EVALUATING THREE FITTING CRITERIA FOR THE CALIBRATION OF THE U.S. GEOLOGICAL SURVEY PRECIPITATION RUNOFF MODELING SYSTEM (PRMS)

by

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ABSTRACT

In automatic calibration, a fitting criteria, which is some function of the difference between the observed and the model generated flows, is optimized to get the best parameter set.

The purpose of this investigation was to calibrate the U. S. Geological Survey Precipitation Runoff Modeling System (PRMS) model using three different fitting criteria; ordinary least squares (OLS), Ln transformation of the discharges using the OLS on the transformed flows (LOG), and maximum likelihood estimator for the heteroscedastic errors (HMLE). The performance of each criteria in terms of their ability to produce reliable forecasts was examined.

The results of the research showed that the winter storms were reproduced best by the parameter sets chosen by the OLS fitting criteria and the summer storms were reproduced best by the HMLE parameter sets. However, the performance in terms of percent bias in different flow groups suggests that HMLE estimator is superior.

CHAPTER 1

INTRODUCTION

The physical processes making up a rainfall-runoff event, can be broken down into the following categories: interception, infiltration, overland flow, subsurface flow, ground-water flow, and channel flow. Researchers model these processes by using equations, such as the Green-Ampt and Manning's equations, to form mathematical models that can be used to simulate rainfall-runoff events. General precipitation-runoff models can be developed which can then be made to simulate the behavior of a specific watershed. This is done by collecting rainfall and discharge data over time and determining basin characteristics for the watershed, and then using the data to help determine the values to be assigned to the variables and parameters of the model. This is called the calibration phase of modeling.

The rainfall and discharge data are used as input and output in the model to fine tune the variables and parameters. Some of the model variables can be determined directly by physical measurement while others have to be determined in the calibration phase. In the calibration phase, the measured parameter values are held constant while the unknown parameters are set at initial values and then a predicted discharge is computed and compared with the observed discharge. Then the initial values are changed by small amounts and the predicted and observed discharges are compared again. This process is repeated until the difference between the observed and the predicted discharge has been reduced as much as possible. When this process is complete, an optimal set of parameter values has been reached.

Automatic Calibration

Automatic calibration techniques can be used in parameter estimation of conceptual rainfall-runoff models such as the one used in this study (PRMS--Precipitation Runoff Modeling System, ref: Leavesly, et al., 1983). The purpose of the calibration is to determine the best set of parameter values for the model. The model then can be used for its intended use, on a specific watershed for which it was calibrated.

In automatic calibration, a fitting criteria compares the measured discharge values with the computed discharge values. The fitting criteria creates a response surface where an optimization algorithm is used to search out the optimal set of parameters. Each fitting criteria creates its own specific response surface. Some may create a surface with local optima which may be far from the global optimum. Others may give irregular contours that make it hard for the optimization algorithm to reach the global optimum. This was shown by Sorooshian and Gupta (1983) where two parameters of the percolation equation of the soil moisture accounting model of the U.S. National Weather Service resulted in an extended valley in the response surface. These irregularities and local optimums may be caused by measurement errors in the input and output data, and model errors which are not accounted for by fitting criteria.

The fitting criteria therefore becomes an important part of the calibration process and should be chosen carefully. In the past decade, some investigators have addressed the problems associated with the selections of estimation criteria for rainfall-runoff modeling. Sorooshian (1978) has developed a procedure using the maximum likelihood function as a fitting criteria. The advantage of one of his proposed estimators is that it filters the effect of inhomogenous errors in the discharge measurements. Application and testing of this criterion, which is known as the maximum likelihood estimator for the heteroscedastic errors (HMLE), has resulted in consistent parameter estimates and hence, better forecasts when compared to estimates obtained by other criteria (see: Sorooshian, Gupta, and Fulton, 1983, Ibbitt and Hutchinson, 1984, Delleur, et al., 1984). The goal of this investigation was to calibrate the PRMS model using different fitting criteria (including the HMLE) and to evaluate the relative performance of each criteria in terms of its ability to produce reliable forecasts.

Objective of this Thesis

The purpose of this study is to compare three fitting criteria, Ordinary Least Squares (OLS), Ln transformation of the discharges using the OLS on the transformed flows (LOG), and Maximum Likelihood Estimator for the Heteroscedastic Errors (HMLE), to determine which fitting criteria gives the best set of parameters for the PRMS model.

Organization of Thesis

The thesis is divided into five chapters. Chapter two will give a brief description of the fitting criteria, comparison criteria, and the PRMS model. Chapter three will describe the procedures followed in the study. Chapter four will describe the results of the research. Chapter five will discuss the conclusions resulting from the research.

CHAPTER 2

DESCRIPTION OF FITTING CRITERIA, COMPARISON CRITERIA, AND THE PRMS MODEL

The Selected Estimation Criteria

The fitting criteria compared were:

1. Ordinary Least Squares (OLS)
2. Maximum Likelihood Estimator for the Heteroscedastic Errors (HMLE)
3. Ln transformation of the discharges using the OLS on the transformed flows (LOG)

Following is a brief description of each fitting criteria.

1. OLS

The OLS fitting criteria minimized the sum of deviations between the observed and the predicted discharges. It has the following properties: the estimates given are unbiased and have a minimum variance. The errors are assumed to be independent and have a normal distribution with a mean zero and constant variance. Ibbitt and Hutchinson (1984) stated that the OLS fitting criteria heavily biases in favor of peak flows:

$$\min_{\underline{\theta}} OLS = \sum_{t=1}^{n} (Q_{t,mes} - Q_{t,com})^2 \tag{1}$$

$Q_{t,mes}$ = the measured streamflow at time t.

$Q_{t,com}$ = is the computed streamflow at time t.

n = the number of measured streamflow values.

2. HMLE Estimator

One instance in which the OLS fitting criterion does not perform well is when the variance of measurement errors is changing as a function of discharge level (or time). In the case of flow data, this is caused by two things. First, Sorooshian and Dracup (1980) point out that the typical rating curve has a concave shape. This causes a unit change at higher stages to have a larger deviation in the resulting discharge values than in the case of the lower stage readings. This would cause the higher flow values to possess an error with a larger variance as compared to the smaller flow values. Secondly, the rating curve at lower stage is defined by current meter measurements with errors ranging between 0 and 10 percent, but at high stages the rating has few current meter measurements with most measurements being indirect. The error in the indirect measurements may range from 10% to 50%, thus, the rating curve is more precisely defined for the lower flows.

Different methods have been used to account for heteroscedastic error. Dawdy and Lichty (1968) proposed a log transformation of the discharges using the OLS on the transformed flows. The idea is to give the lower flows more credibility because they are the more precisely known. Sorooshian (1978) proposed using the maximum likelihood theorem with a power transformation of the flow values. The power transformation becomes a parameter and is estimated as one of the parameters in the HMLE criterion. The power transformation makes the residual variance constant for all discharges. If such error is present, the HMLE results in a response surface with smoother contours than the OLS fitting criteria. Sorooshian and Dracup (1980) showed that the HMLE fitting criteria filtered out streamflow errors of 20% and 30% and, to a lesser degree, precipitation error of 20% and 30%. In the case where heteroscedastic error is not present then the HMLE and OLS should (theoretically) give the same parameter values.

$$\underset{\underline{\theta}}{\mathrm{Min}}\ \mathrm{HMLE} = \frac{\sum_{t=1}^{n} W_t (Q_{t,mes} - Q_{t,com})^2}{n\left[\prod_{t=1}^{n} W_t\right]^{1/n}} \tag{2a}$$

where $W_t = Q_{t,mes}^{2(\lambda - 1)}$

and λ is estimated by solving the implicit equation.

$$0 = \sum_{t=1}^{n} Ln(Q_{t,mes}) \sum_{t=1}^{n} W_t (Q_{t,mes} - Q_{t,com})^2 - K$$

$$K = n \sum_{t=1}^{n} W_t \; Ln(Q_{t,mes})(Q_{t,mes} - Q_{t,com})^2 \qquad (2b)$$

λ = unknown variance stabilizing parameter.

$Q_{t,mes}$ = measured streamflow at time t.

$Q_{t,com}$ = computed streamflow at time t.

n = number of measured streamflow values.

The value of HMLE is computed by first solving the second equation and then using the estimated value of   to minimize equation 2a.

3. LOG

The LOG criteria has the following form:

$$\min_{\underline{\theta}} LOG = \sum_{t=1}^{n} [Ln(Q_{t,mes} + 1) - Ln(Q_{t,com} + 1)]^2 \qquad (3)$$

$Q_{t,mes}$ = measured streamflow at time t.

$Q_{t,com}$ = computed streamflow at time t.

n = number of measured streamflow values.

Comparison Criteria

The performance of each estimation criteria was evaluated based on the forecasting ability of each parameter set obtained. Each parameter set was used to forecast an independent period of record (i.e. no overlap with the calibration period). Among the criteria used to evaluate the forecast performance were:

1. Absolute mean of the residuals (ABMS)
2. Root mean square of residuals (RMS)
3. Percent Bias (PBias)

These criteria were used to analize the difference between the observed and the computed hydrographs.

$$\text{ABMS} = \sum_{t=1}^{n} \left| Q_{t,mes} - Q_{t,com} \right| \tag{4}$$

$$\text{RMS} = \left[\frac{\sum_{t=1}^{n} (Q_{t,mes} - Q_{t,com})^2}{n} \right]^{1/2} \tag{5}$$

$Q_{t,mes}$ = measured streamflow at time t.

$Q_{t,com}$ = computed streamflow at time t.

n = number of measured streamflow values.

$$\text{PBias}(i) = \frac{(\overline{Q}_{t,mes} - \overline{Q}_{t,com})}{\overline{Q}_{t,com}} \tag{6}$$

i = flow group.

$\overline{Q}_{t,mes}$ = mean observed discharge for flow range i.

$\overline{Q}_{t,com}$ = mean predicted discharge for flow range i.

The three comparison criteria can be used directly to give an idea of how the predicted hydrograph fits the observed hydrograph. The absolute mean was used by Leavsley (1973) to compare forecast results of five fitting criteria. He selected it because it eliminates the various weighting effects of comparison criteria. It does not penalize any particular size of discharges. The root mean square, however, penalizes the largest residuals. PBias is used to determine how well all of the flow ranges are reproduced. Sorooshian, Gupta, and Fulton, (1983) used the root mean square and PBias in their studies.

Description of Model

PRMS is a conceptual deterministic rainfall-runoff model with distributed and time variant parameters. The parameters are distributed by breaking down the watershed into hydrologic response units (HRU´s). The HRU is defined as an area that has homogenous basin characteristics. There is a set of parameter values for each of these areas. These HRU values can be optimized separately to allow the model to be used to simulate the effects of land changes. Time variant parameters are used to distinguish between seasonal changes in precipitation, evapotranspiration, and interception. The user specifies when these seasonal changes will occur.

The PRMS model is designed in modular form to allow the user to choose the degree of model complexity. One of several subroutines can be chosen from the PRMS library to simulate a particular physical process or the user can use one of their own subroutines. These subroutines are linked together by a main program which keeps track of the days, months, and years and also the order in which the subroutines are activated. This main program coordinates the entire runoff event.

The model can also be used to simulate daily flows, storm flows, and sediment transport.

The hydrologic process is represented by four nonlinear reservoirs and two linear reservoirs. The four nonlinear reservoirs are the interception reservoir which represents the precipitation that is intercepted by vegetation, the impervious area reservoir represents the rainfall that falls on the area of the HRU that is impervious, the upper soil zone reservoir is the zone where both evaporation and transpiration occur, the lower soil zone reservoir is described as the zone where only transpiration occurs. These reservoirs are shown in figure 1.

The two linear reservoirs are the subsurface reservoir and ground-water reservoir. The subsurface reservoir is in the unsaturated zone and supplies a rapid movement of water to the stream channel. This reservoir can become nonlinear if desired. The ground-water reservoir supplies base flow. These reservoirs are explained in more detail in appendix I.

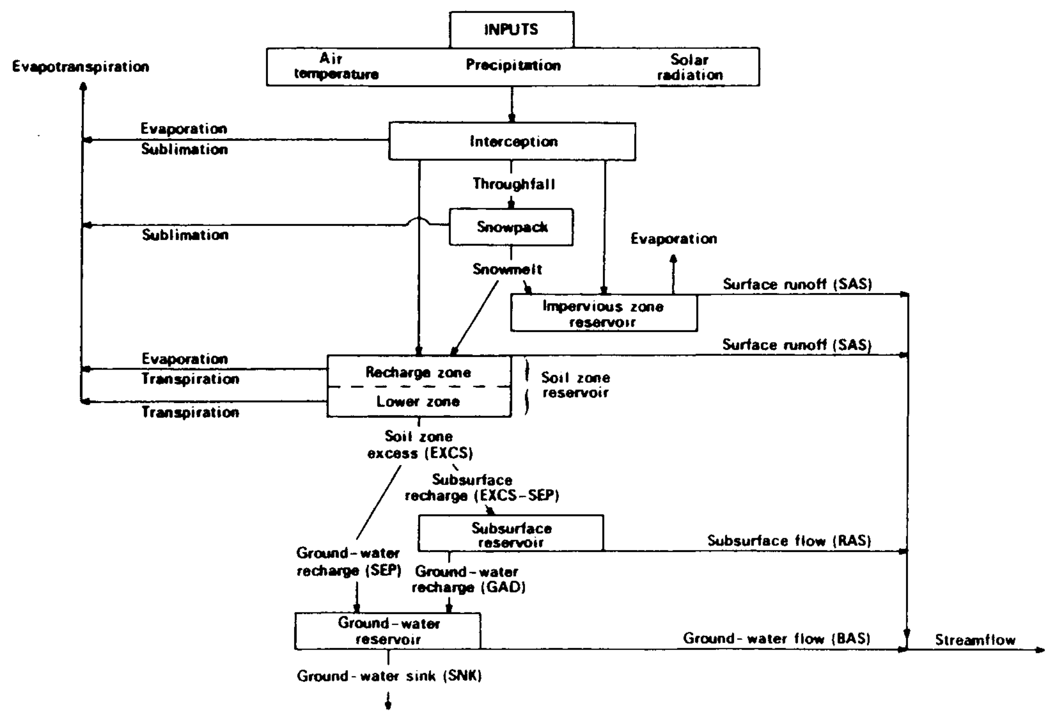


Figure 1. Schematic diagram of the conceptual watershed system and its inputs. (Source: PRMS, Leavesley, et al., 1983).

CHAPTER 3

PROCEDURE FOLLOWED IN RESEARCH

Study Area

The Cane Branch watershed located in southeastern Kentucky, was used for this study. The U.S. Geological Survey has published three professional papers, 427-A, 427-B, and 427-C, that describe the effects of strip mining on the watershed. The study started in 1955 and ended in 1965. The following information describing the climate and other characteristics of the watershed was taken from the Professional Paper 427-A. The area has an annual temperature range of 5 to 100 degrees Fahrenheit. The mean annual precipitation is 46 inches and the annual snowfall is 11 inches. Thunderstorms are common in the spring and summer, while frontal storms are common in the winter.

The drainage area is 0.67 square miles, and the vegetation consists of stands of pines and oaks in the higher elevations and hemlocks and hardwoods in the lower elevations. Also, Cane Branch is a perennial stream.

Figure 2 shows the drainage boundary and the area of strip mining. Figure 3 shows how the watershed was divided into HRUs and

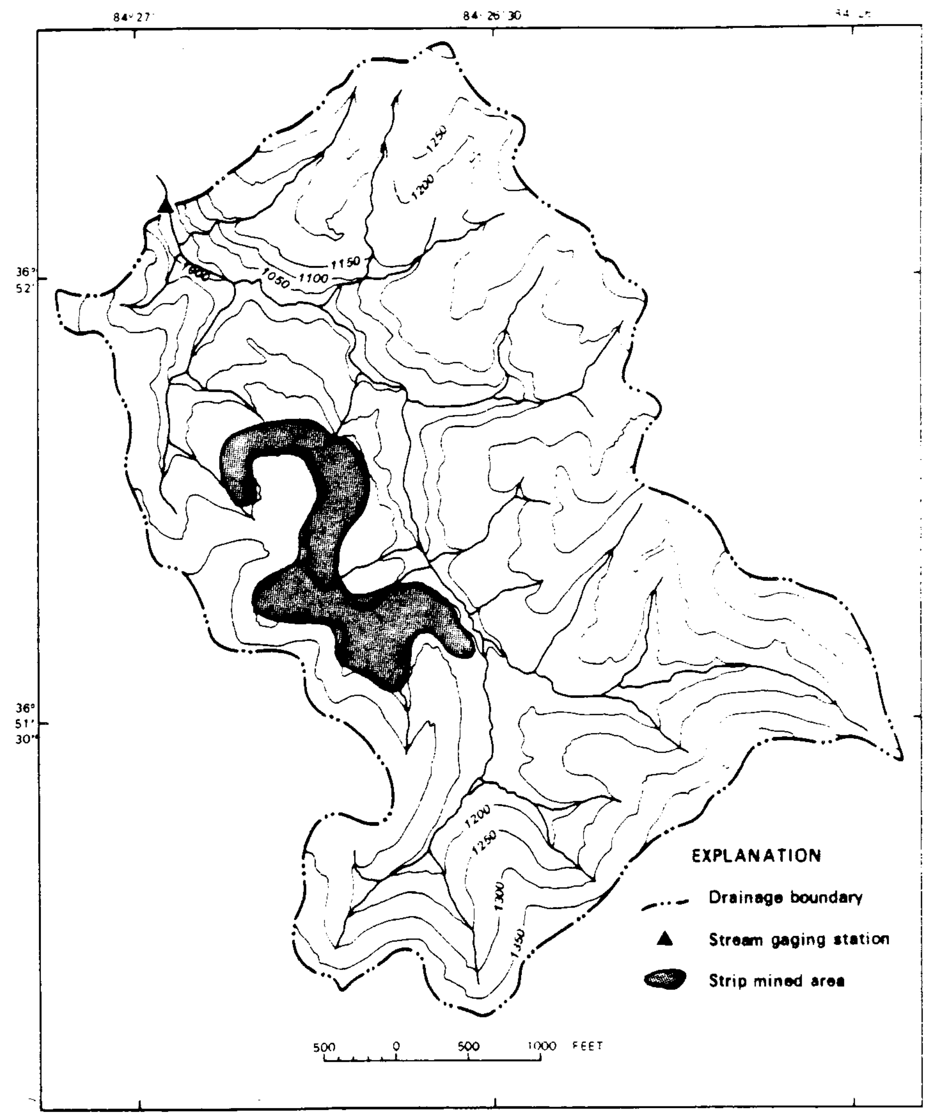


Figure 2. Topography and channel network of Cane Branch watershed. (Source: PRMS, Leavesley, et al., 1983).

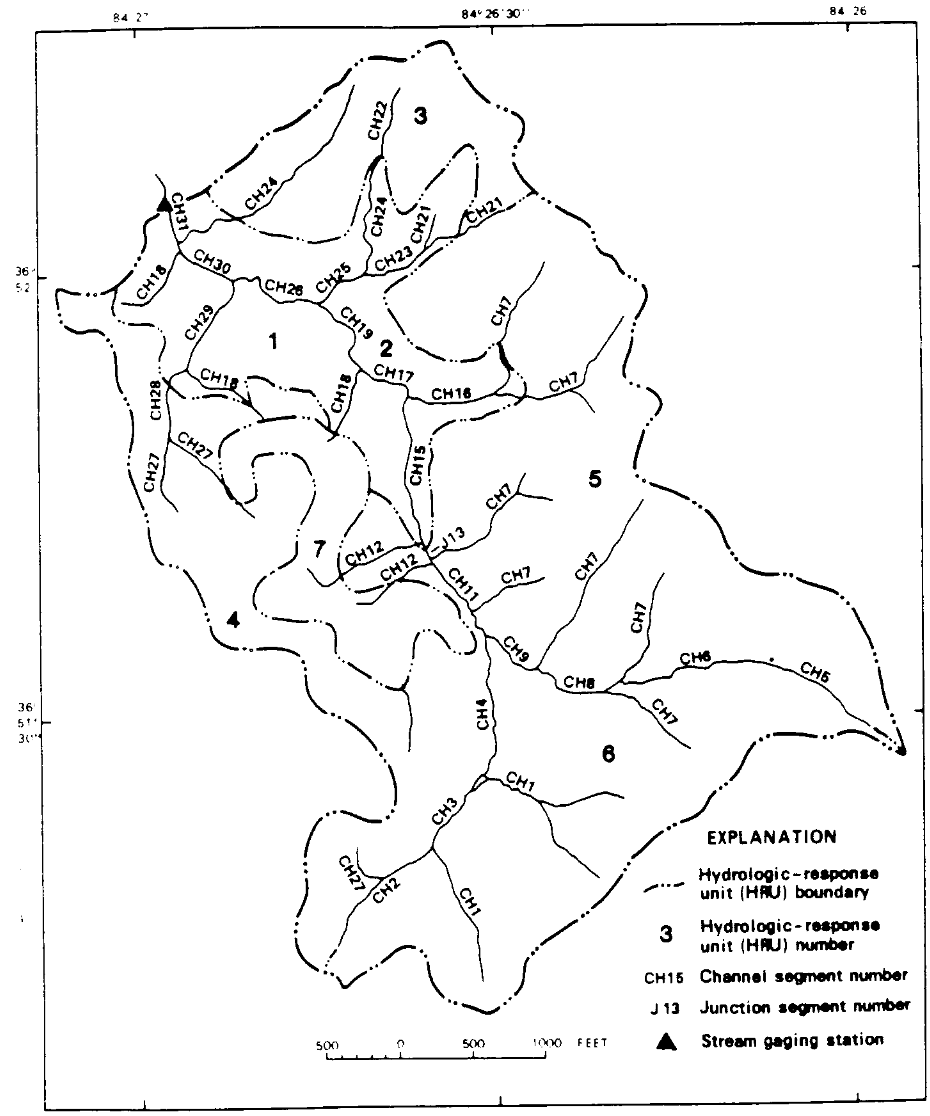


Figure 3. HRU and channel segments delineated for Cane Branch watershed. (Source: PRMS, Leavesley, et al., 1983).

channel segments. Figures 2 and 3 were taken from Precipitation-Runoff Modeling System: User Manual, Leavesly, et al., 1983.

The rainfall and discharge is entered as both daily and unit form. The unit rainfall and discharge are in fifteen minute intervals and represents the storm events.

The storm hydrographs selected for the calibration were those for years 1960 through 1963 and are shown in figures 4-6. The winter storm hydrographs tend to have gently sloping rising and falling limbs. While the summer storms have sharp sloping limbs. Also, the summer storms are smaller than the winter storms, and it can be seen that the two largest storms in the four year period are winter storms. The hydrographs show that there are distinct differences between winter and summer storms.

Modifications to PRMS

Modifications had to be made to the PRMS model so that the comparitive study could be made on the complete storm hydrographs. The first modification to the PRMS model was made to the optimization routine. The optimization of the PRMS model was designed to only allow for the optimization of storm peaks, storm volumes, or storm peaks and volumes together. This had to be adapted to allow more information from the storm hydrographs to be used in optimization.

The hydrograph was divided into 15 minute time intervals, and the observed discharges associated with these intervals were compared to the predicted discharge in the optimization routine. This meant that not

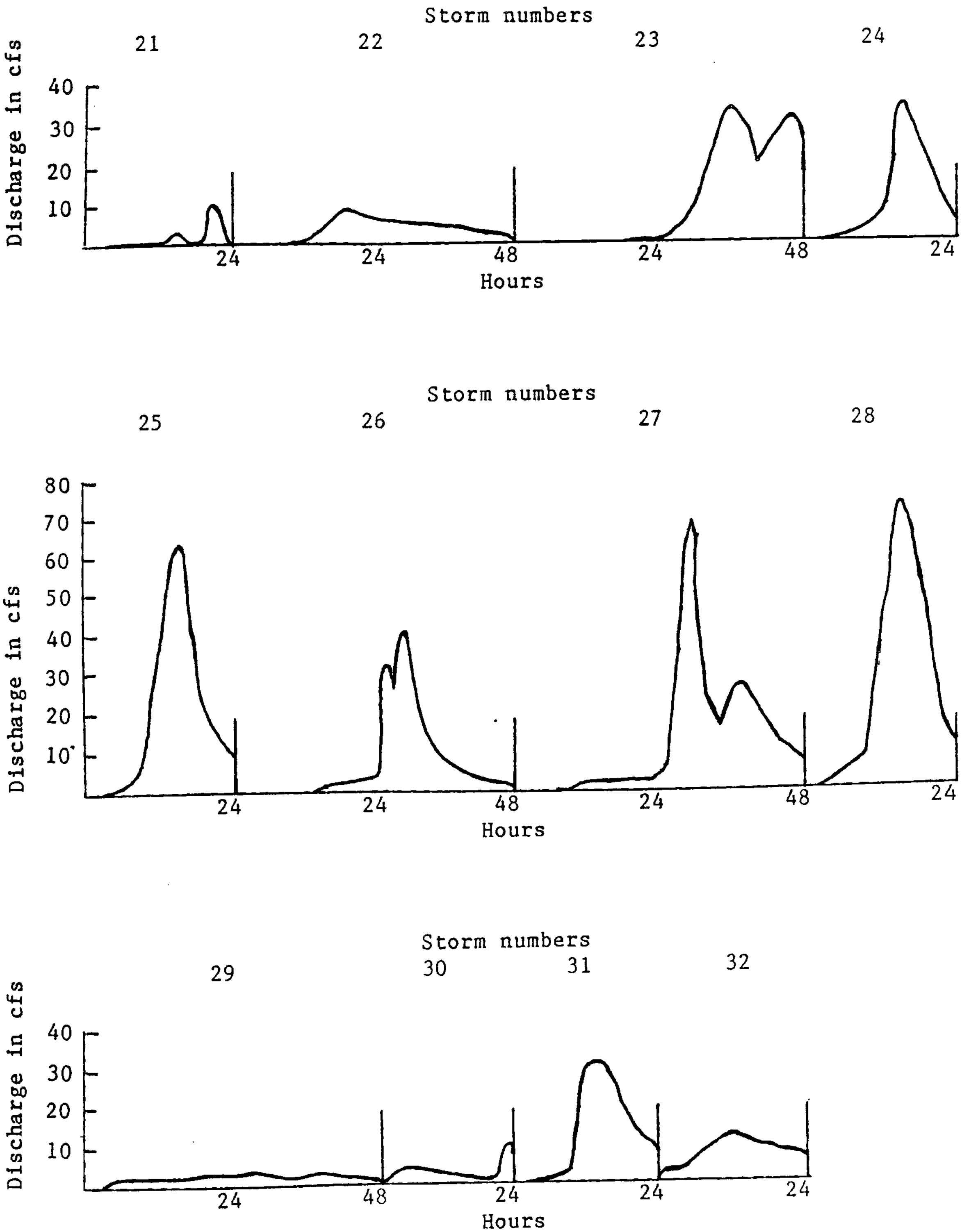


Figure 4. Storm hydrographs 21-32.

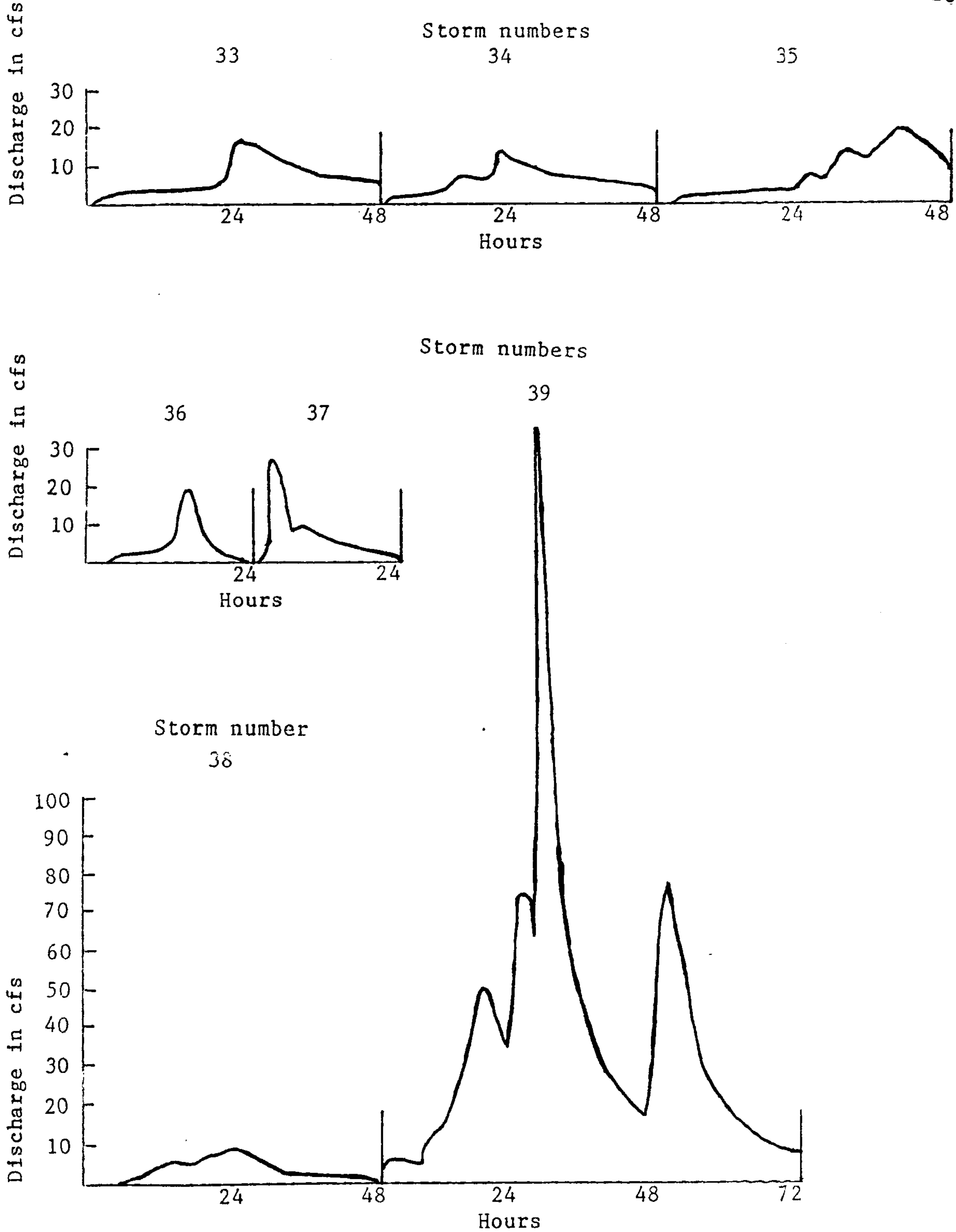
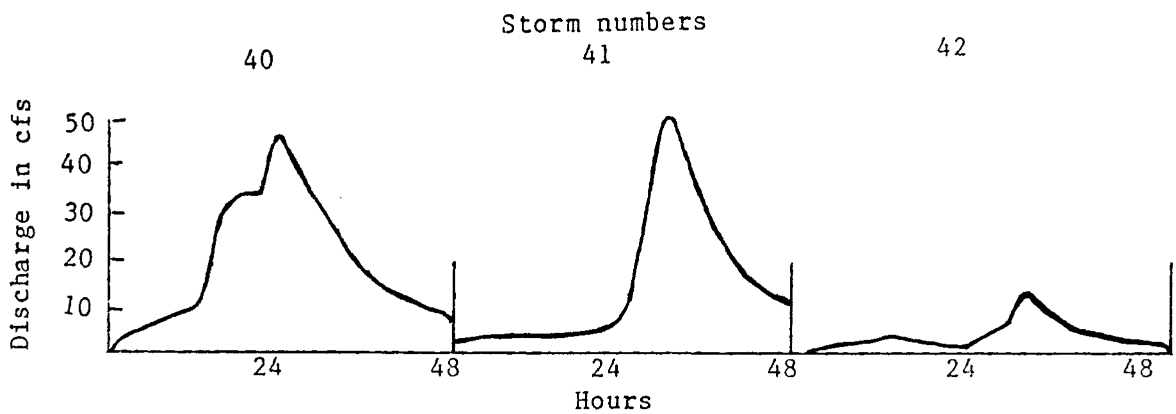


Figure 5. Storm hydrographs 33-39.



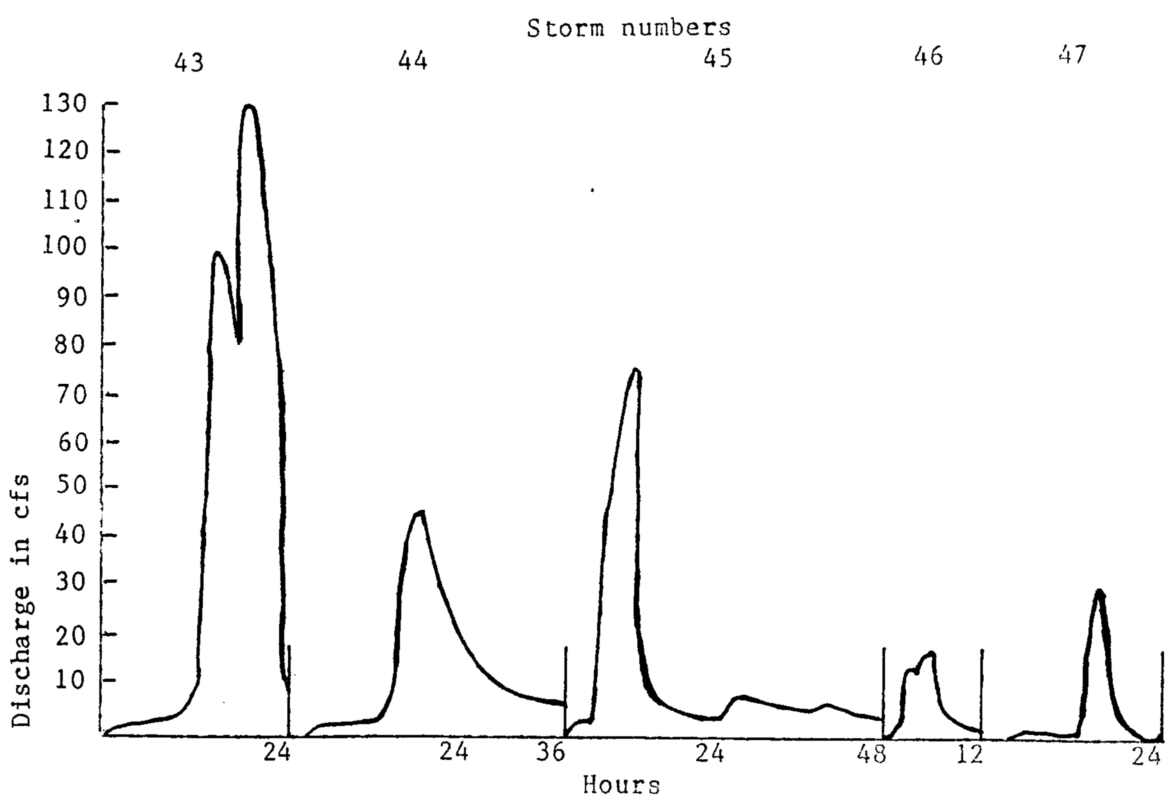


Figure 6. Storm hydrographs 40-47.

only 1 instantaneous peak discharge was used to describe the storm hydrograph, but 96 instantaneous discharges per 24 hours were used.

The second modification was made to the sensitivity routine. It had to be modified to allow for the 15 minute discharge values to be used in the sensitivity analysis which is described later. Two other modifications were made to the optimization routine. First the HMLE fitting criteria was added and then the comparison criteria (described earlier in chapter 1) used to interpret the storm hydrograph had to be entered. All of the modifications were made in the subroutine Hydop or by using the subroutine Hydop.

Synthetic Study

A synthetic study was done to determine whether the optimization routines would work with the new modifications made on the PRMS model. This was done by treating the variables and parameter values supplied by the U.S. Geological Survey as true values and labeling the discharge computed by using these values as the true discharge. The true discharge replaced the observed discharge in the synthetic study. Several parameters were increased by 50% and then the model was run in optimization mode to see if the true parameter set could be reproduced. The OLS and HMLE fitting criteria were used and both fitting criteria were successful at reproducing the true parameter set.

Sensitivity Analysis

A sensitivity analysis was conducted to distinguish between the insensitive and sensitive parameters. An insensitive parameter may have a large range of nearly optimal parameter values but a senstive parameter has a much smaller range of nearly optimal parameters. This was done to limit the number of parameters used in calibration to only a few sensitive parameters so that computer time could be minimized. As it was, an average calibration run took approximately 96 hours of computer time.

Another important consideration is the amount of correlation between parameters. It was decided that only one of the correlated parameters would be used in the optimization. This is because during optimization the two highly correlated parameters would compensate for each other thus slowing down the optimization. It was assumed the correlated parameters not used in optimization were close to their true parameter values thus allowing the true optimal parameter set to be selected.

The PRMS model has a comprehensive sensitivity analysis which was used to determine the level of sensitivity and correlation for each of the parameters. Three phases of the sensitivity analysis used were the information matrix, magnitude of parameter error, and correlation matrix. The information matrix is the transpose of the sensitivity matrix (partial derivative of the flow magnitude and the parameter value) times the sensitivity matrix. The magnitude of parameter error is the extent to which parameter uncertainty is generated to uncertainty in runoff prediction. The correlation matrix shows the correlation between parameters. A more detailed description of these phases can be found in the PRMS manual.

The parameters in table 1, were the only parameters considered for calibration. They were suggested by the developers of the model as being the parameters that would affect the storm hydrograph the most. It was suggested that parameters RM and RMC not be used in the calibration, because the parameter values were well known and fell within the range of 1.5 and 1.66. The remaining 13 parameters were used in two sensitivity runs.

Two different years of data were used for the sensitivity study. The 1962 water year was chosen for the study because it had the largest annual precipitation and runoff for the ten year period. Also, one of the largest storms of the 10 year record occurred in that year. The 1963 water year was used because it had a good balance of summer and winter storms. It is important to have a balance between seasonal storms because some of the parameters are only activated seasonally.

The results from these two runs were different and more weight was given to the results produced by the 1962 run because wetter years may activate all of the parameters while dryer years may not.

The criteria used for picking the parameters for optimization were the following. The parameters were ranked from highest to lowest depending on their value associated with the information matrix. The greatest value was ranked the highest. This was also done for the magnitude of parameter error. Then the correlation matrix was used to determine which parameters were correlated above $\pm$ 0.800. Then the

Table 1.--Definitions of parameters that can be optimized by PRMS in storm mode.

Parameters	Soil Moisture Accounting	Equation
DRN	Drainage factor for redistribution of saturated moisture storage as a fraction of KSAT.	See PRMS manual
KSAT	Hydraulic conductivity of the transmission zone.	(A-I 2.4)
PSP	Value of suction at wetting front for soil moisture at field capacity.	(A-I 2.5)
RGF	Ratio of suction at wetting front for soil moisture at wilting point to that at field capacity.	(A-I 2.5)
REMX	Capacity of recharge zone reservoir.	(A-I 2.5)
SMAX	Maximum available water holding capacity of the two soil zones.	(A-I 2.9)
	Storm Runoff	
ALPHA	Coefficient in kinematic routing equation for pervious area of overland flow plane.	See PRMS manual
RM	Coefficient in kinematic routing equation for pervious area of overland flow plane.	See PRMS manual
ALPHAC	Coefficient in kinematic routing equation for channel flow.	See PRMS manual
RMC	Coefficient in kinematic routing equation for channel flow.	See PRMS manual
	Vegetation	
COVDNS	Summer cover density of major vegetation.	(A-I 1.9)
COVDNW	Winter cover density of major vegetation.	(A-I 1.9)
RNSTS	Interception storage capacity of unit area of vegetation for rain during summer period.	(A-I 1.7)
RNSTW	Interception storage capacity of unit area of vegetation for rain during winter period.	(A-I 1.7)
EVC	The monthly pan-adjustment coefficient for the month.	See PRMS manual

highest ranked parameter was used first to see whether there were any parameters correlated to it. If there were parameters correlated above $\pm$ 0.800 to it they were eliminated. Then the next highest ranked parameter was chosen and the procedure was repeated until all the parameters were evaluated.

The parameters chosen from the 1962 run were RNSTS, RNSTW, KSAT, PSP, ALPHAC, and the parameters chosen from the 1963 run were REMX, TNSTS, RNSTW, KSAT, PSP, ALPHA, and ALPHAC. In the 1962 run, parameters REMX and KSAT were highly correlated and ALPHA and ALPHAC were also highly correlated. More weight was given to the 1962 water year so ALPHA and REMX were dropped from the optimization list. The parameters chosen for optimization were the 1962 parameter set.

Also, a second test was made to see if 5 or 7 parameters were needed for calibration. The 1963 water year was used for two calibration runs and the initial parameter values used were the parameters supplied by the U.S. Geological Survey. The OLS fitting criteria was used in the runs. The optimization runs were allowed to terminate at optimal parameter sets. The run made using the five parameters produced a much smaller OLS function value than the run using the seven parameters. The values for OLS can be compared directly. Thus 5 parameters were chosen.

Calibration Phase

Automatic calibration of a model uses a fitting criteria to compare measured discharge to computed discharge. Three fitting criteria, OLS, LOG, and HMLE, were used, and were described in chapter one. Each of the fitting criteria has its own properties as explained in chapter one. OLS has the property of fitting the large flow values the best. LOG and HMLE fit the small flow values the best. Because of these properties, the optimal parameter sets chosen by these fitting criteria will be different. This produced three different sets of parameters for each calibration period.

The initial parameters supplied by the U.S. Geological Survey were RNSTS = 0.1 inches, RNSTN = 0.05 inches, KSAT = 0.5 inches per hour, for the first six HRU's and 1.0 for the seventh HRU, PSP 0.1 inches and the average value for ALPHAC was 0.33.

The calibration periods range from one year to three years of record. The single years used were 1960, 1961, 1962, and 1963. 1960 was the only year that had intense rainfall even though 1962 was the wettest year of record. The multiple years are 1962-63 and 1961-63. So the total number of periods used for calibration was six. Upper and lower constraints were not planned to be used in this study, but ALPHAC parameter had to have a lower constraint of zero. The reason for the lower constraint on ALPHAC is explained below.

There are 28 stream channels for the Cane Branch watershed. Each of these channels has a value for the parameter ALPHAC. The parameter ALPHAC ranged from 0.03 to 0.69 and the average of these values was used in optimization. During the optimization the value for ALPHAC was being decreased and when the average value for ALPHAC was very small some of the values making up the average parameter became negative. When these values became negative it stopped the program. So the ALPHAC parameter had to be changed by a percentage of the parameter value and this causes a lower constraint of zero to be used for this parameter. Lower constraints were not put on the other four parameters and none of the five parameters had an effective upper constraint put on them.

The optimization continued until the parameters reached an optimal parameter set. Sorooshian, Gupta, and Fulton (1983) pointed out that there is no fair comparison that could be used to compare the values of OLS and HMLE fitting criteria. In their study, a parameter step size convergence criterion was used to end calibration. The precision obtained for each of their parameters was within 0.125% of their nominal value.

For this study the calibration was terminated also for a parameter step size convergence. The termination occurred when 5 cycles of halving step sizes did not improve on the best function value. The precision obtained for each parameter was better than 0.625% of it's nominal value. The optimization also includes a search algorighm. The Rosenbrock Algorithm was used in this study. The Rosenbrock search technique is described by Sorooshian (1981) and is presented in Appendix II.

Forecast

The parameter sets obtained in calibration were used to determine the best fitting criteria by using each of these parameter sets to forecast storms not contained in the calibration period. Parameter sets generated from the single calibration years 1960, 1961, 1962, and 1963 were used to forecast single year periods 1960, 1961, 1962, 1963, 1964, and 1965. So six forecast years were run for each of these 4 single year parameter sets. Then the parameter sets produced by 1962-63 and 1961-63 multi-year calibration runs were used to forecast single years 1960, 1961, 1964, and 1965. Then all the parameter sets were used to forecast a five year period, 1956-60.

CHAPTER 4

RESULTS

Individual storm periods were used to determine the best fitting criteria. This was done by using the three parameter sets generated from the 1961 calibration run to forecast 56 storm events from 1956 to 1965. Then the criteria RMS, ABSM, and PBias were obtained for each of the storms. The most desirable values for the comparison criteria forecasts are: RMS and ABSM are zero or closest to zero, and PBias is close to zero for all flow ranges. The 1961 parameter sets are used in this section to make the discussion of the results easier to follow. The results from using all 18 parameter sets are in Appendix III.

The RMS, ABSM, and PBias were used to compare the forecasted storm with the observed storm. For each parameter set the values of RMS and ABSM were ranked. This ranking was done for each of the 56 storm events. The lowest value was given the ranking of one, and the highest value was given the ranking of three. The parameter set that had the lowest ranking was considered the best for that particular storm. The results of ranking RMS are shown in table 2.

A trend has developed where HMLE outperformed OLS and LOG for the summer storms and OLS outperformed HMLE and LOG for the winter storms.

Table 2. Ranking from 1 to 3 (1 giving the best forecast) of root mean square error.

1961 Calibration Run

Storm No.	OLS	HMLE	LOG	SEASON
1	1	3	2	WINTER
2	1	3	2	WINTER
3	1	3	2	SUMMER
4	2	1	3	SUMMER
5	2	1	3	SUMMER
6	2	1	3	SUMMER
7	2	1	3	SUMMER
8	2	1	3	SUMMER
9	2	1	3	WINTER
10	1	3	2	WINTER
11	1	2	3	WINTER
12	2	3	1	SUMMER
13	1	2	3	WINTER
14	1	3	2	WINTER
15	2	1	3	SUMMER
16	2	1	3	SUMMER
17	2	1	3	SUMMER
18	3	1	2	SUMMER
19	2	1	3	SUMMER
20	3	1	2	SUMMER
21	2	1	3	SUMMER
22	2	3	1	WINTER
23	1	3	2	WINTER
24	2	1	3	WINTER
25	1	3	2	SUMMER
26	2	1	3	SUMMER
27	2	1	3	SUMMER
28	1	2	3	SUMMER
29	2	3	1	SUMMER
30	2	1	3	WINTER
31	2	3	1	WINTER
32	1	3	2	WINTER
33	2	3	1	WINTER
34	2	3	1	SUMMER
35	2	3	1	SUMMER
36	2	1	3	SUMMER
37	1	2	3	SUMMER
38	3	2	1	WINTER
39	1	3	2	WINTER

Table 2.--Continued

Storm No.	OLS	HMLE	LOG	SEASON
40	2	3	1	SUMMER
41	1	3	2	SUMMER
42	3	2	1	WINTER
43	1	3	2	WINTER
44	1	3	2	WINTER
45	2	3	1	SUMMER
46	1	2	3	SUMMER
47	2	1	3	SUMMER
48	1	3	2	WINTER
49	2	1	3	SUMMER
50	2	1	3	SUMMER
51	2	3	1	WINTER
52	1	3	2	WINTER
53	1	2	3	SUMMER
54	2	1	3	SUMMER
55	1	3	2	SUMMER
56	2	1	3	SUMMER

For each parameter set, the value of ABSM was added up for all the winter storms and then for all the summer storms in the forecast period 1956-59, 1960, 1964, and 1965. The results are shown in table 3. For the summer storm, HMLE had the lowest value of ABSM for all the calibration groups except for 1962. A calibration group is made up of the three parameter sets produced from a calibration period. OLS had the lowest value of ABSM for the winter storms.

The percent bias was computed for six flow ranges: 0-3, 3-6, 6-14, 14-45, 45-80, and 80-300 cfs. 28 storms were used; 18 summer and 10 winter to compute the percent bias. These storms occurred between 1956 and 1960. The calibration groups from the 5 calibration periods 1961, 1962, 1963, 1962-63, and 1961-63 were used to forecast the 28 storms. The 1960 calibration group was not used to compute the percent bias, so no calibration periods were contained in the forecast period. The summer and winter storms were used separately to determine whether there was a difference between summer and winter storms. The values of percent bias per flow range were summed up for the 18 storms. This was plotted for each calibration group. Figures 7, 8, 9, 10, and 11 show these plots. Looking first at the summer storms, it can be seen that the LOG and OLS have large values of percent bias for the low and median flow ranges and have a small value of percent bias for the larger flows. HMLE has a nearly constant value of percent bias for all flow ranges. Only for the 1962 parameter set did HMLE not have constant values of percent bias. This was the worst parameter set for HMLE.

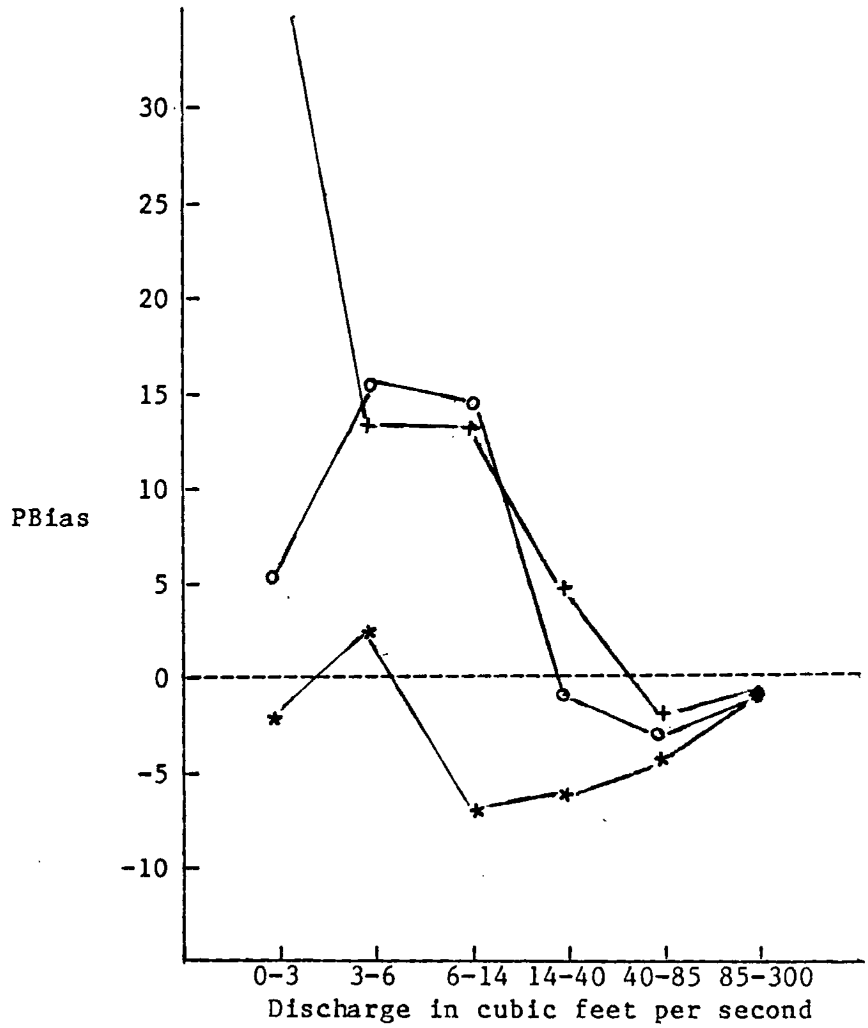
The percent bias for the winter storms was similar for all three fitting criteria. The percent bias was almost constant and was negative

Table 3. Summation of ABSM for summer and winter storms.

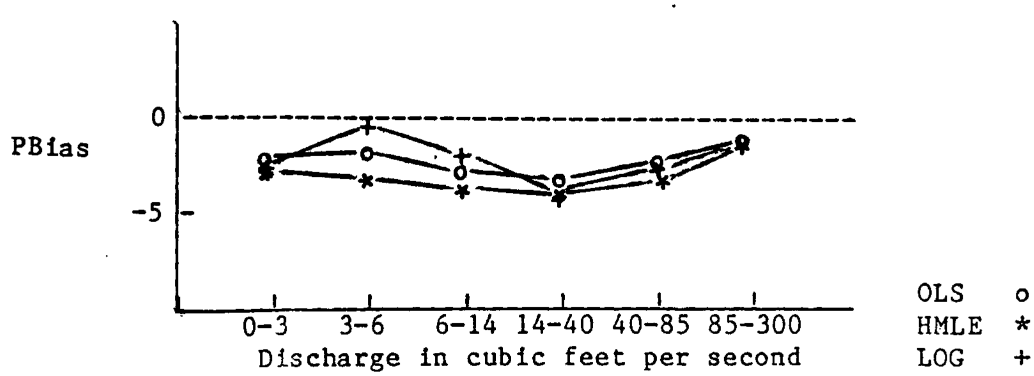
Forecast Periods

Parameter Sets	1956-59 W	1956-59 S	1960 W	1960 S	1964 W	1964 S	1965 W	1965 S	Summation W	Summation S
OLS 1961	70.3	107	14.4	46.3	2.89	9.63	5.37	21.9	92.3	185
HMLE "	81.3	93.3	13.6	47.6	3.71	5.22	6.01	9.82	105	156
LOG "	70.6	149	14.2	58.5	3.07	10.5	4.82	29.0	92.7	247
OLS 1962	74.3	119	115	46.8	2.97	15.7	4.67	10.3	93.4	192
HMLE "	86.2	130	14.2	54.3	3.64	10.6	5.93	26.1	110	221
LOG "	87.9	155	15.5	69.9	4.54	18.5	5.29	40.7	113	284
OLS 1963	72.3	140	14.2	51.4	2.69	2.92	5.32	8.68	94.5	203
HMLE "	91.4	84.4	14.0	49.1	3.63	4.45	5.51	11.4	115	149
LOG "	76.6	106	14.8	49.0	3.16	9.03	4.72	17.4	99.3	181
OLS 1962-63	71.7	94.0	12.9	38.1	3.74	8.20	4.90	20.0	93.2	160
HMLE "	84.8	91.0	14.2	48.1	3.55	3.85	6.27	11.7	109	155
LOG "	81.4	132	13.6	56.0	3.76	13.1	5.28	26.2	104	227
OLS 1961-63	70.2	95.7	12.8	40.4	2.89	6.49	4.71	17.8	90.6	160
HMLE "	81.7	85.7	13.3	50.4	3.35	5.99	4.99	8.06	103	148
LOG "	78.3	130	16.5	54.7	3.16	12.5	4.59	26.1	103	223

W - Winter
S - Summer

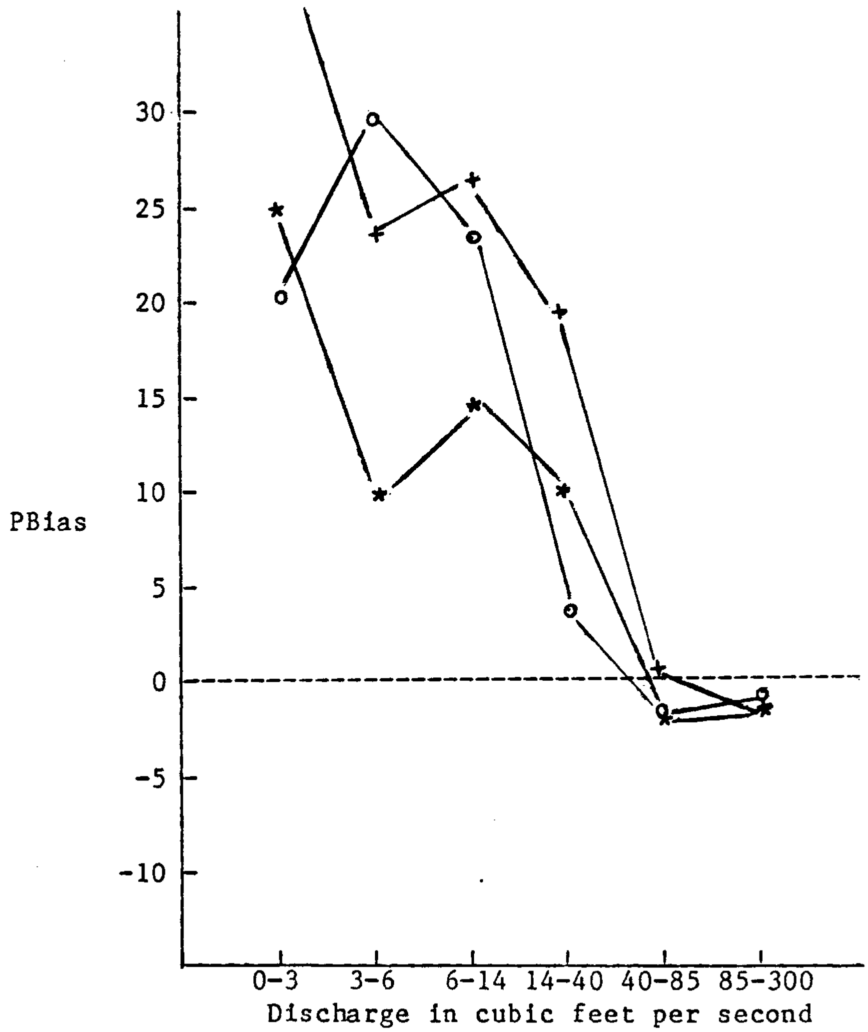


PBias for 1961 parameters forecasting 18 summer storms.

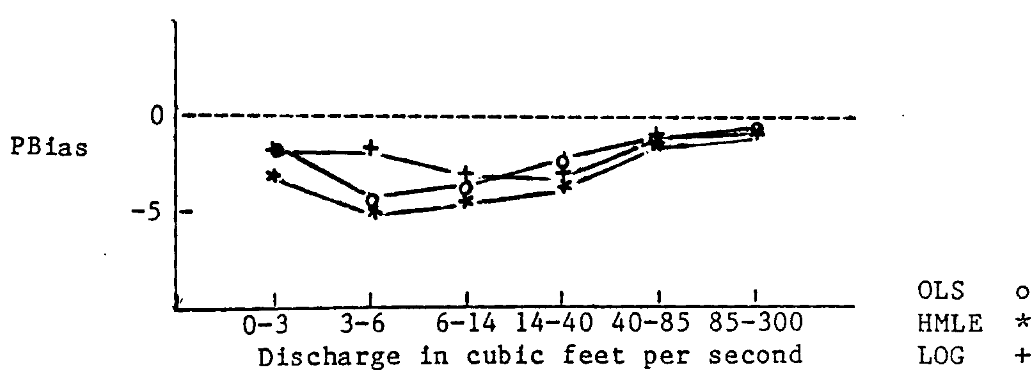


PBias for 1961 parameters forecasting 10 winter storms.

Figure 7. PBias for 1961 parameters.

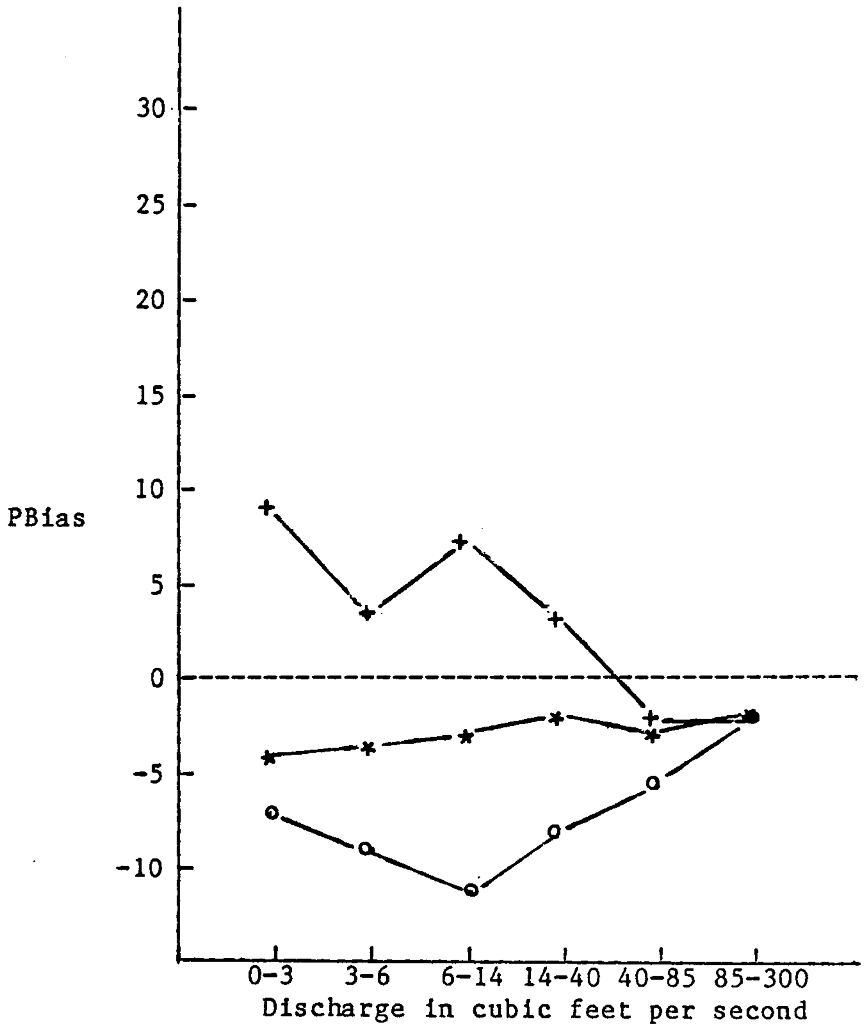


PBias for 1962 parameters forecasting 18 summer storms.

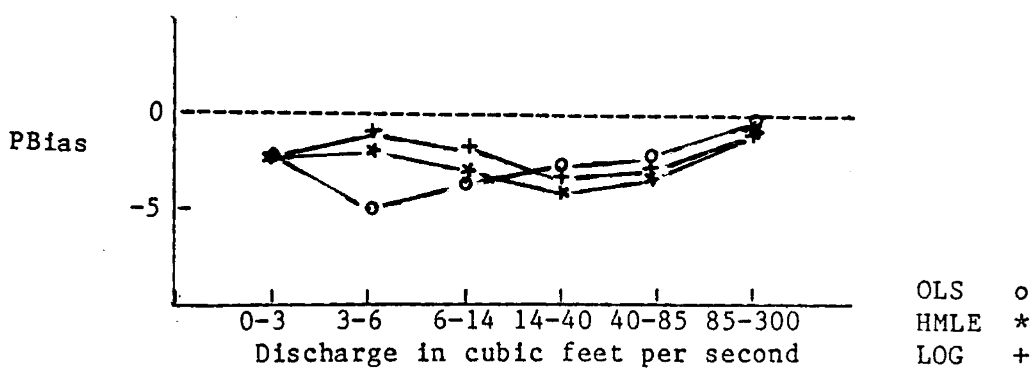


PBias for 1962 parameters forecasting 10 winter storms.

Figure 8. PBias for 1962 parameters.

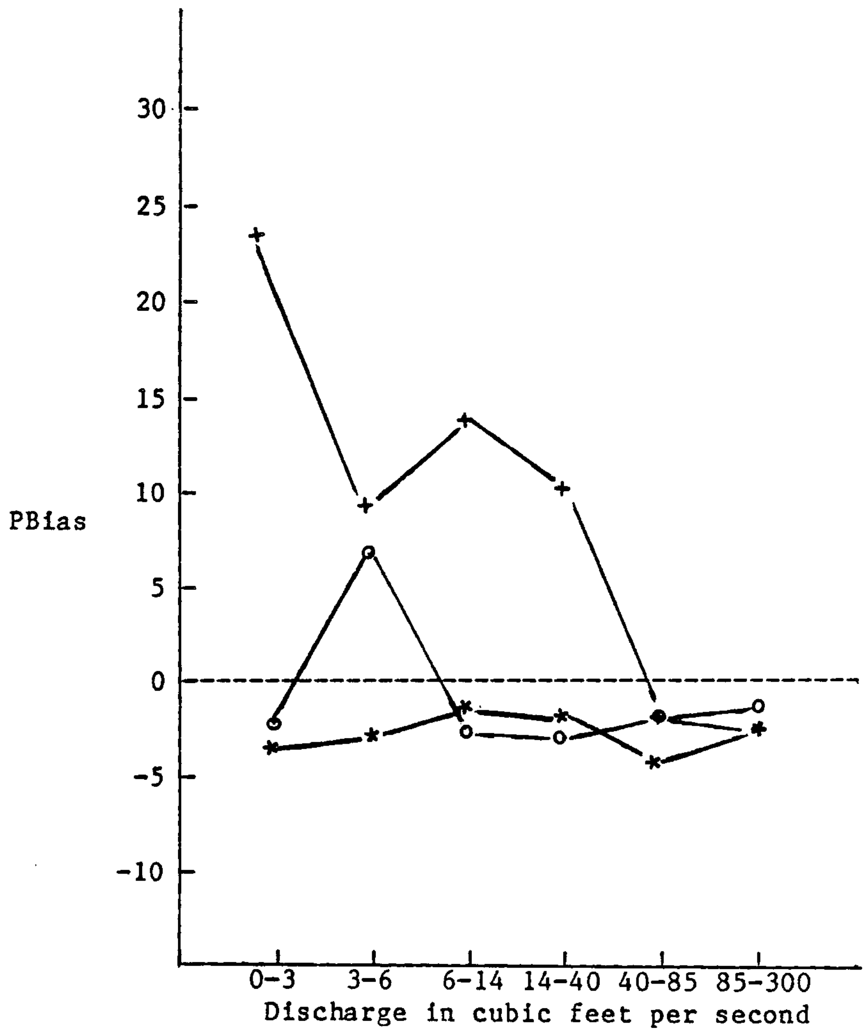


PBias for 1963 parameters forecasting 18 summer storms.

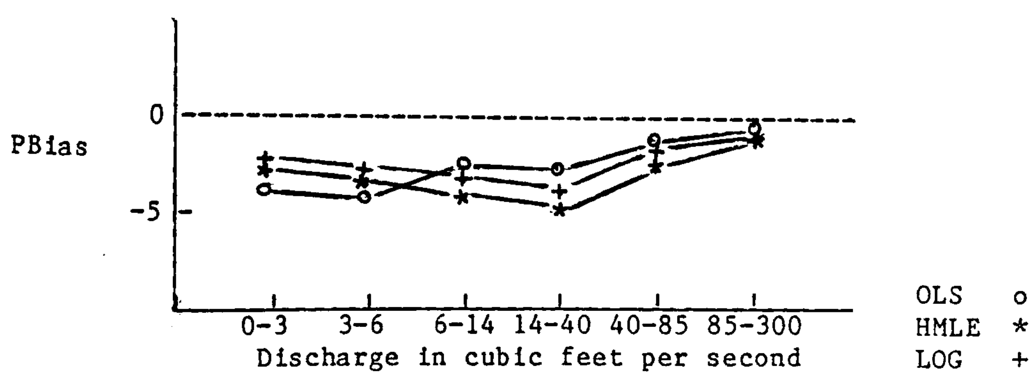


PBias for 1963 parameters forecasting 10 winter storms.

Figure 9. PBias for 1963 parameters.

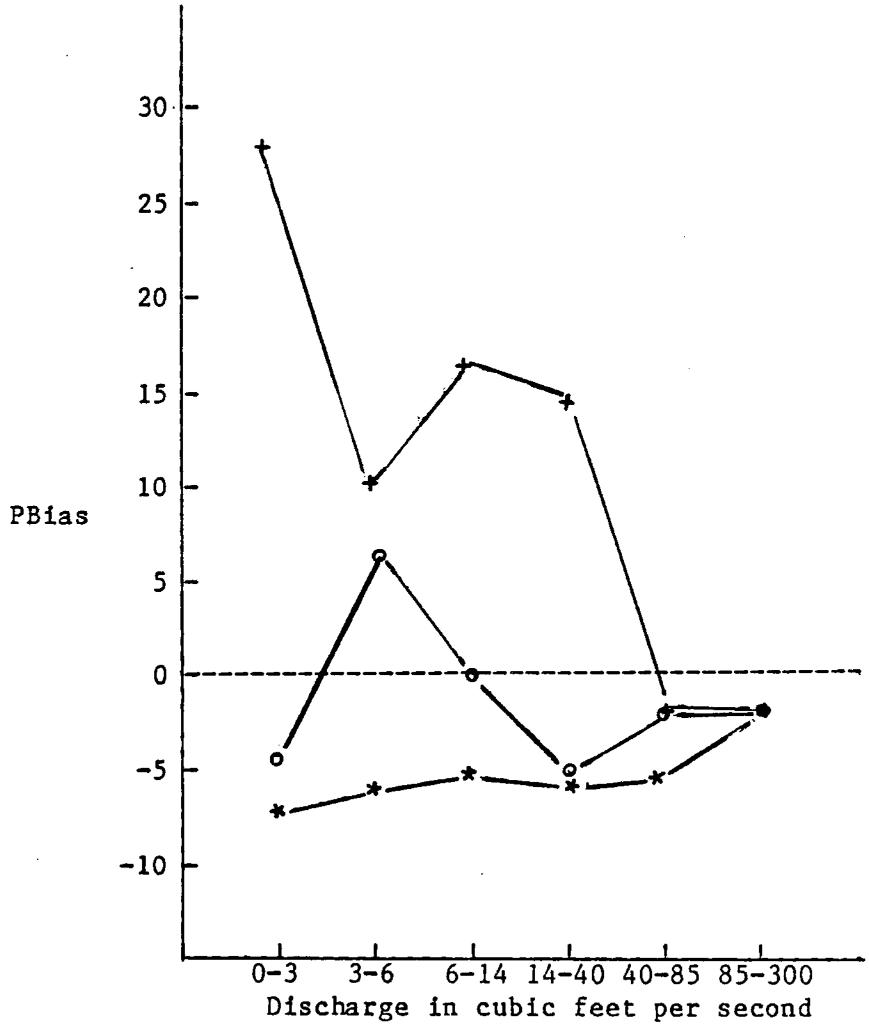


PBias for 1962-63 parameters forecasting 18 summer storms.

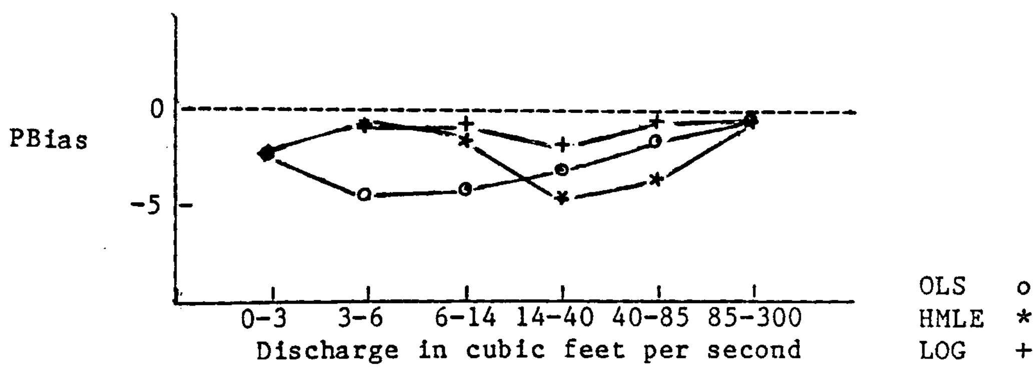


PBias for 1962-63 parameters forecasting 10 winter storms.

Figure 10. PBias for 1962-63 parameters.



PBias for 1961-63 parameters forecasting 18 summer storms.



PBias for 1961-63 parameters forecasting 10 winter storms.

Figure 11. PBias for 1961-63 parameters.

for all flow ranges. This indicates that the winter storms were slightly underestimated for all of the 15 parameter sets. It is important to note that for the 1963, 1962-63, and 1961-63 parameter groups the percent bias for the winter and summer storms was about the same for the HMLE fitting criteria.

The parameter values chosen in calibration were compared to a range of realistic values that the parameters could assume. This is shown in table 4. Very few parameters chosen fell within these parameter ranges. The only parameter that had a majority of realistic values was KSAT. It had 15 out of 18 parameters that could be called realistic. PSP had 7 out of 18 parameters that were realistic and 4 of them were produced by using HMLE. The other three were produced by OLS. Two parameters for RNSTS were in the realistic range and both were chosen by HMLE. No values for RNSTW were considered realistic.

A realistic range of values for the ALPHAC parameter was not used because detailed information on the channel cross section would be needed to compute the range.

Figure 12 shows a graphical comparison of the parameter values chosen by the three fitting criteria. It can be seen that the parameter values take on a large range of values. A few parameters had small ranges. The LOG fitting criteria chose a small range of values for RNSTS and PSP, but neither of these parameters had realistic values. The OLS fitting criteria chose a small range for the ALPHAC parameter.

The ALPHAC value ranged from 0.13 to 5.15 for the HMLE, 0.03 to 2.31 for LOG, and 0.06 to 0.18 for OLS. The difference in the ALPHAC ranges between fitting criteria can be explained by looking at the

Table 4. Parameter Values Produced by Optimization

Parameters

Parameter Sets	RNSTS	RNSTW	KSAT	PSP	ALPHAC	λ
OLS 1960	1.01	1.52	0.39	0.07	0.06	
HMLE "	1.25	21.0	0.41	0.13	0.13	0.24
LOG "	-0.02	0.64	0.21	0.06	0.03	
OLS 1961	0.35	0.42	0.59	0.12	0.18	
HMLE "	0.02	1.01	0.49	0.80	0.14	-0.06
LOG "	-0.12	0.58	1.71	0.004	2.31	
OLS 1962	0.16	2.0	0.12	0.48	0.12	
HMLE "	-0.12	3.16	0.17	0.74	1.36	-0.01
LOG "	-0.02	2.19	0.38	0.08	1.70	
OLS 1963	57.9	2.87	0.02	3.05	0.12	
HMLE "	0.24	2.08	1.53	0.13	5.15	0.06
LOG "	-0.14	0.45	0.57	0.31	1.17	
OLS 1962-63	1.37	2.77	0.11	0.38	0.12	
HMLE "	0.04	3.03	0.18	2.06	3.82	0.11
LOG "	-0.04	2.06	0.36	0.24	1.13	
OLS 1961-63	1.08	2.28	0.13	0.56	0.14	
HMLE "	-0.17	0.85	0.85	0.88	3.0	0.08
LOG "	-0.10	0.62	0.54	0.15	0.88	
Realistic Range	0-0.10	0-0.05	0.05-1.20	0.5-8		

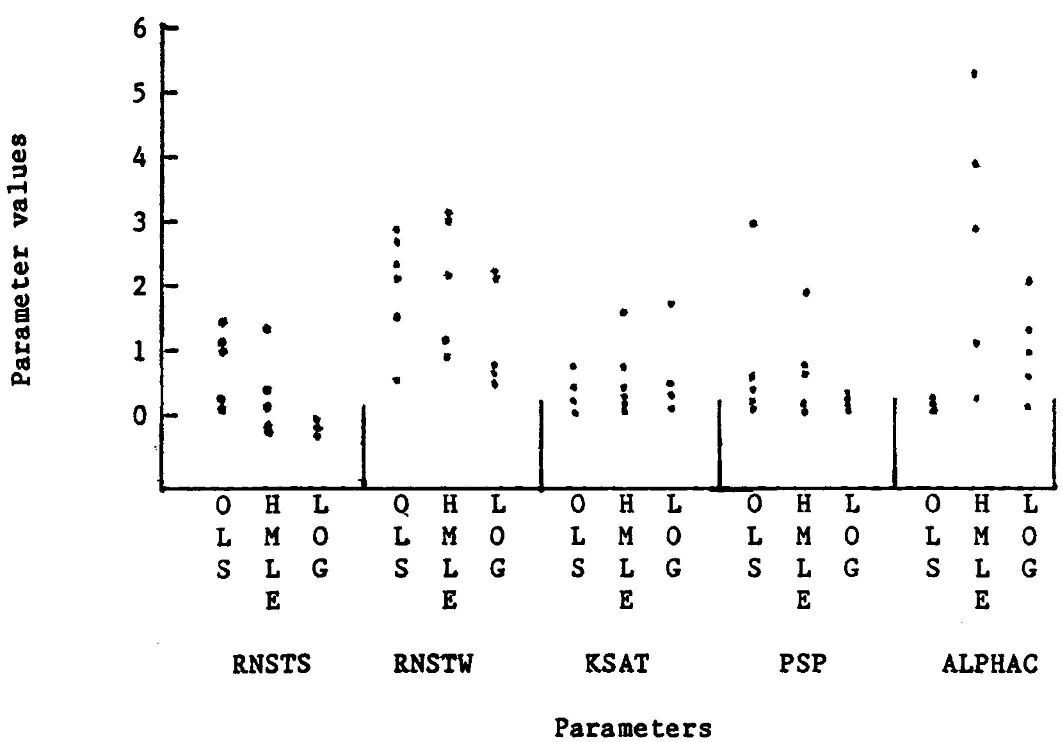


Figure 12. Graphical comparison of 18 parameter values chosen by the three fitting criteria.

storms that had the most emphasis put on them during calibration by the fitting criteria. This can be seen by looking at the 1960 calibration group in table 6, Appendix III. These are the parameter sets with the asterisks next to the ABSM ranking. HMLE placed a lot of emphasis on the summer storms 21, 26, and 27. The storm hydrographs for these three storms are shown in figure 4. These three hydrographs have a sharp rising and receding limb. OLS and LOG both put emphasis on storm 28. Storm 28 is a summer storm with a more gentle rising and receding limb. LOG also relied heavily on summer storm 25. This storm also has a gentle rising and receding limb. HMLE was the only fitting criteria to emphasize the use of winter storm 22. This is a small storm with a very gentle rising and receding limb. LOG and OLS put a lot of emphasis on the winter storm 23. This is the largest winter storm for 1960 and has a multiple peak. All three of the fitting criteria relied heavily on winter storm 24. This storm has a sharper rising limb than 23 and it has a gently sloping receding limb. It has the largest peak for the winter storm of 1960.

The storms that had the most emphasis put on them by the three fitting criteria for the 1961-63 calibration period are shown in table 5. The storm hydrographs for this period are shown in figures 4, 5, and 6. HMLE concentrated on 6 summer storms and 2 winter storms. The five summer storms 36, 37, 45, 46, and 47 have sharp rising and receding limbs. The two winter storms, 30 and 42, have gentle sloping rising and receding limbs. All eight storms are small events.

OLS placed emphasis on four winter storms: 32, 39, 43, and 44. Two of these storms, 39 and 43, were the largest storms for the three

Table 5. Ranking of Root Mean Square Error.

Storm No.	OLS 1961-63	HMLE 1961-63	LOG 1961-63	SEASON 1961-63
30	2	1	3	WINTER
31	2	3	1	WINTER
32	1	3	2	WINTER
33	3	2	1	WINTER
34	2	1	3	SUMMER
35	2	3	1	SUMMER
36	2	1	3	SUMMER
37	2	1	3	SUMMER
38	2	3	1	WINTER
39	1	3	2	WINTER
40	1	3	2	SUMMER
41	1	3	2	SUMMER
42	3	1	2	WINTER
43	1	3	2	WINTER
44	1	3	2	WINTER
45	2	1	3	SUMMER
46	2	1	3	SUMMER
47	2	1	3	SUMMER

year period. The other two winter storms were much smaller. The two summer storms, 40 and 41, were medium flow events. These summer storms have gently sloped rising and receding limbs.

The LOG placed emphasis on three winter storms and one summer storm. The three winter storms are 31, 33, and 38. The summer storm was 35. All of the storms LOG emphasized, were small storm events with gently sloping rising and receding limbs.

Now looking at the ALPHAC parameter in table 4 for 1961-63 parameter group, it can be seen that the value of ALPHAC for HMLE is 3.0. The ALPHAC is large because the storms chosen by HMLE in calibration have sharp rising and receding limbs. The storms were also small storms. The value of ALPHAC for OLS is 0.14. The storms used by OLS in calibration were large and had gently sloping rising and receding limbs. These storms were the largest for the three year period. The value of ALPHAC for LOG was 0.88 and the storms used by LOG were small with gently rising and receding limbs.

Based on the large variations in the ALPHAC parameter values in the HMLE case, it is recommended that the kinematic equation, where ALPHAC is embedded, should be examined. The fact that the ALPHAC value varies widely for different storms suggests that the routing equation may not be the best choice for certain cases.

CHAPTER 5

CONCLUSIONS

The following conclusions were reached for the three fitting criteria--OLS, HMLE, LOG:

OLS.--

1. The winter storms were forecasted the best by OLS.
2. The percent bias for the summer storms was large for the small and medium flow range, but was small for the large flow ranges.
3. The percent bias for winter storms was small and negative for all flow ranges.
4. The summer and winter storms that had the most influence placed on them in calibration by OLS, were large and had gently rising and receding hydrograph limbs.
5. OLS produced a constantly small value for ALPHAC.

HMLE.--

1. The summer storms were forecasted the best by HMLE.
2. The percent bias for summer storms was nearly constant for all flow ranges.
3. The percent bias for the winter storms was small and negative for all flow ranges.

4. HMLE for parameter sets 1963, 1962-63, and 1961-63 had nearly the same value of percent bias for both winter and summer storms. The value of percent bias was small and negative indicating that both summer and winter storms were slightly underestimated.
5. The storms that had the greatest influence placed on them in calibration by HMLE were small summer storms with sharp rising and receding hydrograph limbs and small winter storms with gently sloping rising and receding hydrograph limbs.
6. HMLE produced the largest value of ALPHAC.

LOG.--

1. The percent bias for the summer storms was large for the small and medium flow ranges, but was small for the large flow ranges.
2. The percent bias for the winter storms was small and negative for all the flow ranges.
3. The storms that had the greatest influence placed on them in calibration by LOG were small storms with gently rising and receding limbs.
4. LOG produced larger values of ALPHAC than OLS.

When a full year of storm data is to be used in calibration and there is a greater interest to reproduce the summer storms than the winter storms, HMLE would be the best fitting criteria to use. If more interest is in the winter storms, for the same case, then OLS fitting criteria should be used. Last, if the full year is to be reproduced, then HMLE should be used because it has a nearly constant percent bias for each flow range and for the 1963, 1962-63, and 1961-63 parameter sets had nearly the same small negative value of percent bias for both winter and summer storms. This would indicate that HMLE produces parameter sets that are good for predicting both summer and winter storms.

The HMLE fitting criteria is recommended for use in the PRMS model. The reason for this is that the HMLE produced parameter sets that had a small negative value of percent bias for all flow ranges. This indicates a constant variance for all flow ranges and shows that HMLE reduced the amount of heteroscedastic error associated with stream flow data.

The LOG fitting criteria did not perform as well as OLS or HMLE. The parameter sets that had a large value of ALPHAC reproduced a sharp rising and falling hydrograph limb, but overestimated the flow. For this data set, LOG would not be chosen for calibration.

APPENDIX I

DESCRIPTION OF FORMULAS USED IN DESCRIBING THE RAINFALL-RUNOFF PROCESS IN PRMS

All variable and parameter definitions are referenced directly from the PRMS manual. A brief description of the formulas used in PRMS are described in this section. These are the formulas that were used in this study, and are not the only formulas that could have been used. More detailed descriptions of the formulas can be found in the PRMS manual (ref: Leavesley, et al., 1983).

Temperature

The daily maximum (TMX) and minimum (TMN) air temperatures are computed for each HRU. But first a correction factor (TCRX) is computed for each HRU:

$$TCRX(MO) = [TLX(MO) * ELCR] - TXAJ \qquad (1.0)$$

TLX is the maximum temperature lapse rate, in degrees per 1,000 feet change in elevation for a particular month (MO). ELCR is the difference between the elevation of the climate station and the mean elevation of the HRU in thousands of feet. TXAJ is the average difference in maximum air temperature between a horizontal surface and the slope-aspect of an HRU. This correction factor is computed monthly and then used in the following equation to compute the daily maximum and minimum air temperatures for each HRU:

$$TM = TMX - TCRX(MO) \qquad (1.1)$$

This gives the adjusted daily maximum air temperature. When TMN and TCRN(MO) are substituted for TMX and TCRN(MO) in the above formula, the adjusted minimum daily air temperature is produced.

Solar Radiation

Observed daily shortwave radiation (ORAD), expressed in langleys per day, is used to compute snowmelt. ORAD is measured on a horizontal surface and has to be adjusted so that the daily shortwave radiation received on a slope-aspect (SWRD) is computed:

$$SWRD = ORAD * (DRAD/HORAD) \qquad (1.2)$$

DRAD = Daily potential solar radiation for the slope and aspect of HRU (ly).

HORAD = Daily potential solar radiation for horizontal surface (ly).

For missing days, ORAD is computed using a relationship between solar radiation and sky cover and a relationship between sky cover and a daily range in air temperature:

$$SKY = [RDM(MO) * (TMX-TMN)] + RDC(MO) \tag{1.3}$$

SKY = Daily sky cover.

TMX = Observed maximum air temperature.

TMN = Observed minimum air temperature.

RDC = Intercept of the sky-cover daily air-temperature range relationship month (MO).

Then SKY is used to compute RAJ:

$$RAJ = RDB + (1.-RDB) * [(1.-SKY)**RDP] \tag{1.4}$$

RAJ = Ration of actual to potential solar radiation for a horizontal surface.

RDB = B value obtained from figure 1 of PRMS manual.

RDP = Parameter suggested to be 0.61.

Then ORAD can be computed:

$$ORAD = RAJ * HORAD \tag{1.5}$$

Solar radiation is computed in subroutine SOLRAD and SOLTAB.

Precipitation

Precipitation form for daily mode can be rain or snow, but can only be rainfall when program is in storm mode. The amount of precipitation received by an HRU is determined by the following equation:

$$PPT = PDV * PCOR \qquad \begin{matrix} PCOR = DRCOR \text{ daily mode} \\ \\ PCOR = UPCOR \text{ storm mode} \end{matrix} \tag{1.6}$$

Where PDV is the depth of rainfall collected in a rain gage for a particular time interval in inches and PCOR is a correction factor which corrects for elevation spatial differences, topography, and gage-catch efficiency.

The model can represent rainfall in either a lumped form or can be represented by a distributed form. The distributed representation can use a maximum of 5 rain gages to define the variability of rainfall on the watershed. Each HRU is associated with a rain gage by index KDS.

Subroutine PRECIP is used to compute the measured rainfall (PPT). Input to subroutine is the data from the rain gages (PDV) and location of HRU's with respect to the rain gages. Output is measured rainfall (PPT).

Impervious Reservoir

Impervious area reservoir represents the area of the watershed which has a zero infiltration rate and loses no measured precipitation to interception. The variables that are used to describe the reservoir are (RSTOR) which is a measure of the present depth of water in the reservoir in inches and the reservoir capacity (RETIP) in inches. Input to the reservoir is measured precipitation (PPT) and output is rainfall excess (QR) in cubic feet per second per foot. A second output is potential evapotranspiration (PET) in inches per day which occurs at a rate equal to pan-evaporation rate for that day. Subroutines used in computing the results of the impervious area are SMBAL for daily mode and UNITD for storm mode.

Interception Reservoir

Interception reservoir represents the amount of rainfall intercepted by vegetation. The state or depth (XIN) in inches of the reservoir is updated after each time interval. The variable (STOR) in inches is the maximum depth of the reservoir. The water that overflows the reservoir and reaches the ground (PTF) in inches is calculated by the following equations:

$$PTF = PPT - (STOR - XIN) \qquad PPT \geq (STOR - XIN) \qquad (1.7)$$

$$PFT = 0 \qquad PPT < (STOR - XIN) \qquad (1.8)$$

STOR is equal to RNSTS for summer and RNSTW for winter.

Input to the reservoir is PPT and output is PFT. Evaporation occurs when rainfall is zero and is assumed to occur at a rate equal to pan-evaporation.

Subroutines used to make the calculations are PRECIP when in daily mode, UNITD for storm mode.

Net Precipitation (PTN)

Net precipitation (PTN) in inches is the amount of measured precipitation (PPT) that reaches the pervious area of a hydrologic response unit (HRU). The equation used in the model is:

$$PTN = PPT\ (1 - COVDN) + PTF\ (COVDN) \qquad (1.9)$$

COVDN is the cover density of the major vegetation and PTF is the amount of precipitation that reaches the pervious area after it has been intercepted. The subroutines used to compute PTN are UNITD for storm mode and PRECIP for daily mode.

Soil Moisture Accounting

The soil profile is separated into two zones, the upper zone and the lower zone. The upper zone is called the recharge zone and is defined as the zone which evapotranspiration occurs. The lower zone extends to the maximum root depth of the predominant vegetation and in this zone only transpiration occurs.

The accounting of input, output, and present states of these two soil zones is termed soil moisture accounting. The input to the profile is net infiltration. Outputs from the profile are actual evapotranspiration (AET) in inches per day and water lost to subsurface and ground water reservoirs. The variables for the reservoir capacity are REMX for upper zone and LZMX for lower zone. These two variables when added up equal SMAX. The state variables of the two zones are RECHR in inches for the upper and LZAV in inches for the lower. They represent the amount of water that is presently in the soil zone and before water is lost to the subsurface the sum of the two state variables has to be greater than SMAX in inches. The two subroutines that used to do the accounting are SMBAL for the daily mode and UNITD is for storm mode.

Evapotranspiration

Potential evapotranspiration per day (PET) in inches per day is computed as a function of daily mean air temperature and possible hours of sunshine.

$$PET = CTS(MO) * DYL^2 * VDSAT \tag{2.0}$$

CTS = Coefficient for month (MO).

DYL = Possible hours of sunshine, in units of 12 hours.

VDSAT = Saturated water-vapor density at daily mean air temperature in grams per cubic meter.

VDSAT and VPSAT are computed by:

$$VDSAT = 216.7 * [VPSAT/(TAVC + 237.3)] \tag{2.1}$$

$$VPSAT = 6.108 * EXP\ [17.26936 * TAVC/(TAVC + 237.3)] \tag{2.2}$$

VPSAT = Saturated vapor pressure in millibars (mb) at TAVC.

TAVC = Daily mean air temperature in degrees Celsius.

PET is computed in subroutine PETS. PET is not always met by the available supply of water, so that actual evapotranspiration AET is computed. PET first draws water from the interception reservoir, retention reservoir of impervious area, and snow surface. Next, PET is applied to the upper soil zone, and if not satisfied. Then water is removed from the lower zone. Transpiration is not computed for the winter months, and the period of non-transpiration is set by the user.

Infiltration

Net infiltrátion (FIN) for daily mode is computed as the difference between net rainfall (PTN) and surface runoff (SAS):

$$FIN = PTN - SAS \qquad (2.3)$$

The procedure for computing infiltration rate for storm mode uses a variation of the Green-Ampt equation. first, the point infiltration (FR) inches per 15 minutes, capacity is computed by the following equation:

$$FR = KSAT * (1.0 + PS/SMS) \qquad (2.4)$$

KSAT = Hydraulic conductivity of the transmission zone in inches per hour.

PS = The effective value of the product of capillary drive and moisture deficit in inches.

SMS = Current value of accumulated infiltration in inches.

Then PS is computed by using the following equation:

$$PS = PSP * [RGF - (RGF - 1) * (RECHR/REMX)] \qquad (2.5)$$

Where PSP is the value of PS at field capacity and RGF is the ratio of PS at wilting point devided by PS at field capacity. Then net infiltration (FIN) inches per 15 minutes, is computed as:

$$FIN = PTN - 0.5PTN^2/2FR \qquad PTN < FR \qquad (2.6)$$

$$FIN = 0.5FR \qquad \text{otherwise} \qquad (2.7)$$

Then rainfall excess (QR) is computed:

$$QR = PTN - FIN \qquad (2.8)$$

QR is stored in array UPE (1440). The subroutines used in computing net infiltration (FIN) are PRECIP and SRFRO for daily mode and UNITD for storm mode. Input into subroutine UNITD is net precipitation and the initial value of RECHR. Output form UNITD is net infiltration (FIN and rainfall excess (QR)́. Input to compute daily net infiltration is PTN and SAS.

Subsurface Reservoir

Subsurface flow is represented by a linear reservoir with input from the soil zone being:

$$\text{Input} = [(\text{FIN} - \text{SMAX}) - \text{SEP}] \tag{2.9}$$

SMAX = Maximum holding capacity of soil zone in inches.

SEP = Recharge rate to ground water reservoir in inches/day.

There are two outputs from the reservoirs. One is flow to the stream channel which is represented by:

$$\text{RAS} = \text{RCF} * \text{RES} + \text{RCP} * \text{RES}^2 \tag{3.0}$$

RAS = Amount of water discharged into the channel, per time interval.

RES = Depth of the water in the reservoir, in inches.

RCF = Routing coefficient.

RCP = Routing coefficient.

The second is recharge to ground water which is represented by:

$$\text{GAD} = \text{RSEP}(\text{RES}/\text{RESMX})\text{REXP} \tag{3.1}$$

GAD = Rate of recharge to ground water, in inches per day.

RSEP = Daily recharge coefficient.

RESMX = Coefficient.

REXP = Coefficient.

RES = Current storage in subsurface in inches.

GAD and RAS are computed in subroutine baseflow for daily mode in UNSM for storm mode.

Ground Water Reservoir

Ground water is represented by a linear reservoir which has two inputs: SEP and GAD. Outputs from the reservoir are base flow to the stream channel:

$$BAS = RCB * GW \tag{3.2}$$

BAS = Discharge to stream channel, in acre-inches.

RCB = Reservoir routing coefficient.

GW = Depth of the reservoir in acre-inches.

The second output is to ground water sinks:

$$SNK = GSNK * GW \tag{3.3}$$

SNK = Rate of flow to ground water sink in acre-inches

GSNK = Seepage constant.

In daily mode, BAS is computed in BASFLW and in storm mode it is computed in UNSM.

Overland Flow and Channel Flow for Storm Mode

Overland flow and channel flow are computed using the kinematic wave approximation. This method computes flow by using the explicite finite-difference method. Overland flow is viewed as shallow flow in a very wide channel. There are four equations used to compute flow. Two are for flow in a channel and the other two are for overland flow. All four equations are based on the Manning's equation. Three subroutines are used in storm mode to compute flow: UNITD computes overland flow, AM computes routing parameters, and ROUTE computes channel routine. Input to UNITD is rainfall excess stored in UPE and output is lateral inflow to the channel. Input to AM is basin characteristics and output is the value of the routing parameters. Input to ROUTE is lateral inflow and output is discharge at gage.

The preceding represents the formulas used to generate the storm flows. These flows are of short duration, usually less than one day in length. These short duration storms were used to calibrate the model by using the PRMS's optimization procedure which is described below.

Optimization Procedure

The optimization procedure used for storm mode allows for the optimization of storm peaks, storm volumes, or storm peaks and volumes simultaneously. A parameter is selected to be optimized by choosing the number associated with that parameter. Parameters and their numbers are given in the PRMS manual. With these numbers an array of parameters are created. This array can have a maximum number of 20 parameters, but is is not recommended to use this many parameters in optimization.

There are five fitting criteria that may be used in PRMS. The first two are the sum of the absolute values and OLS. the next two are formed by taking the natural logrithm of the runoff values and using these values in the first two fitting criteria. The last is a form of the maximum likelihood and it is used to fit the storm peaks and storm volumes.

There are two search algorithms, the Rosenbrock and Gauss-Newton, that are available for use in the model. The algorithm searches the response surface created by the values of fitting criteria and parameter values to find the optimal parameter set.

Optimization for a distributed parameter can be done for all of the values together or for any subset of values. These values can be adjusted by the same magnitude or by the same percentage. Upper and lower constraints can be placed on these values.

APPENDIX II

ROSENBROCK'S PROCEDURE (1960)

Rosenbrock's procedure, as described by Sorooshian (1981), is such that successive steps are taken along successive parameter directions. Before a second step can be taken along the first search direction one step along each of the other directions is taken. Therefore, Rosenbrock's procedure takes a series of parallel steps in each direction rather than colinear steps.

Consider a two parameter example with function $f(\theta_1,\theta_2)$ to be minimized (see figure 13). Starting from an initial point, say $(\theta_1^0 , \theta_2^0)$ toward the minimum, the iteration begins exploring along the θ_1 direction by taking a step d_1 to the point $(\theta_1^0 + d_1 , \theta_2^0)$. If the step along the θ_1 direction is a success (i.e., there is no increase in the 60 function value) the step is accepted and the next step size is αd, (where $\alpha > 1$) along the original direction or a direction parallel to it. If the trail is a failure, the point $(\theta_1^{\bullet} + d_1 , \theta_2^{\bullet})$ is rejected and the next step is taken in the opposite direction parallel to θ_1 axis and of length βd_1 where $(-1 < \beta < 0)$.
The search then considers the θ_2 in the same way and determines the success or failure of the step and then reverts to the next parameter direction, θ_1. The process cycles around the parameter direction until

a success followed by a failure has been realized, for both directions. Next, the method concentrates on the establishment of a new search direction for the next stage of the iteration process. When a success, followed by a failure, has been recorded in each direction and a new point (θ_1^1, θ_2^1) has been determined, the line joining the points (θ_1^0, θ_2^0) and (θ_1^1, θ_2^1) is taken as a new axis. This axis then lies in the direction of total progress realized to this point. Furthermore, the second axis is determined at a right angle to the new axis in the (θ_1, θ_2) plane. With specification of the new axes, the second stage will start. The entire process terminates when one of the specified stopping criteria is satisfied (they are discussed in the next section). In the paper by Rosenbrock (1960 the values of $\alpha = 3.0$ and $\beta = -1/2$ was suggested. However, Ibbitt (1970) determined that the algorithm was insensitive to values of α and β.

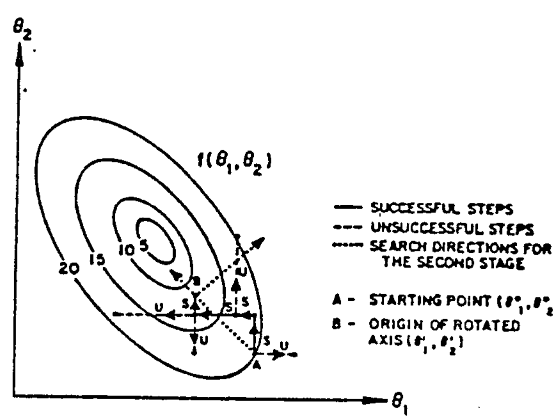


Figure 13. Example of Rosenbrock's search algorithm. (Source: Sorooshian, 1981).

APPENDIX III

RESULTS OF THE 18 PARAMETER SETS

Individual storm periods were used to determine the best fitting criteria. This was done by forming six calibration groups of three parameter sets. The three parameter sets chosen in a specific calibration period are defined as a calibration group.

There are six calibration periods thus six calibration groups of three parameter sets. Each of the calibration periods had to be used separately to compare fitting criteria. This is because each calibration period has a different number of storms and different storm sizes, thus different parameter sets will be chosen. So to determine the best fitting criteria it would not be right to compare a parameter set produced by the 1960 calibration period and chosen by OLS to be compared with a parameter set produced by 1961 calibration year and chosen by HMLE. The comparison has to be made between fitting criteria for the same calibration period. Next, the parameter sets were used to forecast all the storm events from 1956 to 1965. The parameter sets for OLS and LOG produced by the 1960 calibration period could not reproduce the storms in 1958 water year, so the 1960 calibration group was not used to forecast the years 1956-60.

The RMS, ABSM, and PBias were used to compare the forecasted storm with the observed storm. For each parameter set the values of RMS and ABSM were ranked. This ranking was done for each storm event. The lowest value was given the ranking of one and the highest value was given the ranking of the number of parameter sets used in forecasting.

The six calibration groups were used separately to determine the fitting criteria with the lowest ranking of RMS and ABSM. The fitting criteria that had the lowest ranking was gineva win for that calibration group. The number of wins a fitting criteria can have per storm depends on the number of calibration groups used in forecasting. To choose the best fitting criteria for a particular storm, the fitting criteria had to win a majority of the calibration groups. Also, the ranking value could be used to tell how each parameter set compared with all of the parameter sets. This could tell which calibration period produced the best parameter sets.

The results of ranking RMS for each storm was almost identical to the rankinbg of ABSM. Because the ranks of RMS and ABSM produced the same results, only the ABSM ranks are shown in tables 6. Across the top of the table the calibration groups are listed by the calibration period, and on the left side of the table the specific storm number is given. There are 56 storms in all, starting with the first storm on February 17, 1956, and ending with July 23, 1965. In table 6, it can be seen that for the 1961 calibration group the OLS won the first storm event because it had a ranking of three while LOG had a ranking of nine and HMLE had a ranking of twelve. It can also be seen that OLS won five of the groups for the first storm. Table 7 shows the number of wins per

Table 6. Ranking of ABMS for all calibration groups.

Calibration Groups

Storm No.	1960 O	1960 H	1960 L	1961 O	1961 H	1961 L	1962 O	1962 H	1962 L	1963 O	1963 H	1963 L	1962-63 O	1962-63 H	1962-63 L	1961-63 O	1961-63 H	1961-63 L
1				3	12	9	2	11	10	4	13	8	1	15	7	5	14	6
2				6	15	10	3	11	12	2	13	8	1	9	7	4	14	5
3				1	6	4	7	13	15	14	3	8	11	5	12	9	2	10
4				8	7	15	3	12	14	11	6	1	9	4	5	10	2	13
5				6	4	15	9	12	14	8	3	10	5	1	11	7	2	13
6				11	6	14	13	5	15	10	3	1	8	2	7	9	4	12
7				8	4	14	10	11	15	7	1	9	5	2	12	6	3	13
8				9	4	15	13	11	14	7	1	8	6	2	10	5	3	12
9				1	2	10	5	14	15	12	6	7	13	4	11	8	3	9
10				2	15	10	6	8	9	4	14	5	3	12	11	7	13	1
11				5	6	12	1	15	14	4	11	7	2	13	9	3	10	8
12				10	13	9	4	2	6	15	11	5	12	7	1	14	8	3
13				3	7	9	15	10	14	1	11	4	13	6	8	2	12	5
14				1	8	4	11	7	12	15	14	3	6	9	13	10	5	2
15				5	1	10	9	14	15	8	3	11	6	7	13	4	2	12
16				10	6	12	15	11	1	8	2	9	5	3	13	7	4	14
17				8	5	12	10	9	13	15	6	7	2	3	14	4	1	11
18				12	5	7	13	10	14	3	2	6	9	4	15	11	1	8
19				8	5	14	11	10	15	4	2	9	7	3	13	6	1	12
20				11	5	10	15	13	14	4	2	6	7	3	9	8	1	12
21	* 5	3	10	12	2	17	13	14	18	4	9	11	1	8	16	7	6	15
22	*11	3	17	15	16	12	7	1	4	18	6	13	8	2	5	9	10	14
23	* 4	18	1	3	15	9	2	16	13	10	14	5	12	17	11	8	7	6
24	* 1	4	2	11	5	10	3	16	17	8	12	15	6	14	13	7	9	18
25	* 4	10	1	6	16	13	2	7	12	18	15	11	3	14	8	5	17	9
26	* 5	1	17	2	3	16	12	14	18	11	8	10	9	6	15	4	7	13
27	* 5	2	17	13	7	14	12	11	18	10	6	9	1	4	15	3	8	16
28	* 2	6	1	5	13	16	7	12	18	15	11	8	3	10	14	4	17	9
29	*14	15	18	9	12	3	5	1	10	16	7	2	13	8	4	17	11	6
30	13	1	15	*12	6	10	4	11	14	2	3	5	8	9	7			
31	9	8	15	* 4	14	2	11	7	12	6	10	1	5	13	3			
32	8	14	1	* 5	15	10	4	7	13	2	12	9	3	11	6			
33	9	12	6	* 8	3	2	10	15	14	7	4	1	5	13	11			
34	12	7	13	* 6	5	3	11	9	14	15	2	4	10	1	8			
35	9	14	1	* 7	15	4	2	5	3	10	13	8	12	11	6			
36	4	7	15	*10	3	12	13	11	14	6	1	8	5	2	9			
37	1	2	15	* 4	6	8	11	12	14	10	7	3	9	5	13			
38	11	3	12	10	9	5	* 7	1	2	8	4	6						
39	2	12	6	3	11	9	* 1	8	5	7	10	4						
40	11	7	9	8	12	6	* 1	2	3	10	5	4						

* Storms making up the calibration period. Example: the storms 21-29 made up the 1960 calibration period.

Table 6.--Continued.

Storm No.	1960 O	1960 H	1960 L	1961 O	1961 H	1961 L	1962 O	1962 H	1962 L	1963 O	1963 H	1963 L	1962-63 O	1962-63 H	1962-63 L	1961-63 O	1961-63 H	1961-63 L
41	9	6	2	7	11	10	* 1	3	5	12	8	4						
42	10	6	12	8	7	1	11	2	5	* 9	4	3						
43	8	12	5	7	11	9	2	3	4	* 1	10	6						
44	1	11	2	3	9	7	4	10	12	* 5	8	6						
45	4	8	12	5	6	2	9	3	11	*10	7	1						
46	5	6	11	4	3	12	9	8	10	* 7	1	2						
47	7	3	12	6	4	9	10	8	11	* 2	1	5						
48	2	6	1	4	15	8	7	14	18	3	13	9	16	12	17	5	11	10
49	6	2	18	11	9	14	16	12	17	1	8	10	5	7	13	3	4	15
50	12	6	18	10	5	7	16	11	17	1	4	9	13	2	15	8	3	14
51	14	4	18	17	16	12	5	13	8	1	7	11	2	15	9	3	10	6
52	8	17	1	2	12	4	6	15	10	18	14	3	13	16	9	11	7	5
53	14	9	11	7	10	18	5	6	17	15	2	1	12	3	8	13	4	16
54	9	1	17	11	5	16	12	13	18	3	7	10	2	8	14	6	4	15
55	15	14	18	1	10	4	16	13	17	14	7	2	12	5	3	8	9	6
56	11	6	18	10	3	14	16	13	17	2	4	7	9	5	15	8	1	12

Table 7. Summation of wins per storm for the calibration groups (a win indicates which fitting criteria gave the best forcast per calibration group).

Storm No.	OLS	HMLE	LOG	SEASON
1	5	0	0	WINTER
2	5	0	0	WINTER
3	2	3	0	SUMMER
4	1	3	1	SUMMER
5	1	4	0	SUMMER
6	0	4	1	SUMMER
7	1	4	0	SUMMER
8	0	5	0	SUMMER
9	2	3	0	WINTER
10	4	0	1	WINTER
11	5	0	0	WINTER
12	0	1	4	SUMMER
13	3	2	0	WINTER
14	2	1	2	WINTER
15	2	3	0	SUMMER
16	0	4	1	SUMMER
17	1	4	0	SUMMER
18	0	5	0	SUMMER
19	0	5	0	SUMMER
20	0	5	0	SUMMER
21	3	2	0	SUMMER
22	1	3	1	WINTER
23	2	0	3	WINTER
24	4	1	0	WINTER
25	4	0	1	SUMMER
26	3	2	0	SUMMER
27	2	3	0	SUMMER
28	4	0	1	SUMMER
29	0	1	4	SUMMER
30	2	1	1	WINTER
31	0	2	2	WINTER
32	3	0	1	WINTER
33	2	0	2	WINTER
34	0	4	0	SUMMER
35	1	0	3	SUMMER
36	1	3	0	SUMMER
37	2	1	1	SUMMER
38	0	2	1	WINTER
39	2	0	1	WINTER
40	0	1	2	SUMMER
41	1	0	2	SUMMER

Table 7.--Continued

Storm No.	OLS	HMLE	LOG	SEASON
42	0	2	1	WINTER
43	2	0	1	WINTER
44	3	0	0	WINTER
45	1	1	1	SUMMER
46	1	2	0	SUMMER
47	0	3	0	SUMMER
48	4	1	1	WINTER
49	3	3	0	SUMMER
50	1	5	0	SUMMER
51	4	1	1	WINTER
52	2	0	4	WINTER
53	2	3	1	SUMMER
54	3	3	0	SUMMER
55	1	2	3	SUMMER
56	1	5	0	SUMMER

storm for each fitting criteria, and whether the storm is a winter or summer storm.

A seasonal trend has developed where HMLE has outperformed OLS and LOG for the summer storms and OLS has outperformed HMLE and LOG for the winter storms. In fact, out of 34 summer storms, HMLE has won 20, OLS won 5, and LOG won 6, and there were three ties. Out of 22 winter storms, OLS won 13, HMLE won 4, LOG won 2, and there were 3 ties.

When the forecast period was the same as the calibration period the parameter sets chosen in that calibration period were used in the ranking of RMS and ABSM. These parameter sets have an asterisk by them and were not used in the summation of wins. By studying the rankings of these parameter sets, it can be seen which storm events had the most emphasis put on them be the fitting criteria during calibration.

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