AN IMPROVED FLOOD-FREQUENCY MODEL FOR SMALL WATERSHEDS IN THE UPPER OUACHITA MOUNTAINS

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Abstract—A new regional flood-frequency (RFF) model is proposed for small, steep watersheds in the upper Ouachita Mountains of Arkansas. It is derived using Dalrymple's (1960) method and data from 10 monitoring stations with record periods of 15 to 33 years. First, I developed a preliminary RFF model and tested it against Neely's (1987) model using data from just five stations. Next, I compared the preliminary model's prediction accuracy to the accuracy of Neely's model using data from five stations not used to derive the new model. The preliminary model produced more accurate predictions than Neely's for all basins tested. Moreover, it's prediction errors are unbiased whereas those using Neely's model vary with recurrence interval and basin size. I derived a final RFF model using data from 9 of the 10 stations. It is applicable to sites within steep, forested basins of < 100 acres.

INTRODUCTION

Accurate predictions of peak streamflow magnitude are essential for accomplishing forest ecosystem management. Such predictions are required to design adequate drainage and stream crossing structures. They are needed to assess the risk of failure for in-channel or flood-plain structures, and for planning research and restoration projects. Peak flow predictions are made using flood-frequency (FF) models that relate discharge magnitude to the recurrence interval of such events (t_r, the average number of years between events), or its inverse, the probability of such a flow occurring in a given year ($P = 1/t_r$).

A series of equations have been defined by Neely (1987) for predicting peak discharge at given recurrence intervals (Q_r) throughout Arkansas.[2] These equations model Q_r as a function of various basin and climatic characteristics. They apply to all unregulated streams with drainage areas < 3,000 square miles within the entire State. Hereafter, the term "Neely's model" is used to refer in general to these equations.

Two reasons suggest that Neely's model may not be accurate in the smaller, headwater streams of the Ouachita Mountains. First, it is based primarily on catchments with relatively large basin areas. Within the Ouachita Mountains, only 3 of the 23 stations used by Neely have basin areas < 640 acres and only 2 are < 160 acres. Second, Neely's model is defined so as to minimize the influence of channel slope and elevation, two factors that are widely recognized as greatly influencing streamflow in small, mountain basins (Lee 1980). Neely states the latter is done to eliminate "bias" from these variables, but it's not clear from his discussion what exactly is meant by "bias."

In this paper, I present an improved FF model that is applicable to the upper Ouachita Mountain region (see figure 1). This new model is derived using the regional flood-frequency (RFF) method of Dalrymple (1960) and data from 10 small, steep watersheds. The presentation is organized as follows: first, Neely's model and procedures for deriving a preliminary RFF model using a data subset are described; second, Q_r predictions from the preliminary RFF model are compared to those using Neely's model; and last, the final RFF model

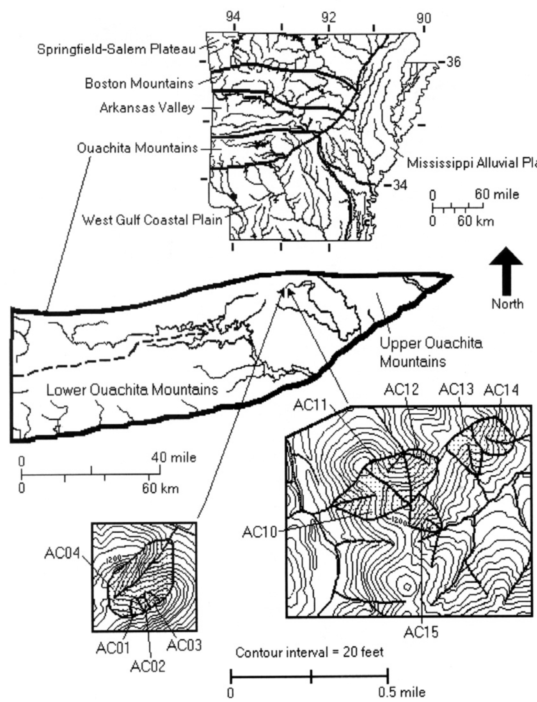

Figure 1—Physiographic provinces in Arkansas (Hodge and Tasker 1995); location of theu Ouachita Mountains; and gauging stations used to derive or test a regional flood-frequency model. Topographic data from Nimrod SE and Paron SW USGS 7.5-minute quadrangles.

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[2] Hodge and Tasker (1995) recently published an updated series of models for Arkansas. I discovered this work too late to include it within this paper, however, I did have time to test their models using the same procedures and found them to actually be less accurate than those of Neely (1987) for small, steep basins in the upper Ouachita Mountains.

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is derived using all appropriate data and its usage considerations are discussed. The region of interest is limited to the upper Ouachita Mountains where data are sufficient for this analysis.

METHODS AND DATA

Overview of Existing and New Models

Neely (1987) derived models for predicting 2-, 5-, 10-, 25-, 50-, and 100-year peak flows. He divided the State into two regions wherein different equations are applicable. The upper Ouachita Mountains region is entirely within Neely's Region B. Using multiple regression, he found that basin area, channel slope, mean annual precipitation, and mean basin elevation were the important factors in predicting Q_r. For small mountain streams like those in the upper Ouachita Mountains, slope and elevation are treated as constants and set equal to 30 feet per mile and 500 feet, respectively.

The RFF method is relatively simple to apply and is used to derive an alternative model for predicting Q_r. Its only assumption is that all individual basins within the region have streamflows with the similar distribution characteristics (Dunne and Leopold 1978). The method actually produces two related models: one for predicting Q_r given the mean annual flood (Q_{maf}) for a basin and the t_r of interest, and a second for predicting the Q_{maf} from basin characteristics. Hereafter, the term "RFF model" is used to refer to both models.

The procedures used in deriving a RFF model are explained in detail in Dalrymple (1960). Briefly, they are

1. Determine the candidate stations and base period. The base period is the time period that provides the greatest overlap in record periods between stations
2. Derive a FF model for each station
3. Predict the Q_{maf} for each station. The Q_{maf} is used as a scaling factor to remove the effect of basin size from the discharge data, so that a single model can predict flows for basins of varying size. It is determined for each station using the respective FF model and the discharge at the 2.33-year recurrence interval
4. Test the homogeneity of data from all stations. This test ensures that all stations have reasonably similar variability in peak discharges for their respective record periods
5. Derive the regional Q_r/Q_{maf} model. This model expresses the change in Q_r/Q_{maf} with t_r. It is derived by predicting the discharges at selected t_r values using the individual FF models, dividing them by their respective Q_{maf} values, determining the median Q_r/Q_{maf} value for all stations at each t_r, and modeling the medians against the t_r
6. Derive the Q_{maf} model. This model predicts Q_{maf} values so that the Q_r can be determined from the Q_r/Q_{maf} model at ungauged sites

Two exceptions are made to Dalrymple's procedures. First, both the Q_r/Q_{maf} ratio and Q_{maf} models are derived using regression procedures rather than fit-by-eye curves. Nonlinear regression is used to model Q_r/Q_{maf} versus return period, while linear regression is used to model Q_{maf}. Second, several basin characteristics are used to model Q_{maf} rather than just basin area.

Model Derivation and Testing Procedures

Data from 10 gauging stations located within the region (see figure 1) were used to develop and test the RFF model.[3] These stations are all located in small, steep basins. None of the other stations in the region were used because either they have drainage areas that are too large or have catchments that are too low in relief (see Neely 1987 for these data). The 10 stations used have basin areas from about 1 to 32 acres (see table 1). Their base record period is a little over 30 years, which is quite long for stations within such small basins. The data constitute annual maximum instantaneous discharges during the record periods for each station.

The 10 watersheds all have continuous, pine-hardwood forest cover, but vary in stem density, biomass, and overstory age as a result of past logging (see table 1). In this way, they are representative of small basins throughout the upper Ouachita Mountains where forest management has produced a mosaic of forest conditions.

The data were divided into two groups: one for developing a preliminary RFF model and a second for testing its accuracy against predictions using Neely's model. The model group includes five stations, four of which were chosen at random. One station, AC04, purposely was included in the model group because its basin area is substantially larger than all other stations (see table 1). This ensures that the preliminary model represents the range of conditions found among all 10 stations. The testing group includes the remaining five stations. Both groups include data from basins that cover the range of forest conditions found among the 10 stations.

Data for developing the FF models for each station were taken from the same base period of 1961–93. Where data are missing, they were estimated by finding the station among the other nine that was most highly correlated to the station with the missing data, regressing the discharges from those years when both stations have data, then estimating the missing data using the resulting model. Missing data estimates were used only in determining the ranks of valid data; they were not used in computing the FF models.

FF models were derived for each station in both the model and test groups. Nonlinear regression is used to fit one of two exponential decay models, either

$$Q_r = b_1 e^{-b_2 P} \tag{1}$$

or

$$Q_r = b_0 + b_1 e^{-b_2 P} \tag{2}$$

where

b_0, b_1, and b_2 = regression coefficients.

[3] Unpublished data on file at the USDA Forest Service, Southern Research Station, P.O. Box 1270, Hot Springs, AR 71902.

Table 1—Environmental characteristics of Forest Service gauging stations used in the regional flood-frequency model development and testing

Station	Basin area	Basin relief	Forest conditions	Mean annual flood	Data group
	acres	*feet*		*cfs*	
AC01	1.63	75	Undisturbed	1.34	Test
AC02	1.28	75	Shelterwood harvest in 1970 and 1977, thinned in 1981	1.16	Test
AC03	1.44	60	Clearcut 1970, replanted in 1976	2.04	Model
AC04	32.50	220	Undisturbed	19.94	Model
AC10	14.17	220	Selection harvest in 1980 and 1987	13.14	Test
AC11	12.18	180	Undisturbed	9.00	Model
AC12	14.60	180	Clearcut, burned, and replanted in 1980	13.91	Model
AC13	11.71	180	Undisturbed	9.78	Model
AC14	10.76	140	Selection harvest in 1980 and 1987	11.14	Test
AC15	12.64	150	Clearcut, burned, and replanted in 1980	11.86	Test

Note: Record periods are 1961–93 for stations AC01-AC04 and 1979–93 for stations AC10-AC15.

This allows the FF models to be expressed as equations rather than graphs, which greatly facilitates their use. The models were computed using SigmaPlot and derived using the Marquardt-Levenberg algorithm (SPSS 1998).

Different modeling approaches and weighting schemes were used to derive a variety of candidate models for each station. Models were derived both by forcing b_0 to equal 0 and by computing b_0. Different weighting values were explored to de-emphasize the leverage of the largest peak flows in deriving the individual FF models. The largest discharges have the most uncertain probabilities and can have a disproportionate influence on model parameters. In contrast, the lower discharges have more certain probabilities, but have less influence because their residuals are typically small. Weighted regression can be used to minimize this effect (Myers 1990). Because this uncertainty varies with discharge (Q), then $1/Q$ and $1/Q^2$ were tested as weights, in addition to an unweighted model.

I chose the best model to be the one that maximizes overall model fit while conforming most closely to the higher discharge probabilities. I used the model R^2 to measure overall fit and visual inspection to determine quality of fit at the lower discharge values. When different models were equivalent using these criteria, I chose the simplest model (fewest parameters, least weighting).

The preliminary Q_r/Q_{maf} model was derived using the median values at 24 probabilities from 0.01 to 0.99. The probabilities were selected so as to adequately define the change in Q_r/Q_{maf} across the probability range for the five stations in the model group.

The preliminary Q_{maf} model was derived using linear regression to relate Q_{maf} to basin morphometry variables for all stations in the model group. Basin morphometrics considered were basin area, relief, length, and slope (see table 1). The best model was chosen considering R^2, model mean square error, and Mallow's C_p factor (Myers 1990).

Model accuracy for both the preliminary RFF and Neely's model was tested by comparing discharge predictions using these models against those predicted by the individual FF models for stations in the test group. My rationale was that because the individual models are based solely on the measured data at each station, they should provide the best estimate of the "true" Q_r at each station. This rationale is only as good as my assumption that the exponential decay functions used to fit individual models provide an accurate representation of annual peak discharge distribution. Because all selected models had R^2 terms of 0.92 to 0.97, I concluded this assumption was valid. Accuracy for both the preliminary RFF and Neely's model was evaluated qualitatively by visually determining which model predicts discharges closest to the individual FF predictions. It was assessed quantitatively by computing the root mean square (RMS) error of model predictions from corresponding station Q_r values. Hereafter, Q_r values predicted from individual station models are referred to as "station" values while those predicted using either the RFF or Neely's model are referred to as "predicted" values.

RESULTS AND DISCUSSION

Model Comparisons

The FF models for individual stations are fairly similar and all were fit with a high degree of accuracy, as noted above. An example is shown in figure 2. Best model fits were most often obtained using a two-parameter model ($b_0 = 0$) with $1/Q$ weighting. Stations AC03 and AC04 were best fit using the three-parameter model. Stations AC01 and AC10 were best fit using no weighting, while station AC03 was best fit using $1/Q^2$ weighting. With the exception of AC04, the two-parameter model derived using $1/Q$ weighting is almost as good as the selected model for these stations. The three-parameter model is clearly better for AC04. A possible—albeit unproven—physical interpretation of the need for the b_0 value is that due to its larger basin area (table 1), AC04 exhibits a minimum, positive discharge even at the lowest recurrence intervals, whereas the other, smaller basins approach 0 discharge.

Station AC10 is the only station that fails to pass the homogeneity test. Its variance exceeds the recommended limits (Dalrymple 1960); therefore this station was excluded in deriving both the preliminary and final RFF models. Why it differs from the other watersheds is not readily apparent. It is located adjacent to AC11-AC15 and has similar physical characteristics (see table 1).

The component models of the preliminary RFF are

$$\frac{Q_r}{Q_{maf}} = 2.237e^{(-1.885)P} \tag{3}$$

and

$$Q_{maf} = -0.317 + 0.423A + 0.031E \tag{4}$$

where

A = basin area (acres)

E = basin relief (feet).

The Q_r/Q_{maf} model is extremely well fit using a two-parameter function. This exceptional degree of accuracy is due to the smoothing effect produced by modeling only the median ratios at each probability. The best Q_{maf} model uses basin area and basin relief to predict Q_{maf}. Its R^2 is 0.95.

All comparison tests clearly show that the preliminary RFF model is more accurate than Neely's model for the basins considered. Plots of station versus predicted Q_r for three of the test group stations clearly show the difference (fig. 3). The stations used in figure 3 show the entire range in overpredictions and underpredictions using the preliminary RFF model. Surprisingly, the preliminary RFF model is most accurate for station AC10, the one station whose variance caused it to be excluded from the model group. The RMS errors confirm the visual evidence. The RMS error for the preliminary RFF varies between 0.6 and 4.7 cubic feet per second; while it varies from 4.7 to 27.9 cubic feet per second for predictions using Neely's model.

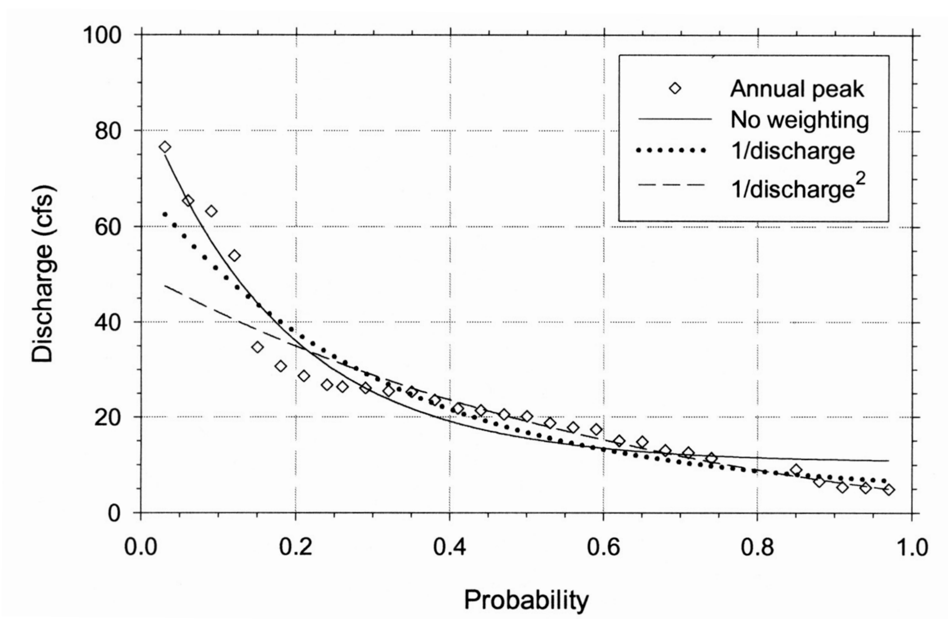

Figure 2—Flood-frequency models for watershed AC04. Different models are produced using nonlinear regression with the weighting methods listed. Scales are arithmetic and are the ones used in all regression analyses.

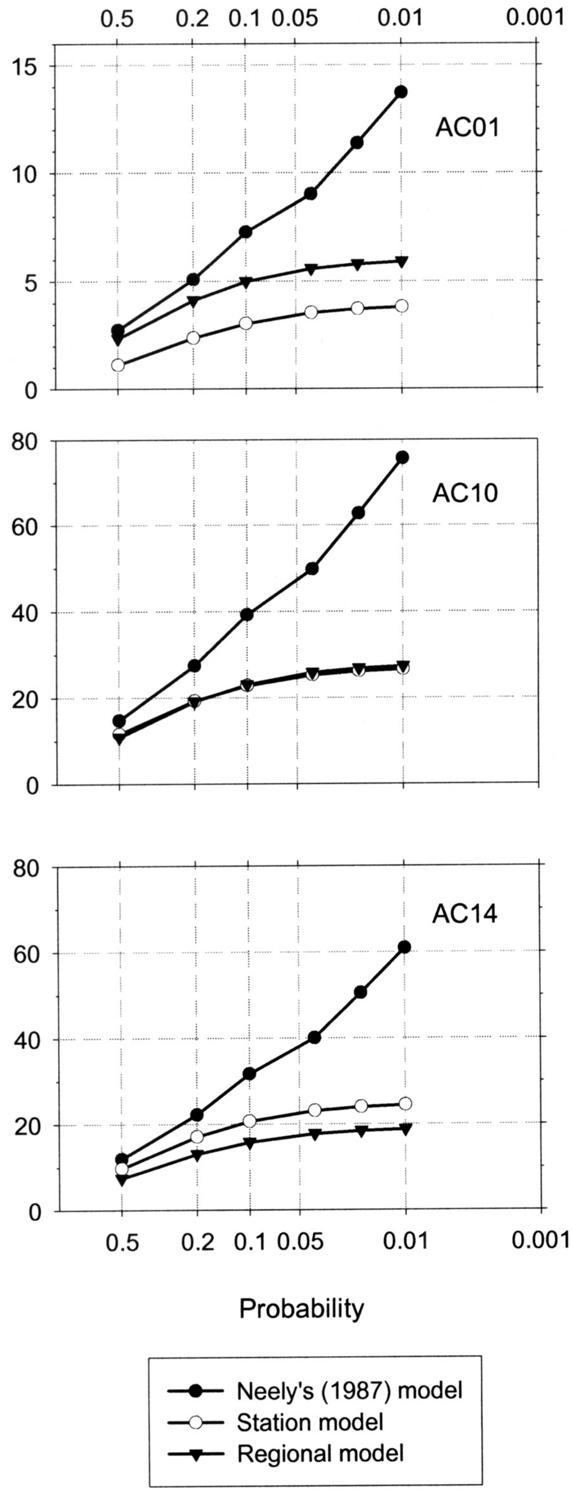

Figure 3—Comparison of discharge predictions using the preliminary regional and Neely's (1987) models. "Observed" discharges are predictions based on observed data for each station.

Discharge is consistently overpredicted using Neely's model and the error increases with both t_r and basin size. The distributions of prediction errors are shown in figure 4. Both the median error and the variance clearly increase in positive value (overprediction) as t_r increases; i.e., probability decreases, and basin size gets larger. Errors are especially pronounced at $P < 0.1$ (10-year flow) and area > 10 acres. In contrast, the preliminary RFF predictions show no bias with t_r and only minor fluctuations around 0 error with varying basin size.

Given the successful performance of the preliminary RFF model, a full model is derived using data from all stations except AC10. Its component Q_r/Q_{maf} and Q_{maf} models are

$$\frac{Q_r}{Q_{maf}} = 2.273e^{(-1.922)P} \quad (5)$$

and

$$Q_{maf} = -1.262 + 0.416A + 0.040E \quad (6)$$

The final Q_r/Q_{maf} model is shown in figure 5. Like the preliminary RFF, the selected best model for Q_{maf} uses basin area and relief. It has an R^2 of 0.94. Similarly, the Q_r/Q_{maf} model is fit with a two-parameter exponential decay function.

Model Application Considerations

Neely's (1987) model is not a *bad* model. The results presented above do not invalidate using Neely's model for sites where basin characteristics correspond more closely to the data used to develop that model. Given that Neely's objective was to provide a method for estimating Q_r throughout the entire state of Arkansas, it is not surprising that his model can be improved on in smaller areas like the upper Ouachita Mountains where additional data are available.

The final RFF model resulting from this work has limited applicability. Its accuracy outside of the upper Ouachita Mountain region is unknown. The model is based upon data from sites of approximately 1 to 35 acres and can be applied to similar basins within this size range. In addition, it has been my experience that basins with very similar relief and environmental characteristics occur up to about 100 acres in the upper Ouachita Mountains. Therefore, I think that where conditions are determined to be similar to those listed in table 1, the model should be applicable to catchments up to approximately 100 acres.

Past design and risk assessments based on Neely's model for sites in basins like those discussed here may still be valid. They may overpredict peak discharge, but factors other than discharge often need to be considered when designing in-channel structures or assessing their risk of failure. Such factors include the possibility that a structure like a culvert will become plugged with woody debris and leaves during high-flow events. Such factors typically act to increase the design flow that must be accommodated, thus overpredictions may be entirely appropriate.

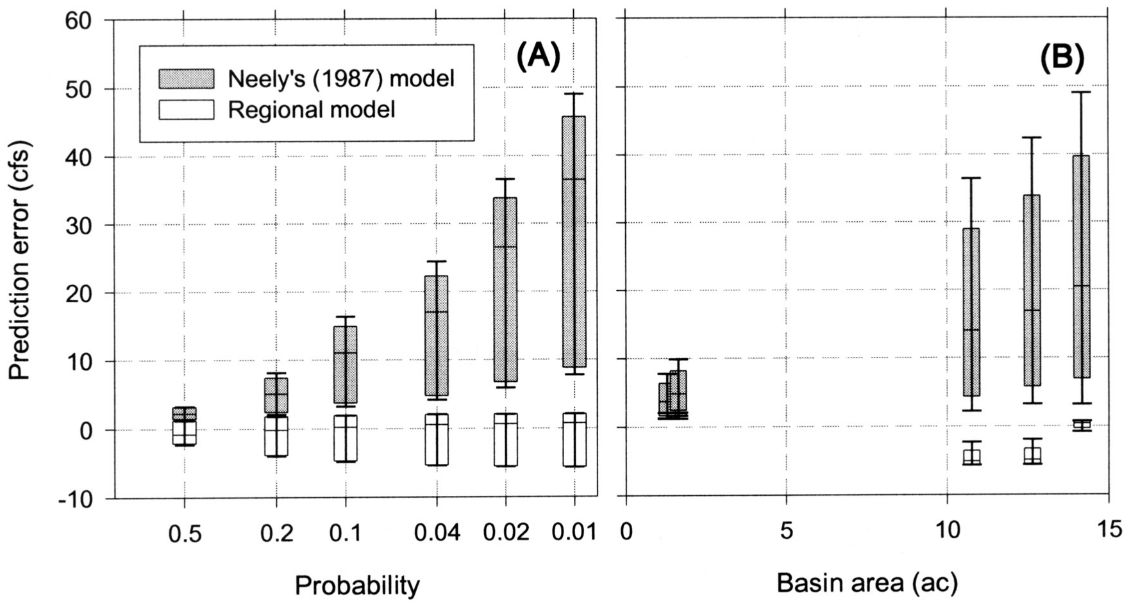

Figure 4—Box plots comparing the effects of (A) recurrence probability and (B) basin area on prediction errors using both the preliminary regional and Neely's (1987) models. Errors are plotted at six probabilities corresponding to 2-, 5-, 10-, 25-, 50-, and 100-year events, and at the basin areas for each of the five stations in the test group.

If a common frequency distribution for small-basin peak discharges can be determined, then a still better model might be developed. Such a model would allow more accurate prediction of extreme values, which are always the most uncertain estimates when using regression methods. It would also allow shorter record periods to be used in developing local models. However, identifying a common frequency distribution is difficult due to the short records generally available for small, mountain stations and the relatively large variability inherent in hydrologic processes at such fine spatial scales.

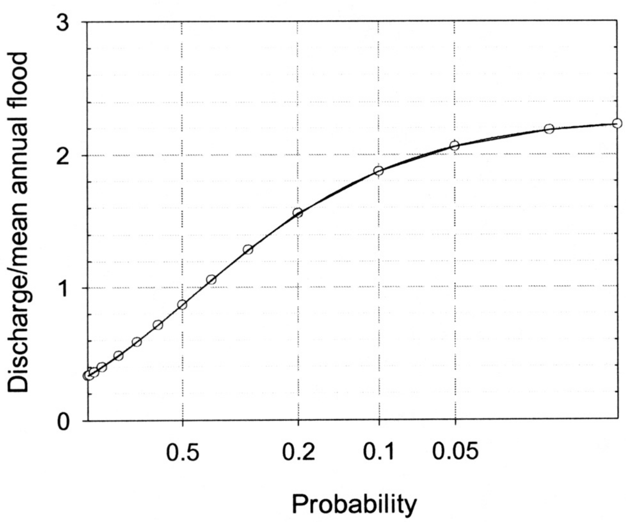

Figure 5—Final regional flood-frequency model for small, steep catchments in the upper Ouachita Mountains. For a given location, discharge for a given recurrence interval is predicted by calculating the Q_r/Q_{maf} ratio at the probability then multiplying this value by the Q_{maf} for the location. Q_{maf} is predicted from the second model. Both models are based on data from nine stations.

SUMMARY AND CONCLUSIONS

For small, steep watersheds in the upper Ouachita Mountains, the RFF model described here more accurately predicts Q_r than Neely's (1987) model. Neely's model overpredicts discharge for such basins. Using the RFF model requires measurement of the basin area and relief for the site in question. The RFF can be applied with confidence to watersheds of 1 to 35 acres, and probably can be applied up to 100 acres if environmental characteristics remain similar to those listed in table 1. Model accuracy is unknown outside of these limits where, if appropriate, previously developed models should be used. Factors in addition to discharge should be considered in designing and assessing failure potential for in-channel structures in headwater basins.

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