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THE USE OF A MULTIZONE HYDROLOGIC MODEL WITH DISTRIBUTED RAINFALL AND DISTRIBUTED PARAMETERS IN THE NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM

David G. Morris
Lower Mississippi River Forecast Center
Slidell, La.

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DAVID G. MORRIS
Lower Mississippi River Forecast Center
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ABSTRACT. Tests were conducted on a basin with a less-than-optimum rain gage network to evaluate the possibility of improving streamflow simulation through the use of zonal precipitation input and zonally varied parameters. Preliminary results for the 959-mi^2, 4-zone watershed indicate that improved hydrograph reconstitution is obtained for rises caused by convective rains where the model parameters are adjusted to reflect hydrologic differences between upstream and downstream zones. The multizone approach used is model independent and should be valid for any conceptual hydrologic model employing a unit hydrograph to define the temporal distribution of runoff volumes.

1. INTRODUCTION

Continuous streamflow hydrologic models appear to offer significant improvements in river forecasting accuracy over the traditional API, empirical techniques. Hydrologists may very well be faced with demands for not only high-flow flood forecasts, but also extended low-flow forecasts as well. Before the advent of conceptual hydrologic models, the hydrologist was often forced to develop entirely different forecasting procedures to handle the two spectra of flows. The National Weather Service River Forecast System (NWSRFS) now allows all River Forecast Centers to take a uniform approach to common problems in hydrograph synthesis.

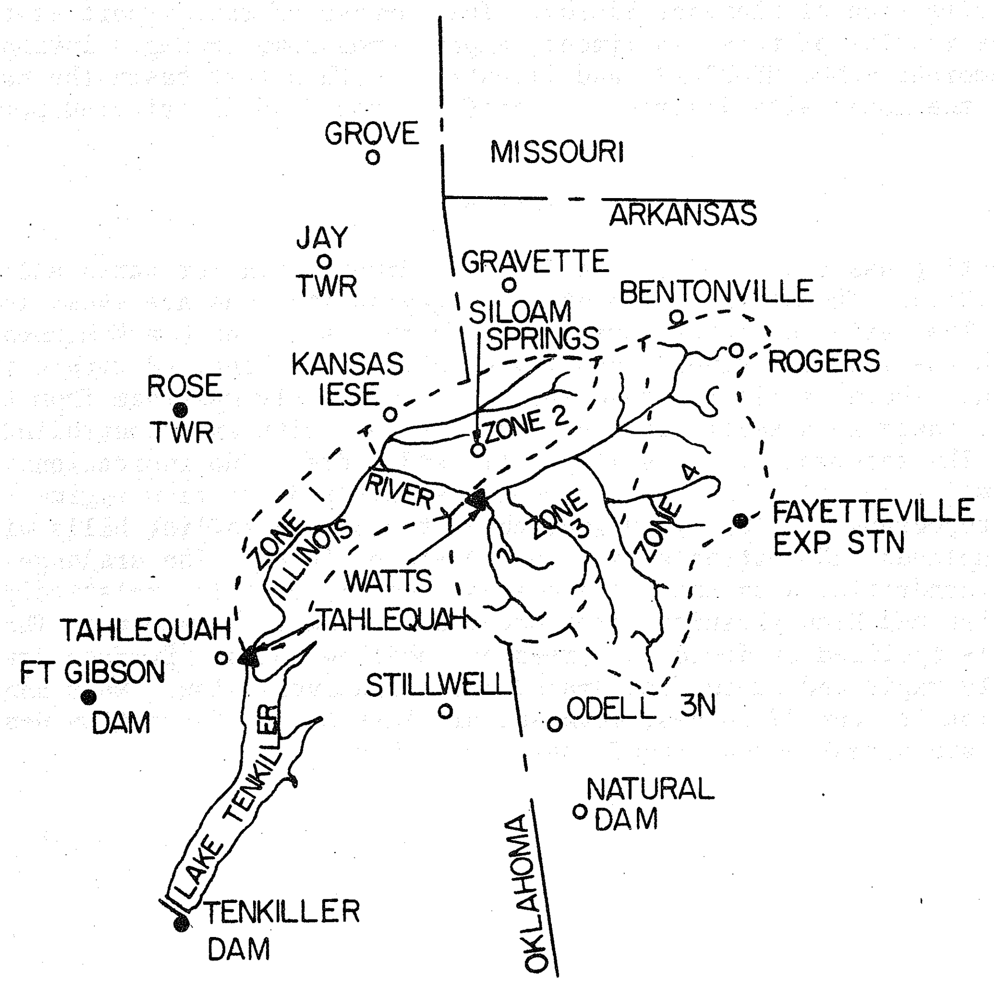
The fitting of a model to a basin requires skill and experience. In particular, difficulty may be encountered in fitting the model to historical major rises without detracting from the low-flow calibration. This sort of error in basin response simulation has been noted by Vicroy (1974) for watersheds in Mississippi and Louisiana, and by the author for watersheds in the Arkansas River drainage. Part of the problem could be that the temporal distribution process, which is physically nonlinear, is modelled by a linear mathematical function. Some of the error may be due to averaging precipitation over the entire basin, because the intense convective rains that occur in the southwest and southeast are likely to cover only a fraction of the basin in any given storm event. Since a uniform distribution of rainfall over a basin is more the exception than the rule, any river forecasting procedure that requires such an averaged basin (lumped) rainfall input has inherent deficiencies. The rain gage network is seldom optimum, so that an exact delineation of the true rainfall pattern is probably impossible. However, more often than not, sufficient point rainfall values are available so the analyst can at least determine "heavy upstream or downstream" rainfall distributions, thus allowing for subarea (distributed) rainfall input to a forecast procedure. The NWSRFS allows one to divide a basin into zones or mean basin precipitation (MBP) subareas and apply computed subarea runoff to some fraction of the basin inflow time-delay histogram. The histogram is based upon the concept of basin travel time zones or isochrones. The concept of simulating the headwater or ungaged local area hydrograph at a flowpoint by routing runoff from the contributing area above the river gage is not new. Several authors; e.g., Linsley et al. (1958), and Clark (1945), addressed the runoff distribution problem by assuming an inflow hydrograph that is derived by lagging runoff from various basin zones in proportion to the travel time above the gaging station. To this gage inflow there is then applied storage routing, resulting in a basin outflow hydrograph. Yates (1972) and Sallee (1972) have long advocated this approach, using the Tulsa RFC effective precipitation zone routing (EP) scheme to forecast downstream hydrographs successfully for storm events that could not be handled by a unit hydrograph. Inflow runoff volumes are obtained from an API-type rainfall-runoff relation. The Tulsa RFC EP method for synthesizing streamflow also allows one to apply a variable K (storage factor) and additional L (lag) to the inflow hydrograph, as does the NWSRFS. However, the NWSRFS conceptual model goes one important step farther. Separate soil moisture accounting is kept for each zone, effectively maintaining individual zone moisture storage and rainfall-runoff relationships.

Further refinement in this inflow travel time concept of streamflow synthesis is possible if one considers the possibility of differing model parameter values between zones. As presented in NOAA Technical Memorandum NWS HYDRO-14, the Stanford IV conceptual hydrologic model is essentially a lumped parameter model. "Lumped" means that each parameter value obtained during calibration represents an average value for that parameter over the entire basin in question. It is recognized, for example, that such parameters as infiltration rate (CB) or lower zone nominal storage (LZNS) may take on widely differing values over the basin. It is also possible that there exist over a basin upstream hydrologically homogeneous zones with a uniform parameter set that is significantly different from the downstream parameter set. A typical case would be the low infiltration, low moisture storage, high runoff characteristics of the basin headwaters vs. the downstream hydrologic characteristics of an alluvial plain. The NWSRFS method has the flexibility to allow model parameters to be distributed according to basin zones (MBP subareas), rather than employing a lumped parameter set for the total gage area as is customary.

While the author was Procedure Development Hydrologist at the Tulsa RFC, an experiment was conducted at the suggestion of the Hydrologist-in-Charge (HIC) to determine the feasibility of utilizing the NWSRFS in a manner similar to the EP solution, thus retaining the advantages of the EP while adopting the model. The study has continued at the Lower Mississippi RFC under the direction of Clarence Vicroy. The purpose of this report is to present the results of this experiment, expand upon some concepts introduced in NOAA Memorandum NWS HYDRO-14, and illustrate with a test basin the calibration of the model with distributed rainfall input and distributed parameters.

2. THE TEST BASIN

Model testing was conducted on the Illinois River basin for Watts and Tahlequah, Okla. The basin and location of gaging stations are shown in figure 1. The basin headwaters are in the foothills of the Ozark Mountain chain, with the Illinois River channel generally deeply incised within its flood plain. There is little urbanization. Immediately upstream from the Watts gage, there is a small water supply reservoir with an uncontrolled spillway. The reservoir is generally full, and there is no indication from streamflow records that the reservoir has altered the flow regime. The basin topography is fairly rugged, characterized by rolling hills with about 25% uplands, 25% bottomlands, and 50% steep slopes. The drainage pattern is dendritic, with the basin composed mostly of thin, relatively flat Silurian and Pennsylvanian limestones, shales, and sandstones. The landscape is typified by deciduous trees and shallow soils. Surface drainage is generally rapid and subsurface drainage is relatively slow. Mean annual precipitation is near 42 inches, mean annual Class A pan evaporation near 65 inches, and normal annual runoff near 10 inches.



LEGEND:

▲ FLOWPOINT
● HOURLY PRECIP
○ DAILY PRECIP
- - - BASIN DIVIDE OR MBP ZONE DEMARCATION

MBP CODINGS FOR NWSRFSI; WATTS TOTAL AREA= 635 MI^2; TAHLEQUAH TOTAL AREA= 959 MI^2; ZONE 1 = 162 MI^2; ZONE 2=162 MI^2; ZONE 3= 317 MI^2, ZONE 4=318 MI^2

Figure 1 -- Illinois River basin map and rain gage development network.

3. DATA PREPARATION

The record length chosen for calibration was the 8-year period 10/63 through 9/71. Data reduction was performed as follows:

A. Program PRELIM1 run to strip from NCC master data tapes hourly precip for selected stations. Output from run on scratch tape.

B. Program PRELIM2 run to strip from NCC master data tapes daily precip for selected stations. Output from run on scratch tape.

C. Program DAILYF run to strip from U.S.G.S. master data tapes the mean daily flows for Watts and Tahlequah. Output from run on scratch tape.

D. PE (potential evaporation) data derived from Ft. Gibson Dam Class A pan records coded on punch cards in O/H standard card format (this service provided by the Ft. Worth RFC). Program NWSRFS2 run to load PE data onto tape in NWSRFS standard tape format.

E. Program NWSRFS1 run using output tapes from PRELIM1 and PRELIM2 as input data. NWSRFS1 MBP output for total area above Watts and Tahlequah as well as for the MBP zones loaded on scratch tape. The procedure for determining the zone areas over which MBP is to be computed is discussed in section 4.

F. Program SUPERTP run to consolidate MBP, PE, and DAILYF tape files onto one master tape that will serve as a complete input data set for calibration programs NWSRFS4 (Verification mode) and NWSRFS3 (Optimizer mode).

4. RAINFALL DISTRIBUTION

Figure 2 displays the relationship between basin inflow histogram, isochrones, and NBP zones for the drainage area above Tahlequah. For multizone simulation at the upstream Watts gage, only zones 3 and 4 were used. Figure 3 presents the Watts and Tahlequah MBP-histogram assignments. The development of the Tahlequah input rainfall distribution will be discussed to illustrate the method.

A Tahlequah total area unit graph was backrouted using an assumed K, as discussed on pages 7 and 8 of HYDRO-14, resulting in a time delay histogram. On a basin map displaying the main drainage pattern of the basin, and moving upstream from the Tahlequah gage, unit distances were marked off along the main stem and tributaries representing watercourse travel times. The unit distance per unit time varies according to arbitrary water velocity values, and may be considered a function of the basin terrain only. For example, let V=1 unit distance for flat topography; V=2 unit distance for rolling hills and V=3 unit distance for steep slopes. Six-hour isochrones were then drawn connecting these marks of equal watercourse travel time so that the area between isochrones was equal to the fraction of the total basin area indicated by the associated histogram element. The histogram element gives the size of area drained in 6 hours--the area defined by the isochrone. One may now view the isochronal analysis in conjunction with the rain gage network to determine suitable MBP zones. One could conceivably choose a separate MBP area for each zone, although it is obvious from the rain gage network in figure 1 that such a fine zone definition could hardly be justified in the case of the Illinois basin. By exercising some imagination (hydrologists are brilliant practitioners of this art), considering what weight each rain gage would have in a proposed zone, and the general west-to-east movement of showers across the basin, it was decided to define four MBP zones. The zone boundaries were drawn to encompass certain isochrones. One could, of course, bound each of the four zones by an isochrone, but such precision is probably unwarranted. Also, the histogram may be modified considerably before calibration is complete. It is perhaps a reasonable rule to keep the MBP zones within 20% of the sum of the encompassed isochronal areas. This is an arbitrary figure based upon limited experience using a distributed input model.

Having defined the zones for the basin, which hopefully will better reflect the areal distribution of convective rains, the basin and interior zones may be gridded for card input to program NWSRFS1. This requires an 80-card deck for each basin and zone. Table 1 lists the station weights computed by NWSRFS1 for flowpoint total area (TA) and each zone.

Table I. -- Precipitation station weights

	Basin		Zones		
Station	Tahl TA	Watts TA	1	2	3
Bentonville	.07	.10		.05	.11
Fay Exp. Stn.	.21	.31		.03	.17
Gravette	.03	.02		.10	.03
Jay				.01	
Kansas Iese	.13	.02	.42	.23	.04
Natural Dam					.01
Odell	.10	.16		.01	.13
Rogers	.08	.11			.02
Rose	.02		.11		
Siloam Springs	.24	.23	.03	.56	.39
Stillwell	.05	.05	.08	.01	.10
Tahlequah	.07		.36		

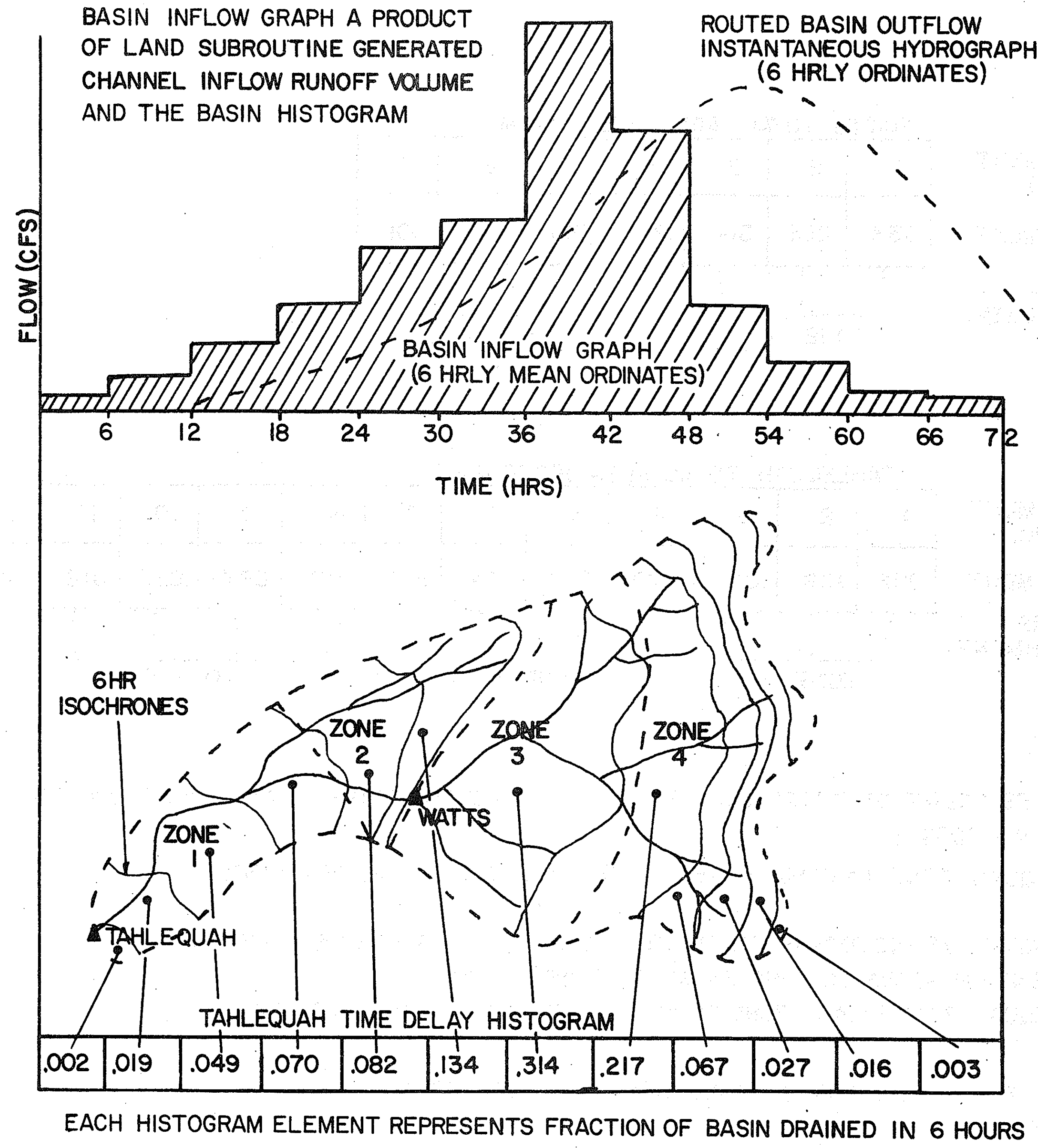


Figure 2. -- Derivation of Tahlequah basin inflow.

WATTS TOTAL AREA HISTOGRAM

ELEMENT NO.	1	2	3	4	5	6	7
ELEMENT	.033	.255	.314	.263	.091	.043	.001

MBP ASSIGNMENT

ZONE 3 ZONE 4

TAHLEQUAH TOTAL AREA HISTOGRAM

ELEMENT NO.	1	2	3	4	5	6	7	8	9	10	11	12
ELEMENT	.002	.019	.049	.070	.082	.134	.314	.217	.067	.027	.016	.003

MBP ASSIGNMENT

ZONE 1 ZONE 2 ZONE 3 ZONE 4

ZONE PER CENT OF TOTAL DRAINAGE AREA CODED FOR MBP*: WATTS ZONE 3 = 50%, ZONE 4 = 50%

TAHLEQUAH ZONE 1 = 17%, ZONE 2 = 17%, ZONE 3 = 33%, ZONE 4 = 33%

SUMMATION OF HISTOGRAM ELEMENTS ASSIGNED TO EACH ZONE EXPRESSED IN PERCENTAGE*: WATTS ZONE 3 = 60%, ZONE 4 = 40%.

TAHLEQUAH ZONE 1 = 14%, ZONE 2 = 22%, ZONE 3 = 31%, ZONE 4 = 33%.

* ALL PER CENT FIGURES ROUNDED (TO SUM) TO 100%

Figure 3. -- Assignment of MBP areas to channel inflow histogram elements.

5. CALIBRATION PROCEDURE AND HYDROGRAPH ANALYSIS

Before attempting multizone simulation at Watts and Tahlequah, we felt it was necessary to first obtain reasonable simulation at both flowpoints using the computed MBP for the total area above Watts and the total area above Tahlequah. This standard lumped input - lumped parameter approach, which is within the model fitting skill range of the author, would provide a reasonable set of initial model parameters for final multizone calibration. The calibration procedure is outlined in HYDRO-14 and so is not discussed here in detail. Ten trial-and-error (verification) runs were made, simulating both Watts and Tahlequah for the period 10/63 - 9/71, and two pattern search optimizer runs were made for each of the flowpoints for the period 8/65 - 9/69. The warping routine feature of the Calibration Model (NWSRFS3), as described in HYDRO-14, improved basin simulation once flow volumes were reasonably correct. The final abridged simulation error statistics are presented in table 2-A.

Table 2. -- Final run multiyear simulation error statistics

	A. Total area		B. Multizones	
Statistic	Watts	Tahlequah	Watts	Tahlequah
Sim. mean	493.9	778.6	537.2	744.4
Obs. mean	524.7	757.7	524.7	757.7
Bias	-30.8	20.9	12.5	-13.3
O/O bias	-5.8	2.8	2.4	-1.7
COR COEF	.92	.92	.94	.95
Line fit				
A	11.6	69.8	-15.4	8.6
B	1.03	0.88	1.01	1.00
RMS	446.8	626.3	406.7	540.3

At this point in calibration, attention was turned to the possibility of improving simulation through the use of multizone distributed rainfall, distributed parameters. A verification run for Watts and Tahlequah was made, assigning the zone MBP areas to appropriate histogram elements, as shown in figure 3, and the total area parameters to each zone. The result was a slight degeneration in the run error statistics for each flowpoint. However, as Sittner (1974) has pointed out, these statistics may not necessarily reflect simulation improvement. And it should be stressed that the parameters used were developed for a lumped rainfall input, to which some error must be assigned. A visual examination of the plotted hydrographs, simulated vs. observed, is an essential supplement to statistical analysis, and it is here that one encounters some interesting results. At both Watts and Tahlequah, for spring and summer rises when areal variability of precipitation is likely to be greatest there was evidence of improved simulation. This observation was validated to some extent by the flow interval statistics, which indicated improvement in simulation at high flows. Subsequently, we decided to adjust individual zone parameters to better reflect the sub-basin hydrology, and hopefully, to improve overall basin simulation. The obvious place to start was the Tahlequah downstream zones 1 and 2. Considering that the difference in individual parameters between Watts and Tahlequah reflects the change in hydrology between headwater zones and downstream local zones, adjusted parameter values for zones 1 and 2 were computed as

TAHL total DA = 959 mi^2 Watts total DA = 635 mi^2

Zones 1 & 2 DA = 324 mi^2 Watts EPXM = 0.366 TAHL EPXM = 0.526

$$\frac{(0.366) \cdot (635) + X \cdot (324)}{959} = 0.526; \; X = 0.840$$

Hence, the parameter EPXM value of 0.840 was assigned to both zones 1 and 2. Similarly, adjustments were made to other selected parameters, and the new values coded for verification. This time the verification run error statistics indicated slightly improved simulation over a majority of the flow intervals, with the most significant gain occurring at high flows. Rational but rudimentary parameter adjustments were then made to the individual zones 3 and 4 above Watts, mostly on the basis of the parameter trend between Watts zones and the Tahlequah local zones. Example: for a Watts total area LZSN parameter value of 9.25 inches and a Tahlequah zone 1 and 2 LZSN value of 10.00 inches, the decision was made to arbitrarily assign a Watts zone 4 LZSN = 8.75 inches, and a zone 3 LZSN = 9.50 inches. The subsequent verification run revealed no significant change in simulation at either Watts or Tahlequah. It appears, based upon the statistics used, that the model is not sensitive to minor and closely compensating parameter changes between adjacent zones. Perhaps this is true regardless of the gage network density. Therefore, the decision was made to abandon further attempts at individual zone parameter manipulation, but rather continue assigning the same parameter set according to an upstream (zones 3,4) vs. downstream (zones 1,2) demarcation, still utilizing the four-zone MBP. However, it should be emphasized that different statistics tailored to single storm analysis, or different parameter combinations, might indeed reveal a degree of model sensitivity between individual zones that was not evident. One should not conclude, based upon success in zone parameter adjustment at Tahlequah but lack of success at Watts, that an intermediate gage is necessary to utilize the technique. In-depth research on the subject could conceivably prove that significant improvement in simulation is obtained by varying parameters within a single catchment defined by one streamflow record. The problem is one of determining how best to do this. For the Illinois River basin, the Watts gage calibration simply provided additional hydrologic intelligence that reduced the number of "trial and error" simulation runs needed to fit a distributed parameter model to Tahlequah.

At this point it would be worthwhile to document the improvement in Tahlequah high-flow simulation obtained with multizones. Table 3 presents a simulation evaluation for Tahlequah, gleaned from inspection of storm hydrographs and monthly standard error statistics. For storm mean daily flow peaks, the comparison was the absolute value of simulated minus observed flow. This error value was, tabulated for (a) total area simulation (lumped input-lumped parameter) vs. distributed input simulation, table 3-A; (b) total area simulation vs. distributed input-distributed parameter simulation, table 3-C (parameter adjustments to downstream zone set 1, 2 and upstream zone sets 3,4). Rises 3/4 bankfull or greater were considered significant. The multizone simulated peak was evaluated in this manner: If multizone simulation error was within ± 10% of the total area simulation error, the multizone peak fell into the "same" category. In other words, we felt that no simulation improvement was achieved over total area simulation. Otherwise, the multizone peak was classified as "better" or "worse", depending upon whether the multizone simulation error was less than or greater than the total area simulation error. No allowance was made for simulation timing errors; the value of the simulated ordinate at the observed peak day was considered to be the simulation peak. Similarly, using the 10% change criterion, the end-of-month total flow standard error values were categorized and tabulated (tables 3-B and 3-D). Table 3-A admittedly does not indicate a great advantage in simulation with zone-distributed rainfall over the lumped input simulation, but it should be pointed out that the greatest improvement did occur for over-bank rises. And careful examination of table 3-A certainly reveals a trend toward improved simulation during months of most prevalent and intense convective activity. Table 3-C clearly indicates the high flow simulation improvement obtained by adjusting the downstream Tahlequah zones, and this is supported by the figures in table 3-D. These tabulations and visual inspection of the hydrographs indicate that for the test basin a multizone model can better reconstitute a storm hydrograph. Figure 4 presents sample hydrograph traces for each simulation mode. Unless shown otherwise, the hydrographs for multizone rainfall only and multizone rainfall and parameters are superimposed.

Having manually adjusted the Tahlequah lower zone parameters with satisfactory results, it was decided to rely on the calibration Model (NWSRFS3), using two MBP zones (3 and 4), as input for a Watts optimization run. NWSRFS3 is restricted to two zones for parameter optimization, and the same parameters are assigned to each zone. The optimizer output parameters were then tested with the verification program. Some improvement in simulation was of course obtained, and the new upstream parameters were coded for a Tahlequah verification run. The resulting Tahlequah hydrograph set did not differ significantly from previous runs. Table 2-B presents the Watts and Tahlequah abridged final run multiyear statistical summaries for distributed input and distributed parameters.

Table 3. -- Tahlequah simulation evaluation for individual rises and monthly standard error: 39 storms and 96 months of data

A. Peak flow evaluation criterion

Total area vs. 4-zone distributed rainfall

Zone simulation	J-F	M-A	M-J	J-A	S-O	N-D	Total
Better	0	3	3	2	2	0	10
Same	1	6	4	4	5	0	20
Worse	2	2	1	1	1	2	9

B. Monthly std error evaluation criterion

Total area vs. 4-zone distributed rainfall

Zone simulation	J-F	M-A	M-J	J-A	S-O	N-D	Total
Better	3	5	4	5	5	2	24
Same	8	8	9	8	8	10	51
Worse	5	3	3	3	3	4	21

C. Peak flow evaluation criterion

Total area vs. 4-zone distributed rainfall - distributed parameters

Zone simulation	J-F	M-A	M-J	J-A	S-O	N-D	Total
Better	0	5	4	4	2	0	15
Same	2	4	3	2	5	1	17
Worse	1	2	1	1	1	1	7

D. Monthly std error evaluation criterion

Total area vs. 4-zone distributed rainfall - distributed parameters

Zone simulation	J-F	M-A	M-J	J-A	S-O	N-D	Total
Better	4	6	6	5	4	4	29
Same	8	8	8	9	10	7	50
Worse	4	2	2	2	2	5	17

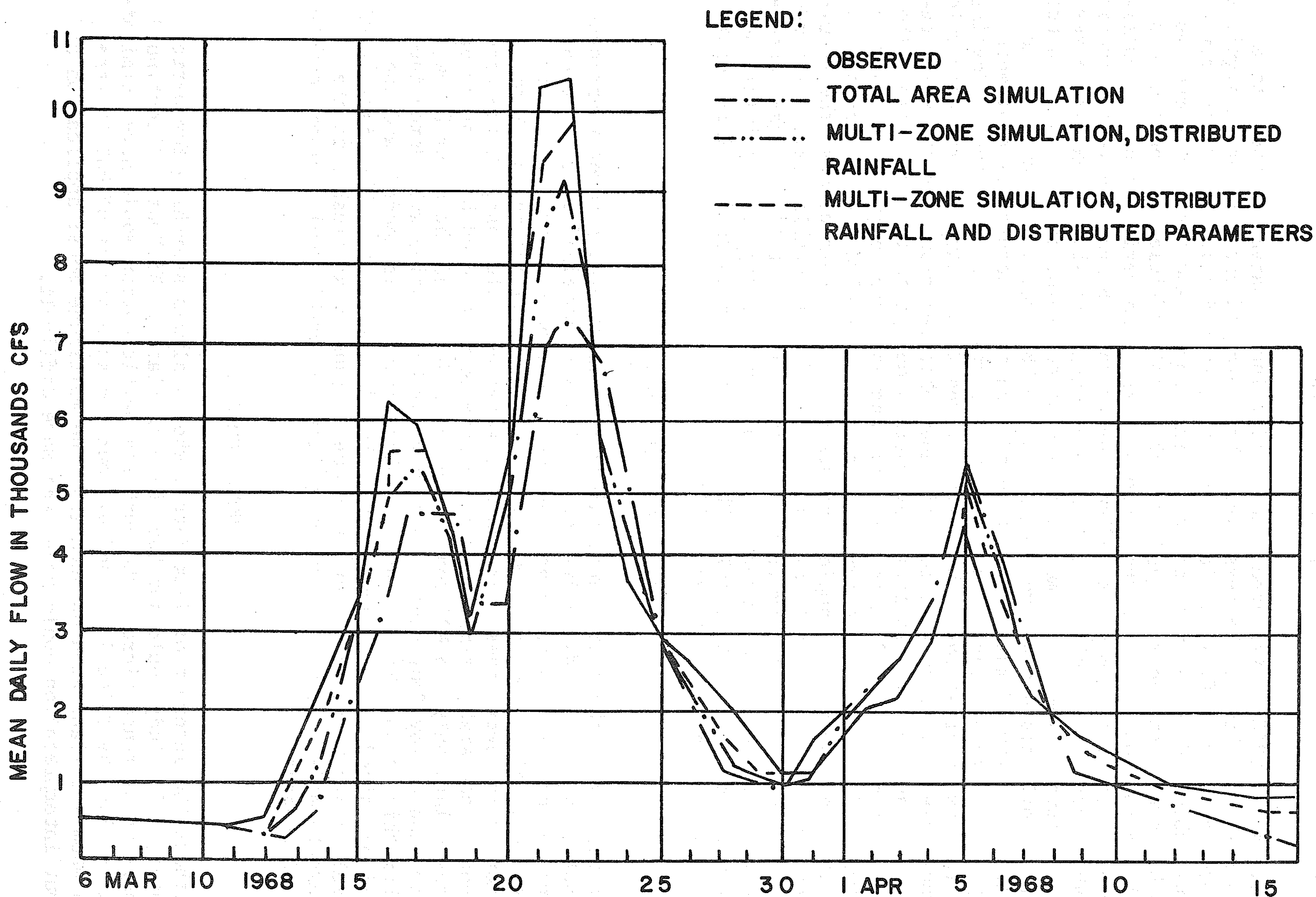


Figure 4. -- Sample hydrograph simulation at Tahlequah.

6. CONCLUSIONS

Fitting a NWSRFS distributed input - distributed parameter model to a basin has been shown to be feasible. There are indications that a significant improvement in high-flow simulation may be obtained using multizones for basins subjected to intense convective rainstorms, and the improvement is possible even when the rain gage network is not sufficiently dense across the basin to closely define the storm pattern. The verification run multi-year error statistics may not reflect the improved hydrograph reconstitution for major storms, as this results in some degenerate simulation for lesser rises. Improved low flow simulation is also possible, perhaps due to a more accurate soil moisture accounting within the MBP areas. The crux of the argument in favor of multizones is based upon the interpretation of mean daily flow storm hydrographs and resulting statistics. When one is dealing with too few major storms with cresting times 2 to 5 days to draw conclusions, it would seem better to also code six-hour observed flows for the verification runs, and key the simulation hydrograph output to the same form. The use of mean daily flow figures for error analysis can be justified only on the basis of having a large number of events peaks with random diurnal distribution. Where the sample consists of so few storm events, the results are open to question. Certainly, more sophisticated statistics are in order for the type of analyses required. In particular, a statistic that measures the degree of simulation improvement related to the degree of rainfall non-uniformity would be most useful. The error categories used in this report are simply <u>indices</u> to areal variability.

7. RECOMMENDATIONS

The utility of the distributed rainfall - distributed parameter approach has not been proven. While similar results were obtained over two other basins in the Arkansas drainage, one must question the possibility of achieving equally adequate simulation by a more skillful manipulation of parameters in fewer zones. At least it seems possible that, in the case of Tahlequah, comparable simulation could have been achieved by breaking up the basin into only two MBP zones, one above Watts and the other below, rather than employ four zones. But only further testing will determine whether this is so. This is an area where research is needed, and the questions raised in this report should be addressed soon. The distributed rainfall-distributed parameter technique is equally applicable to the Sacramento Model, although such an application would require minor computer program changes.

ACKNOWLEDGMENTS

Without the interest of Jack Yates, who is always searching for better methods, this study would not have been initiated. Without the continued support of Clarence Vicroy, the author's participation would have terminated upon leaving the Tulsa RFC. And without the sage advice of Walt Sittner, with whom I collaborated on occasion, the multizone model application and output interpretation would have been more difficult.

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