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DISCUSSION by H.B. Osborn, W.C. Mills & L.J. Lane[7] of General Reports by P. O'Connell and I. Rodriguez-Iturbe.

The purpose of this reply is to answer pertinent questions raised by the reporters and others during the symposium. Although it is difficult to credit each person specifically, the authors are indebted particularly for the formal reviews by O'Connell and Rodriguez-Iturbe, informal comments by O'Connell and some searching questions raised by Court in open session and informal discussion.

The authors referred to a paper presented by Osborn, Lane and Kagan in 1971 which describes the thunderstorm rainfall model in detail. The paper traces the development of the model in greater detail and provides further insight into the selection of model components. Unfortunately, this paper had not been published at the time of the symposium, but it should be in the near future. Some of the questions raised at the symposium are answered in this yet-to-be published paper, and it would have been helpful if the reviewers could have had this background material available to them.

O'Connell questioned the model accuracy based on short periods of record. Although the model was based on 12 years of thunderstorm rainfall records from the Walnut Gulch Watershed, there were an average of about 40 significant air mass thunderstorms per season, or a total of about 500 events with which to develop the model.

In the same vein, there were a few significant runoff-producing thunderstorms during the 12 years that were classed as other than air mass thunderstorms. Although these few events were insignificant in terms of annual runoff on Walnut Gulch, they are of interest on a broader base. Runoff-producing storms other than air-mass thunderstorms produce significant runoff from rangelands on other parts of the Southwest, so the development of a regional thunderstorm rainfall model must include these "other" thunderstorms. It is probable that such regionalization will be accomplished through largely empirical methods--topographic differences, distance from moisture sources, etc., but hopefully some meteorological parameters can be utilized. The authors are working on the problem of regionalization at present.

O'Connell questioned the statistical testing used by the authors, the independence of variables, and asked about other rainfall variables not included in the model. Each of these questions deserves comment.

The authors used a two-sided Kolmogorov-Smirnov test (K-S statistic) designed for comparing two empirical distributions as a basis for comparing the sample cumulative distribution functions of the historic and synthetic peak flows. This test was used because it does not require the specification or assumption of the underlying distribution functions for the samples being compared (see Feller, 1966). It was believed that to make an assumption of these distribution functions when they were actually unknown would camouflage uncertainty in the model.

The sample cumulative distribution functions for the historic and synthetic peak flows were compared under the null hypothesis that the population cumulative distribution functions are equal. Birnbaum and Hall (1960) computed and tabulated the distribution of the maximum

absolute discrepancy between two empirical distributions (K-S statistic) for various small sample sizes. Given that the population functions are equal, these tabulations indicate that there is a 95 percent probability that the above defined K-S statistic will be 0.5 or less.

The K-S statistic was used in this paper only as an indicator in the sensitivity testing of the model parameters. The authors recognize that the distribution of this statistic only gives probabilities for Type I errors. This is a disadvantage of the test. Even so, results of the tests do suggest that the model generates rainfall amounts that can be used to predict peak discharge for major events that compare favorably to major peak discharges from actual data.

The authors have pointed out the difficulty in testing the model components independently. This is due primarily to the difficulty in accurately separating real data components for testing with model components. It may be appropriate, however, to comment further on the simplified unit cell component of the model.

There is variability in the radius of the individual thunderstorm cells, but as best as can be determined, this variability is very small compared to the variability of the rainfall depth. This made the cell radius relatively insensitive, so it was held constant. Also, in reality, depth varies with distance both in time and space in every direction from the maximum point of rainfall, although there obviously are constraints on this variability. Again, the relative insensitivity of this variable suggested that this complex distribution could be simplified for purpose of this model.

In answer to one of O'Connell's questions, the authors feel that if the variables in the model are truly thunderstorm rainfall variables they are independent. The problem is to decide or to define what the thunderstorm variables really are. Theoretically, the rainfall variables should all be based on meteorological concepts and topographic and position parameters. The model variables might be called the "result" variables, for want of a better word. The model is, basically, a physical model developed for practical engineering use.

The values that were held constant for the sensitivity analysis were 0.425 inch, 3.6 miles, 210 miles, and 60 degrees for the mean cell center depth, cell radius, mode of distance between cells, and standard deviation of direction change, respectively. These values were about in the middle of the range for the variables that appeared to match the sampled data. The values that were held constant may not have been optimum, but they should have been close enough so that the sensitivity analysis was not affected by their choice.

Court asked specifically for clarification of assumption 10 of the thunderstorm rainfall model. In the model rainfall decreases linearly to a distance of $\sqrt{1/\pi}$ miles, where precipitation is 0.85 of that at the center, and logarithmically thereafter.

Assumption 10 was based on both fitting Walnut Gulch data and computational convenience. The logarithmic part of the assumption was chosen

because it appeared to fit Walnut Gulch data better than other models when the distance from the storm center exceeded about 0.6 miles. From Walnut Gulch data the average rainfall at about 0.6 mile was 0.85 of the maximum center depth. With more and better records both of these values might be changed somewhat, since the specific value of $\sqrt{1/\pi}$ was obviously chosen for computational convenience. Since there are very few gages closer than 0.5 mile on Walnut Gulch, and since rain gages provide only an estimate of the rainfall, the authors do not know the depth-area relationship between the center depth and about one square mile. A straight line relationship was assumed since it was the simplest and nothing more complex could be justified. Osborn, Lane, and Hundley (1972) calculated that approximately 1400 rain gages would be needed on the 57 square mile Walnut Gulch Watershed to define maximum 15-minute intensities with a correlation of 0.90 between gages. This approximate rain gage density would be needed, as well, to identify the depth-area relationship for thunderstorm cells from the center depth to a radius for about one square mile. A few closely spaced gages would do the same job, but only with a much longer record.

The question of persistence (or lack of it) in the model was raised by several persons. The authors modeled storm occurrence as a Bernoulli random variable based on occurrence of storms of more than 0.2 inch on Walnut Gulch. Several investigators including Sellers (1960) and Osborn (1968) have reported on the persistence wet periods of several days and longer throughout the summer season in southern Arizona. This persistence can be seen by looking at USWB records from standard rain gages that are published monthly, as well. However, persistence based on any amount of rain, whether or not it can be considered runoff-producing, may be misleading in a model designed basically for runoff prediction. A comparison of 12 years of simulated and actual storms 1 inch or larger on Walnut Gulch, indicated that the occurrence of runoff-producing events on Walnut Gulch on successive days were similar for simulated and actual data. There were 17 cases in the 12 years of both simulated and actual data in which rains of 1 inch or more were recorded on successive days. For the simulated record, twice there were 3 consecutive days of 1 inch or more rainfall, and on one occasion each there were 4 and 5 successive days with 1 inch or more of rainfall. For the actual data there was one period each of 3 and 4 successive days of 1 inch or more of rainfall. Each record contained one period in late July when there were 6 storms in 8 days.

Although there was no statistical difference in the persistence pattern between model and actual data, there was a suggestion that the model, if any thing, simulated greater persistence than the actual data for the occurrence of major runoff-producing events. On the other hand, 12 years may not be enough to model persistence accurately. For these reasons, the authors chose to continue to use a Bernoulli random variable rather than go to a persistence model, which was considered in the early development of the model. Comparison of simulated and actual data suggest that if a persistence model were used, based on the occurrence of any rainfall at a point or on a watershed, some constraints based on rainfall

magnitude would be needed. Obviously, because of antecedent effects, generating storms that are too closely spaced could increase runoff appreciably, just as spacing them too far apart could appreciably decrease runoff.

Comparisons of real and simulated data does suggest that the simulated storms are too widely scattered early in the season. When conditions are such that moist air can flow into Southern Arizona from the south, the season begins rather abruptly. The very low average occurrence probabilities in the early part of the season do not allow for this circumstance. The authors have added a normally distributed random variable centered at July 15 to predict the beginning of the season as suggested by Diskin and Lane (1972). The beginning of the season does not guarantee rainfall on that date, and occurrence is still determined with use of a Bernoulli random variable.

It was suggested that the model should be compared with the one presented by Amorocho and Morgan 1971. Although not familiar with the Amorocho-Morgan model, the authors realize that it is based, at least in part, on some data from the Walnut Gulch Watershed, and it would be interesting to compare the 2 models. Possibly such a comparison can be made in the future.

Finally, the authors admit that there are uncertainties in the rainfall-runoff regression model that was used to test the sensitivity of the input variables. This particular rainfall-runoff equation was developed from the 30 greatest peak discharges on Walnut Gulch (Osborn, 1971), however; so it was felt that comparing the largest 10 events as the variables were independently varied would avoid the problem of uncertainty in the watershed model. The authors still feel this to be basically true.

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