CALIBRATION PROCEDURE FOR A DAILY FLOW MODEL OF SMALL WATERSHEDS WITH SNOWMELT RUNOFF IN THE GREEN RIVER COAL REGION OF COLORADO

By J. Michael Norris and R. S. Parker

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METRIC CONVERSION FACTORS

Inch-pound units used in this report may be converted to International System (SI) Units by the following conversion factors:

Multiply	*By*	*To obtain*
cubic foot per second	0.0283	cubic meter per second
foot	0.3048	meter
$foot^{-1}$	3.281	$meter^{-1}$
mile	1.609	kilometer
square mile	2.590	square kilometer

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°F=9/5°C+32$$

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ABSTRACT

A calibration procedure is developed for the U.S. Geological Survey's Precipitation-Runoff Modeling System for watersheds in which snowmelt is the major contributor to runoff. The main time-series inputs to the model are daily values of air temperature and precipitation, and the output is mean daily discharge. Preliminary results indicate that the procedure is sufficient to calibrate both streamflow volume and the timing of mean daily discharge.

From the model structure and sensitivity analysis, one of the most important parameters is the available water-holding capacity of the soil (SMAX). Changing this parameter through a series of iterations, the calibration procedure minimizes the error between observed and predicted annual discharge. Three small watersheds in western Colorado were calibrated using the procedure. The calibration indicates that the single parameter SMAX may be sufficient for optimizing both the volume and the timing of runoff if other model parameters are reasonably estimated.

Additional optimization on parameters sensitive to timing does not appear to improve prediction. However, this may be a result of reasonable initial estimates of these parameters. Further investigation is needed on more watersheds to determine SMAX's ability to calibrate discharge volume and timing with a constant set of other model parameter values.

INTRODUCTION

As coal and oil-shale mining increases in western Colorado, the number of questions regarding the hydrology of these energy resource areas also increases. Unfortunately, these areas typically do not have long-term gaging networks and, without such data, analysis of the surface-water flow system is much less accurate. Even in those few areas with streamflow-gaging stations, the length of record is too short to use standard techniques of record analyses such as flow-duration curves.

Even if longer term surface-water data existed in parts of these energy resource regions, analysis techniques would need to include methods to transfer the results to ungaged sites. Unfortunately, knowledge of surface-water characteristics often is needed where no information has been collected in the past.

The U.S. Geological Survey's Precipitation-Runoff Modeling System (Leavesley and others, 1983) is a technique which can provide record extension for short-term gages and a method to transfer results from gaged areas to ungaged areas. This paper presents the initial results of a study, made in cooperation with the U.S. Bureau of Land Management, to determine the application of this model to energy resource areas having little or no streamflow data.

The major objective of this paper is to describe and test a calibration procedure for the U.S. Geological Survey's Precipitation-Runoff Modeling System. As in most calibration procedures, the steps are:

1. Sensitive model parameters are identified.
2. Sensitive parameters are calibrated to reduce error.

Items discussed include: (1) The physical setting for three watersheds in northwest Colorado, (2) a model overview including sensitive parameters for predicting streamflow, (3) a calibration procedure description, and (4) annual volume calibrations for the three watersheds. In addition, a sensitivity analysis and optimization is given for those parameters influencing streamflow timing.

THE SETTING

The study area is located in Routt County, southeast of Hayden (fig. 1). Physical characteristics of the study watersheds are in table 1. The region is characterized by high relief, with elevations ranging from less than 6,800 feet to more than 8,800 feet above sea level. The climate is semiarid, with elevation having a strong effect on precipitation. Precipitation ranges from about 12 inches at low elevations to over 20 inches at the higher elevations. Most annual discharge is from snowmelt. Summer temperatures in the area may exceed 100°F and winter temperatures may drop as low as -40°F.

Table 1.--*Physical characteristics of the study watersheds*

Gaging station number and name	Drainage area (square miles)	Relief[1] (feet)	Percent vegetation cover			
			Sagebrush	Oak	Aspen	Other
09243700 Middle Creek near Oak Creek---------	23.5	3,250	40	17	43	
09243800 Foidel Creek near Oak Creek---------	8.6	3,060	35	10	55	
09243900 Foidel Creek at mouth, near Oak Creek--	17.5	3,250	39	9	27	25

[1]Difference between maximum and minimum watershed elevation.

The area is underlain by consolidated sedimentary rocks of the Williams Fork and Iles Formations of Late Cretaceous age. The rocks are a sequence of sandstones (57 percent), shales (23 percent), siltstones (10 percent), and coals (10 percent), and are highly faulted (U.S. Bureau of Land Management, 1976).

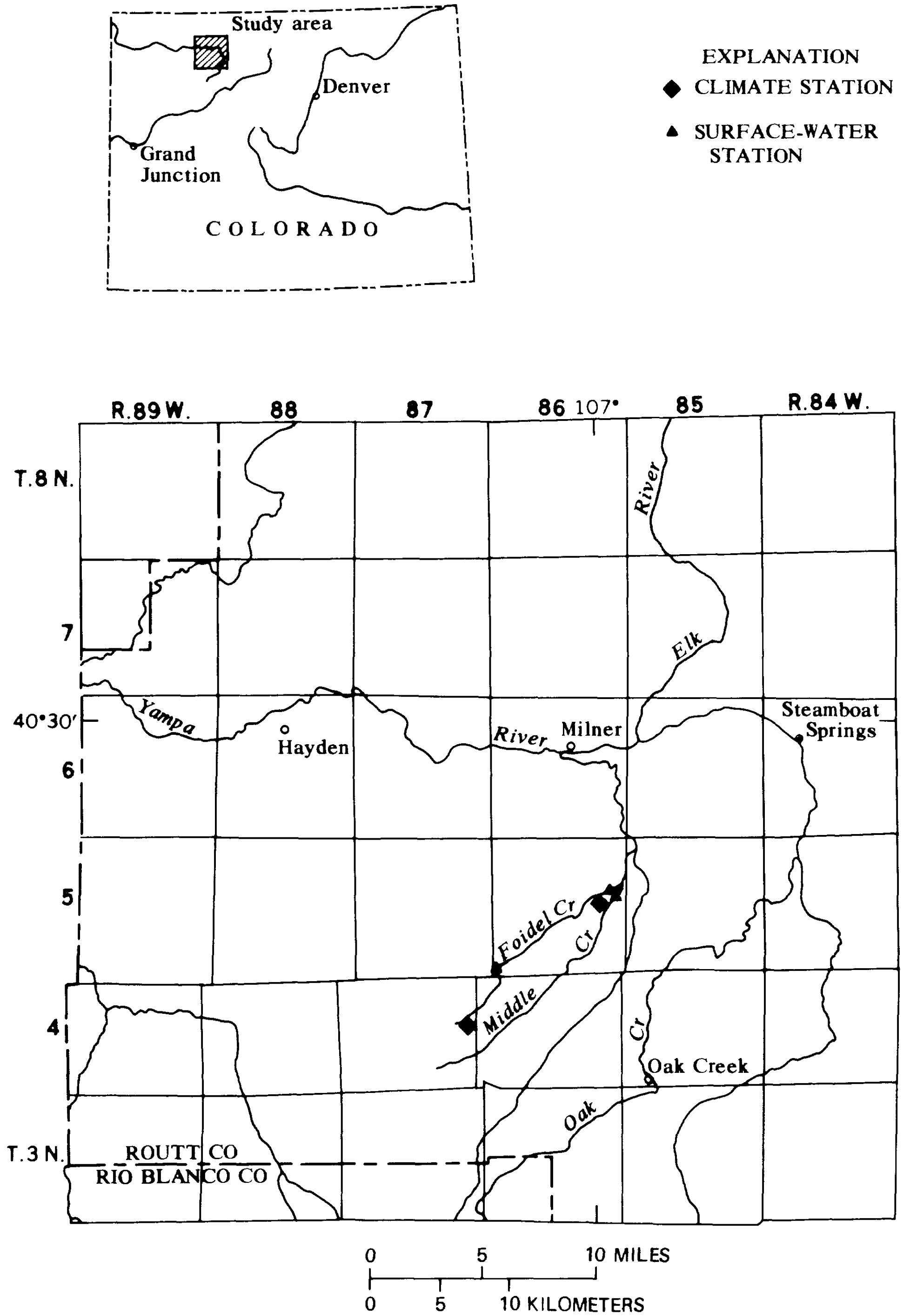


Figure 1.--Location of study area.

Aspen is the dominant vegetation for approximately 42 percent of the area; sagebrush, 38 percent; and oak, 12 percent. The remaining 8 percent is either farmland or is mined.

Soils are loamy and generally deep. They have a fairly rapid infiltration rate and high water-holding capacity contributing to a general lack of runoff from summer thunderstorms.

THE MODEL

The U.S. Geological Survey's Precipitation-Runoff Modeling System originally was developed by Leavesley (1973) and is documented in the user's manual (Leavesley and others, 1983). It is a deterministic, distributed, physical-process model, capable of predicting the response of the hydrologic system resulting from changes in system input; for example, changes in precipitation and land use. The model works with either storm or daily data as input. The input data for the daily mode are daily maximum and minimum air temperature, precipitation, and solar radiation. Model output is daily mean discharge.

The model uses the concept of partitioning a basin into hydrologic-response units (HRU's). HRU's are delineated on the basis of measurable climatic, physiographic, vegetative, land-use, and soils features. The resulting subunits are considered homogeneous with respect to hydrologic response. The overall system response is determined daily by calculating the water balance for each HRU, then summing each HRU's response. Partitioning into HRU's attempts to account for the spatial and temporal variations of basin characteristics influencing the hydrologic response.

Hydrologic components in the model are described by known physical laws or empirical relations, which have a physical interpretation and attempt to reproduce the physical reality of the hydrologic system as nearly as possible. In the model, the watershed system is simulated by a series of linear and non-linear reservoirs (fig. 2) whose output combines to produce the total system response.

Water enters this reservoir system (fig. 2) at the soil-moisture reservoir at some infiltration rate. Water also can leave this reservoir at some evapotranspiration (ET) rate. The ET rate is a function of time of year, amount of water in the soil-moisture reservoir, temperature, solar radiation, soil type, and vegetation type. If the rate of water supplied to the system exceeds the infiltration rate, excess water becomes surface flow and moves to the stream channel (R_1). When the amount of water in the soil-moisture reservoir (SMAV) equals the given available water-holding capacity of the soil (SMAX), water can no longer enter the soil-moisture reservoir and moves to the subsurface reservoir (R_2). Water leaves the subsurface reservoir by two routes. Some of the water drains to the ground-water reservoir (R_3) at a rate which is equal to the amount of water in the subsurface reservoir times a given constant. Water also can leave the subsurface reservoir directly to the stream (R_4) as a linear or nonlinear function of the amount of water in the reservoir on that day. Water in the ground-water reservoir moves to the stream (R_5) as a linear function of the amount of water in the ground-water reservoir. Total daily streamflow is the sum of R_1, R_4, and R_5 for each HRU weighted by area.

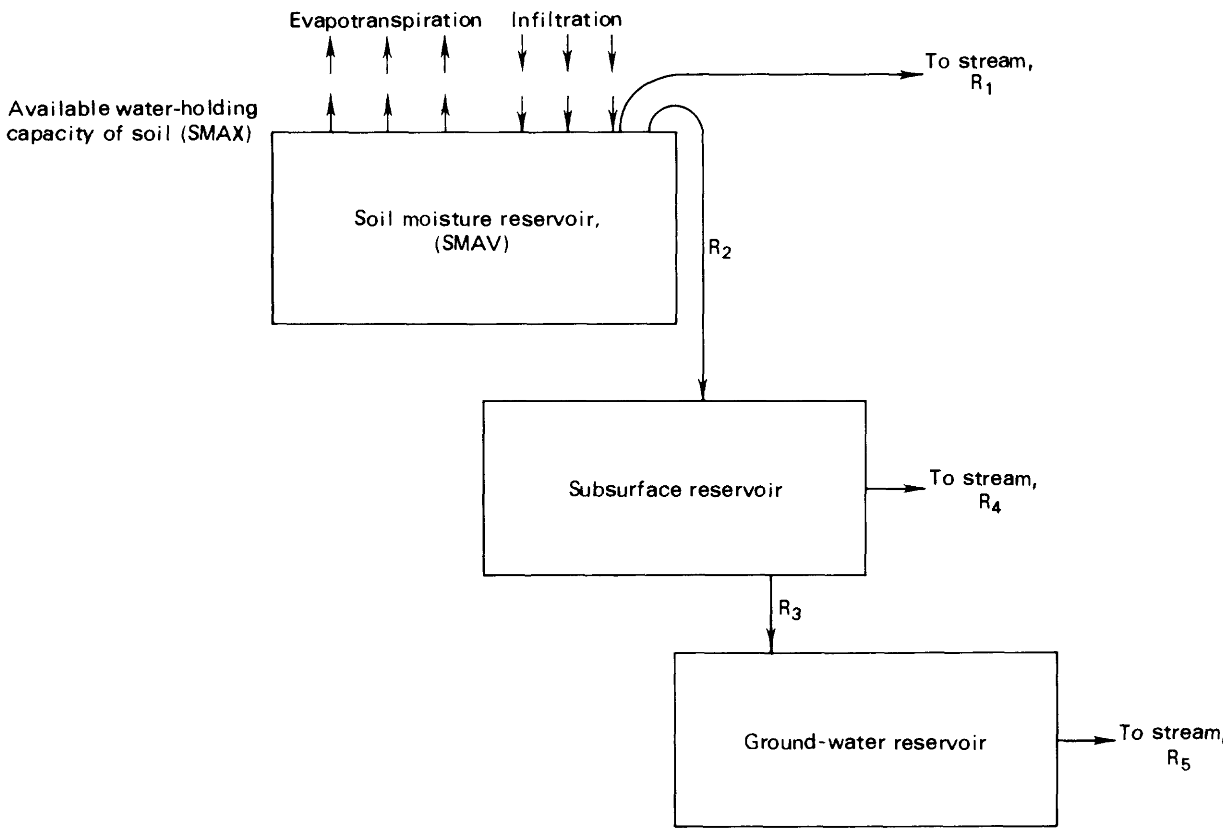


Figure 2.--Relations of model reservoirs.

The flow chart in figure 3 shows the general model structure and operations. For each day of simulation, the model steps from Input B through the evapotranspiration algorithm for each HRU. After completing the water-balance accounting for all HRU's, the subsurface and ground-water reservoirs are routed. The reservoirs' output, plus any surface flow, are summed to produce the model output, mean daily streamflow.

Model parameters found statistically sensitive in predicting streamflow (Leavesley and others, 1981) are listed in table 2. SMAX is the most sensitive parameter for predicting streamflow volume, and also influences predicted streamflow timing, in areas where snowmelt is the major contributor to streamflow. SMAX is defined as the amount of water held in the soil between field capacity and wilting point. SMAX is the threshold above which soil water

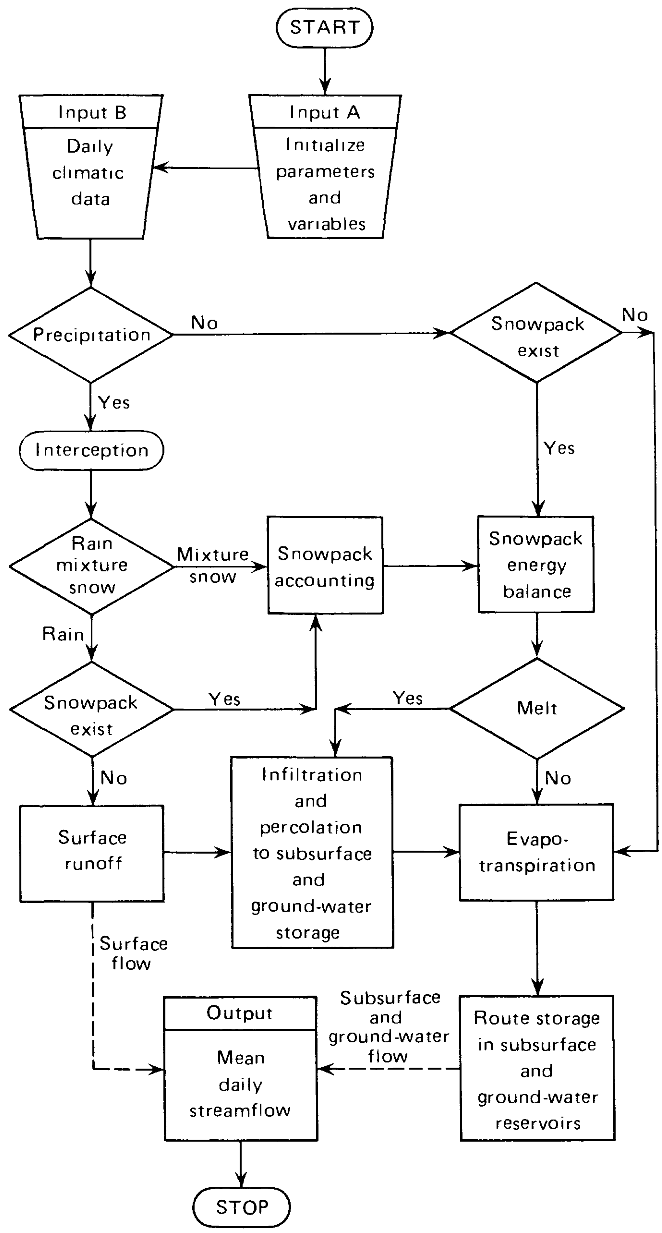


Figure 3.-- Generalized flow chart of the U.S. Geological Survey's Precipitation-Runoff Modeling System. (From Weeks and others, 1974.)

Table 2.--*Definitions of model parameters influencing streamflow prediction from snowmelt*

Name	Definition
COVDNW-----	Winter vegetative cover density
TRNCF------	Solar radiation transmission coefficient
SMAX-------	Available water-holding capacity of soil
RSEP-------	Rate water moves to ground-water reservoir
RCB--------	Ground-water routing coefficient
TLX--------	Lapse rate for maximum air temperature
CTS--------	Air temperature evapotranspiration coefficient
TST--------	Temperature index to determine start of evapotranspiration
BST--------	Temperature above which all precipitation is rain

moves to the model's subsurface and ground-water reservoirs and ultimately to the stream channel (fig. 2). As SMAX increases, more water can be stored in the soil moisture reservoir and is available to ET losses. Conversely, as SMAX gets smaller, more water can reach the stream channel and therefore is not available for ET losses. Similarly, the SMAX value chosen can affect the predicted streamflow timing. If SMAX is small, less water is required to fill the soil, allowing water to reach the channel sooner than if SMAX were large.

Evapotranspiration losses can occur only from the soil-moisture reservoir (fig. 2). Water can be held or lost to evapotranspiration only in the soil-moisture reservoir in order to reduce discharge volumes and control timing. Water directed to any other reservoir shown in figure 2 is routed past the stream gage. Consequently, the parameter SMAX is extremely important.

In areas where snowmelt is the major contributor to streamflow, the soil-moisture reservoir has a role similar to the variable source area concept used by Hewlett and Nutter (1970) to predict streamflow in the southern United States. In that part of the country, the majority of streamflow is derived from rain, whereas in this study area, most of the annual discharge is from a melting snowpack. In the South, the fraction of the watershed that actually contributes water to streamflow affects the amount and timing of runoff. In the Colorado study area, the amount of maximum available water the soil can hold and the time that it reaches this maximum amount affects the discharge volume and timing. This model assumes soil moisture must be at the maximum capacity during snowmelt situations before water can be supplied to the stream channel (fig. 4). The SMAX value must be chosen so water is not supplied to the channel too early, which could make the streamflow volume too large, or too late, which could make the volume too small. In figure 4, the rise in the hydrograph in July illustrates that summer thunderstorms can supply water to the channel without soil moisture being at capacity. With summer thunderstorms, the amount and timing of runoff in this model are related to the contributing area.

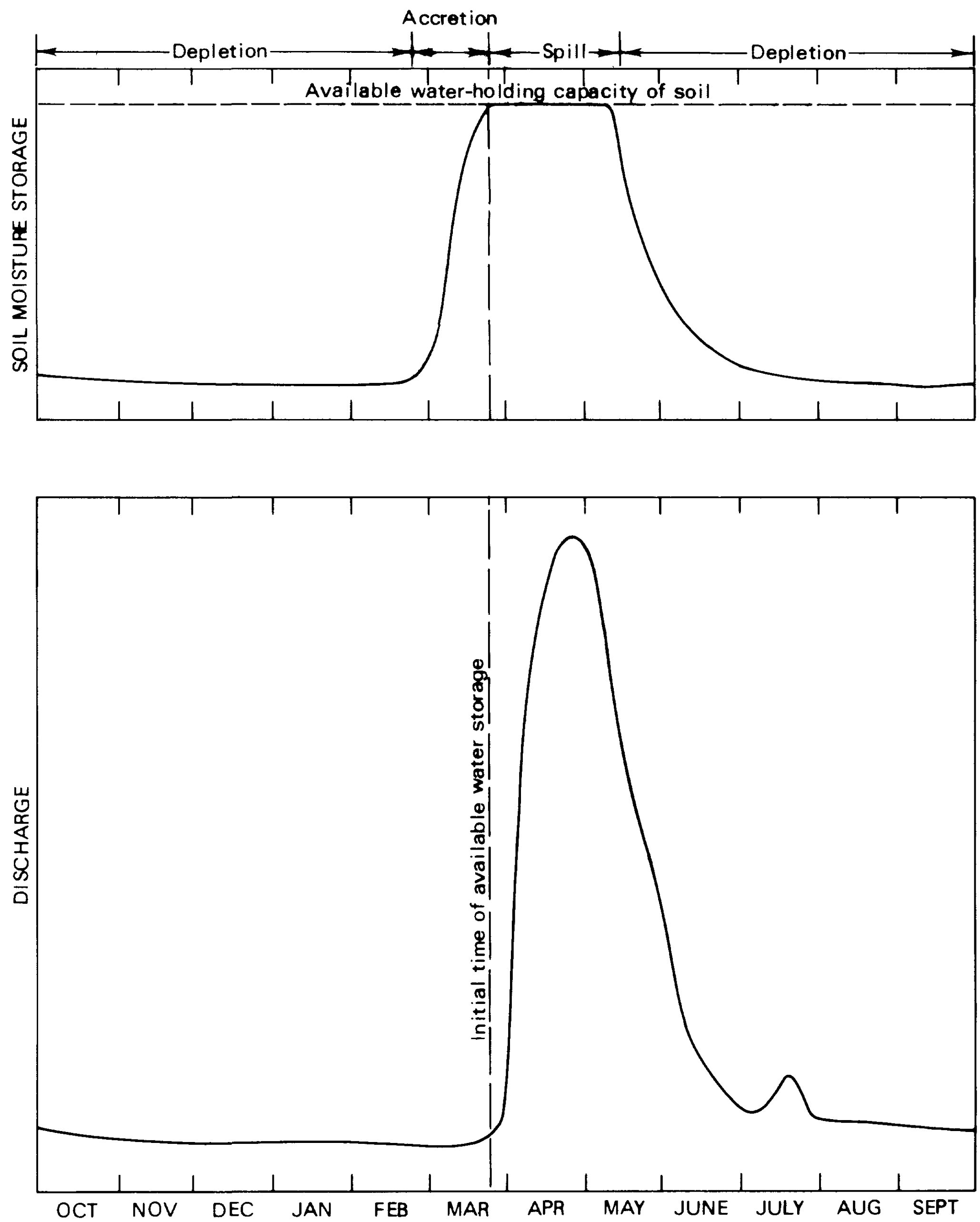


Figure 4.--Available water-holding capacity of a soil in relation to stream discharge.

From the preceding discussion, model calibration should be a straightforward process of choosing an SMAX value which supplies the correct volume of water at the right time. However, the calibration process evaluates as many SMAX's as there are HRU's in the watershed. The calibration process is thus complicated with many HRU's, some contributing water to streamflow earlier than others, some contributing more water than others. This underscores the fact that good soil-moisture information could be important to calibrating the model in areas where snowmelt is the major contributor to streamflow. Unfortunately, there is little soil-moisture information available in the study area.

SOIL-MOISTURE INFORMATION

Wymore (1974), in a water-balance study of a similar area in western Colorado, estimated the available water-holding capacity of the soils, defined as water held between field capacity and wilting point, of that area, and found a relation between elevation and the available water-holding capacity of the soils for several different vegetation types (fig. 5). It is interesting to note that Wymore's available water-holding capacity of soils associated with sagebrush has an inverse relation with elevation, whereas that for oak shows a positive relation with elevation. Aspen has no relation to elevation. In Wymore's report (1974), oak is grouped into a mountain shrub category.

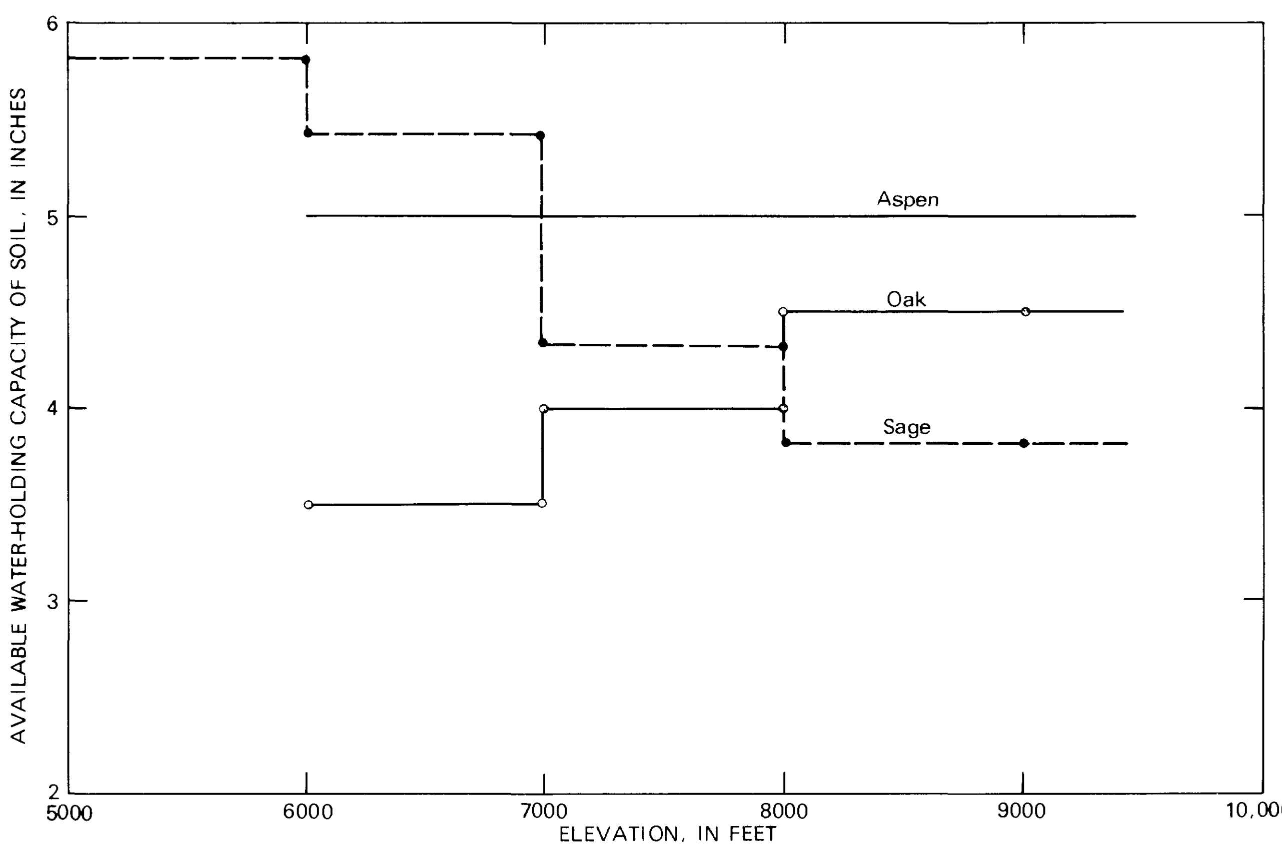


Figure 5.--Wymore's (1974) relation between elevation and the available water-holding capacity of soils associated with aspen, oak, and sagebrush.

For the present study area, Heil (1976) reported values of the available water-holding capacity of soils at different sampling sites. The data collected by Heil (1976) are shown in figures 6 and 7 for those sites with vegetation similar to those used in the model. Wymore's (1974) values are plotted as a comparison. The wide range of Heil's data shows that the available water-holding capacity of the soils is highly variable. Also note that Heil's data does not show the relation described by Wymore. This indicates that it may prove impractical to collect enough soil-moisture data to get a reasonable estimate of SMAX or to use measured soil-moisture data in the model where some HRU's are several hundred acres. Available soils maps of the study area indicate sufficient variability of available water-holding capacity within a soil type to preclude the use of these data in the calibration of the model.

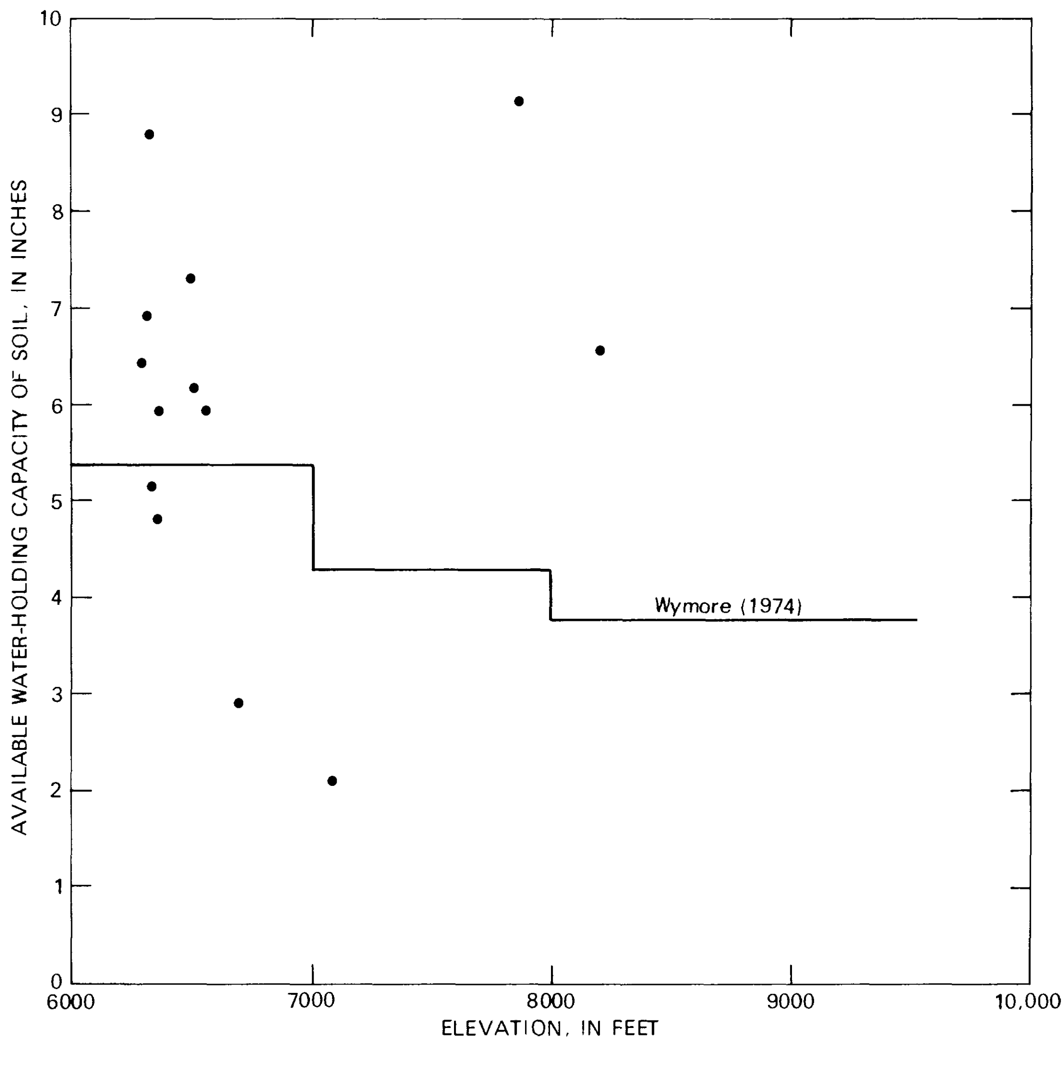


Figure 6.--Heil's (1976) data showing relation between elevation and the available water-holding capacity of soils associated with sagebrush. Wymores (1974) relation given for comparison.

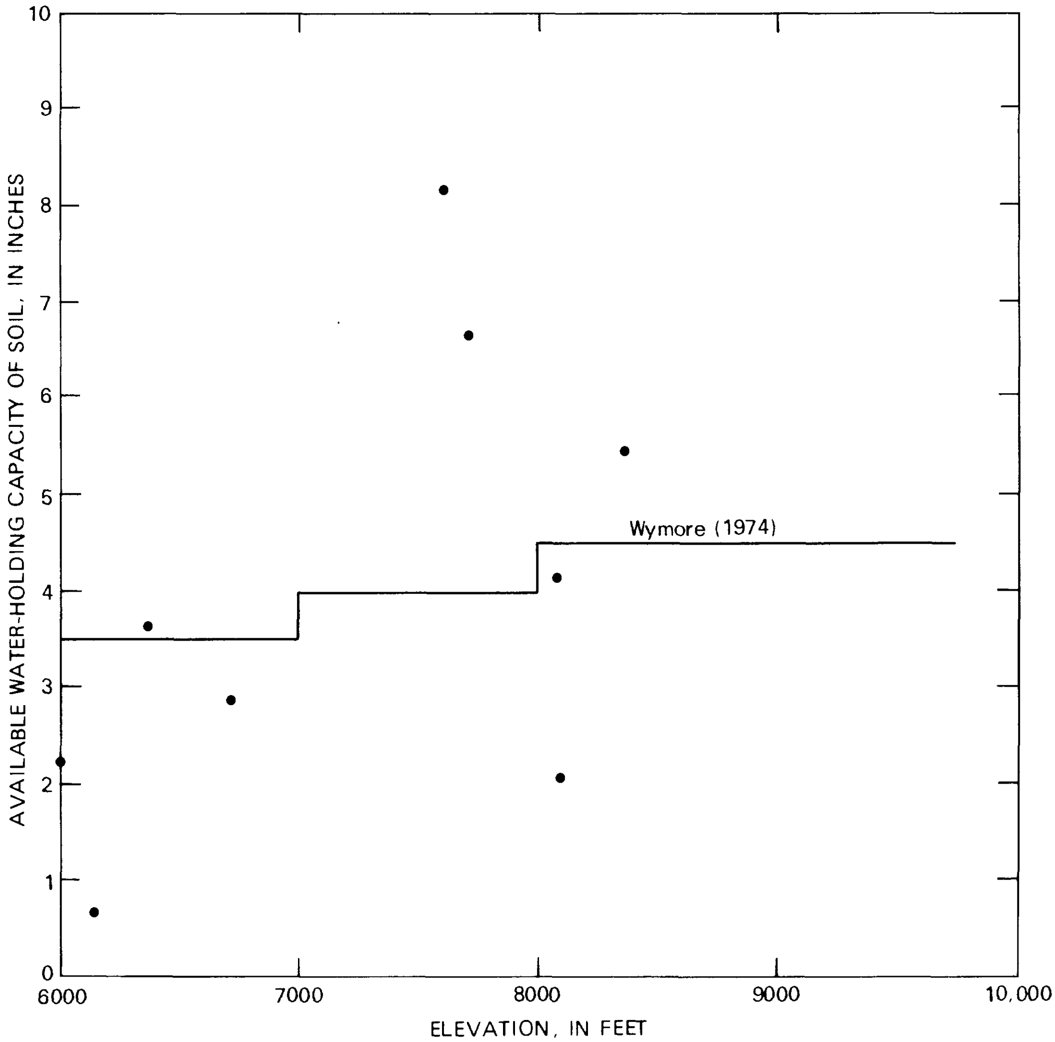


Figure 7.--Heil's (1976) data showing relation between elevation and the available water-holding capacity of soils associated with oak. Wymore's (1974) relation given for comparison.

CALIBRATION PROCEDURE

Assumptions

The calibration process is governed by four main assumptions. These are: (1) The step sizes of Wymore's (1974) relations of elevation and the available water-holding capacity of soils are correct, (2) all HRU's have equal opportunity to contribute water to streamflow, (3) SMAX contains all of the errors from other sources, and (4) SMAX only needs to be calibrated to the nearest one-half inch.

The first assumption is that the step sizes of Wymore's (1974) relations are correct for the given elevations. Wymore's (1974) values for the available water-holding capacity of soils may not be valid for the study area, but by assuming the step size is correct, the calibration process is simplified. The relation for each vegetation type is allowed to change only by its intercept value (fig. 5). Thus, the rate at which values of available water-holding capacity change with respect to elevation is assumed correct, but the magnitude is changed during the calibration process. Though the validity of Wymore's (1974) relations of elevation and the available water-holding capacity of soils is unknown, they are used here as a convenient means of distributing SMAX among HRU's within a vegetation type. The other option would be to vary both the magnitude and rate of change with elevation of available water-holding capacity. Although this is possible to do, the calibration process would become extremely complicated.

The second assumption, that all HRU's have equal opportunity to contribute water to streamflow, is included because it is unknown at the start which HRU's actually contribute water to streamflow. By initially allowing all HRU's an equal opportunity to contribute, the calibration process is able to assign which HRU's are supplying water, and how much they supply based on observed streamflow data.

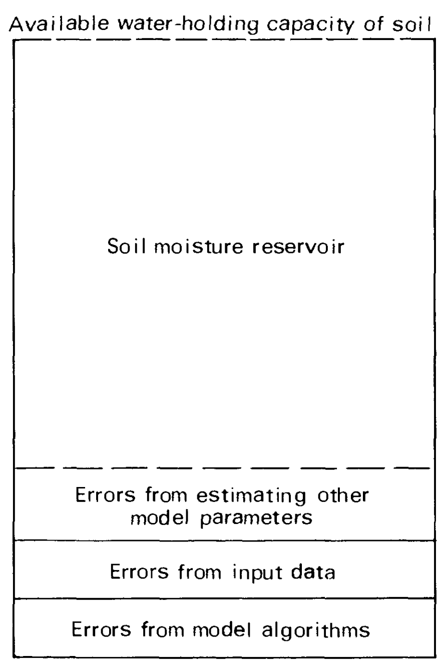


Figure 8.--Components of the estimate of the available water-holding capacity of a soil (SMAX).

The third assumption is that SMAX largely will compensate for all of the errors from other sources. These other error sources include errors in model algorithms, errors in the input data, and errors in estimating other model parameters, which are held constant at some assumed value (fig. 8). Model parameters other than SMAX are initially estimated as accurately as possible from the results of other model applications, physical characteristic-model parameter relations that have been established and tested, and other related research. This assumption simplifies the calibration process by lumping both known and unknown errors into a single parameter. The last assumption, that SMAX only needs to be calculated to the nearest one-half inch, is included for later efforts of transferring the SMAX relations to other basins.

Calibration Process

The calibration procedure is a series of model runs in which the SMAX values are changed for a particular vegetation type within a watershed, holding all other model parameters constant. For each run, the objective function, expressed as the average annual percent error, is the average of the observed annual discharge minus the predicted annual discharge, divided by the observed annual discharge. The flow chart in figure 9 shows the procedure. As a starting point, Wymore's (1974) values for SMAX were assigned to each HRU. The SMAX values were varied around Wymore's (1974) values for one vegetation type, maintaining Wymore's (1974) step sizes, while the other vegetation types were held constant at Wymore's (1974) values.

From these iterations, a relation was developed between the objective function and a function of SMAX. The function of SMAX used was a water-holding-capacity ratio defined as the sum of the SMAX values for that vegetation type divided by the sum of Wymore's (1974) available water-holding capacity of the soil values for that vegetation type. For example, if the sum of SMAX values for a vegetation type equaled 30 inches and the sum of Wymore's (1974) available water-holding-capacity values for that vegetation type also equaled 30 inches, the water-holding-capacity ratio would equal 1. However, if the sum of the chosen vegetation type SMAX values were 60 inches, the water-holding-capacity ratio would equal 2. Other SMAX functions could be used to give similar results. Plots of average annual percent error and the water-holding-capacity ratio described above for a vegetation type are shown in figure 10 for a typical iteration of the above procedure.

After establishing the relation for a vegetation type, its SMAX values were returned to their original Wymore (1974) values and another vegetation type was chosen to increment SMAX. The preceding process then was repeated for each vegetation type. When all vegetation types were run, the point on each vegetation-type curve that yielded the minimum objective function was used to establish new SMAX-elevation relations, rounded to the nearest one-half inch, as the new starting point to replace Wymore's (1974) values for repeating the entire process. The entire sequence was repeated until a minimum error for the objective function was found.

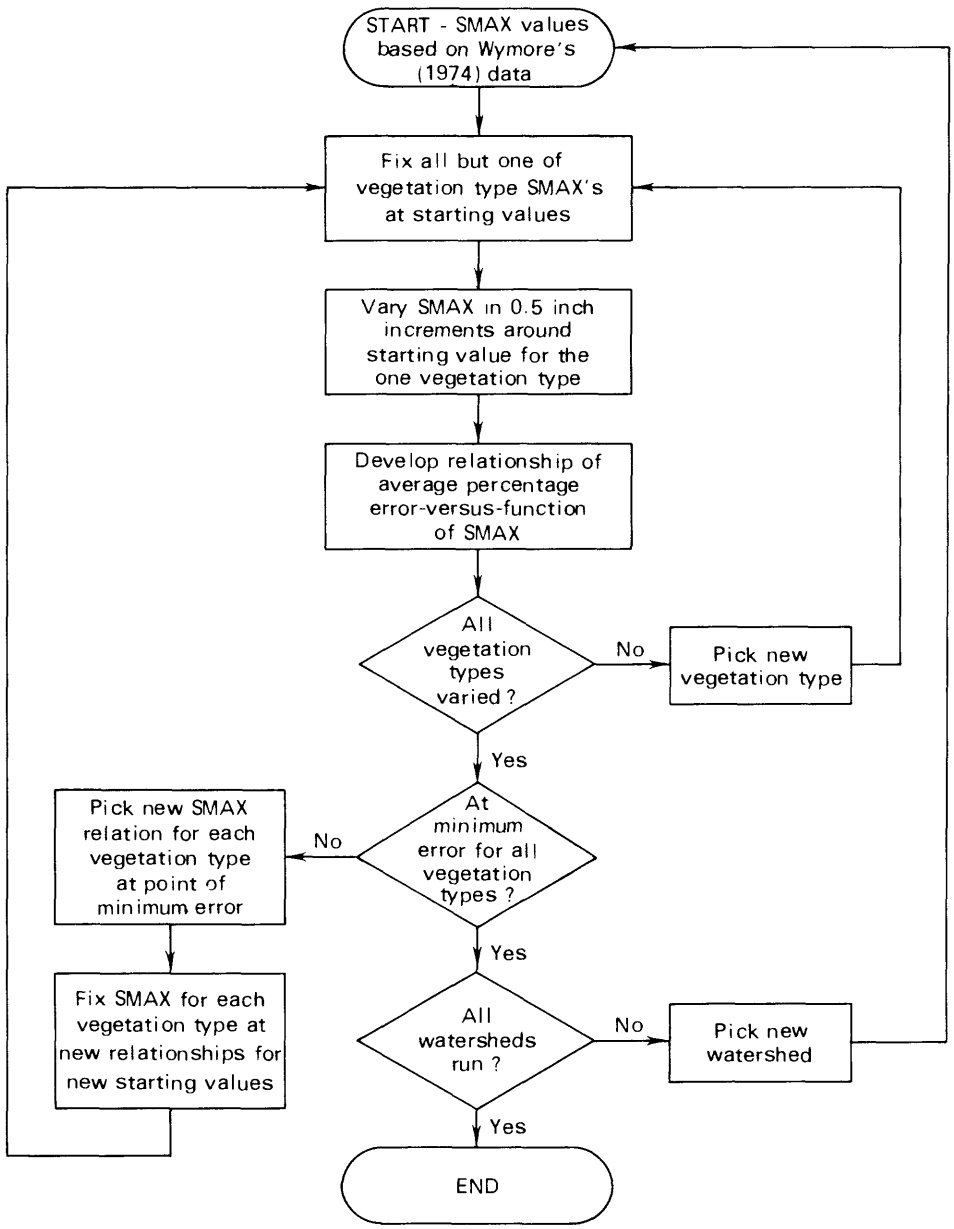


Figure 9.--Flow chart of calibration process.

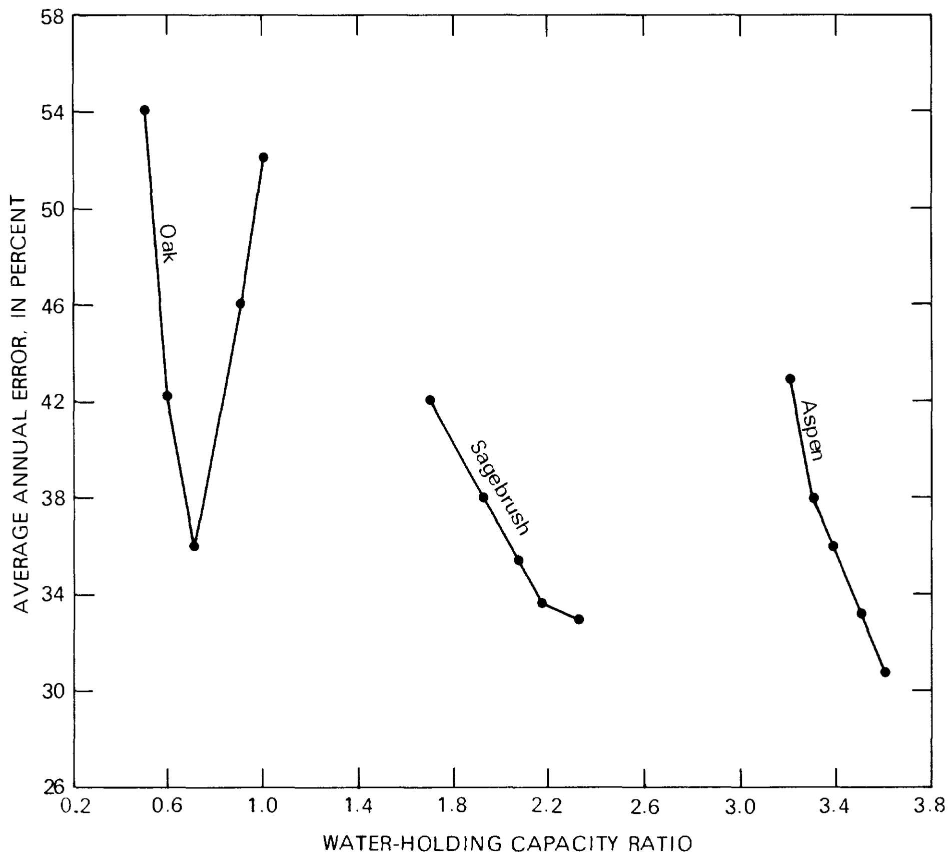


Figure 10.--Typical relations developed from one iteration of the calibration process. SMAX is the available water-holding capacity of the soil.

RESULTS

Volume Calibration

The watersheds used in the calibration process, each with 3 years of observed data, were station 09243700 Middle Creek near Oak Creek, station 09243800 Foidel Creek near Oak Creek, and station 90243900 Foidel Creek at mouth, near Oak Creek (fig. 1 and table 1). Observed annual precipitation and discharge totals are shown in table 3. The model was calibrated for runoff volume on the last two water years, 1977 and 1978; water year 1976 was used to initialize the model. The first year initialization was incorporated to reduce errors due to estimating the initial conditions of the basin.

Table 3.--*Annual observed precipitation and discharge*

Water year (inches)	Precipitation (inches)	Discharge (cubic feet per second-days)	Discharge (inches)
	Station 09243700 Middle Creek near Oak Creek		
1976	18.84	728	1.13
1977	12.86	182	.28
1978	20.74	1,280	1.99
	Station 09243800 Foidel Creek near Oak Creek		
1976	17.27	66	.29
1977	11.54	7.9	.03
1978	19.44	289	1.25
	Station 09243900 Foidel Creek at mouth, near Oak Creek		
1976	16.43	485	1.02
1977	10.86	26	.05
1978	18.71	832	1.76

The annual observed and predicted stream discharge volumes and the error between them for the three watersheds after volume calibration are given in table 4. Runoff predicted by the model was close to observed runoff, except for water year 1978 at station 09243700 Middle Creek near Oak Creek. The percent error of runoff on the other watersheds during some years was similar to the percent error in the runoff of Middle Creek in water year 1978, but this was the result of taking the percent differences of small numbers. For example, in water year 1977 at station 09243900 Foidel Creek at mouth, near Oak Creek, the percent error was 23.1 percent, but the difference between observed and predicted annual discharge was only 6 cubic feet per second-days. At station 09243700 Middle Creek near Oak Creek, water year 1978, the percent error was 21.9 percent, but the difference between annual observed and predicted discharge was 280 cubic feet per second-days (table 3).

The final SMAX values resulting from the calibration procedure are plotted in figures 11 through 14 with Wymore's (1974) relations plotted as a comparison. Plots of SMAX values for both Foidel Creek watersheds are combined because their SMAX values for like vegetation types and elevation are equal. SMAX values for aspen HRU's are not plotted because they have no relation to elevation. SMAX values for aspen at station 09243800 Foidel Creek near Oak Creek are 15.5 inches; at station 09243900 Foidel Creek at mouth, near Oak Creek, 15.0 inches; and at station 09243700 Middle Creek near Oak Creek, 19 inches. These values are within the range of reported values for available water-holding capacity (Brown and Thompson, 1965). Since aspens in Middle Creek are at higher elevations than in either of the Foidel Creek locations, this may imply a positive relation of aspen SMAX values with elevation, but a relation cannot be developed until more watersheds have been calibrated.

Table 4.--*Observed and predicted annual discharge after volume calibration*

Water year	Observed discharge (cubic feet per second-days)	Predicted discharge (cubic feet per second-days)	Difference (cubic feet per second-days)	Error (percent)	Average error (percent)
		Station 09243700 Middle Creek near Oak Creek			
1977	182	158	24	13.2	
1978	1,280	1,560	280	21.9	
		Station 09243800 Foidel Creek near Oak Creek			
1977	7.9	8.9	1.0	12.7	6.5
1978	289	288	1.0	.3	
		Station 09243900 Foidel Creek at mouth, near Oak Creek			
1977	26	20	6.0	23.1	11.8
1978	832	829	3.0	.4	

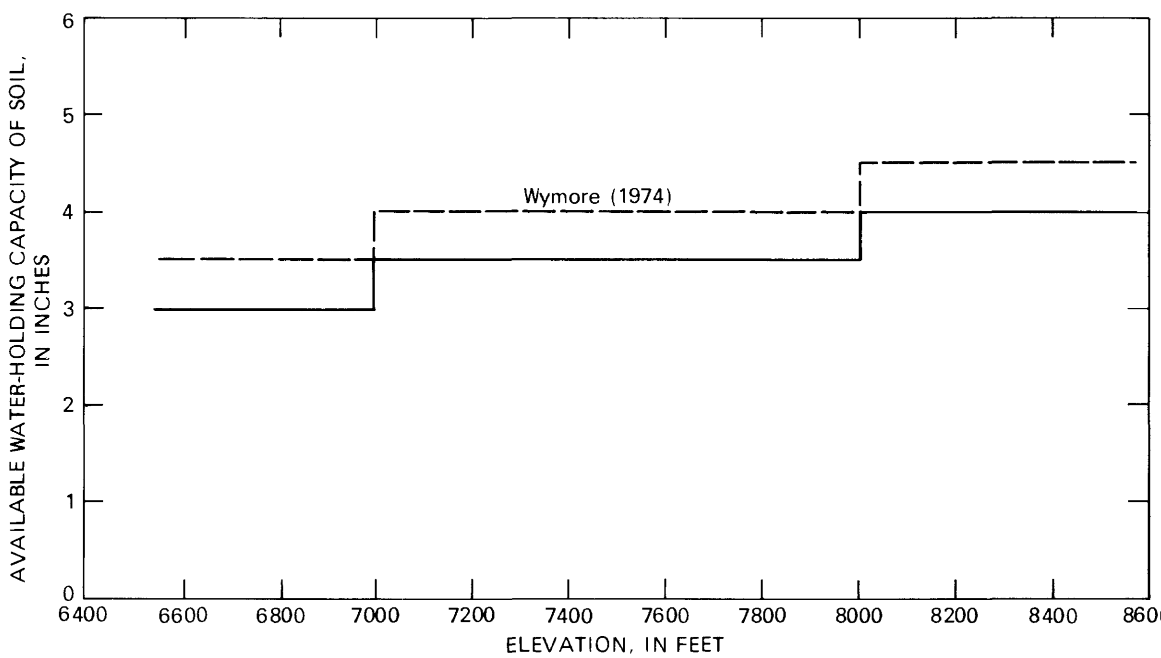


Figure 11.--Relation between elevation and the available water-holding capacity of soils (SMAX) associated with oak in the watersheds of station 09243800 Foidel Creek near Oak Creek, and station 09243900 Foidel Creek at mouth, near Oak Creek, after calibration.

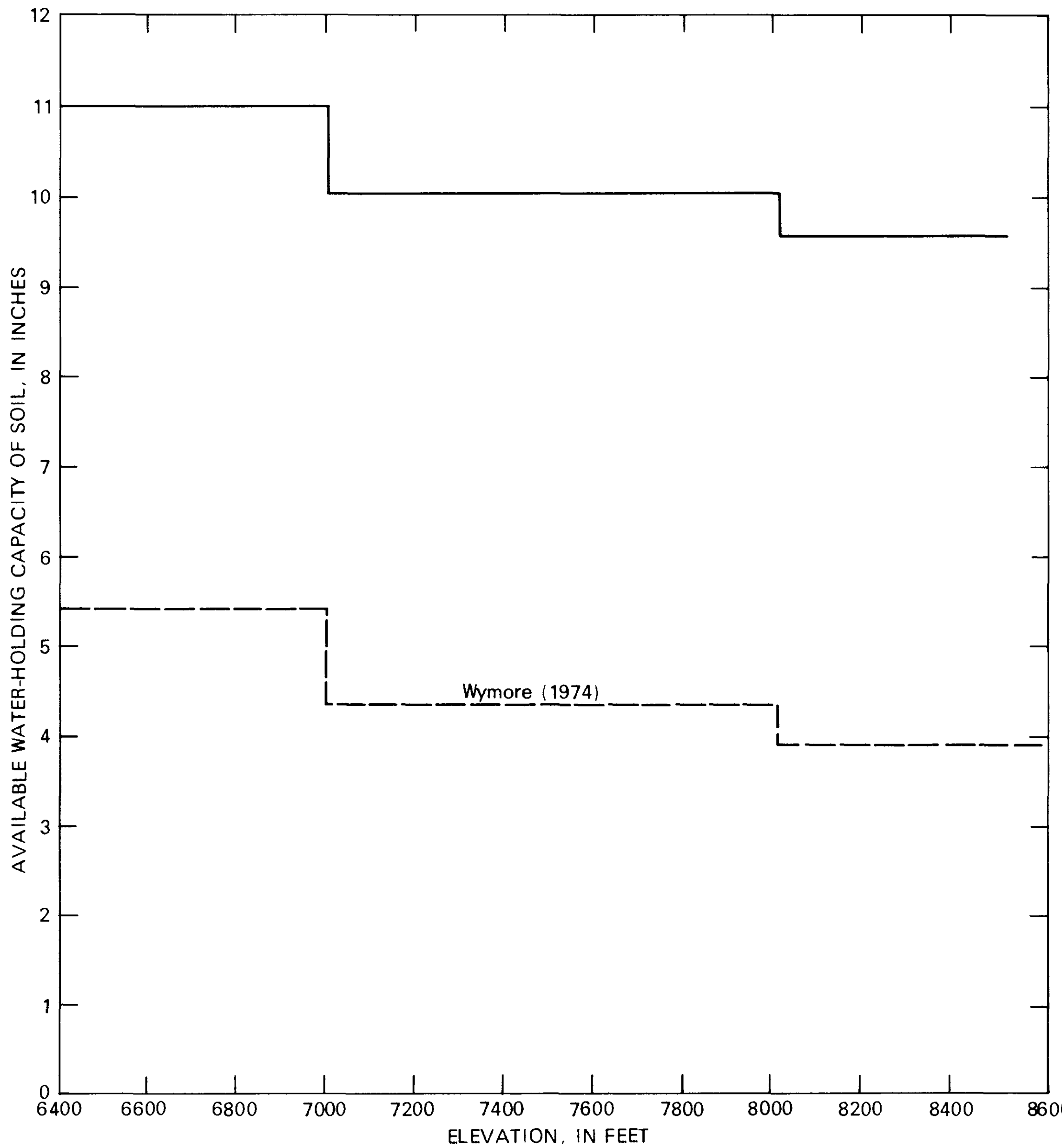


Figure 12.--Relation between elevation and the available water-holding capacity of soils (SMAX) associated with sagebrush in the watersheds of station 09243800 Foidel Creek near Oak Creek, and station 09243900 Foidel Creek at mouth, near Oak Creek, after calibration.

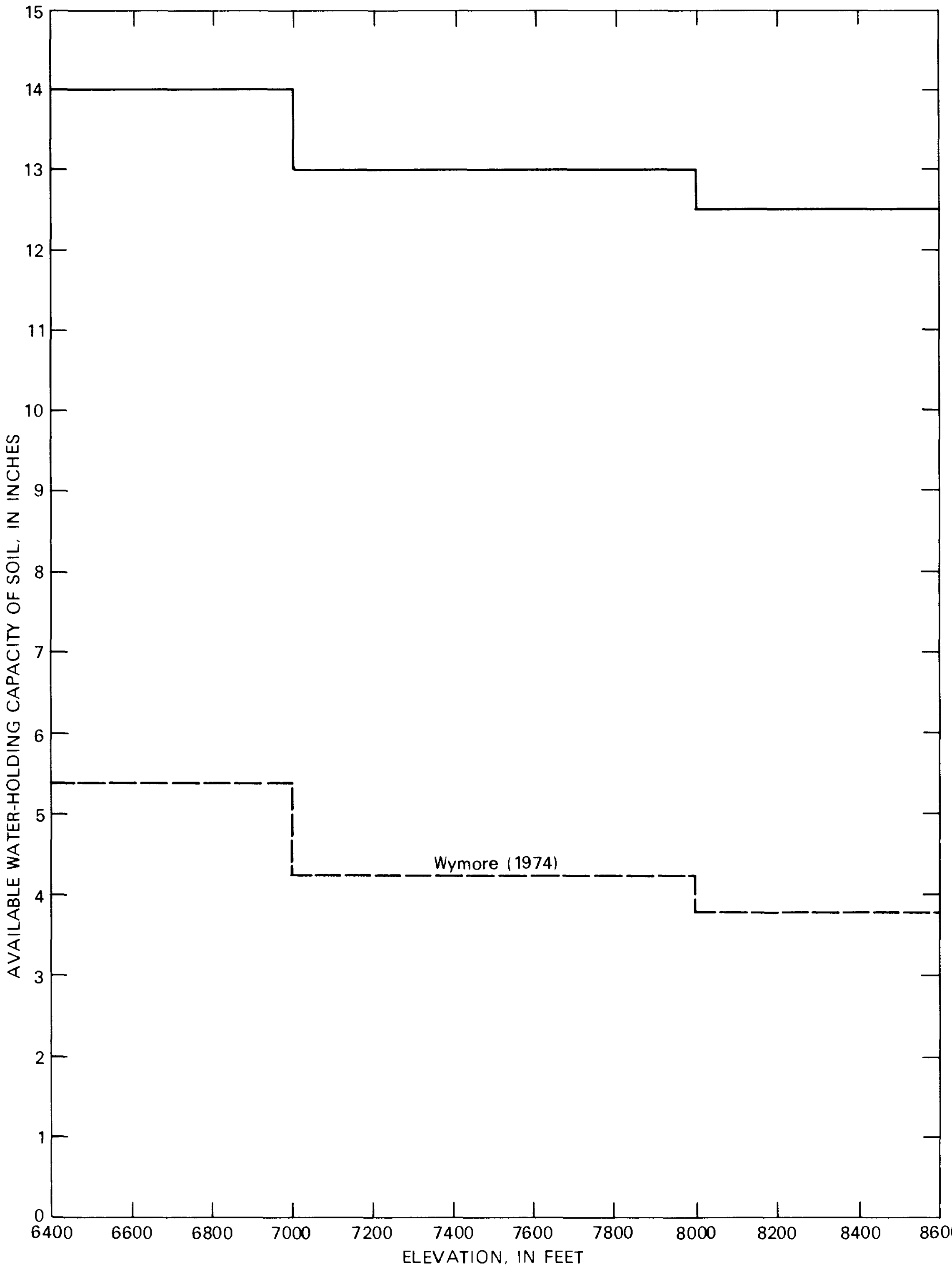


Figure 13.--Relation between elevation and the available water-holding capacity of soils (SMAX) associated with sagebrush in the watershed of station 09243700 Middle Creek near Oak Creek, after calibration.

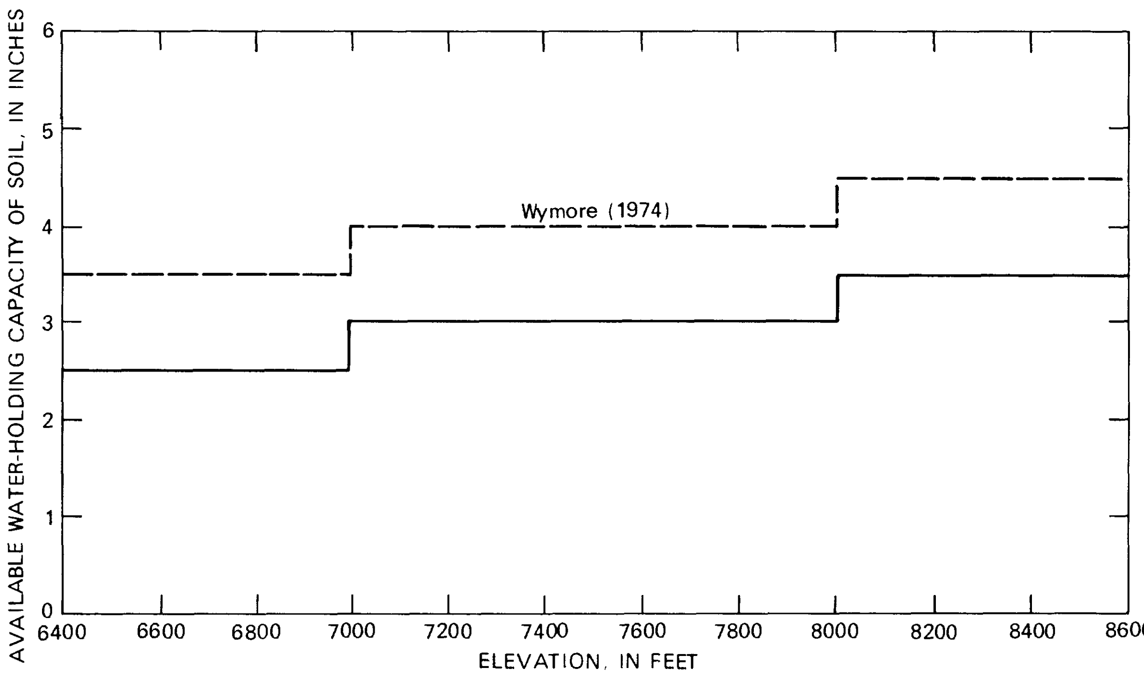


Figure 14.--Relation between elevation and the available water-holding capacity of soils (SMAX) associated with oak in the watershed of station 09243700 Middle Creek near Oak Creek, after calibration.

As shown in figures 11 through 14, SMAX values for oak HRU's increased by 0.5 and 1.0 inch above Wymore's (1974) values, and SMAX values associated with sagebrush increased from 5.5 to 8.5 inches above Wymore's values. SMAX values associated with aspen HRU's increased from 10.0 to 14.0 inches above Wymore's values. Some of the difference between Wymore's values and those found in calibration may be due to the assumption that SMAX contains errors from other sources, and some differences also may be due to differences in local factors such as soils, slopes, and aspects. Another possible reason for the differences is Wymore's values are not correct for the study area.

Calibrated values of the sensitive parameters listed in table 2 for the three watersheds are shown in table 5.

Table 5.--*Calibrated values of timing parameters*

[COVDNW, winter vegetative cover density; TRNCF, solar radiation transmission coefficient; RSEP, rate water moves from subsurface to ground-water reservoir; RCB, ground-water routing coefficient; TLX, lapse rate for maximum air temperature; CTS, air temperature evapotranspiration coefficient; TST, temperature index to determine start of evapotranspiration; BST, temperature above which all precipitation is rain]

Parameter	Station 09243700 Middle Creek near Oak Creek	Station 09243800 Foidel Creek near Oak Creek	Station 09243900 Foidel Creek at mouth, near Oak Creek
COVDNW----	0.15[1], 0.20[2], 0.50[3]	0.20[1], 0.25[2], 0.50[3]	0.31[1], 0.41[2], 0.51[3]
TRNCF-----	0.68[1], 0.58[2], 0.25[3]	0.57[1], 0.48[2], 0.25[3]	0.40[1], 0.30[2], 0.22[3]
RSEP------	0.20	0.20	0.94
RCB-------	0.118	0.118	0.073
TLX[4]------	1.46-6.94	1.46-6.82	1.46-6.94
CTS-------	0.014	0.014	0.014
TST-------	950	950	950
BST-------	34.0	34.0	34.0

[1]Values for units with sagebrush as the dominate vegetation type.
[2]Values for units with oak as the dominate vegetation type.
[3]Values for units with aspen as the dominate vegetation type.
[4]Parameter varies by month.

Timing Optimization

Parameter Sensitivity

After the streamflow volume in each watershed was calibrated, an investigation was begun to determine if the timing of that volume through the year could be improved. A sensitivity analysis was done on the parameters in table 2 which Leavesley and others (1981) found to primarily influence streamflow timing. It should be noted that parameters other than those shown in table 2 also influence streamflow timing; for example, the subsurface reservoir-routing coefficients. Because of the calibration, the parameter SMAX was not included in the analysis. The sensitivity of the eight parameters is shown in table 6, which shows the error-variance increase between observed and predicted discharge for a given percent change in the parameter value. The larger the variance increase for a given percent change in the parameter value, the more sensitive the parameter. For all three watersheds, BST, the base temperature above which all precipitation is rain, was the most sensitive of the parameters examined. This parameter is most sensitive due to the small range of meaningful values it can have. If BST has a value that makes all precipitation either all rain or snow, changing it by some small amount will have no effect on the error of predicted discharge. The next two most sensitive parameters examined for the Foidel Creek watersheds are TRNCF, the solar radiation transmission coefficient, and CTS, the air temperature evapotranspiration coefficient.

Table 6.--*Sensitivity of timing parameters*

[Table entries represent the change in error variance resulting from deviations of selected parameters from their initial values. Definitions: COVDNW, winter vegetative cover density; TRNCF, solar radiation transmission coefficient; RSEP, rate water moves from subsurface to ground-water reservoir RCB, ground-water routing coefficient; TLX, lapse rate for maximum air temperature; CTS, air temperature evapotranspiration coefficient; TST, temperature index to determine start of evapotranspiration; BST, temperature above which all precipitation is rain]

Parameter	Increase in error variance (cubic feet per second squared)			
Percentage change in parameter value---	5	10	20	50
Station 09243700 Middle Creek near Oak Creek				
Error variance is 12.178 cubic feet per second squared				
COVDNW---------------------	0.074	0.295	1.180	7.374
TRNCF----------------------	0.651	2.604	10.415	65.095
RSEP-----------------------	0.248	0.993	3.972	24.826
RCB------------------------	0.045	0.130	0.719	4.492
TLX------------------------	0.381	1.522	6.088	38.050
CTS------------------------	0.270	1.078	4.312	26.952
TST------------------------	0.086	0.348	1.383	8.646
BST------------------------	1.635	6.541	26.164	163.528
Joint variance-----------	1.259	5.035	20.141	125.882
Station 09243800 Foidel Creek near Oak Creek				
Error variance is 5.093 cubic feet per second squared				
COVDNW---------------------	0.039	0.158	0.631	3.945
TRNCF----------------------	0.118	0.471	1.884	11.778
SEP------------------------	([1])	([1])	([1])	([1])
RCB------------------------	0.002	0.008	0.033	0.205
CTS------------------------	0.011	0.042	0.169	1.058
TST------------------------	([1])	([1])	([1])	([1])
BST------------------------	0.205	0.818	3.272	20.452
Joint variance-----------	0.071	0.284	1.137	7.107
Station 09243900 Foidel Creek at mouth, near Oak Creek				
Error variance is 15.827 cubic feet per second squared				
COVDNW---------------------	0.047	0.089	0.757	4.733
TRNCF----------------------	0.337	1.347	5.388	33.677
SEP------------------------	([1])	([1])	([1])	([1])
REC------------------------	0.013	0.061	0.204	1.277
TLX------------------------	0.028	0.113	0.453	2.833
CTS------------------------	0.275	1.102	4.407	27.547
TST------------------------	([1])	0.002	0.007	0.047
BST------------------------	0.741	2.965	11.861	74.132
Joint variance-----------	0.258	1.031	4.122	25.764

[1]Value less than 0.001.

In Middle Creek, the sensitive parameters other than BST are TRNCF; TLX, the maximum air temperature correction for elevation; CTS; and RSEP, the rate water moves from the subsurface to the ground-water reservoir, in that order. Probably the reason TLX and RSEP are sensitive in the Middle Creek and not in the Foidel Creek watersheds is because the elevation differences in the Middle Creek watershed are greater than the elevation differences in the Foidel Creek watersheds. TLX is directly related to elevation. RSEP is indirectly related to elevation because precipitation depths are greater at the higher elevations. As the amount of water moving through the subsurface to the ground-water reservoir on Middle Creek becomes greater, the value of RSEP becomes more sensitive.

Parameter Optimization

After the sensitivity analysis, the eight parameters influencing discharge timing were optimized using the model's optimization subroutine, a standard Rosenbrock (1960) method. The optimization was done for two purposes. The first was to check the calibration procedure. Because all other errors were assumed included in the SMAX estimate and the calibration objective function was to minimize average annual percent error, optimization on the other parameters could not improve the objective function if the calibration was correct. The second reason for the optimization was to check the estimates initially made on the other parameters. Although every effort was made to make the best estimates possible, it was felt that these estimates may not be the optimal value for each parameter. Optimization on these eight parameters was done with SMAX set at the calibrated values to check the error of the initial estimates.

Optimization was done only on the wet year (water year 1978) because the objective function used in the optimization was to minimize the sum of squares of the differences between daily observed and predicted discharge. Optimizing on both water years 1977 and 1978 gave only slightly different results because the larger discharge in water year 1978 dominated the optimization.

Although the value of the objective function (sum of the square of the differences between daily observed and predicted discharge) of each watershed dropped significantly after optimization (table 7), a comparison of table 4 to table 8 shows that the timing optimization adversely affected the average annual percent error between observed and predicted discharge on all three watersheds. Timing optimization improved only the annual percent error during 1978 for the Middle Creek watershed. Because the optimization should not be able to improve the average annual percent error if the calibration procedure is correct, it is assumed the procedure is correct and the SMAX values found are the best for the given set of timing parameters.

Table 7.--*Timing parameter values before and after optimization*

[COVDNW, winter vegetative cover density; TRNCF, solar radiation transmission coefficient; RSEP, rate water moves from subsurface to ground-water reservoir; RCB, ground-water routing coefficient; TLX, lapse rate for maximum air temperature; CTS, air temperature evapotranspiration coefficient; TST, temperature index to determine start of evapotranspiration; BST, temperature above which all precipitation is rain]

Parameter	Before	After	
	Station 09243700 Middle Creek near Oak Creek		
COVDNW	0.19-0.51	0.24-0.46	
TRNCF	0.22-0.67	0.20-0.65	
RSEP	0.94	0.99	
RCB	0.07	0.06	Objective function
TLX	1.67-7.93	1.36-6.48	before = 3,224.4;
CTS	0.015	0.018	Objective function
TST	1,969.00	1,993.70	after = 1,342.6.
BST	33.96	34.99	
	Station 09243800 Foidel Creek near Oak Creek		
COVDNW	0.30-0.50	0.67-0.87	
TRNCF	0.25-0.43	0.46-0.64	
RSEP	1.0	0.71	
RCB	0.12	0.07	
TLX	1.46-6.94	1.30-6.18	Objective function
CTS	0.01	0.02	before = 1,517.7;
TST	950.0	1,882.97	Objective function
BST	34.00	33.73	after = 283.95.
	Station 09243900 Foidel Creek at mouth, near Oak Creek		
COVDNW	0.05-0.50	0.36-0.81	
TRNCF	0.33-0.90	0.12-0.77	
RSEP	1.0	1.5	
RCB	0.12	0.16	
TLX	1.46-6.94	1.37-6.49	Objective function
CTS	0.01	0.02	before = 4,716.5;
TST	950.0	659.03	Objective function
BST	34.00	31.55	after = 3,185.3.

Table 8.--*Observed and predicted annual discharge after timing optimization*

Water year	Observed discharge (cubic feet per second-days)	Predicted discharge (cubic feet per second-days)	Difference (cubic feet per second-days)	Error (percent)	Average error (percent)
		Station 09243700 Middle Creek near Oak Creek			
1977	182	90	92	50.6	
1978	1,280	1,280	0.0	0.0	25.3
		Station 09243800 Foidel Creek near Oak Creek			
1977	7.9	15	7.1	89.9	
1978	289	291	2.0	0.7	45.3
		Station 09243900 Foidel Creek at mouth, near Oak Creek			
1977	26	11	15	57.7	
1978	832	698	134	16.1	36.9

Average initial and final values for the eight parameters used in the optimization also are shown in table 7. Initial parameter values are those estimated and assumed correct during the volume calibration. The largest change in values occurred in the average cover density of the two Foidel Creek watersheds. In the lower Foidel Creek watershed, the value of cover density changed from an average of 34 percent to an average of 65 percent and in the upper Foidel Creek watershed from an average of 40 percent to an average of 77 percent. These increases appear to be an attempt by the optimization to increase the snowmelt rates earlier in the snowmelt season.

Other than the changes in the cover densities, the other parameters optimized indicated little change after optimization (table 7). This implies that the original estimates made for these parameters were reasonable but there was some error, part of which (those errors which influence annual discharge) are included in the calibrated SMAX values.

Observed and predicted hydrographs before and after the timing optimization for the three watersheds for water year 1978 are shown in figures 15 through 17. The predicted hydrographs before timing optimization were computed from results of the volume calibration process described earlier. Results after timing optimization are not greatly different for any of the watersheds except for station 09243800 Foidel Creek near Oak Creek (fig. 17). The small differences on the hydrographs after optimization are the result of reasonable initial estimates made on the timing parameters. This indicates that for similar watersheds, if care is taken to make the most accurate estimates possible on the other model parameters, model calibration can be done with only one parameter, SMAX, with reasonable volume and timing results.

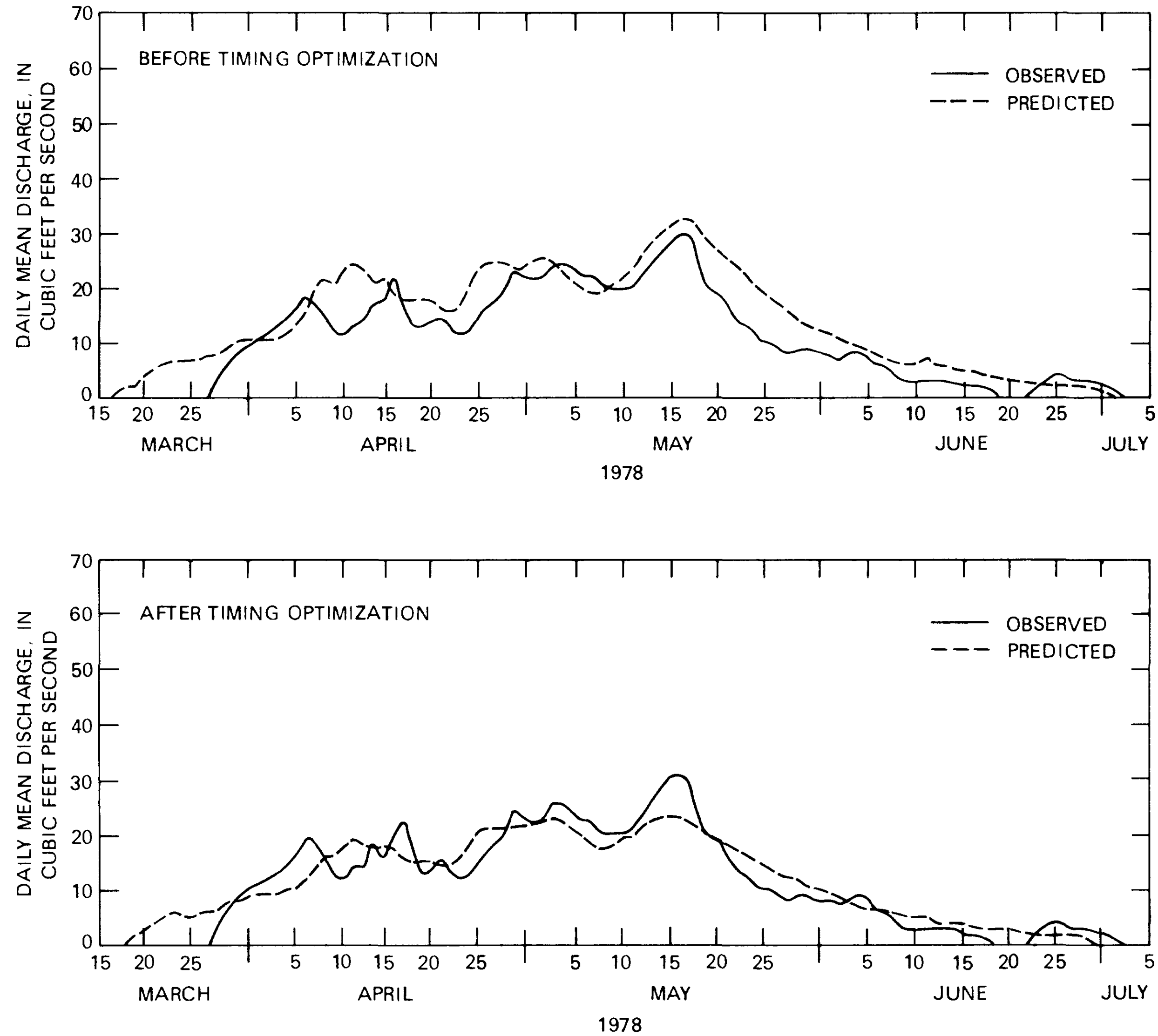


Figure 15.--Observed and predicted hydrographs for station 09243700 Middle Creek near Oak Creek, before and after timing optimization.

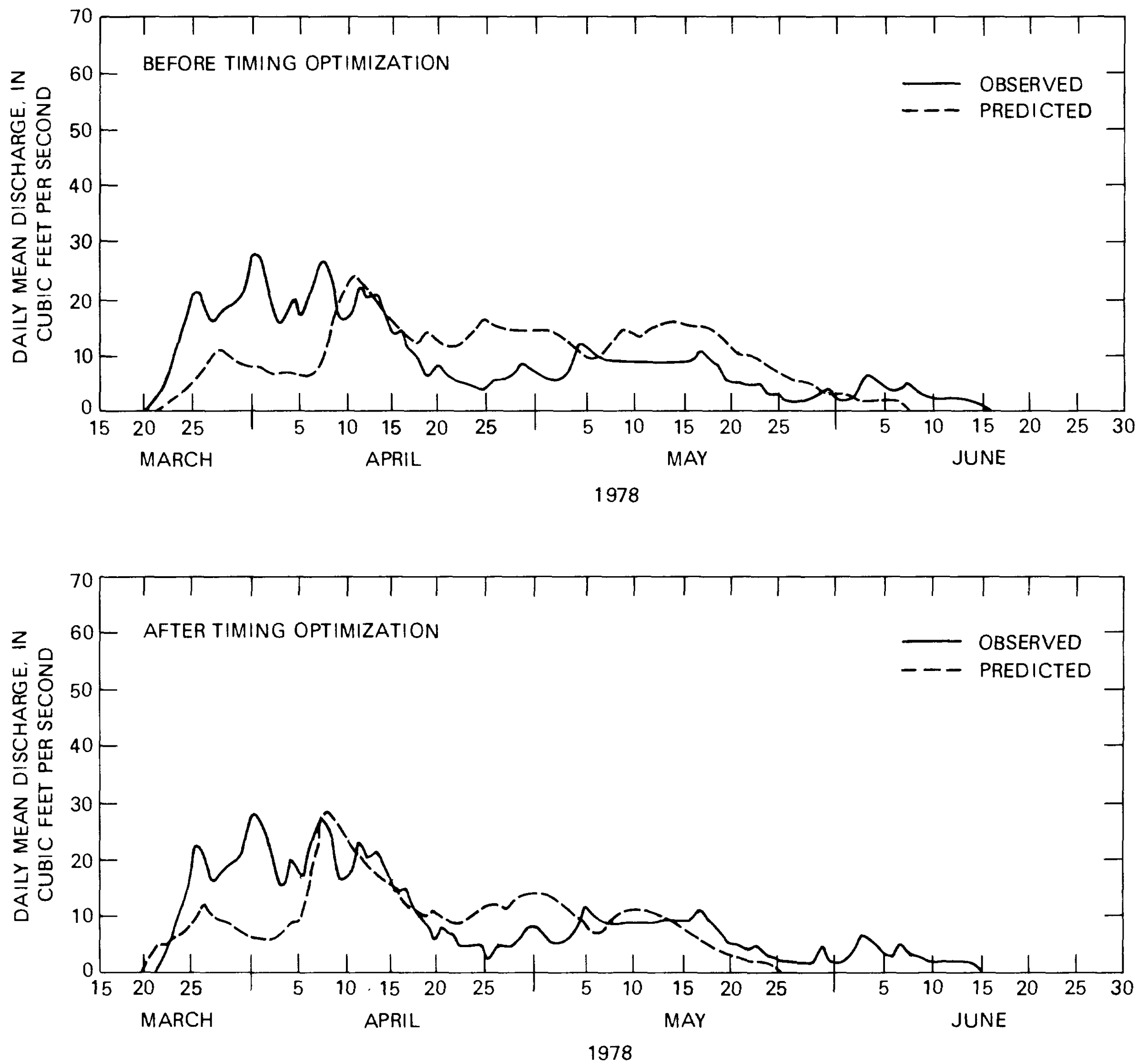
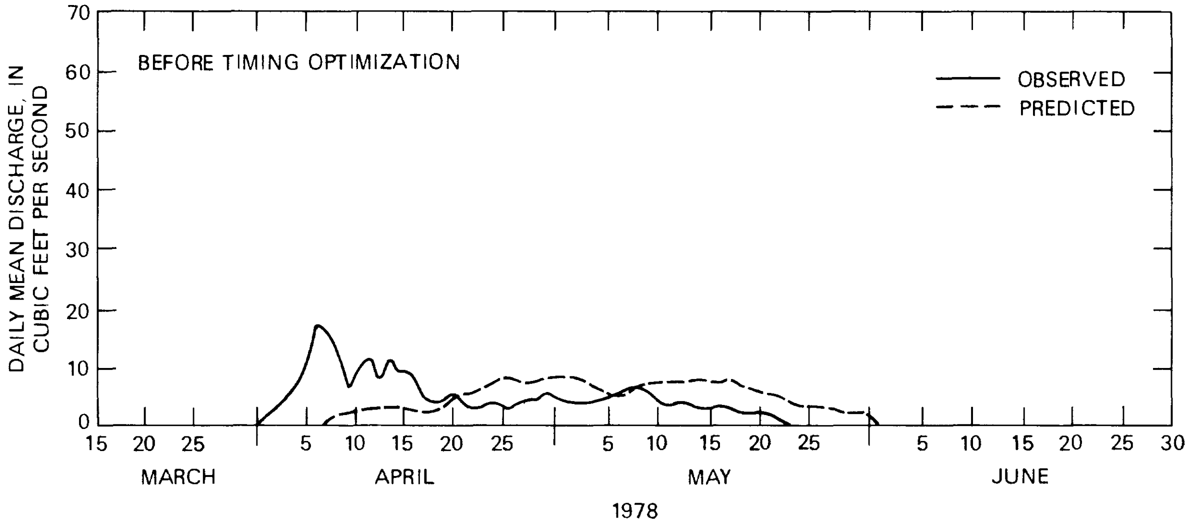


Figure 16.--Observed and predicted hydrographs for station 09243900 Foidel Creek at mouth, near Oak Creek, before and after timing optimization.



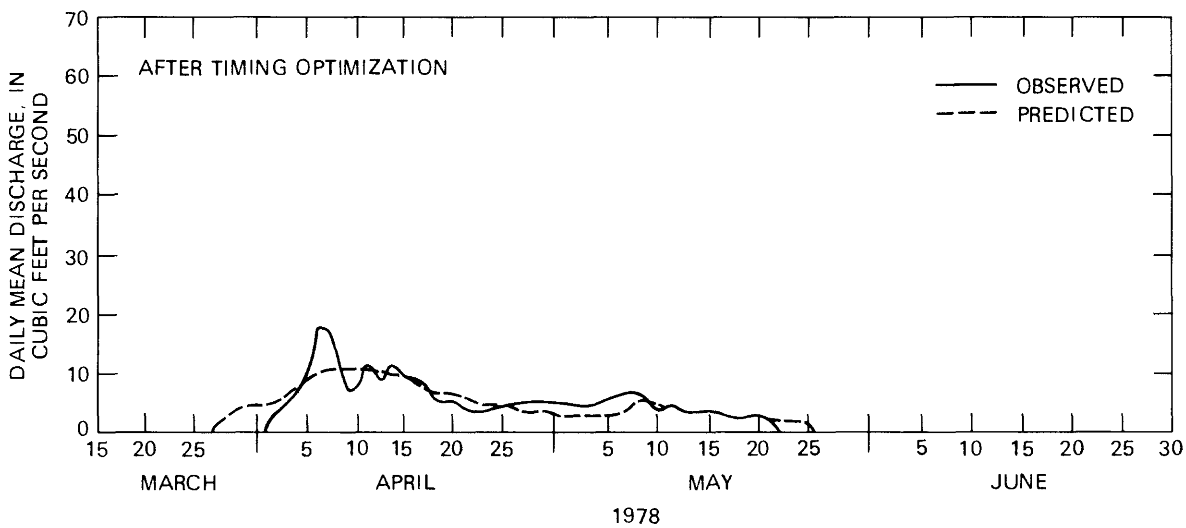


Figure 17.--Observed and predicted hydrographs for station 09243800 Foidel Creek near Oak Creek, before and after timing optimization.

DISCUSSION

Volume Calibration

As the calibration process proceeded, two definite curve shapes for the relation between the function of SMAX and average annual percent error emerged, the "U" shaped curve and the "L" shaped curve, as shown in figure 18. The "U" shaped curve can be interpreted more easily than the "L" shaped curve because it has a definite minimum. During calibration, the SMAX function associated with oak vegetation plotted as the first, and sometimes only, "U" shaped curve in all three watersheds. This was because oak HRU's were dominant in contributing water to the channel in the dry year, water year 1977. Thus, the oak HRU's had specific SMAX values that resulted in a minimum error in water year 1977.

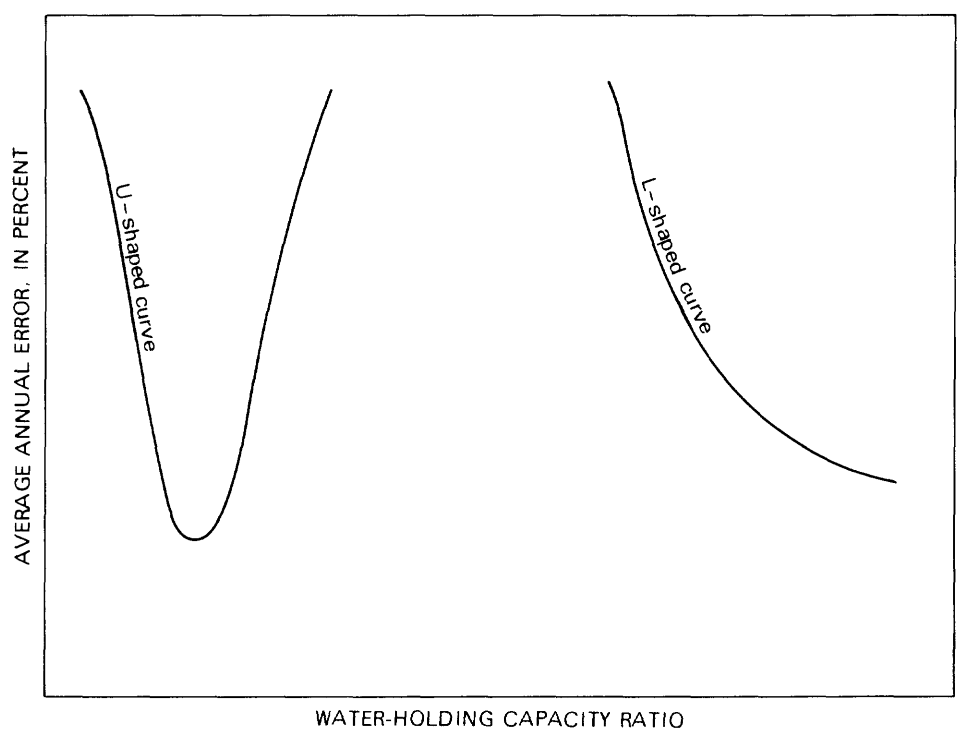


Figure 18.--Typical curve shapes (schematic) obtained during the calibration of the available water-holding capacity of soils (SMAX) with the average annual error.

The "L" shaped curves could have two meanings. One was that these HRU's were insensitive or unimportant in contributing to streamflow. The other was that there was an error in SMAX within another vegetation type. For example, the SMAX values for a particular vegetation type could be set too low, allowing too much streamflow to be derived from them. In this case, the SMAX values on the other vegetation types could be raised to a point where no streamflow originated from them, and the curve would stay "L" shaped.

Once the SMAX values associated with oak were at the minimum error value, the next step was to minimize the error for SMAX values associated with sagebrush and aspen. To achieve the minimum error for the oak HRU's, the calibration routine made the oak SMAX values small (2.5 to 3.5 inches). This meant that the oak HRU's contributed much of the water in the wet year, water year 1978. This contribution caused the SMAX values for both sagebrush and aspen to calibrate near the point where the sagebrush and aspen HRU's no longer contributed water. Some annual volume errors could be reduced by not allowing sagebrush and aspen HRU's to contribute to streamflow, but this was not permitted in order to uphold the assumption that all HRU's have equal opportunity to contribute. It was considered unrealistic to have HRU's of a particular vegetation type not contribute in the wet year (water year 1978).

A possible source of error in the calibrated SMAX values is associated with the particular sequence of years used in the calibration process, going from a dry year to a wet year. In the volume calibration, the dry year dominated the results, whereas in the timing optimization, the wet year dominated. Further study is needed to see what effects, if any, a different sequence of years may have. It is unknown at this point what would happen if several wet or dry years fall sequentially.

Because the Rosenbrock (1960) optimization subroutine already in the model will optimize on SMAX, it is worthwhile to discuss why this new volume calibration using SMAX was developed. The Rosenbrock technique is commonly used in model parameter optimization. Basically, the technique attempts to minimize some objective function by allowing the parameter being optimized to move between given upper and lower bounds in the following manner: The technique moves the parameter up by a given step size, and if that lowers the value of the objective function, it moves the value up three times the original step size. If the first increase raises the objective function, the value is lowered from the original value by the step size. If the first step lowers the objective function but the second step raises it, it sets the value halfway between the two. The Rosenbrock optimization technique continues in this manner through a given number of iterations (Rosenbrock, 1960).

The new procedure is a modification of the Rosenbrock technique. The main difference is the ability of the new procedure to easily accommodate directly the constraints of the stated assumptions. There are other advantages to using the new procedure to calibrate volumes over the Rosenbrock method. As has been discussed, the new procedure is not dominated by years of higher discharges. In a sequence of years in which the discharges are similar, the two methods should give similar results. In a sequence of years in which the discharges differ, the new procedure should give better results.

The new process allows the user to see the tradeoffs involved in the calibration and gain insight into the hydrologic system being calibrated, especially if little is known about the watershed. An example is that HRU's associated with oak were apparently the only areas contributing water to streamflow in a dry year, water year 1977. This indicates that the soils associated with oak in the study watersheds are shallower than those associated with sagebrush or aspen. It should be kept in mind, however, that any insight into the hydrologic system using this calibration procedure may be biased by the lumping of errors into SMAX.

SUMMARY

A volume calibration process is developed for the U.S. Geological Survey's Precipitation-Runoff Modeling System (Weeks and others, 1974). The process uses the parameter indexing available water-holding capacity of the soil (SMAX) and appears able to calibrate both streamflow volume and timing if other model parameters are reasonably estimated. The calibration process is for use in those watersheds in which snowmelt is the major contributor to the annual discharge. The process requires a series of iterations in which the HRU's available water-holding-capacity parameter is changed to minimize the error between observed and predicted annual discharge. Three watersheds were calibrated by the process and the parameters sensitive to timing prediction were optimized. The results indicated that with other model parameters reasonably estimated, calibrating to SMAX not only calibrated discharge volumes but also the timing of the discharge. Optimization on the timing parameters was done for two purposes. The first was to check on the calibration procedure and the second was to check the initial estimates made on those parameters influencing discharge timing.

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