 (1103*)	154 (370*)
1962	680 (636*)	665 (636*)
1963	252 (441*)	174 (246*)
1964	1420 (1217*)	1420 (1217*)
1965	665	470

(Table 5 Contd.)

Year	Peak, cfs	Rain Peak, cfs
1966	1390	278
1967	535	305
1968	1010	1010
1969	1610	1230
1970	1010	435
1971	1420	553
1974-1975	(1013*)	(942*)

* Corrections made for pumping operations

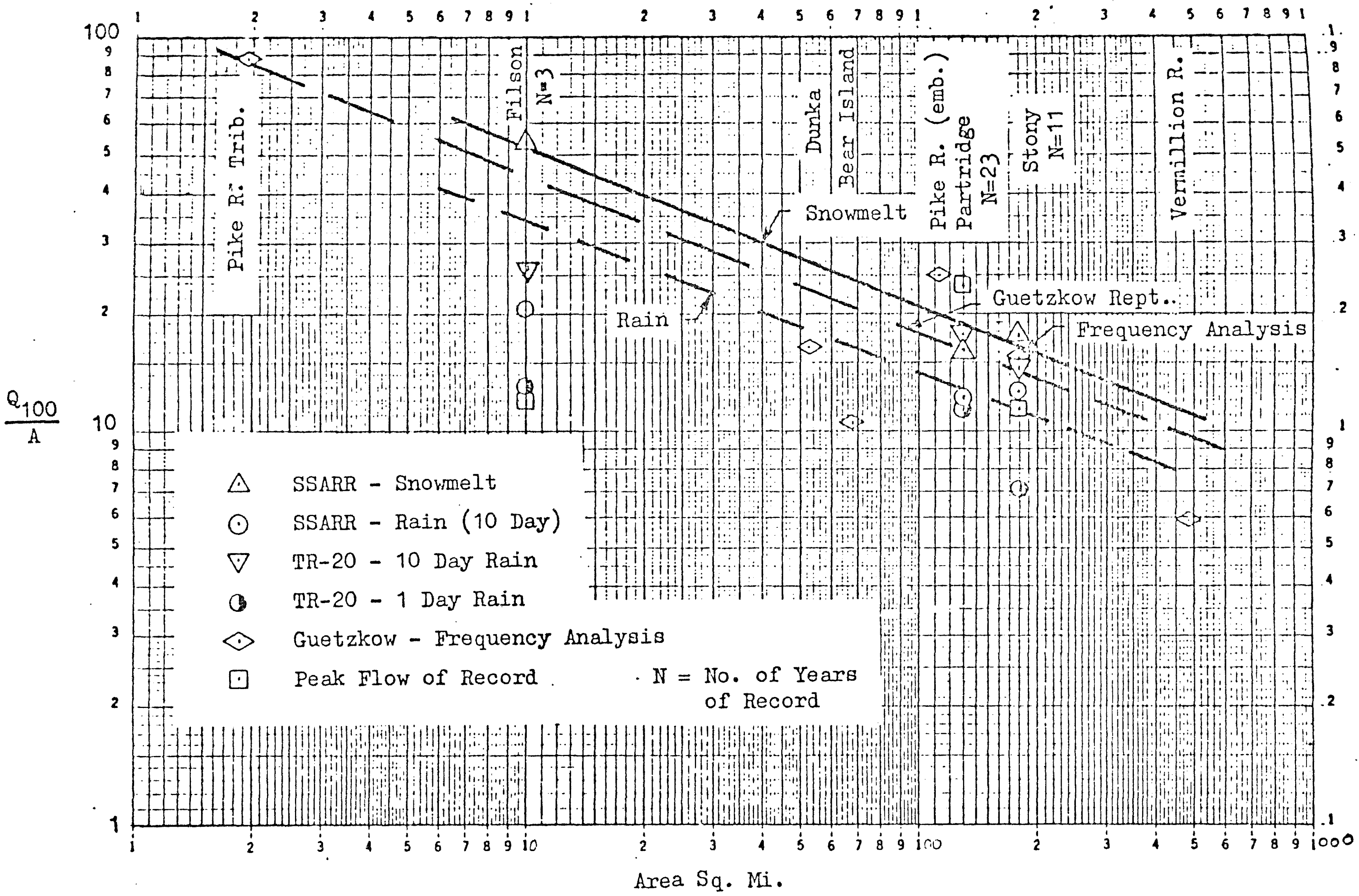


Fig. 78 - Drainage Intensity (Q_{100}/A) As a Function of Area

observed flood. As noted in Figure 77, this suggests further study of the Partridge for larger events. The data for the Stony River are generally in good agreement with the lines, but the short record of 11 years is a matter of concern. As additional data are obtained for the Stony River, the points will move upward and the parameters will require adjustment.

Observed data for the Bear Island River and the Vermillion River in Figure 78 fall well below the curves. Both of these have large lakes producing considerable attenuation of flood waves. They probably should be eliminated from Figure 78.

For the present, Figure 78 does provide a guide or check on the application of the SSARR and TR-20 models to the Copper-Nickel area, for both gaged and ungaged watersheds.

CONCLUSIONS

1. On the basis of studies conducted to date, the SSARR model provides a good model for continuous synthesis of flow in watersheds in the Copper-Nickel area. The model has not been used for continuous synthesis in a system of watersheds in this region, but should be applicable. The short records in Filson Creek and the Stony River may not include sufficient major events to thoroughly evaluate the parameter curves. Some additional fitting is desirable. It is anticipated that the SMI and BII curves will be different for major events than for frequent events with probabilities in the regions from 20 to 99%. Low flow may be modified as well as high flow. Continuing studies of the SSARR in the Copper-Nickel area are desirable.
2. Application of the TR-20 to past events, particularly complex or multiple storms, is not the procedure for which it was developed. After initial problems based in part on inexperience with this model, good fittings could be obtained for past events. To achieve the fitting of 3 past floods with the same parameters, it was necessary to divide the precipitation into 2 amounts. These were a base flow based on about 1.5 inches of precipitation and a faster component of runoff for rainfall above 1.5 inches. Snowmelt

procedures are not available in the TR-20; efforts to use snowmelt by the SSARR as input to the TR-20 were partially successful. A comparison of 1-day and 10-day floods suggests that the 10-day floods (in this area) were closer to the SSARR snowmelt floods and more conservative. Use of the TR-20 to compute 100-year to 2-year floods was moderately successful, particularly for the 10-day floods.

3. The primary benefit of the TR-20 in this investigation may be the analysis of the change in runoff from selected areas due to modifications of topography, soil and vegetation due to mining and processing of ore. The runoff from these areas, up to 20 square miles in area, could be used with a SSARR analysis of the remainder of the watershed. Information on runoff (and curve numbers) for tailings and reclaimed areas is necessary.

4. The annual floods in this region may be either snowmelt, rain, or a combination. However, most of the large floods are primarily snowmelt, with some rain during the melt period.

5. In calibrating these models, the rain and water content of snow were the weakest part of the system, and of these two, rain data was the weakest. Raingages are not spaced closely enough in this region to provide reasonably accurate data. This was true even for the small watershed of Filson Creek. The snowmelt flood problem is not as serious as the summer flood problem because snow accumulations, or water content thereof, are much more uniform than summer rainstorms. Likewise, the snowmelt temperatures are reasonably uniform over the watershed area. More raingages and more snowcourses are recommended, in selected watersheds, as an ongoing monitoring system.

6. Another streamgage should be installed on the Partridge River above Colby Lake as part of a monitoring system because of the extensive mining activity in this region, pumping effects, and the importance of this watershed.

7. The Corps of Engineers model HEC 1 should be considered in future studies for the analysis of individual storms.

8. Associated with this study was an investigation of soil moisture prediction by Professor Curtis L. Larson and Mr. Francis I. Idike of the Department of

Agricultural Engineering. This resulted in Addendum No. 1 of this report entitled "Predicting Initial Moisture Condition for Runoff Event Models". This should be of considerable interest to users of the TR-20, HEC 1 and other models concerned with individual runoff events. Three soil moisture models were studied: (1) 5-day antecedent rainfall; (2) depletion ratio model; and (3) evaporation pan model. Data from Lamberton and Cloquet were used in the study. At Lamberton the depletion model and evaporation pan models were superior to the 5-day antecedent index as predictors of soil water content in the topsoil. At Cloquet both models resulted in higher errors than at Lamberton, with the pan model superior in some respects.

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5. Guetzkow, Lowell C., "Techniques for Estimating Magnitude and Frequency of Floods in Minnesota", U.S. Geological Survey Water Resources Investigation 77-31, May 1977.

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APPENDIX A

Miscellaneous Notes

The TR-20 model's runoff curve numbers must be adjusted when using the 10-day storms because there is no provision for watershed drying or for continued losses to groundwater. For the 10-day storms this would result in peaks and volumes which are unrealistically high. The SCS publication "Hydrology Guide for Minnesota" gives the suggested reduction in curve number for 10-day storms.

The problems associated with this approach are shown by the graphs of the Stony River 1-day and 10-day storms. While a 1-day storm begins showing runoff from the watershed after about .8" of precipitation, the 10-day storm, with the curve number lowered, requires over 1.2" of precipitation to begin producing runoff. Yet at the end of the 10-day storm, the watershed is producing over 90 percent runoff from the .36" per day of precipitation. This represents an extreme change in the character of the watershed and may cause a distortion of the hydrograph, making the rising limb low and the receding limb high. Whether these two changes balance to produce an accurate peak is uncertain.

Future Applications of the SSARR

The desirability of extending the SSARR simulations to include other watersheds and determine the hydrologic impact of tailing ponds is possible. Some recalibration of watershed parameters would have to be done when going to other watersheds than fitted ones.

The exact method of changing the watershed parameter has not been determined yet. There are two possible groups of watershed parameters, the conceptual reservoir models and the remaining parameters such as SMI, BII, and S-SS, that could be changed in the recalibration. Both of these watershed parameter groups are functions of the watershed's soil types, depth of soils and unconsolidated material, the percentage of lakes, bogs, forested area, and bedrock outcrops, and the physical layout of the watershed including the slope, length, and area. Any changes in the watershed parameters would be changed because of differences in the calibrated watershed and the new watershed.

Modeling the effect of tailings ponds could be accomplished by the use of a subwatershed system. The watershed of concern would be split into two subwatersheds consisting of the main watershed minus the area of the tailings pond and a subwatershed representing the tailings pond. The watershed parameters for a section of the watershed unaffected by the tailings pond would remain the same as the fitted values as long as the tailings pond size was small in comparison with the watershed. During operation of the tailings pond, no outflow would be computed for the tailings pond subwatershed. After reforestration, the runoff hydrograph for the tailings pond would have to be developed. The SSARR would not be a good tool to develope the hydrograph though. However, once the hydrograph was determined by other methods, it could be routed to the basin outflow. The routed flow would then be added to the remaining outflow for the rest of the watershed and a total impact hydrograph obtained.

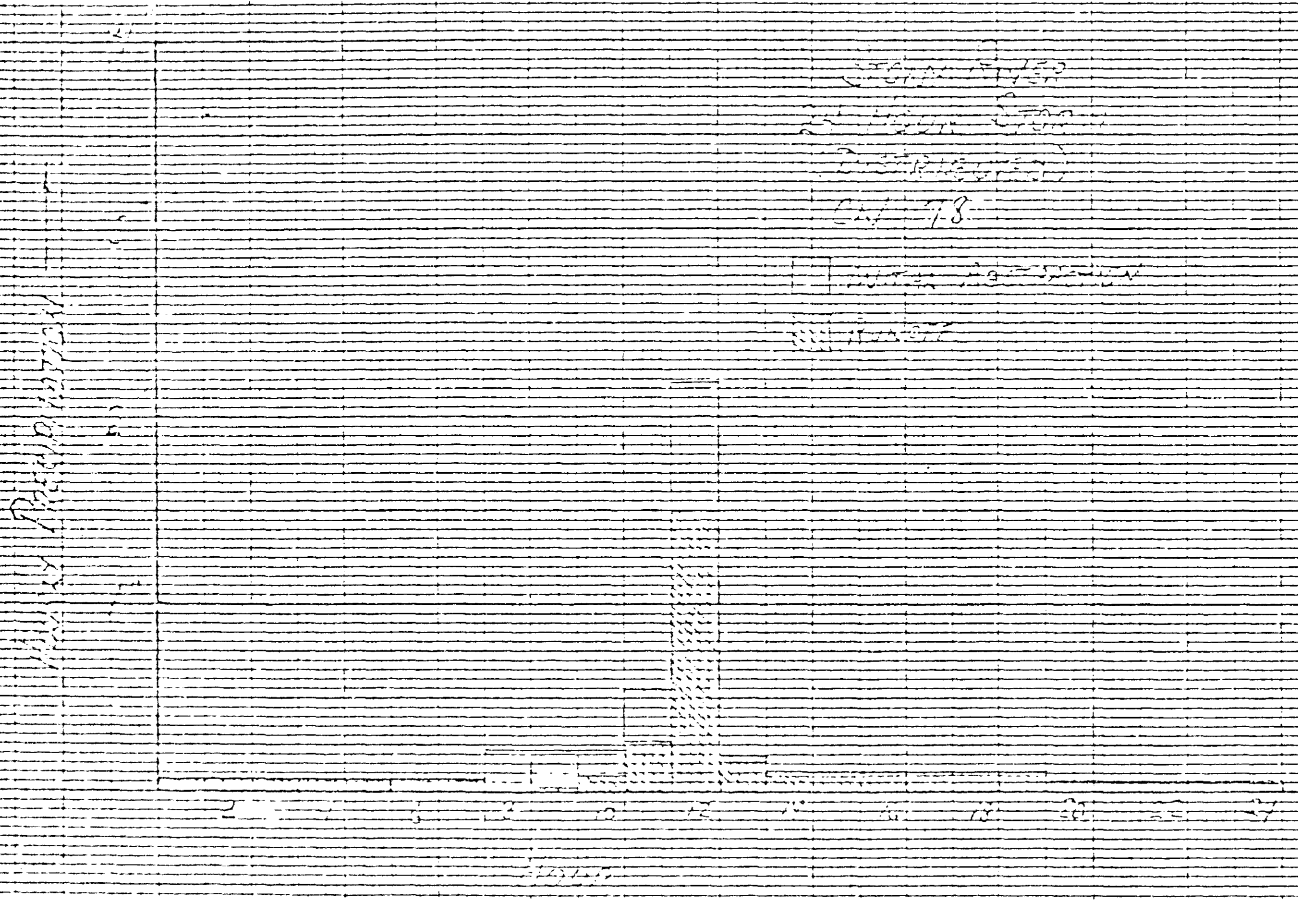

Fig. 4-6 — Precipitation for 78-79.

Precipitation Events for Northeastern Minnesota

Data Obtained from Weather Bureau TP 40 and TP 49.

The point for determing precipitation amounts was midway across Lake County; directly west of Cook County, Lake County, and Lake Superior border intersection.

Procedure: 1) Determine point rainfall amounts for the different durations and frequencies required from the ISO pluvial maps.

2) Apply the depth area correction factor from Figs. 10 and 15.

3) Determine the rainfall increments.

4) Rearrange the storm about the middle of the time period, oscillate the rainfall amounts about the middle value.

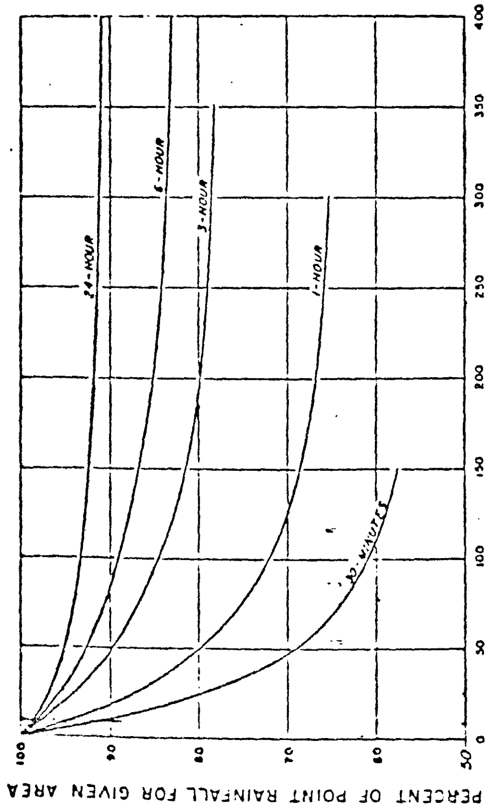

Figure —Area-depth curves.

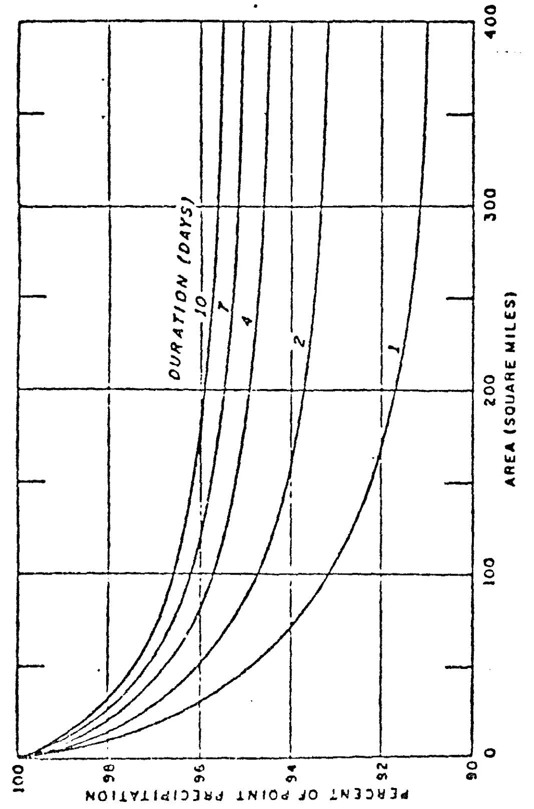

Figure —Depth-area curves.

Calculations for Daily Storm - Filson Creek Watershed (8 Sq Mi)

Duration (Hours)	Precipitation Amount	Correction Factor	Corrected Precipitation	Change in Precipitation	Rearranged Hours	Storm Hourly Amount
2 Year						
1	1.05	.95	1.00	1.00	1-7	.01
2	1.35	.96	1.30	.30	8-10	.10
3	1.45	.975	1.41	.11	11	.30
6	1.75	.98	1.72	.31	12	1.00
12	2.20	.98	2.16	.44	13	.11
24	2.40	.985	2.30	.14	14-19	.07
					20-24	.01
10 Year						
1	1.60	.95	1.52	1.52	1-7	.05
2	1.90	.96	1.82	.30	8-10	.13
3	2.20	.975	2.15	.33	11	.30
6	2.60	.98	2.55	.40	12	1.52
12	3.10	.98	3.04	.49	13	.33
24	3.65	.985	3.60	.56	14-19	.08
					20-24	.05
25 Year						
1	1.85	.95	1.76	1.76	1-7	.05
2	2.30	.96	2.21	.45	8-10	.17
3	2.50	.975	2.44	.23	11	.45
6	3.00	.98	2.94	.50	12	1.76
12	3.55	.98	3.48	.54	13	.23
24	4.10	.985	4.04	.56	14-19	.09
					20-24	.05
100 Year						
1	2.30	.95	2.19	2.19	1-7	.06
2	2.85	.96	2.74	.55	8-10	.23
3	3.00	.975	2.93	.19	11	.55
6	3.70	.98	3.63	.70	12	2.19
12	4.40	.98	4.31	.68	13	.19
24	5.05	.985	4.97	.66	14-19	.11
					20-24	.06

Calculations for 10-Day Storm - Stony River Watershed (180 Sq Mi)

Duration (Days)	Precipitation Amount	Correction Factor	Corrected Precipitation	Change in Precipitation	Rearranged Days	Storm Daily Amount
2 Year						
1	2.40	.918	2.20	2.20	1-3	.10
2	2.85	.938	2.67	.47	4	.47
4	3.50	.950	3.33	.66	5	2.20
7	3.80	.956	3.63	.30	6-7	.33
10	4.30	.960	4.13	.50	8-10	.17
10 Year						
1	3.65	.918	3.35	3.35	1-3	.33
2	4.10	.938	3.85	.50	4	.50
4	5.05	.950	4.80	.95	5	3.35
7	6.05	.956	5.78	.98	6-7	.48
10	6.85	.960	6.58	.80	8-10	.27
25 Year						
1	4.10	.918	3.76	3.76	1-3	.39
2	4.90	.938	4.60	.84	4	.84
4	6.00	.950	5.70	1.10	5	3.76
7	7.20	.956	6.88	1.18	6-7	.55
10	8.15	.960	7.82	.94	8-10	.31
100 Year						
1	5.05	.918	4.64	4.64	1-3	.51
2	6.10	.938	5.72	1.08	4	1.08
4	7.50	.950	7.13	1.14	5	4.64
7	9.05	.956	8.65	1.52	6-7	.71
10	10.15	.960	9.74	1.09	8-10	.36

Calculations for 10-Day Storm - Partridge River Watershed (130 Sq Mi)

Duration (Days)	Precipitation Amount	Correction Factor	Corrected Precipitation	Change in Precipitation	Rearranged Days	Storm Daily Amount
2 Year						
1	2.40	.925	2.22	2.22	1-3	.10
2	2.85	.943	2.69	.47	4	.47
4	3.50	.953	3.34	.65	5	2.22
7	3.80	.958	3.64	.30	6-7	.33
10	4.30	.963	4.14	.50	8-10	.17
10 Year						
1	3.65	.925	3.38	3.38	1-3	.33
2	4.10	.943	3.87	.49	4	.49
4	5.05	.953	4.81	.94	5	3.38
7	6.05	.958	5.80	.99	6-7	.47
10	6.85	.963	6.60	.80	8-10	.27
25 Year						
1	4.10	.925	3.79	3.79	1-3	.39
2	4.90	.943	4.62	.83	4	.83
4	6.00	.953	5.72	1.10	5	3.79
7	7.20	.958	6.90	1.18	6-7	.55
10	8.15	.963	7.85	.95	8-10	.32
100 Year						
1	5.05	.925	4.67	4.67	1-3	.51
2	6.10	.943	5.75	1.08	4	1.08
4	7.50	.953	7.15	1.40	5	4.67
7	9.05	.958	8.67	1.52	6-7	.70
10	10.15	.963	9.77	1.10	8-10	.37

ADDENDUN NO. 1

Predicting Initial Moisture Condition for Runoff Event Models

by

1-18-78

Curtis L. Larson and Francis I. Idike*

Some watershed models are intended for prediction of hydrographs for individual runoff events, usually for design storms. Two well known examples are the TR-20, of the Soil Conservation Service and the HEC-1, of the U.S. Corps of Engineers. With such models, (in contrast to continuous watershed models) the initial soil moisture condition of the watershed for the event must be assumed or estimated in some manner.

The TR-20 model utilizes the Mockus (SCS) equation for estimating storm runoff amounts, described elsewhere (1)(2)(3). The runoff producing characteristics of the watershed, including the initial soil moisture condition, are embodied in the curve number (CN). Three antecedent moisture conditions, AMC I, II, and III (low, medium and high), are utilized, and the choice has a major effect on the calculated runoff amount. For design storms, AMC II, defined as the "average case for annual floods" (1), is usually assumed.

In recent years, the SCS runoff equation has been used occasionally where a simplified continuous runoff model is desired (4). Daily rainfall amounts are used as input and the curve number is adjusted for the antecedent moisture condition, which is based on the 5-day antecedent rainfall as follows (1):

	5-day antecedent rainfall (in.)	
AMC	Dormant Season	Growing Season
I	Less than 0.5	Less than 1.4
II	0.5 to 1.1	1.4 to 2.1
III	More than 1.1	More than 2.1

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* Professor and Research Assistant, Department of Agricultural Engineering, University of Minnesota.

The TR-20 watershed model likewise can be used for observed rainstorms. In this application, the antecedent rainfall is known and the AMC can be determined as above. The question then arises, is the 5-day antecedent rainfall a satisfactory index of soil moisture conditions? If not, is there a daily soil moisture model that is better and still easy to use?

The objective of this substudy was to provide answers to the above question(s) that would be sufficient for the purposes of the main study. A secondary question, which was not studied, is whether or not it would be desirable to use a continuous scale of AMC or to add some additional AMC classes.

Three methods of estimating or predicting soil moisture conditions were studied, as follows:

1. 5-day antecedent rainfall
2. depletion ratio model
3. evaporation pan model

All three methods were applied to the moisture content of the upper soil layer, on the assumption that it's effect on storm runoff is dominant. The study is concerned only with predicted vs. observed soil moisture contents. The results, therefore, are potentially useful in applying any event-type runoff model.

Locations, Data Sources

Two Minnesota locations were used for testing the above methods. The first is the Southwest Agricultural Experiment Station of the University of Minnesota at Lamberton in Redwood County. The area is highly developed agriculturally with heavy textured, highly productive soils. The data used are for a Webster silty clay loam soil with continuous corn as the crop.

The data were provided by Dr. Donald G. Baker, Professor of Soil Science, St. Paul, and were collected at Lamberton with the assistance of the station staff, Dr. Wallace Nelson, Superintendent.

The second location is the Cloquet Forestry Center of the University of Minnesota. It is located in the forested area of N.E. Minnesota, in Carlton County. The soil at the site is Omega loamy sand, which has a low moisture holding capacity. The vegetative cover is white pine forest. The soil moisture data were provided by Dr. Bruce Brown, Director of the station.

Soil moisture parameters or characteristics for the two soil types were needed. For the Webster silty clay loam, the wilting point and field capacity are 16.8% and 27.2% by volume, respectively. For the Omega loamy sand, the corresponding values (WP and FC) are approximately 4.6% and 12.9%, respectively.

For the pan model, daily pan evaporation values observed at the Lamberton station and published in Minnesota Climatalogical Data were used. For the Cloquet portion of the study, the corresponding data for Hoyt Lakes, Minnesota, near Virginia, were used.

Description of Models

Each of the three methods used in the study constitutes a model for predicting soil moisture content. All are approximate models, selected for study because of their simplicity. More complex and more accurate models are available (evapotranspiration models), but these require much more data.

The 5-day antecedent rainfall is simply the sum of the recorded rainfall amounts for the preceding 5 days. It is clearly an index (only) of soil moisture, since it is independent of soil depth and since no adjustment is made for runoff or for evapotranspiration during the 4-day period following a rain. Instead, after 5 days as a part of the antecedent rainfall, each recorded rainfall is dropped from the total.

The depletion ratio method is a conceptual model also, since no attempt is made to calculate evapotranspiration. Instead, soil moisture content is simulated directly by use of a depletion ratio, k, a parameter whose value is less than one. Since it has no theoretical basis, k must be evaluated by fitting. Using S_o and S_1, as the soil moisture stored in the soil on consecutive days,

$$S_1=kS_o \tag{1}$$

For a period of n-days, therefore,

$$S_n=k^nS_o \tag{2}$$

In this substudy, S was defined as the "available water", i.e., the water storage in excess of the wilting point, both for a specified soil depth. The total water content, M, is equal to (S + d · WP) where d is the soil depth in the same units as S (inches were used). Thus, when there is no rainfall for an extended period, S approaches zero and total water storage (M) approaches the wilting point value as the lower limit.

For each day, any observed rainfall is added to the total water storage after the daily depletion. When a heavy rainfall occurs, total soil water storage may go beyond field capacity. When this occurs, it was assumed that the soil drains to field capacity one day later (the same assumption was used with the pan model.) In that event, field capacity is used as the beginning point for depletion.

With the pan model, potential evapotranspiration, PET, is simulated on a daily basis as

$$PET = C_pE_p \tag{3}$$

where E_p is the daily pan evaporation and C_p is the pan coefficient. Values of E_p can be the observed values for individual years or average values for a number of years, but for specified dates of the year.

When applied to the moisture stored in the entire root zone, the pan coefficient often is assumed to be 0.70, more or less. In this study, it was used to estimate ET for the plow layer only, giving a much lower value for C_p. Accordingly, C_p was treated as a fitted parameter.

With the pan model, one must recognize that, when soil moisture is limited, the actual ET can be considerably less than PET. A method of adjusting PET values to ET values is therefore needed. Based on various studies in the literature, as well as discussions with Dr. Donald G. Baker (Professor of Soil Science, University of Minnesota), a submodel for relating ET to PET was developed earlier by the senior author. The model defined ET ratio (ETR) as ET/PET, M as total moisture content and M_{50} as the moisture content at 50% available moisture, i.e., midway between WP and FC. The following assumptions are made:

1. At moisture contents equal to and greater than M_{50}, ETR = 1.0.
2. At a moisture content corresponding to WP, ETR = 0.30.
3. ETR varies linearly with soil moisture content, passing through these two points and down to a minimum value of zero (at some moisture content less than WP).

These assumptions give a general expression for ETR as a function of the moisture content, M, as follows:

$$\mathrm{ETR} = a\,M + b \qquad (0.0 \leq \mathrm{ETR} \leq 1.0) \tag{4}$$

For convenience, M is taken as the total moisture content for the soil depth being considered, while a and b vary with soil type. The constants a and b can be evaluated directly, given the values of WP and FC. In general,

$$a = \frac{0.70}{M_{50} - WP} \quad (5)$$

$$b = 1.0 - a\,M_{50} \quad (6)$$

Finally, to apply the pan model,

$$ET = PET \cdot ETR \quad (7)$$

The soil moisture content is, of course, calculated day by day by subtracting the ET and adding the rainfall, if any, for each day.

Table 1. Five-day antecedent rainfall vs. observed soil moisture at Lamberton, 1970[1]

Date	Observed water Content[2] (in.)	5-day antecedent rainfall (in.)	Error %
April 27	2.22	1.54	-31
May 13	1.95	1.49	-24
June 5	2.11	1.34	-36
June 19	2.19	3.06	40
July 1	1.68	1.34	-20
July 20	1.88	1.37	-27
August 3	1.77	2.15	21
August 21	1.39	1.34	- 4
September 2	1.53	1.75	14
September 18	2.18	2.52	16
October 5	1.87	1.34	-28
October 16	2.25	1.59	-29
MEAN	1.91	1.74	24

1/ At Southwest Agricultural Experiment Station, University of Minnesota. Webster silty clay loam, field of corn

2/ For 0 - 8 inch depth

Table 2. Model values of soil water content, 0-8 in depth at Lamberton 1/, 1970, using two models with fitted coefficients.

Date	Observed soil water (in.)	Model soil water: Depletion model 2/ (in.)	Model soil water: Pan model 3/ (in.)	Error: Depletion Model (%)	Error: Pan Model (%)
April 27	2.22	-----	-----	---	---
May 13	1.95	1.79	1.66	- 8	-15
June 5	2.11	1.89	1.84	-10	-13
June 19	2.19	1.99	1.91	- 9	-13
July 1	1.68	1.67	1.35	0	-20
July 20	1.88	1.89	1.87	1	0
August 3	1.77	1.98	1.87	2	6
August 21	1.39	1.71	1.56	23	12
September 2	1.53	1.85	1.66	21	8
September 18	2.18	2.11	2.08	- 3	- 4
October 5	1.87	1.74	1.78	- 7	- 5
October 16	2.25	1.94	2.18	-14	- 3
MEAN	1.92	1.87	1.80	8.9	9.0

1/ At Southwest Agricultural Experiment Station, University of Minnesota. Webster silty clay loam, field of corn

2/ Daily depletion coefficient, fitted value = 0.92

3/ Pan coefficient (applied to water loss from 0-8 inch depth), fitted value = 0.25

Table 3. Predicted vs. observed soil water at Lamberton 1/, 1973, 0-8 inch depth, by two models 2/.

Date	Observed soil water (in.)	Predicted soil water		Error	
		Depletion model 3/ (in.)	Pan model 4/ (in.)	Depletion Model	Pan Model
April 27	2.22	----	----	----	----
May 15	1.88	1.74	1.62	- 7	-14
June 1	2.45	1.94	1.86	-21	-24
June 15	2.05	1.93	1.59	- 6	-22
July 3	1.96	2.11	1.85	8	- 6
July 16	1.51	1.85	1.57	22	4
August 2	1.68	1.86	1.84	10	9
August 15	1.38	1.80	1.55	31	13
August 31	1.35	1.57	1.33	16	- 2
September 18	1.79	2.11	2.14	18	20
October 19	2.12	1.81	2.07	-14	- 2
MEAN	1.85	1.87	1.74	15.3	11.6

1/ At Southwest Agricultural Experiment Station, University of Minnesota. Webster silty clay loam, field of corn.

2/ Model parameters determined by fitting to 1970 data.

3/ Daily depletion constant = 0.92.

4/ Pan coefficient (applied to water loss from 0-8 inch depth) = 0.25.

Table 4. Model values of soil water content, 0-6 inch depth at Cloquet[1/], 1963, using two models with fitted coefficients.

Date	Observed soil water (in.)	Model soil water: Depletion model[2/] (in.)	Model soil water: Pan model[3/] (in.)	Error: Depletion Model	Error: Pan Model
May 13	1.07	----	----	----	----
May 24	.88	.64	.63	-27	-28
June 3	.74	.73	.70	- 2	- 6
June 11	.88	.75	.77	-14	-12
June 21	.71	.68	.63	- 4	-11
June 28	.65	.68	.68	5	5
July 3	.52	.66	.65	26	24
July 12	.46	.88	.71	90	54
July 23	.40	.47	.44	17	10
July 29	.61	.73	.72	20	19
August 1	.70	.73	.74	5	6
August 9	.46	.66	.49	43	6
August 15	.73	.68	.66	- 7	-10
August 26	.58	.74	.72	27	24
September 10	.49	.50	.49	3	1
September 19	.80	.73	.74	- 9	- 8
MEAN	0.67	0.68	0.65	19.9	14.9

[1/] At Cloquet Forestry Center, University of Minnesota, Omega loamy sand, white pine forest.

[2/] Daily depletion coefficient, fitted value = 0.90

[3/] Pan coefficient (applied to water loss from 0-6 inch depth), fitted value = 0.30

Table 5. Predicted vs observed soil water content, 0-6 inch depth, at Cloquet[1], 1964, by two models[2].

Date	Observed soil water (in.)	Predicted soil water		Error	
		Depletion model[3] (in.)	Pan model[3] (in.)	Depletion model (%)	Pan model (%)
May 11	.97	----	----	---	---
May 21	.83	.64	.54	-23	-35
May 27	.85	.64	.54	-25	-37
June 9	.88	1.13	1.16	29	32
June 16	.70	.58	.49	-17	-30
June 25	.92	.78	.76	-16	-18
July 8	.55	.68	.40	24	-27
July 16	.40	.45	.26	12	-35
July 23	.39	.38	.25	- 3	-36
July 29	.40	.73	.63	82	57
August 3	.44	.73	.70	67	60
August 13	.43	.73	.76	71	78
August 18	.43	.68	.68	60	60
August 26	.83	.68	.73	-18	-12
September 15	.92	.59	.63	-36	-32
September 25	.94	.78	.77	-17	-18
MEAN	0.68	0.68	0.62	33.3	37.8

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[1] At Cloquet Forest Experiment Station, University of Minnesota, Omega loamy sand, white pine forest.

[2] Model parameters determined by fitting to 1963 data.

[3] Daily depletion coefficient = 0.90.

[4] Pan coefficient (applied to water loss from 0-6 inch depth) = 0.30.

Results at Lamberton

Field data for the years 1970 and 1973 at Lamberton were utilized to test the different models. Daily precipitation is observed at the Southwest Experiment Station and, since this is one of the NWS regular stations, is published in Minnesota Climatologic Data. The soil moisture data are measured by 6-inch intervals. For the purposes of this study, however, water contents for the 0 to 8-inch depth were calculated and used, since this is the plow layer (tilled portion) of the soil.

First, for the 1970 growing season, 5-day antecedent rainfall amounts were calculated and compared to the water content of the top 8 inches of the soil (Table 1). The results indicate wide differences between the two on the various dates, from -36% to + 40%, with a mean error of 24% (average of absolute values). The mean value of the 5-day antecedent rainfall is seen to be about 9% below that of the observed water content. This is probably acceptable and could be adjusted. The mean error is rather high, which is not surprising, considering the over-simplified approach being used. Further efforts, therefore, were directed to the other two models.

With the depletion and pan models, the 1970 data were used to fit the models. By trial and error fitting, it was found that the best value of the depletion coefficient was 0.92. With this fitted value (Table 2), the depletion model gives fairly good individual values, with an acceptable range of error. The mean error is less than 9% and the mean calculated soil water content is quite close to the mean of the observed values (1.87 vs. 1.92 inches).

With the pan model, the best value of the coefficient for 1970 was found to be 0.25, quite low, as expected, since water loss only from the top 8 inches of soil is considered. The range of errors and the mean error are about the same as for the depletion model. The mean value (1.80 inches) does not compare quite as well as that for the depletion model, but differs only about 6% from the observed mean water content. Thus both models performed quite well on a fitted basis.

It should be noted that modeling ETR by Eq. (4) was a necessary part of using the pan model. For Lamberton, value of WP and FC for the 8-inch soil depth are 1.34 and 2.18 inches, respectively, based on the percent-by-volume values given earlier. This makes M_{50} equal to 1.76 inches, a equal to 1.667 inches^{-1} and b equal to -1.934. ETR goes to zero at M = 1.16 inches and ET = PET for $M \geq 1.76$ inches.

Independent tests of the two models were made for the year 1973, using coefficients obtained for the 1970 data. The results are given in Table 3. In terms of error, the pan model predicted soil water contents better than the depletion model. The mean value of soil water content for the depletion model was very close to the mean observed value. The pan model was less accurate in this respect, but only about 6% low. In general, both models predicted soil moisture contents during 1973 reasonably well. Considering the simplicity of the models, perhaps the results should be considered good.

Results at Cloquet

The two models were fitted and tested at Cloquet in much the same manner, using data for 1963 and 1964. Here too, precipitation is observed daily and published in Minnesota Climatological Data. In this case, since the soil is untilled and has forest cover, the soil moisture content was modeled for the 0 to 6-inch depth, which is the way it was measured.

The 1963 data were used for "fitting tests" of both models (Table 4). Trial and error fitting led to values of 0.90 for the depletion coefficient and 0.30 for the pan coefficient. These values suggest higher rates of water loss than at Lamberton, though not greatly different. Possible reasons are the very sandy soil and the use of a 6-inch depth as compared to 8 inches at Lamberton.

The range of error for both models was somewhat greater than at Lamberton. The unusually large error with both models on July 12 boosted the average error by several per cent, especially for the depletion model. This suggests the possibility of a data error for that date. The mean values of the soil water content according to the two models are both very close to the observed value.

With the pan model, Eq. (4) was again utilized to determine ETR values. For the 6-inch depth of Omega sand, WP, M_{50} and FC are 0.138, 0.263 and 0.388 inches, respectively. From this, one finds that, in Eq. 4, a is 5.60 inches^{-1} and b is -0.473. ETR becomes zero at $M = 0.084$ inches and $ET = PET$ for $M \geq 0.388$ inches.

Results of using the two models to predict soil water contents for the 1964 season are given in Table 5. These results are not nearly as good as the preceding ones, at least in terms of per cent error. The mean water contents for the season by the two models are still good, with perfect agreement in one case and -9% in the other. Errors on individual values of soil water content range up to about 0.30 inch, both positive and negative, which is not so high in absolute value, though high as a percentage. It may be noted that a very sandy soil, such as the Omega, when at field capacity, is holding a relatively small amount of water and is still able to infiltrate a lot of water. Its ability to retain much water is low, even if initially very dry.

Discussion of Results

Inspection of the values in Tables 4 and 5 shows that at Cloquet there is a strong tendency to predict high on moisture contents during midsummer and to be low during spring and fall. This is obvious with both models for the 1963 data, and also for the depletion model in 1964. This pattern of error can be explained for the depletion model by the fact that it depletes the soil moisture at the same rate throughout the year. The pan model, on the other hand, varies the loss rate by relating it to pan evaporation and therefore should do better in this respect. With the Lamberton results (Tables 2 and 3), one sees the same pattern of error for both models. In general, the pan model is somewhat better in this respect than the depletion model, as one would expect.

This pattern of error could be at least partially corrected by varying the coefficients for both models seasonally. This possibility was explored to a limited extent with the Lamberton data. In general, this yielded higher values of the pan coefficient in spring and early summer and lower values in midsummer and fall. The results were not conclusive, however. A more extensive study of the seasonal variation of the pan and depletion coefficients might give a useable set of monthly or seasonal values. This was, however, outside the scope of the present study.

Time did not permit testing the models with different soil depths, which could possibly improve the results. At Cloquet, for example, perhaps a soil depth of 8 inches would have given better results. However, there is nothing in the results obtained to suggest this.

A more important, related question is "What soil storage depth is best from the standpoint of predicting runoff by a particular model, in this case the TR-20 model?" This can be determined only by making trials with the watershed model and this would require considerable effort. The idea of relating runoff amounts to the water content of the upper layer of soil is a well accepted one. There is nothing definitive, however, on what depth to use for this "control" layer and, therefore, this question remains unanswered.

Conclusion

Since the studies reported herein were quite limited, only tentative conclusions can be drawn, as follows:

1. Based on the Lamberton results, both the depletion and pan models are superior to 5-day antecedent rainfall as predictors of soil water content in the topsoil.
2. At Lamberton both models yield satisfactory predictions of soil water content. The pan model was slightly better (Table 3).
3. At Cloquet, higher errors were obtained with both models than at Lamberton. The results for the independent tests were only "fair", although the mean values for the year agreed well with the observed values.
4. Using fixed coefficients, both models exhibited a tendency to predict soil water contents that are too high during the summer (ET underestimated) and too low during spring and fall (ET overestimated).

5. The pan model does a somewhat better job of representing seasonal variations in ET and soil water content than the depletion model.
6. Both models are relatively simple, utilizing readily available data. In addition to precipitation data, the pan model requires daily evaporation data.
7. The pan model is somewhat more involved than the depletion model, since it requires adjustment of potential ET to actual ET and some knowledge of the soil's moisture holding characteristics. A simple and general method for determining actual ET from potential ET is presented.

Further improvements in the two models would no doubt be possible by means of more extensive studies.

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