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FINAL REPORT

EFFECTS OF BASIN RAINFALL ESTIMATES ON DAM SAFETY DESIGN IN ILLINOIS

by

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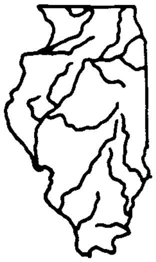
prepared for

Illinois Department of Transportation
Division of Water Resources



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INTRODUCTION

In a previous report, Huff (1980) proposed a set of rainfall frequency estimates and precipitation time distributions for use in determining basin runoff for the dam safety investigations conducted in Illinois. This information was in response to a general need for guidelines which more strictly define precipitation characteristics and other hydrologic design criteria to be used in the Illinois Dam Safety Program. In order that the precipitation relations proposed by Huff may be properly evaluated by the Illinois Division of Water Resources, which administers the Dam Safety Program, it is necessary to obtain some understanding of the responses of various reservoirs to variations in basin-wide precipitation. To achieve such an understanding, this study: 1) reviews alternative methods of describing the magnitude and temporal distribution of basin rainfall, and 2) determines the effects of use of the alternative precipitation estimates on the basin runoff and the resulting reservoir outflow hydrographs. The objective of this study is to recommend a procedure for representing basin rainfall for future dam safety studies in Illinois which will give conservative, yet realistic estimations of reservoir design floods. This recommended procedure is presented in the final section of this report.

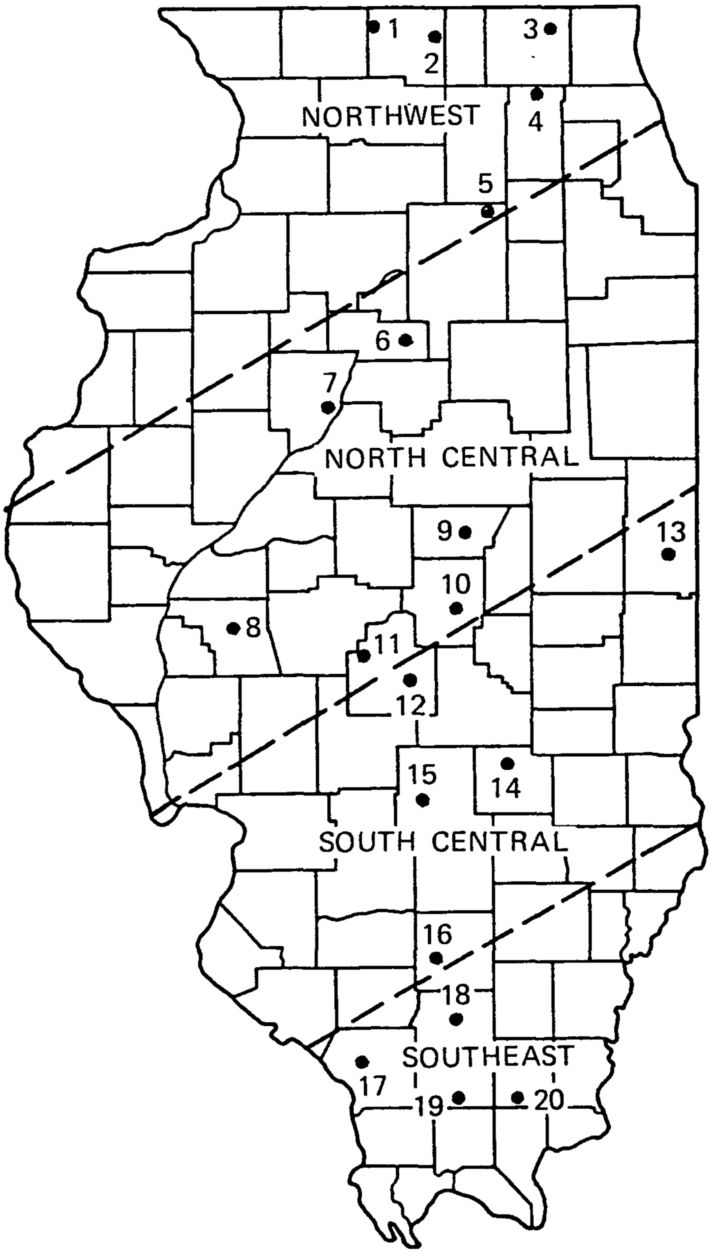
METHOD OF ANALYSIS

Twenty reservoirs were selected by the Illinois Division of Water Resources for measurement of the effects of the precipitation variation on the reservoir design floods. The reservoirs were chosen such that a wide variety of basin sizes from various regions in the state were represented. The locations of these reservoirs are shown in Figure 1. Various watershed and hydrologic information associated with these reservoirs is given in Table 1. Dam safety investigation reports have been completed for each of the twenty reservoirs, and reservoir routing and basin runoff information from these reports was supplied by the Division of Water Resources and the U.S. Army Corps of Engineers, Chicago District. The non-precipitation inputs provided in the completed dam safety reports were duplicated or closely approximated for use in the basin runoff and reservoir routing computations in this study.

Approximately 50 variations in the precipitation characteristics were applied to the watersheds of each reservoir. The changes in precipitation input are classified as follows:

1) Precipitation magnitude estimates - Estimates of the probable maximum precipitation (PMP) and 100-year storm precipitation were chosen between the values presented by Huff (1980); three National Weather Service publications (Riedel et al., 1956; Hershfield, 1961; Schreiner and Riedel, 1978); and the U.S. Soil Conservation Service National Engineering Handbook (SCS, 1972).
2) Precipitation distribution techniques - The four distributions to be considered are the HEC-1 Standard Project Storm (U.S. Army Corps of Engineers, 1952); SCS Type-II distribution (Kent, 1968); NEH-4 Emergency Spillway rainfall distribution (U.S. SCS, 1972); and the Huff family of distributions (1967; 1980).
3) Storm durations - Varying in duration from 1 to 48 hours.

The available alternatives in each of these three categories are reviewed and evaluated in the initial sections of this study. Then the range of response of the basin runoff and reservoir outflow to the alternatives within each category is examined, as is the effect of various combinations of magnitude, distribution, and duration. Basin runoff and reservoir outflow data are based on computations performed using the HEC-1 Dam Safety Flood Hydrograph Package (U.S. Army Corps of Engineers, 1978). The sensitivity of the probable maximum and 100-year design floods to changes in the precipitation input is measured by



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3. Wonder Lake
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5. Lake Holiday
6. Lake Wildwood
7. Hollis Park Lake
8. Mauvaise Terre Lake
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16. Waltonville Lake
17. Kinkaid Lake
18. New City Lake
19. Lake of Egypt
20. Glen O. Jones Lake

Figure 1. Locations of the reservoirs analyzed and of the four Illinois rainfall regions

Table 1. Basin Runoff and Reservoir Storage Characteristics for the Twenty Reservoirs Studied

	(1) D.A.	(2) T_p	(3) w_{50}	(4) S_{af}	(5) S_{in}	(6) S_5
Northwest Region						
Tara Lake	1.11	1.0	1.3	57	.97	.17
Lake Summerset	6.38	1.1	1.5	4985	14.65	7.32
Pierce Lake	13.1	4.2	3.7	2660	3.81	.71
Lake Holiday	64.6	10.0	15.0	2223	.65	.36
Wonder Lake	97.2	15.1	21.0	4877	.94	.42
North Central Region						
Hollis Park Lake	.82	.15	.3	533	12.04	4.07
Lake Wildwood	12.1	5.6	12.0	6496	10.07	1.07
Mauvaise Terre Lake	34.3	9.5	14.0	1820	.99	.24
Sangchris Lake	74.0	14.0	15.0	34000	8.61	2.13
Clinton Lake	291.5	15.0	25.0	74200	4.77	1.87
Lake Decatur	906.0	34.0	42.0	17456	.36	.26
South Central Region						
Waltonville Lake	.53	.9	1.1	75	2.70	1.73
Lake Sara	12.3	1.5	1.7	11720	17.87	6.75
Vandalia City Lake	25.0	9.0	12.0	5560	4.17	1.05
Lake Taylorville	125.0	17.0	25.0	10394	1.56	.32
Lake Vermilion	298.0	35.0	43.0	4641	.29	.04
Southeast Region						
Glen 0. Jones Lake	1.51	1.3	1.3	1433	17.91	5.22
New City Lake	7.78	5.1	6.0	1700	4.09	.89
Lake of Egypt	33.3	4.5	3.2	41215	23.21	6.15
Kinkaid Lake	62.3	4.0	4.0	78500	23.63	4.66

(1) Drainage area of the watershed (square miles)

(2) Time to peak of the unit hydrograph (hours)

(3) Width of the unit hydrograph at 50% of peak discharge (hours)

(4) Storage of the reservoir at normal pool level (acre-feet)

(5) Storage of the reservoir at normal pool level (basin-inches)

(6) Surcharge storage index - the surcharge storage required to incur a corresponding outflow equal to the peak of the unit hydrograph (basin-inches)

three parameters: 1) the peak of the basin runoff hydrograph, 2) the peak reservoir discharge after reservoir routing, and 3) the maximum reservoir stage.

EFFECT OF PRECIPITATION MAGNITUDE ESTIMATES ON BASIN RUNOFF AND ROUTED HYDROGRAPHS

Probable Maximum Precipitation

Four publications are currently available for estimating the PMP in Illinois: the National Weather Service Hydrometeorological Reports 33 (Riedel et al., 1956) and 51 (Schreiner and Riedel, 1978), the NEH-4 6-hour PMP estimates (U.S. SCS, 1972), and the PMP values listed by Huff (1980). The PMP estimates in Hydrometeorological Report (HMR) 51 are revised from the all-season PMP values given in HMR-33. The revisions in HMR-51 provide for 1) an average 3% increase over the HMR-33 values for the 24-hour PMP in Illinois, and 2) geographically smoothed estimates of the PMP for other durations, in effect causing a slight increase in the 6-hour and 12-hour PMP estimates for the southern three-fourths of the state (see Table 2). The Huff values are estimated directly from HMR-33 with two alterations: 1) they are averaged for each of the four Illinois rainfall regions shown in Figure 1 and 2) the estimates are extrapolated for durations less than six hours and for watershed areas less than 10 mi^2.

The methodology given in HMR-51 for estimating the PMP for durations not listed involves drawing a smooth curve on linear graph paper between given points in the depth-duration relationship. Several estimates of the PMP for durations less than six hours (U.S. Bureau of Reclamation, 1977; U.S. Soil Conservation Service, 1972) are similar to the short duration estimates developed using this HMR-51 methodology. In contrast, the short duration PMP estimation technique used by Huff (1980) uses linear extrapolation of the depth-duration relationship on a logarithmic scale. The PMP values estimated by Huff tend to be up to 50% greater than those values developed using the HMR-51 methodology, and they do not represeat much of a reduction of rainfall with decreasing duration. Because of this discrepancy, the Huff estimates for durations less than six hours are not recommended.

A final estimate of the 6-hour PMP is given in the U.S. SCS National Engineering Handbook, Section 4 (NEH-4) for use in estimating the emergency spillway design flood. Table 2 shows that this PMP estimate compares closely with the Huff (and HMR-33) 6-hour PMP. However, the ratios given in NEH-4 which adjust the 6-hour PMP values for longer durations provide for estimates which are 20% larger than the values of the other PMP estimates. Use of these ratio should be avoided.

Though it is believed that the HMR-51 provides the best estimates of the 24-hour PMP, differences between the three PMP estimates listed in Table 2 are well within the conceptual errors inherent with any PMP estimate. Therefore, use of any of the three 24-hour PMP estimates appears reasonable. For all basins smaller than 10 mi^2, the Huff PMP values should be used unless individual depth-area analysis is conducted for small drainage areas following the procedure suggested in HMR-51.

The PMP values listed by all four sources are commonly considered large, mainly because the PMP estimates are calculated using optimum basin shape and storm orientation. If the basin is not aligned with the storm, the total volume of rainfall that falls over the basin should be reduced. The Hopbrook reduction factor (Table 3), developed in the Corps of Engineers and used in the HEC-1 dam safety computer program, is an empirical estimate of the rainfall reduction associated with the basin orientation. It is understood that the Hopbrook factor, which causes a 10 to 20% reduction in the estimate of the PMP, was developed for one site in the eastern United States and has little widespread basis. Nevertheless, this factor has been applied to the PMP for most of the dam safety studies in Illinois. As will be shown shortly, this reduction greatly affects the magnitude of the routed discharges.

Table 2. Comparison of the PMP Estimates for the Twenty Reservoirs

	24-hour PMP Estimates (in.)			Ratio to Huff estimate	
	HMR-51	HMR-33	Huff	HMR-51	HMR-33
Northwest Region					
Tara Lake	31.0	31.4	31.2	.99	1.01
Lake Summerset	31.0	31.0	30.8	1.01	1.01
Pierce Lake	30.6	30.3	30.0	1.02	1.01
Lake Holiday	27.0	26.1	25.6	1.05	1.02
Wonder Lake	25.2	24.2	24.4	1.03	.99
(regional average)				1.02	1.01
North Central Region					
Holliis Park Lake	33.0	30.6	32.0	1.03	.96
Lake Wildwood	31.9	29.4	30.8	1.03	.95
Mauvaise Terre Lake	29.9	28.7	28.4	1.05	1.01
Sangchris Lake	28.1	27.0	26.5	1.06	1.02
Clinton Lake	23.8	23.0	23.0	1.04	1.00
Lake Decatur	19.8	20.4	20.2	.98	1.01
(regional average)				1.03	.99
South Central Region					
Waltonville Lake	33.7	33.8	33.5	1.01	1.01
Lake Sara	33.2	33.2	32.2	1.03	1.03
Vandalia City Lake	31.6	29.8	30.4	1.04	.98
Lake Taylorville	26.4	26.2	26.6	.99	.99
Lake Vermilion	23.1	23.0	22.9	1.03	1.02
(regional average)				1.02	1.01
Southeast Region					
Glen 0. Jones Lake	35.8	34.4	35.0	1.02	.98
New City Lake	35.2	33.8	34.4	1.02	.98
Lake of Egypt	32.8	30.6	31.1	1.05	.98
Kinkaid Lake	30.2	29.3	29.4	1.03	1.00
(regional average)				1.03	.99
Statewide Average				1.03	1.00

	6-hour PMP Estimates (in.)			Ratio to HUff estimate	
	HMR-51	NEH-4	Huff	HMR-51	NEH-4
Northwest Region					
Tara Lake	25.6	24.8	25.9	.99	.96
Lake Summerset	25.4	24.7	25.3	1.01	.98
Pierce Lake	24.8	24.2	24.5	1.01	.99
Lake Holiday	21.4	20.7	20.7	1.03	1.00
Wonder Lake	20.1	19.3	19.6	1.03	.98
(regional average)				1.01	.98
North Central Region					
Hollis Park Lake	26.7	25.4	25.1	1.06	1.01
Lake Wildwood	25.8	24.9	23.9	1.08	1.04
Mauvaise Terre Lake	24.1	23.3	22.1	1.09	1.05
Sangchris Lake	22.0	21.2	19.8	1.11	1.07
Clinton Lake	18.1	16.7	16.5	1.10	1.01
Lake Decatur	14.5	13.4	13.8	1.05	.97
(regional average)				1.08	1.03
South Central Region					
Waltonville Lake	28.0	26.5	27.2	1.03	1.03
Lake Sara	26.9	25.6	25.7	1.05	1.00
Vandalia City Lake	25.2	24.5	23.8	1.06	1.03
Lake Taylorville	20.8	19.4	20.3	1.02	.96
Lake Vermilion	18.0	16.6	17.9	1.00	.93
(regional average)				1.03	.99
Southeast Region					
Glen 0. Jones Lake	28.5	27.4	27.7	1.03	.99
New City Lake	28.1	27.0	27.0	1.04	1.00
Lake of Egypt	25.3	24.8	24.3	1.04	1.02
Kinkaid Lake	23.6	22.7	22.8	1.04	1.00
(regional average)				1.04	1.00
Statewide Average				1.04	1.00

Table 3. Hopbrook Reduction Factor for Probable Maximum Precipitation

Drainage Area Sq. Mi.	Reduction in Precipitation	Adjustment Factor
1000	10 %	.90
500	10	.90
200	11	.89
100	13	.87
50	15	.85
<10	20	.80

The National Weather Service HMR-52, currently planned for publication around August, 1981, provides a methodology to be used for individual basins to estimate the precipitation reduction caused by basin shape and orientation. Reduction factors produced by the HMR-52 methodology are accepted as being vastly superior to the Hopbrook reduction factor, and the use of HMR-52 is suggested for all PMP estimates after the report's release. Although no advantage is seen in using the Hopbrook factor, its use is favored during the interim so that continuity in methodology with previous dam safety reports may be maintained. It is believed that the magnitude of reduction using the HMR-52 methodology will be less than the Hopbrook reduction for most basins in Illinois.

For each reservoir, the basin runoff hydrographs and their respective routed hydrographs have been computed applying three separate values of the 24-hour PMP. The three PMP estimates used are 1) the HMR-51 PMP estimate with the Hopbrook factor, 2) the Huff PMP estimate with the Hopbrook factor, and 3) the Huff PMP estimate without the Hopbrook factor. The HMR-33 PMP estimates are not sufficiently dissimilar to the Huff values to warrant individual analysis. In each case the precipitation was distributed by the HEC-1 24-hour Standard Project Storm distribution which is described in a later section. The HEC-1 time distribution was chosen because of its standard usage in the dam safety investigations.

Table 4. Maximum Basin Runoff and Reservoir Discharge for Various Precipitation Estimates Using the HEC-1 Rainfall Distribution

Peak Basin Runoff (cfs)

	PMP Estimates			100-Year Rainfall Estimates	
	HMR-51 with Hopbrook	Huff with Hopbrook	Huff w/o Hopbrook	TP-40	Huff
Northwest Region					
Tara Lake	3989	4011	5047	760	1063
Lake Summerset	22248	21856	27448	4429	5867
Pierce Lake	29516	29065	36234	5286	7370
Lake Holiday	46390	44002	51948	8417	12072
Wonder Lake	46430	44706	51714	9319	14132
North Central Region					
Hollis Park Lake	6189	5802	7279	1277	1399
Lake Wildwood	11831	11181	14105	1944	2224
Mauvaise Terre Lake	25786	23928	29603	5854	6051
Sangchris Lake	43990	41071	48355	8652	9332
Clinton Lake	132609	126438	143875	22288	26957
Lake Decatur	170062	172512	194638	38975	1(2695
South Central Region					
Waltonville Lake	2535	2432	3061	459	582
Lake Sara	43814	41832	51902	8427	10503
Vandalia City Lake	23978	23177	28238	4566	5878
Lake Taylorville	58082	59091	68355	11342	15683
Lake Vermilion	65159	65295	74024	12116	18080
Southeast Region					
Glen O. Jones Lake	5669	5591	7021	1175	1508
New City Lake	14733	14029	17614	3005	3793
Lake of Egypt	86452	82047	99056	18809	23045
Kinkaid Lake	124136	123858	141441	28211	34990

Peak Reservoir Discharge (cfs)

	PMP Estimates			100-Year Rainfall Estimates	
	HMR-51 with Hopbrook	Huff with Hopbrook	Huff w/o Hopbrook	TP-40	Huff
Northwest Region					
Tara Lake	3975	4000	5007	756	1058
Lake Summerset	18702	18604	24748	564	686
Pierce Lake	27466	27027	33809	4234	6201
Lake Holiday	45410	42849	51046	7034	10363
Wonder Lake	45617	43830	50740	7489	12969
North Central Region					
Hollis Park Lake	5173	4837	6186	127	151
Lake Wildwood	11161	10460	13866	886	1026
Mauvaise Terre Lake	24752	22674	29637	5414	5611
Sangchris Lake	31839	29296	35594	3021	3680
Clinton Lake	105364	99892	117532	8442	10714
Lake Decatur	160846	162713	184218	34181	37421
South Central Region					
Waltonville Lake	2483	2365	3023	245	309
Lake Sara	23320	20714	32831	1512	2174
Vandalia City Lake	21784	20703	26811	2665	3588
Lake Taylorville	54885	56070	65615	9660	14286
Lake Vermilion	63965	64061	73217	11859	17695
Southeast Region					
Glen O. Jones Lake	3291	3207	4148	219	334
New City Lake	12334	11586	15728	2212	2865
Lake of Egypt	28640	26861	33701	3928	5478
Kinkaid Lake	42910	41414	5830	6247	8943

The basin runoff peaks for each of the three PMP estimates, shown in Table 4, are predictably proportional to the precipitation magnitudes, thereby producing average ratios for peak runoff of 1.03 between the HMR-51 and Huff PMP estimates and 1.21 between the Huff estimates with and without Hopbrook. Although the routing characteristics of each reservoir vary, in general the routing procedure tends to slightly magnify the differences in peak runoff between the three PMP estimates. Use of the HMR-51 estimates over the Huff estimates results in an average increase in peak discharge of 4%. The peak discharges derived from using the Huff estimates without the Hopbrook factor show an average 26% increase over those discharges derived using the Hopbrook factor.

Table 5 lists the maximum stage reached at each of the reservoirs with the routed hydrographs from each PMP estimate. The dams at fourteen of the reservoirs are overtopped by all of their respective PMP estimates. The average differential in maximum stage for these fourteen reservoirs is .1 ft. between the HMR-51 and Huff estimates (with Hopbrook) and .8 ft. between the Huff PMP estimates with and without Hopbrook. In this group of fourteen reservoirs, the maximum differential between the floods of HMR-51 and Huff PMP is .3 ft., occurring for Mauvaise Terre Lake. This differential at Mauvaise Terre has the effect of almost doubling the depth of overtopping and increasing the duration of overtopping from 4½ to 6½ hours, both factors seriously influencing possible breaching.

The dams not overtopped by the PMP-with-Hopbrook floods have reservoirs which experience an average differential in stage of .25 ft. between floods using the HMR-51 and Huff PMP values. The average differential in stage between those floods developed with the Hopbrook factor and those developed without the reduction factor is 1.2 ft. Two of the six dams in this group overtop when the Hopbrook factor is used. Thus, the differences in stage dependent upon the choice of whether to use the Hopbrook factor are much more significant than are the differences in stage which occur when comparing the HMR-51 and Huff PMP estimates.

Table 5. Maximum Reservoir Stage for Various Precipitation Estimates Using the HEC-1 Rainfall Distribution

Maximum Pool Level (ft above top of dam)

	PMP Estimates			100-Year Rainfall Estimates	
	HMR-51 with Hopbrook	Huff with Hopbrook	Huff w/o Hopbrook	TP-40	Huff
Northwest Region					
Tara Lake	2.0	2.0	2.3	0.5	0.7
Lake Summerset	2.2	2.2	2.6	-3.6	-2.3
Pierce Lake	3.3	3.2	5.4	-6.0	-4.6
Lake Holiday	1.7	1.5	2.3	-10.0	-7.9
Wonder Lake	5.4	5.2	6.0	-0.4	1.6
North Central Region					
Hollis Park Lake	2.8	2.7	3.1	-0.8	-0.4
Lake Wildwood	0.5	0.4	1.0	-7.2	-6.5
Mauvaise Terre Lake	0.7	O.k	1.5	-5.9	-5.8
Sangchris Lake	-2.4	-2.6	-2.0	-6.8	-6.6
Clinton Lake	-4.9	-5.2	-4.2	-16.1	-15.2
Lake Decatur	6.2	6.3	7.4	=4.7	-4.2
South Central Region					
Waltonville Lake	0.9	0.9	1.1	-1.1	-0.7
Lake Sara	0.7	0.5	1.4	-7.0	-6.0
Vandalia City Lake	1.4	1.3	1.9	-6.6	-5.8
Lake Taylorville	0.0	0.1	1.0	-8.8	-7.7
Lake Vermilion	-0.2	-0.2	1.2	-7.3	-5.6
Southeast Region					
Glen O. Jones Lake	-1.6	-1.7	-0.7	-6.6	-5.9
New City Lake	0.7	0.5	1.4	-5.0	-4.4
Lake of Egypt	-3.2	-3.7	-1.9	-11.9	-11.1
Kinkaid Lake	-0.6	-1.0	0.5	-11.0	-10.0

100-Year Precipitation

Precipitation estimates for return periods of 25, 50, and 100 years are available from both Huff (1980) and the National Weather Service Technical Paper (TP) 40 (Hershfield, 1961). The Huff estimates are listed in the final section of this report. The Huff values represent 40 years of hourly precipitation for approximately 40 locations across Illinois. The TP-40 precipitation estimates employed fewer hourly rainfall measurements and are based to a great extent on adjustments of daily rainfall. For this reason, the Huff values are considered to be more indicative of rainfall frequencies in Illinois.

Rainfall estimates computed for the study reservoirs indicate that for most of the regions in Illinois the Huff precipitation estimates are markedly greater than the corresponding TP-40 estimates (Table 6). However, the North Central region of the state is anomalous in that the Huff precipitation estimates for this region are comparatively low and are only slightly greater than the TP-40 estimates. In the three other "standard" regions of the Northwest, South Central, and Southeast, the 100-year precipitation estimate differentials are 42%, 30%, and 29%, respectively. The average differential between the Huff and TP-40 estimates diminishes with decreasing storm duration and also with decreases in the return period of the precipitation estimates.

As expected, the regional differences between the Huff and TP-40 100-year precipitation estimates are maintained with the subsequent basin runoff. The average ratios between the peak basin runoff resulting from the two 100-year rainfall estimates are 1.41, 1.11, 1.34, and 1.25, for the Northwest, North Central, South Central, and Southeast regions, respectively. After reservoir routing, the average ratios of the maximum flow rate between the two rainfall inputs are increased to 1.46, 1.16, 1.39, and 1.41 for the respective rainfall regions. Thus, the hydrograph routing procedure attenuates the peak of the lesser TP-40 floods to a greater extent than it attenuates the larger Huff floods. However, individual reservoirs will vary in their response because of varying storage-outflow characteristics.

Table 6. Comparison of the 25-Year, 50-Year, and 100-Year Rainfall Estimates for the Twenty Reservoirs

	100-Year 24-hour rainfall		Ratio of 24-hour Huff rainfall to 24-hour TP-40 rainfall		
	Huff	TP-40	100-Year	50-Year	25-Year
Northwest Region					
Tara Lake	8.30	5.70	1.46	1.38	1.21
Lake Summerset	8.24	5.94	1.39	1.36	1.19
Pierce Lake	8.16	5.88	1.39	1.36	1.20
Lake Holiday	7.87	5.55	1.42	1.33	1.19
Wonder Lake	7.81	5.35	1.46	1.39	1.23
(regional average)			1.42	1.33	1.17
North Central Region					
Hollis Park Lake	7.20	6.40	1.13	1.05	.99
Lake Wildwood	7.08	6.08	1.17	1.09	.97
Mauvaise Terre Lake	6.93	6.43	1.08	1.01	.94
Sangchris Lake	6.74	6.16	1.09	1.02	.95
Clinton Lake	6.51	5.73	1.14	1.04	.97
Lake Decatur	6.25	5.76	1.09	1.01	.93
(regional average)			1.11	1.04	.96
South Central Region					
Waltonville Lake	8.40	6.70	1.25	1.13	1.05
Lake Sara	8.28	6.37	1.30	1.17	1.09
Vandalia City Lake	8.10	6.40	1.27	1.15	1.07
Lake Taylorville	7.85	5.98	1.31	1.18	1.10
Lake Vermilion	7.50	5.55	1.35	1.23	1.15
(regional average)			1.30	1.17	1.09
Southeast Region					
Glen O. Jones Lake	8.79	6.80	1.29	1.16	1.13
New City Lake	8.65	6.73	1.29	1.17	1.13
Lake of Egypt	8.47	6.58	1.29	1.17	1.13
Kinkaid Lake	8.38	6.02	1.29	1.14	1.11
(regional average)			1.29	1.16	1.12
Statewide Average			1.28	1.17	1.09

	100-Year 6-hour rainfall		Ratio of 6-hour Huff rainfall to 6-hour TP-40 rainfall		
	Huff	TP-40	100-Year	50-Year	25-Year
Northwest Region					
Tara Lake	5.80	4.30	1.35	1.26	1.16
Lake Summerset	5.74	4.31	1.33	1.24	1.14
Pierce Lake	5.66	4.22	1.34	1.25	1.15
Lake Holiday	5.24	4.10	1.28	1.21	1.11
Wonder Lake	5.11	3.74	1.37	1.26	1.16
(regional average)			1.33	1.25	1.14
North Central Region					
Hollis Park Lake	5.10	4.70	1.09	1.00	.92
Lake Wildwood	4.95	4.46	1.11	1.03	.89
Mauvaise Terre Lake	4.66	4.61	1.01	.95	.88
Sangchris Lake	4.50	4.37	1.03	.96	.90
Clinton Lake	4.11	3.95	1.04	.98	.93
Lake Decatur	3.80	3.89	.98	.96	.89
(regional average)			1.04	.98	.90
South Central Region					
Waltonville Lake	5.90	4.90	1.20	1.08	.98
Lake Sara	5.75	4.45	1.29	1.11	1.01
Vandalia City Lake	5.60	4.66	1.20	1.10	.99
Lake Taylorville	5.15	4.22	1.22	1.11	1.00
Lake Vermilion	4.80	3.78	1.27	1.15	1.06
(regional average)			1.24	1.11	1.01
Southeast Region					
Glen O. Jones Lake	6.29	4.90	1.28	1.15	1.08
New City Lake	6.15	4.85	1.27	1.16	1.08
Lake of Egypt	5.83	4.70	1.24	1.12	1.06
Kinkaid Lake	5.67	4.69	1.21	1.09	1.03
(regional average)			1.25	1.13	1.06
Statewide Average			1.21	1.12	1.03

The increases in peak discharge associated with the 100-year Huff precipitation estimates translate into a mean increase in maximum reservoir stage of .9 ft (Table 5). Again, the average maximum stage response varies between rainfall regions with maximum variance in peak stage occurring in the Northwest region. The dams at two reservoirs, Tara Lake and Wonder Lake, are overtopped using the Huff 100-year rainfall.

COMPARISON OF PRECIPITATION DISTRIBUTIONS

It is generally agreed that the temporal distribution of rainfall plays nearly as important a role in flood occurrence as does the precipitation amount. However, knowledge of the response of basin models to variations in the distribution of precipitation is sorely lacking. Three precipitation distributions, 1) the HEC-1 Standard Project Storm distribution (U.S. Army Corps of Engineers, 1952), 2) the Soil Conservation Service Type-II distribution (Kent, 1968); and 3) the Huff rainfall distribution curves (Huff, 1980), are examined as to their effects on basin runoff and reservoir routing. A brief description of each of these distribution techniques follows.

HEC-1 Standard Project Storm Distribution

The Standard Project Storm (HEC-1) distribution, which was developed by the U.S. Army Corps of Engineers, is routinely used for the dam safety investigations in Illinois. The HEC-1 rainfall distribution requires the user to supply the percentages of the 24-hour precipitation to be allocated to the maximum six- and twelve-hour segments of the 24-hour storm. The maximum six-hour precipitation is placed in the third quartile of the 24-hour storm; the six hours within this maximum quartile are assigned the following percentages of distribution: 10%, 12%, 15%, 38%, 15%, 11%. All other storm quartiles are given a uniform rainfall distribution.

The Standard Project Storm time distribution was developed through observations of selected extreme storms. As originally designed, the third quartile in a storm of the PMP magnitude was allocated approximately 55% of the 24-hour total. However, in common use this quartile contains the maximum PMP 6-hour precipitation, which is 75% to 80% of the 24-hour PMP. With this practice, the HEC-1 distribution cannot be considered representative of historic storms; however, it does represent the maximum possible concentration of rainfall within each quartile of the 24-hour probable maximum storm. Such a rainfall distribution is agreeable for use with the PMP because it describes extreme, yet possible conditions. An example of a common 24-hour HEC-1 distribution is shown in Figure 2a.

SCS Type-II Storm Distribution

The SCS Type-II distribution is structured from the 25-year frequency rainfalls listed in the National Weather Service TP-40 (Hershfield, 1961). The distribution was developed by first placing the 25-year 30-minute rainfall depth at the center of a 24-hour storm. The second largest 30-minute depth (needed to cumulate to the 25-year one-hour depth) was assumed to occur directly after the maximum 30-minute depth. Rainfall depths were subsequently arranged so that the most intense rainfall for a storm of any duration was centered in the 24-hour distribution. This procedure was carried out for several locations in the United States, exclusive of the west coast. The non-dimensionalized graphs of these rainfall accumulations form the basis for the Type-II rainfall distribution, pictured in Figure 2b. The Type-II rainfall was developed by the Soil Conservation Service primarily for use in small watersheds.

NEH-4 Emergency Spillway Storm Distribution

The NEH-4 Emergency Spillway storm is a six-hour distribution visually similar to the six-hour Type-II curve. However, the NEH-4 distribution appears to more accurately depict the depth-duration

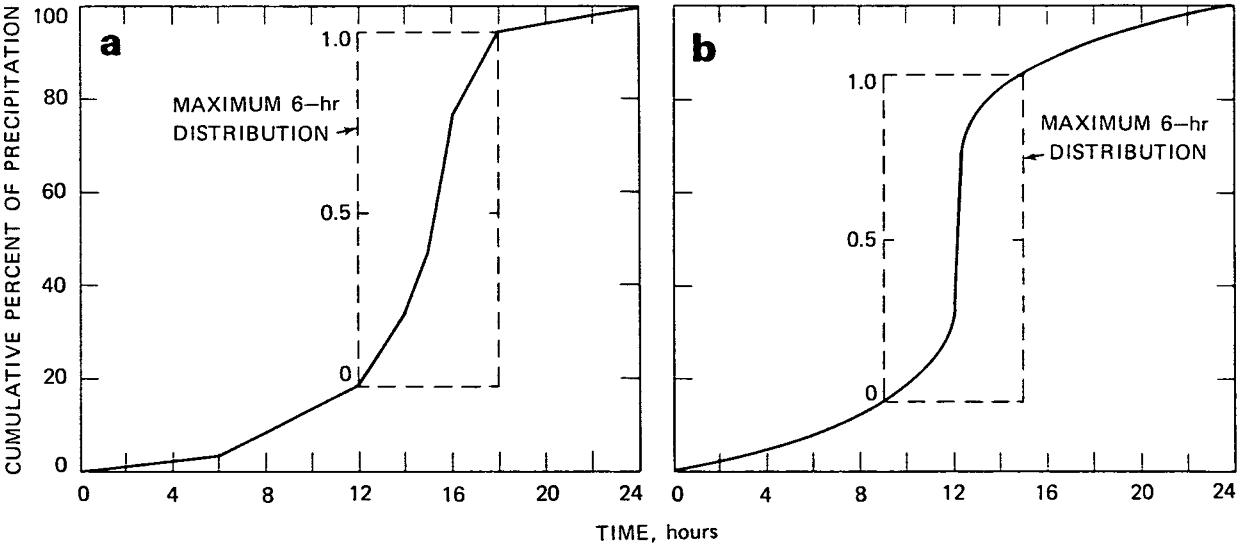

Figure 2. Time distribution of the 24-hour a) HEC-1 storm, and b) SCS Type-II storm

relationship associated with the PMP. As such, this distribution contains maximum intensities similar to, but slightly greater than, the HEC-1 distribution. Expansion of this distribution destroys its maximal rainfall qualities; therefore it is best used as a six-hour distribution, and as such is compatible for use with the PMP in small basins. This distribution does not receive much detailed analysis in this study because its effect on basin runoff and routed hydrographs is similar to that of the six-hour HEC-1 distribution.

Huff Rainfall Distributions

The Huff rainfall distributions are a family of curves developed by Huff (1967) based on 261 heavy rainfall events in Illinois. Huff classified the rainstorms depending on which quartile of the storm period received the heaviest rainfall. Within each classification, various curves of exceedance probability were computed (see Figure 3). The 50% curve in each figure represents the median time distribution of storms within that classification. Though these curves do not contain rainfall bursts characteristic of point rainfall, they adequately describe a realistic rainfall time distribution for all sizes of natural watersheds.

For storms of duration less than 12 hours Huff recommends that first and second quartile distributions be used. Further investigation has showed that first quartile storms are much more prevalent for these durations. Huff also recommends that storms of duration 12 to 24 hours should use a Huff 3 (third quartile) distribution and that storms of duration greater than 24 hours should use a Huff 4 (fourth quartile) distribution. All applications of the Huff distribution in this report follow these storm type-duration recommendations. The 50% curve of the recommended storm type is used in all cases.

Comparison of Rainfall Distributions

When the SCS Type-II, HEC-1, and Huff 3 time distributions of 24-hour rainfall are plotted together, the SCS Type-II curve appears pronounced with its inclusion of extremely heavy rainfall intensity. The

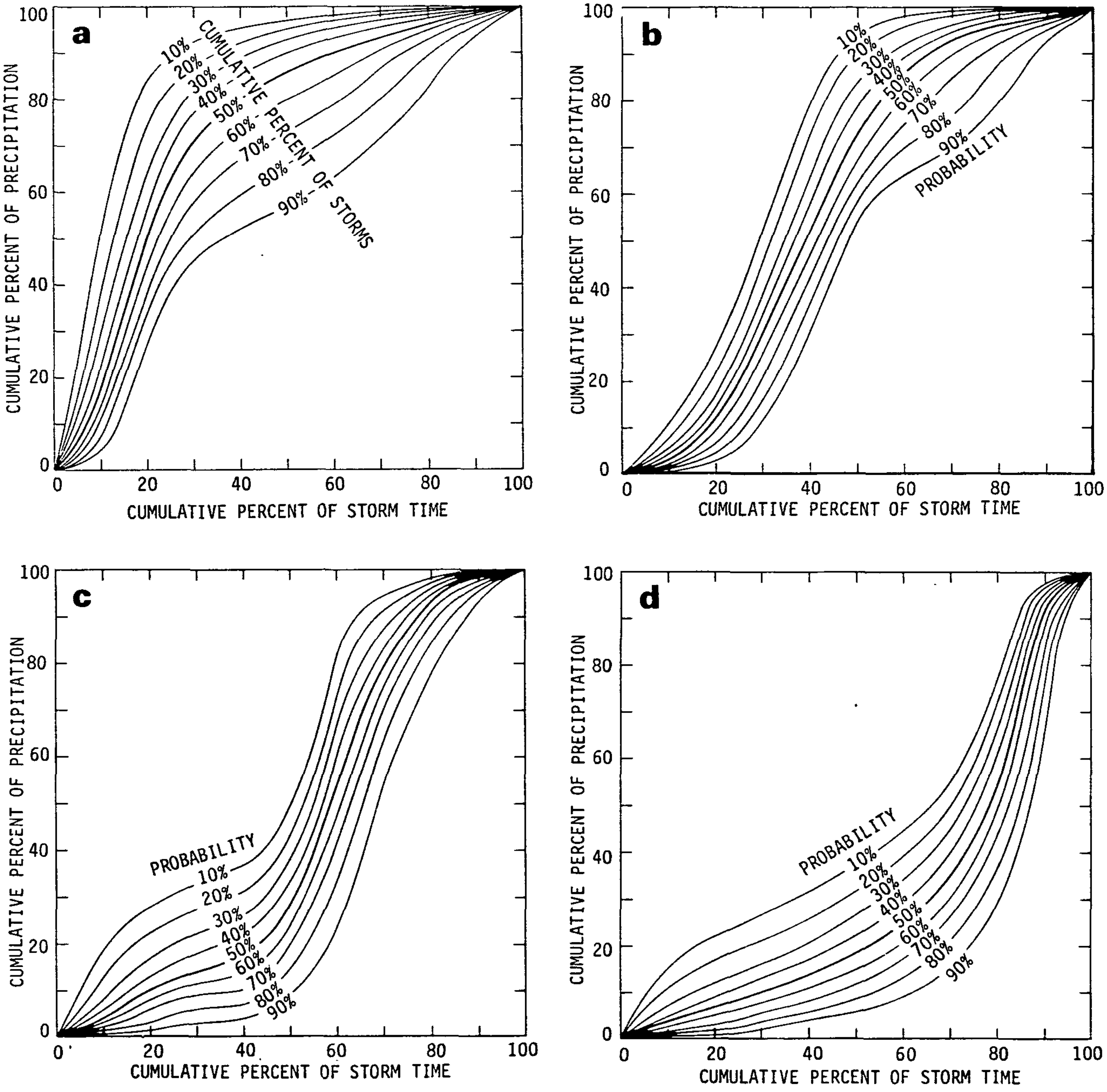

Figure 3. Time distribution of the Huff rainfall curves: a) first quartile, b) second quartile, c) third quartile, d) fourth quartile

HEC-1 distribution has the second highest intensities and is also distinguished in that it concentrates the greatest amount of rainfall within a six-hour period. The Huff 3 distribution tends more toward a uniform distribution of rainfall. Figures 4b and 4c illustrate the relationship between the three distribution techniques as the duration of the design storm decreases. The intensities in the HEC-1 and SCS Type-II curves are independent of duration, remaining virtually unchanged as the length of the storm is varied. On the other hand, the intensities of the Huff distributions increase markedly as the storm duration decreases. The maximum intensities in the Huff distributions approximate the maximum intensity in the HEC-1 distribution at a storm duration of four hours. The maximum intensity in the SCS Type-II distribution is characteristic of the maximum intensity in a 30-minute or 1-hour Huff distribution storm. An example of the rainfall depth and intensity that may be experienced in the three rainfall distributions for various storm durations is given in Table 7.

It is desirable that storms of realistic time distribution be used for all hydrometeorological applications. The HEC Standard Project Storm and SCS Type-II idstributions are developed from rainfall frequency-duration relationships, which are best described as series of unrelated severe rainfall (Pilgrimand Cordery, 1975). These distributions are not representative of actual storm rainfall. The Huff family of distributions faithfully represents average conditions of heavy rainfall and should be used for describing the distribution of rainfall in Illinois for storms of almost any frequency. However, when treating the probable maximum storm, the potential maximum rainfall event should be the main consideration and not the representativeness of the rainfall distribution. Tests reported in HMR-51 indicate that the inclusion of the 6-hour and 12-hour PMP within the 24-hour storm, as occurs with the HEC-1 distribution, is an acceptable maximization procedure when describing the PMP storm. The NEH-4 6-hour PMP distribution also maximizes the depth-duration relationship for the probable maximum storm; however, because this storm distribution is only six hours long, it will not produce maximum discharge except for very small

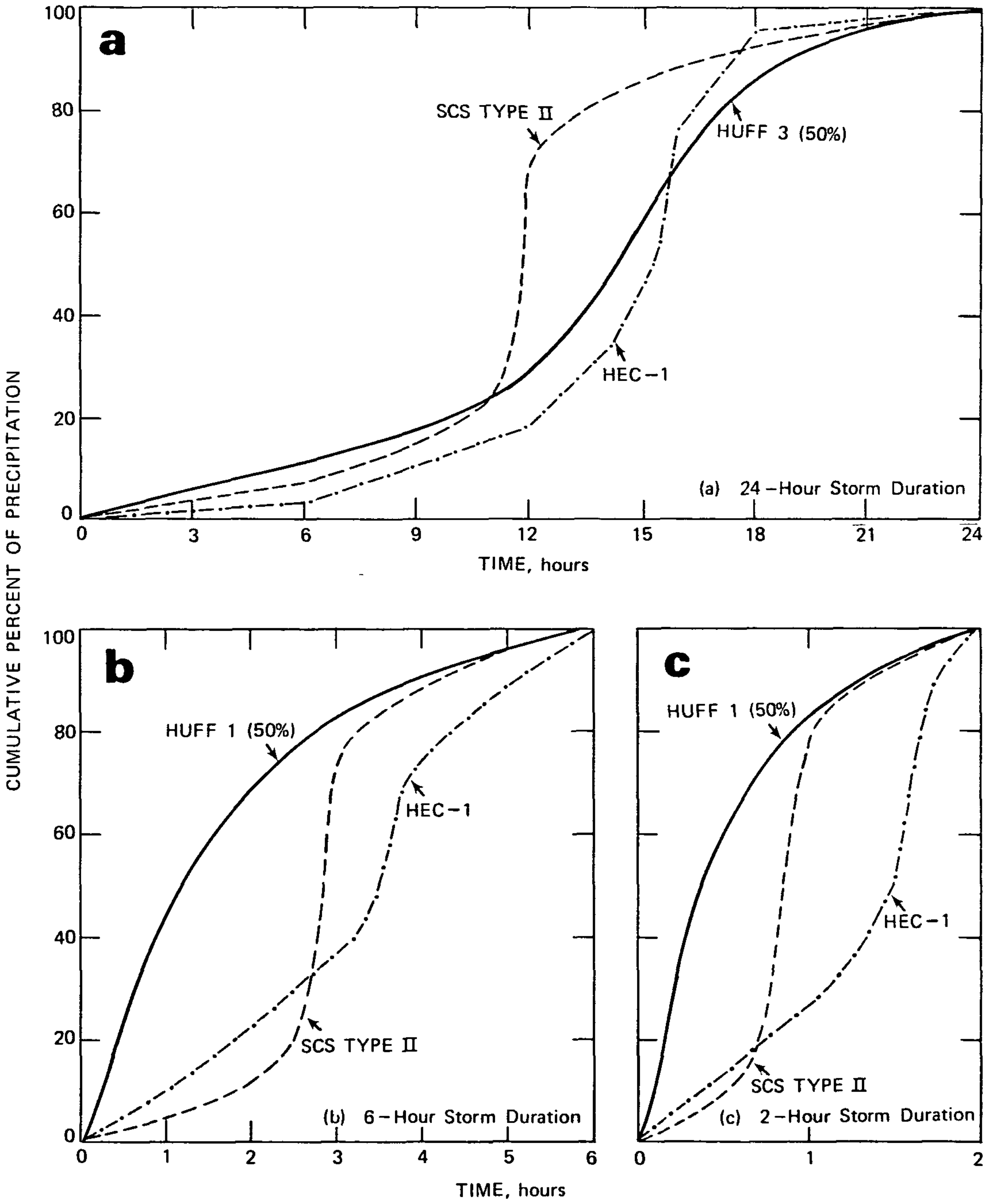

Figure 4. Comparison of the HEC-1, Type-II and Huff distributions for storms of various durations

Table 7. Comparison of the Maximum 15-minute Rainfall Intensity in Inches for Storms of Various Distribution and Duration; Pierce Lake

Rainfall Distribution	Storm Duration (hours)							
	PMP				100-Year			
	2	6	12	24	2	6	12	24
Huff	5.51	2.30	1.11	.61	1.41	.66	.34	.20
SCS Type-II	8.53	7.73	7.30	6.71	2.17	2.21	2.22	2.25
HEC-1	-	4.21	4.21	4.21	-	1.21	1.21	1.21
NEH-4	-	4.75	-	-	-	1.36	-	-

watersheds. The SCS Type-II curve does not represent a realistic distribution of PMP and should not be used for estimation of the probable maximum flood.

The HEC-1 and Huff distributions are herein suggested for application of the PMP and 100-year rainfall, respectively. The following section examines the relative effects on design floods of using the suggested rainfall distributions as opposed to the other available distributions. The variation in runoff and routed hydrographs due to changes in the duration of each of the precipitation distributions is also examined. In this examination, the PMP and 100-year rainfalls recommended by Huff are used to compute basin runoff. The Hopbrook factor is applied to the PMP estimate.

In the following comparisons of the effects of time distribution and storm duration, it is assumed that for a given rainfall distribution and rainfall frequency the storm duration which produces the most conservative flood discharge is desirable for reservoir design. This practice of choosing durations with the most conservative flow results in discharges which are representative of a greater return period than that intended. However, this practice cannot be avoided until enough information is made available to calibrate a relationship between rainfall frequency and flood frequency. It is felt that once such information is available, a duration of a Huff storm can be found which results in a representative 100-year flood. This question relating storm duration to flood frequency demands treatment in subsequent investigations.

EFFECTS OF PRECIPITATION TIME DISTRIBUTION ON BASIN RUNOFF AND ROUTED HYDROGRAPHS

The response of a watershed to variations in the precipitation distribution used is highly dependent on the natural storage in the watershed and the size and shape of the basin, characteristics which are mainly revealed in the basin unit hydrograph. For basins in which the unit hydrograph's time of concentration is short, the peak runoff is sensitive to the temporal variation of rainfall. These basins, which are typically small basins, will experience the greatest peak discharges from storms with extremely intense rainfall. The SCS Type-II rainfall is expected to produce high discharge estimates for these basins because of its period of very intense rainfall. Similarly, with storms of the Huff distribution, the shorter duration storms are expected to result in greater peak discharge for these basins. Figures 5 and 6 illustrate that flood hydrographs for Waltonville Lake possess these qualities. The probable maximum and 100-year basin hydrographs computed using the Type-II rainfall, shown in Figure 5, have the greatest peak discharge of all of the rainfall distributions. The 24-hour Huff 3 distribution produces a very low peak discharge; however, when the storm duration is diminished, the Huff storms produce peak discharges exceeding those of the HEC-1 storms and approaching the discharges associated with the Type-II rainfall.

The peak discharge in most large basins is less dependent on rainfall distribution than it is in small basins because the greater variation in travel times and greater valley storage present in large basins tend to temporally distribute the effect of storm bursts. The runoff hydrographs resulting from a given storm duration in a large basin tend to be very similar, regardless of the precipitation time distribution

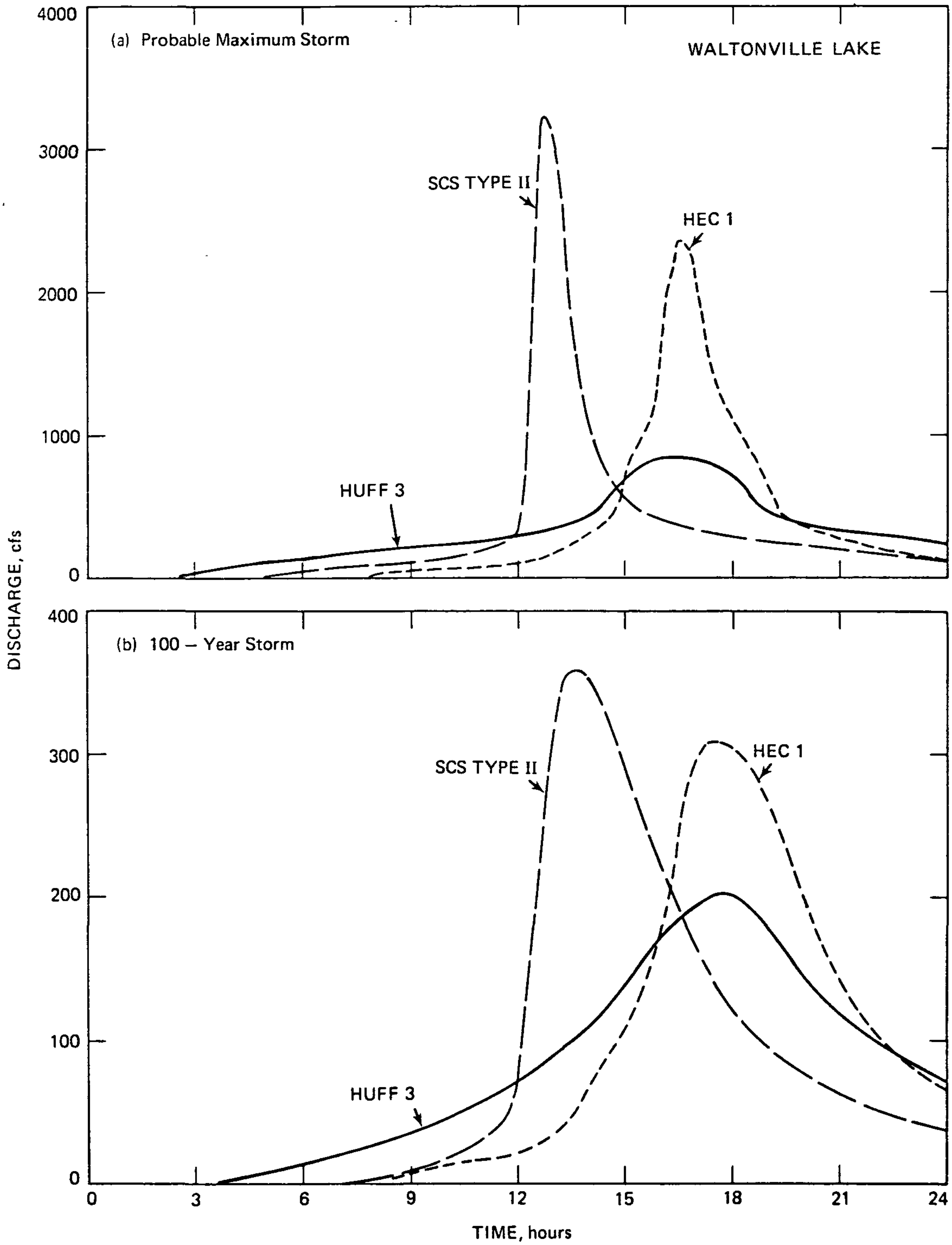

Figure 5. Comparison of the basin runoff hydrographs for Waltonville Lake using different 24-hour storm distributions

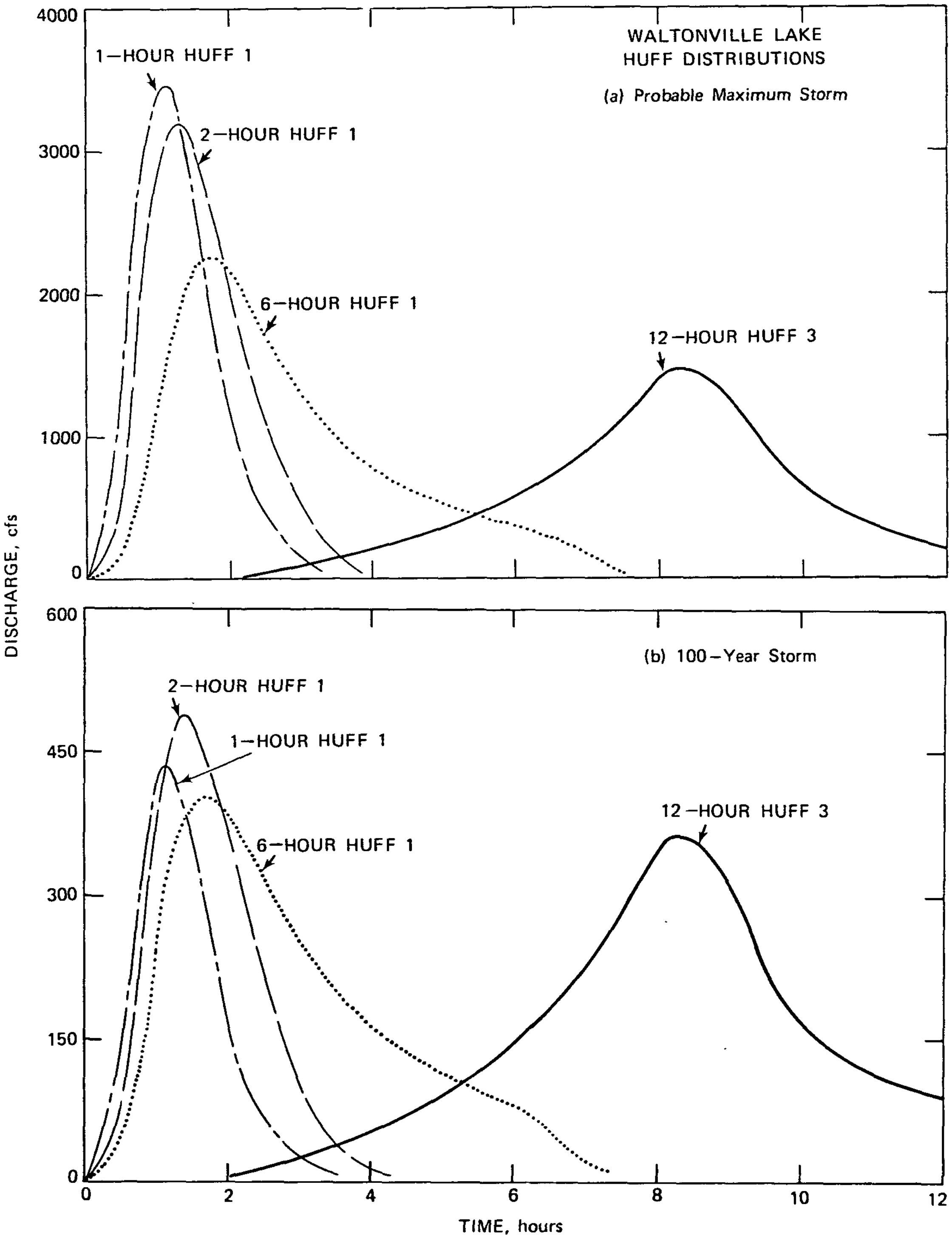

Figure 6. Comparison of the basin runoff hydrographs for Waltonville Lake using different durations of Huff distributional storms

used (see Figure 7), although the HEC-1 rainfall generally results in slightly higher peak discharge. The inflow hydrographs of Huff storms applied to the Lake Vermilion watershed (Figure 8) show that storms of longer duration exhibit greater peak discharge. This suggests that for larger basins, the greater rainfall depth associated with a lengthy storm is a more important factor in the creation of high peak discharge than is the magnitude of the rainfall intensity.

Although the size of a watershed is mentioned as a major influence in the response of runoff to the rainfall input, the shape of the unit hydrograph is the only element which directly controls this response. "Small" watersheds typically possess unit hydrographs which peak and recede quickly and have relatively high peak discharge, whereas "large" watersheds typically feature a much broader unit hydrograph time base. However, drainage area alone is not a sufficient indicator of expected hydrologic response. For example, the hydrologic response of the Kinkaid Lake watershed, 62 mi^2, is more representative of a small watershed than is the response of the Lake Wildwood watershed, 12 mi^2 (see Table 1). This is explained in that the average slope of the Kinkaid Lake watershed is much greater than the average slope of the Lake Wildwood watershed. Examination of Table 1 shows that six watersheds can be classified as "small" watersheds based on the time to peak and the width of the unit hydrograph. The reservoirs associated with these watersheds are Tara Lake, Lake Summerset, Hollis Park Lake, Waltonville Lake, Lake Sara, and Glen O. Jones Lake.

Critical Storm Duration

For every reservoir and selected rainfall distribution technique there exists a storm of duration which produces maximum peak runoff. This duration is termed the "critical duration" when applied to the use of the Huff distribution. However, use of the term "critical duration" for the HEC-1 and Type-II storms is misleading because both of these distribution techniques are designed to produce increasing peak discharge with increasing storm duration. A few exceptions occur with the Type-II distribution, because these storms possess slightly greater intensity for short durations of the PMP, thereby causing some small basins

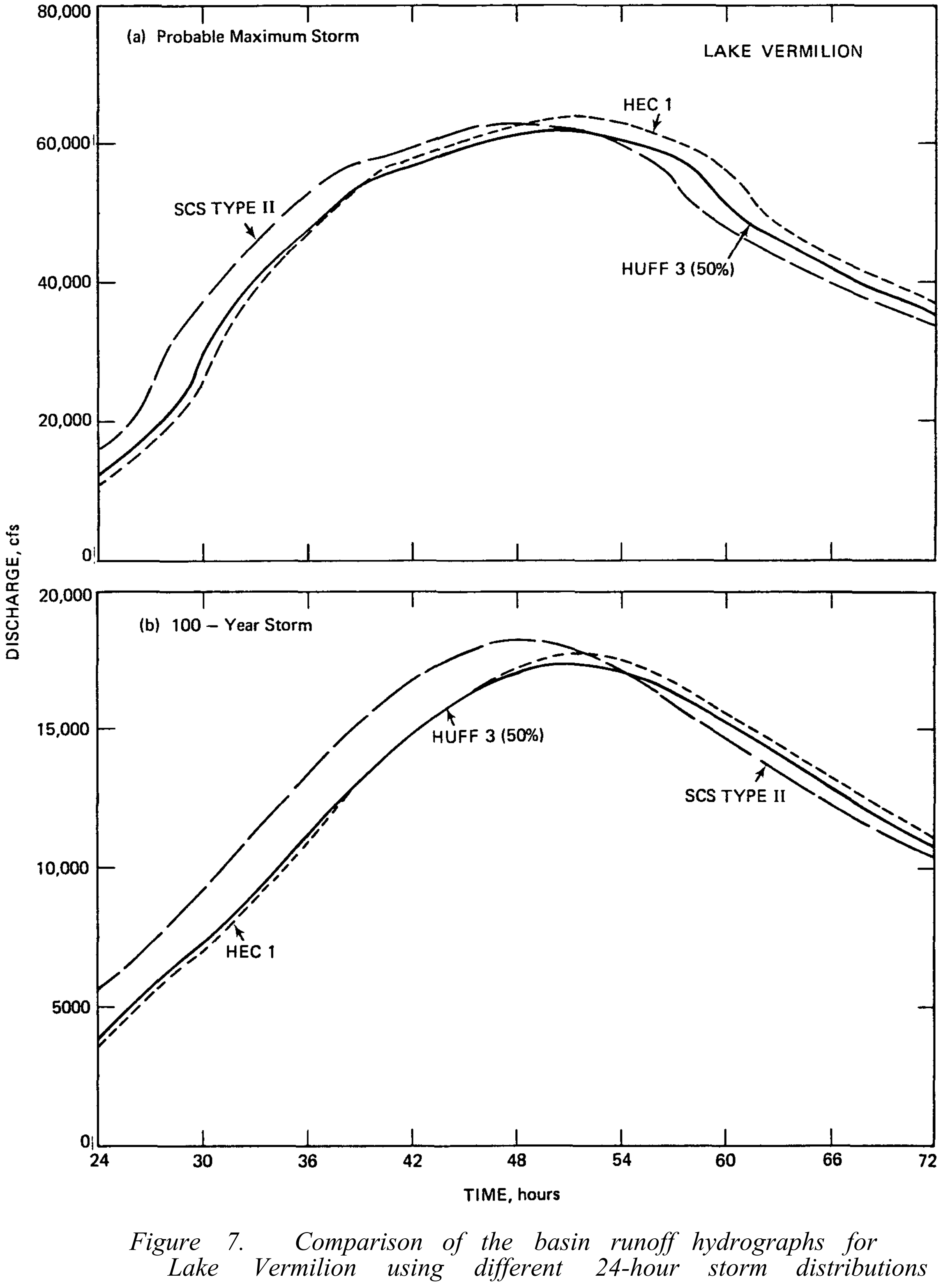

Figure 7. Comparison of the basin runoff hydrographs for Lake Vermilion using different 24-hour storm distributions

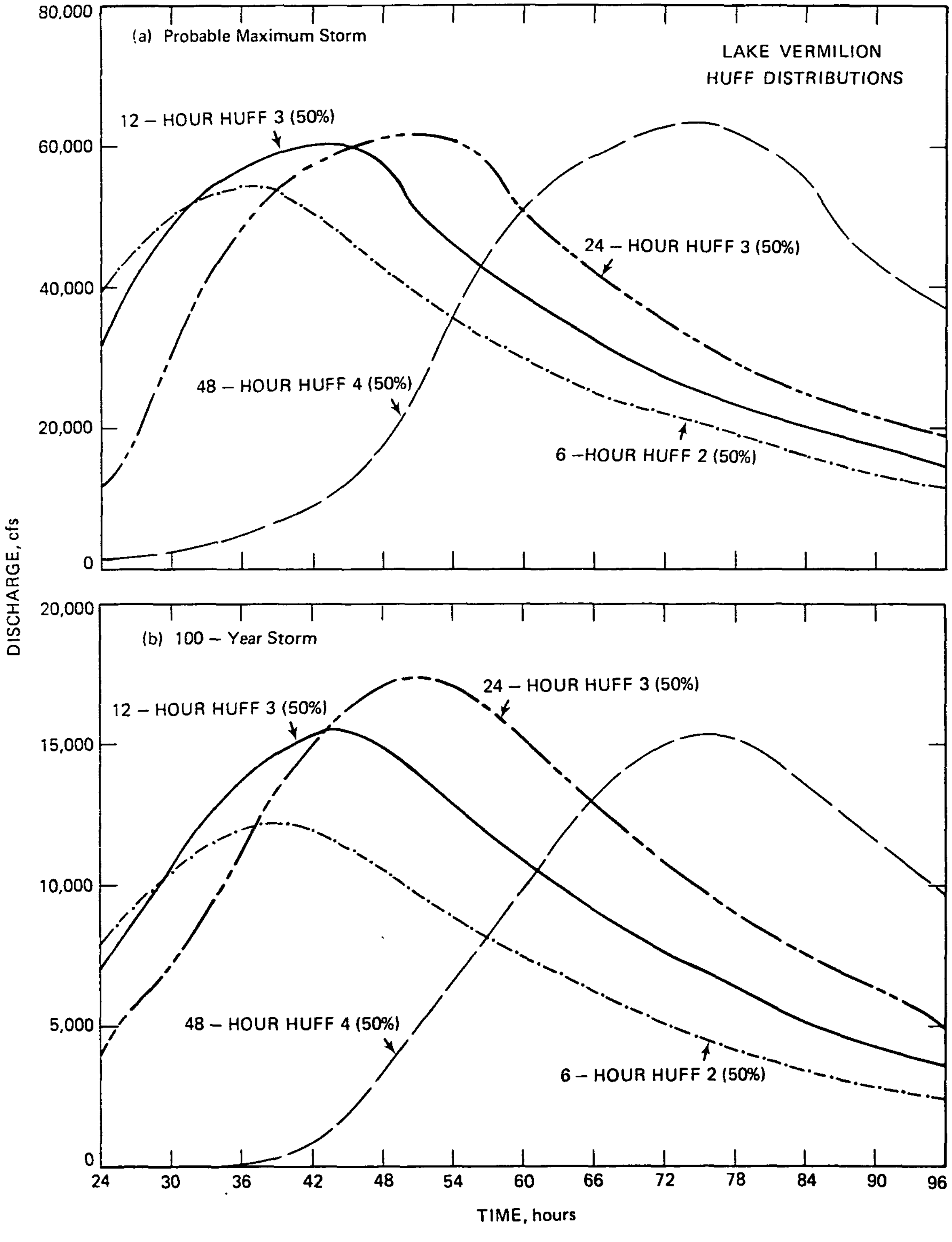

Figure 8. Comparison of the basin runoff hydrographs for Lake Vermilion using different durations of Huff distributional storms

to have slightly greater discharges with shorter duration storms. Figures 9 and 10 illustrate the response of the Pierce Lake outflow hydrograph to changes in the duration of the Type-II and HEC-1 storms, respectively. Both of these distributions would continue to experience larger discharges with storms of duration longer than 24 hours; however, the increase in discharge due to lengthier duration is slight and the 24-hour storm is viewed as a practical upper limit on usable storm duration.

When the Huff family of distributions is used to distribute storm rainfall, the critical duration may vary greatly from one basin to another, ranging from 1 hour for small watersheds up to 48 hours for large watersheds. Table 8 lists the peak discharge of the basin runoff hydrograph for each reservoir for various durations of the Huff distributed rainfall, with critical durations appropriately marked. The most common critical duration of the basin runoff hydrograph is 12 hours.

Effect of Reservoir Routing

Table 8 indicates that the storm duration which produces the maximum peak outflow is often not of the same duration as the storm which causes the greatest reservoir discharge. This occurs because the reservoir routing process demands that a certain amount of runoff volume be put into surcharge storage before a given outflow can occur; a longer duration storm provides the greater runoff volume for surcharge storage. This need for increased storm duration is greatest for reservoirs with a large storage-outflow ratio. An example of the inflow and outflow hydrographs for a reservoir with high surcharge storage is shown in Figure 11. Lake Sara, the subject of this figure, is in a small watershed which must be treated as a large watershed in order to achieve maximum reservoir outflow.

Prediction of Critical Duration for Huff Rainfall

The above comparisons illustrate that proper application of the Huff rainfall distributions requires selection of an appropriate storm duration. The critical duration of the storm required to produce the

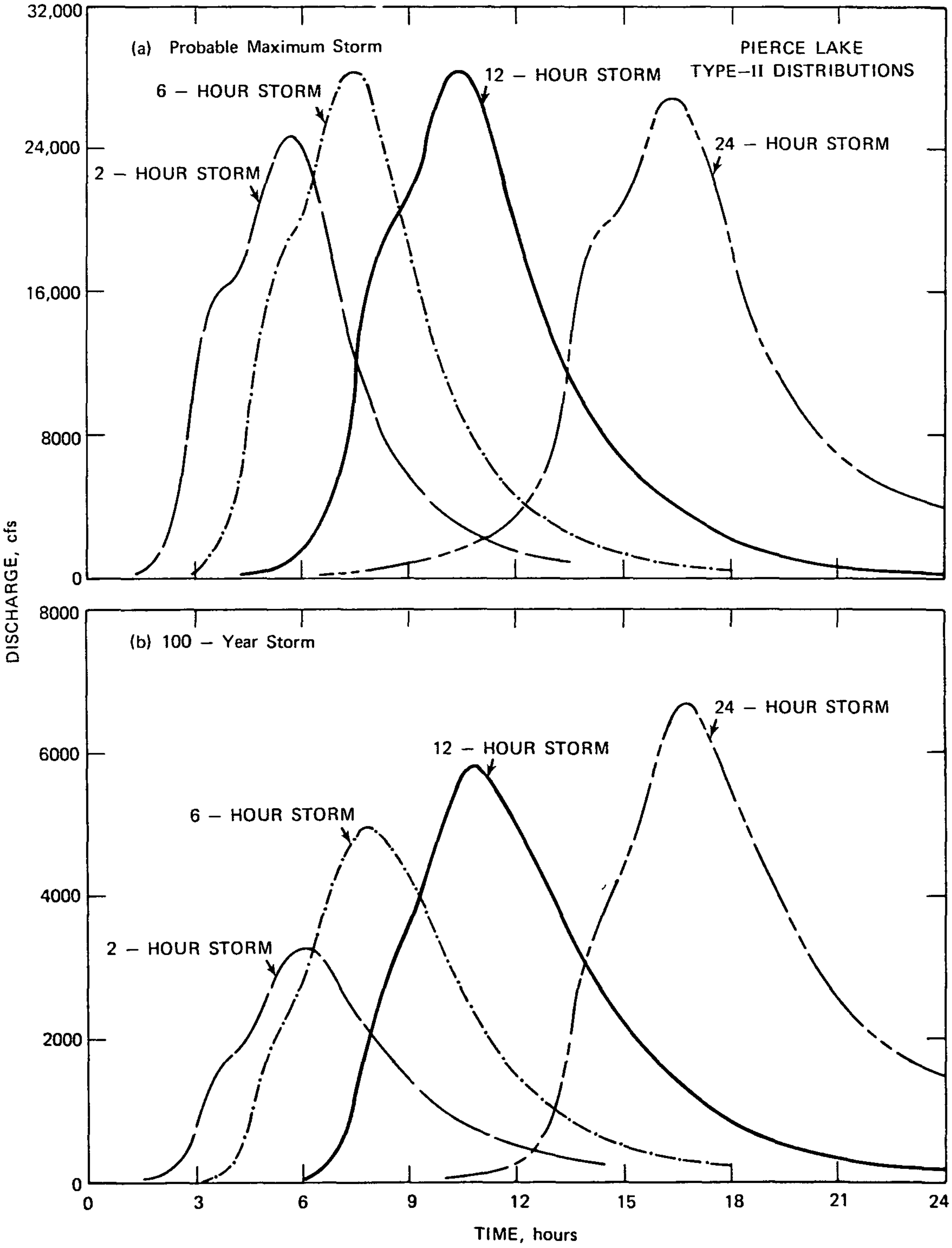

Figure 9. Comparison of the effects of storm duration on basin runoff hydrographs for the Type-II distribution; Pierce Lake

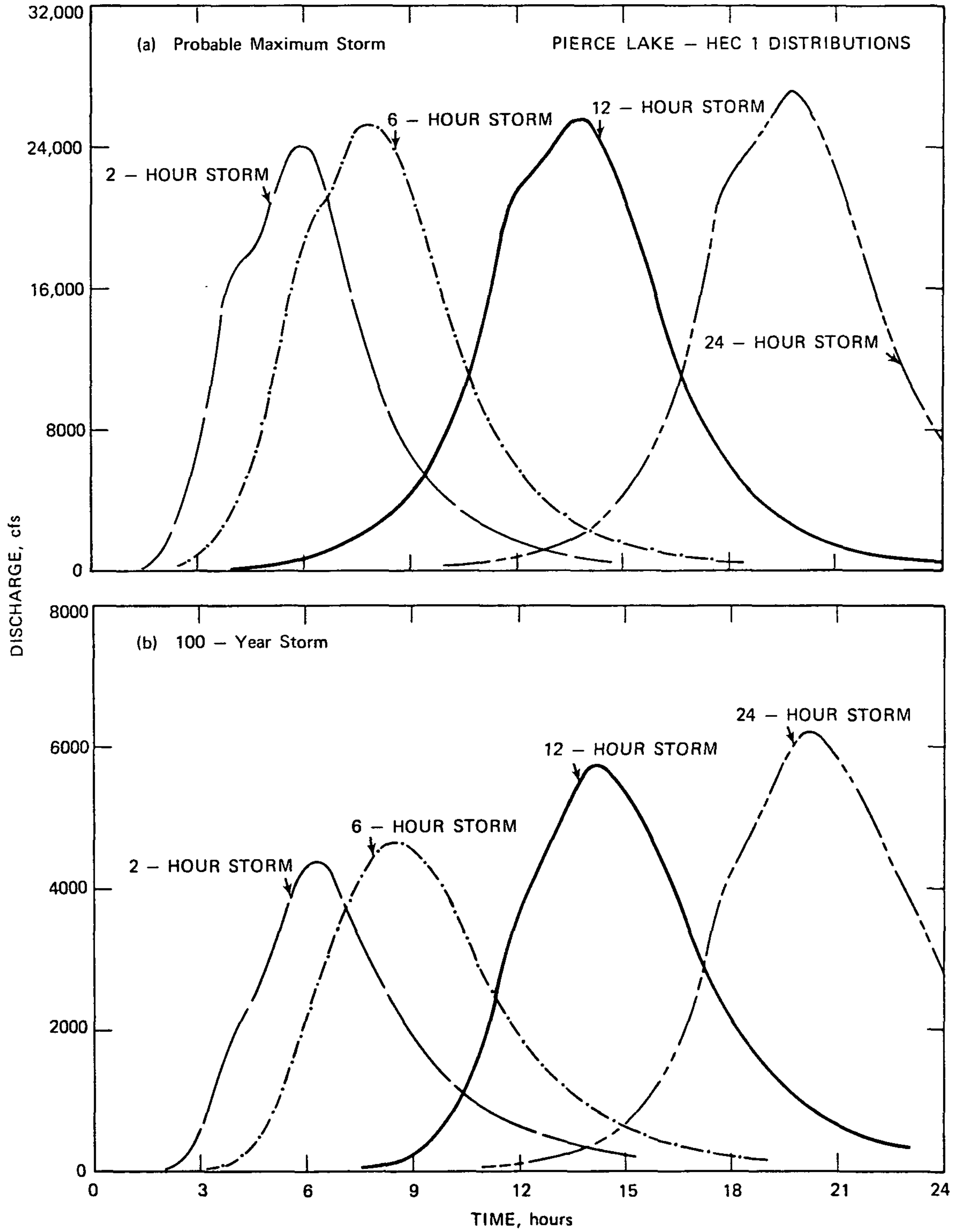

Figure 10. Comparison of the effects of storm duration on basin runoff hydrographs for the HEC-1 distribution; Pierce Lake

Table 8. Effect of Storm Duration on the Basin Runoff and Reservoir Outflow Resulting from Huff Distributional Rainfall

Duration	Probable Maximum Inflow	Probable Maximum Outflow	100-Year Inflow	100-Year Outflow
Waltonville Lake (da = .53 mi^2)				
1	3411 *	3174*	431	173
2	3191	3032	482*	222
3	2879	2717	464	223
6	2265	2121	401	223
12	1454	1447	359	246*
24	1134	1126	234	203
Hoi 1i5 Park Lake (da = . 82 mi^2)				
1	8035*	5528*	1329*	116
2	6976	5170	1283	120
3	6051	4768	1207	122
6	4479	3709	956	123*
12	2193	2154	479	121
24	1249	1213	275	112
Tara Laike (da = 1.1 mi^2)				
1	5729*	5804*	1022	1012
2	5361	5313	1092*	1083*
3	4802	4829	1065	1063
6	3939	3925	945	944
12	2600	2595	724	722
24	1542	1540	455	455
Glen O. Jones Lake (da = 1.5 mi^2)				
1	8903*	2769	-	-
2	8115	2940	1832*	200
3	7251	3002	1475	187
6	5216	2641	1341	245
12	3563	2530	979	263*
24	2136	1799	610	239
Lake Summerset (da = 6.4 mi^2)				
1	29566*	14953	5084	472
2	28127	17497*	5926*	546
3	24232	15498	5652	566
6	21284	15180	5194	604
12	14465	13557	4044	637*
24	8688	8519	2579	605
Hew City Lake (da = 7.8 mi^2)				
2	12223	8626	2735	1738
3	12829*	9095	-	-
6	12712	9644	3225	2310
12	12046	9997*	3295*	2552*
24	9064	7920	2640	2231

Duration	Probable Maximum Inflow	Probable Maximum Outflow	100-Year Inflow	100-Year Outflow
Lake Sara (da = 12.3 mi^2)				
1	49071*	9367	-	-
2	48909	12066	8559*	-
3	46096	13246	8471	980
6	39851	13573	8092	1335
12	30090	15291*	7791	1771
24	18394	12613	5426	1891
Lake Wildwood (da =12.3 mi^2)				
6	9396	7931	1474	722
12	10231*	9216*	1723*	829*
24	8603	7872	1562	809
Pierce Lake (da = 13-1 mi^2)				
2	27039	23778	4330	3219
3	28764*	24933*	-	-
6	27473	24480	5482	4235
12	22171	21202	5597*	4887*
24	16338	15461	4877	4297
Vandalia City Lake (da = 25.0 mi^2)				
6	19876	15670	4498	2613
12	21746*	18769*	5426*	3257
24	20114	18164	5366	3434*
Lake 1of Eqypt (da = 33.3 mi^2)				
3	96518*	20117	-	-
6	94709	21994	26315*	4138
12	75348	24858*	22097	5010
24	53970	23087	16966	5224*
48	-	-	10073	2256
Mauvaise Terre Lake (da = 34.3 mi^2)				
6	20561	18760	4866	4367
12	22839*	21411*	5507	5047
24	21524	20467	5668*	5332*
48	-		4964	4699
Kinkaid Lake (da = 62.3 mi^2)				
3	124866	28981	-	-
6	130223*	33125	35952*	6407
12	116311	38469*	34127	7938
24	87198	37753	27728	8857*
48	-	-	21656	7833

* indicates critical duration

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Table 8. Concluded

Ourat ion	Probable Maximum Inflow/Outflow		100-Year Inflow/Outflow	
Lake Holiday (da = 6*4.6 mi²)				
6	39091	37186	9568	8010
12	41424*	40410*	11181*	9532
24	38773	38045	11207	9850*
Sangchris Lake (da = 74.0 mi²)				
6	35045	22947	7920	2184
12	39425*	27220	8773*	3073
24	37570	27936*	8751	3445*
48	33172	25751	7920	2184
Wonder Lake (da = 97.2 mi²)				
6	38926	37911	10702	8556
12	41931*	41086*	12638	10962
24	41372	40796	13750*	12713*
48	38077	37515	12578	11667

* indicates critical duration

Duration	Probable Maximum Inflow/Outflow		100-Year Inflow/Outflow	
Lake Taylorville (da = 125 mi²)				
12	55563	52149	14682	12902
24	55836*	53162*	15027*	13796*
48	50890	*i88*i6	12556	11246
Clinton Lake (da = 291 mi²)				
12	108416	79756	19668	7016
24	122924	98010	26935	10720
48	123620*	105961*	28770*	12332*
Lake Vermilion (da = 298 mi²)				
12	61135	60140	15781	15443
24	62933	61886	17770*	17378*
48	64314*	63267*	15652	15333
Lake Decatur (da = 906 mi²)				
12	146506	137237	36956	32*460
24	169236	159986	42465*	3716*1*
48	170632*	162357*	37435	33022

Table 9. Determination of the Critical Storm Duration for the Huff Distribution from the Width of the Unit Hydrograph at 50% Peak Discharge (W_{50})

Critical Storm Duration (hrs)	W_{50} (hrs)
1	< 0.9
2	0.9 - 1.9
3	2.0 - 2.6
6	2.7 - 8.2
12	8.3 - 16.7
24	16.8 - 44.0
48	>44.0

maximum peak inflow is dependent upon a number of basin characteristics, but the most important factor appears to be the temporal character of the unit hydrograph, represented by the width of the unit hydrograph at 50% of the peak discharge, W_{50} For the purpose of predicting the critical duration, it is assumed that the critical duration is that duration of storm which possesses the greatest rainfall depth over the time period W_{50}. Given this assumption, Table 9 may be used to predict the critical duration of the 25-year, 50-year, and 100-year rainfall for any basin. This type of procedure is not provided for the PMP because the Huff distribution is not recommended for the estimation of the probable maximum flood.

Table 9 predicts the correct critical duration (as shown in Table 8) for 75% of the reservoirs studied. For those cases in which Table 9 does not give the critical duration, the Huff storm of the duration predicted only slightly underestimates the discharge produced by the storm of critical duration. The greatest underestimation of the most conservative 100-year discharge is 6.4%. So although the assumption of greatest rainfall within the W_{50} time period is not absolutely valid, it is nonetheless effective for the prediction of conservative 100-year inflows.

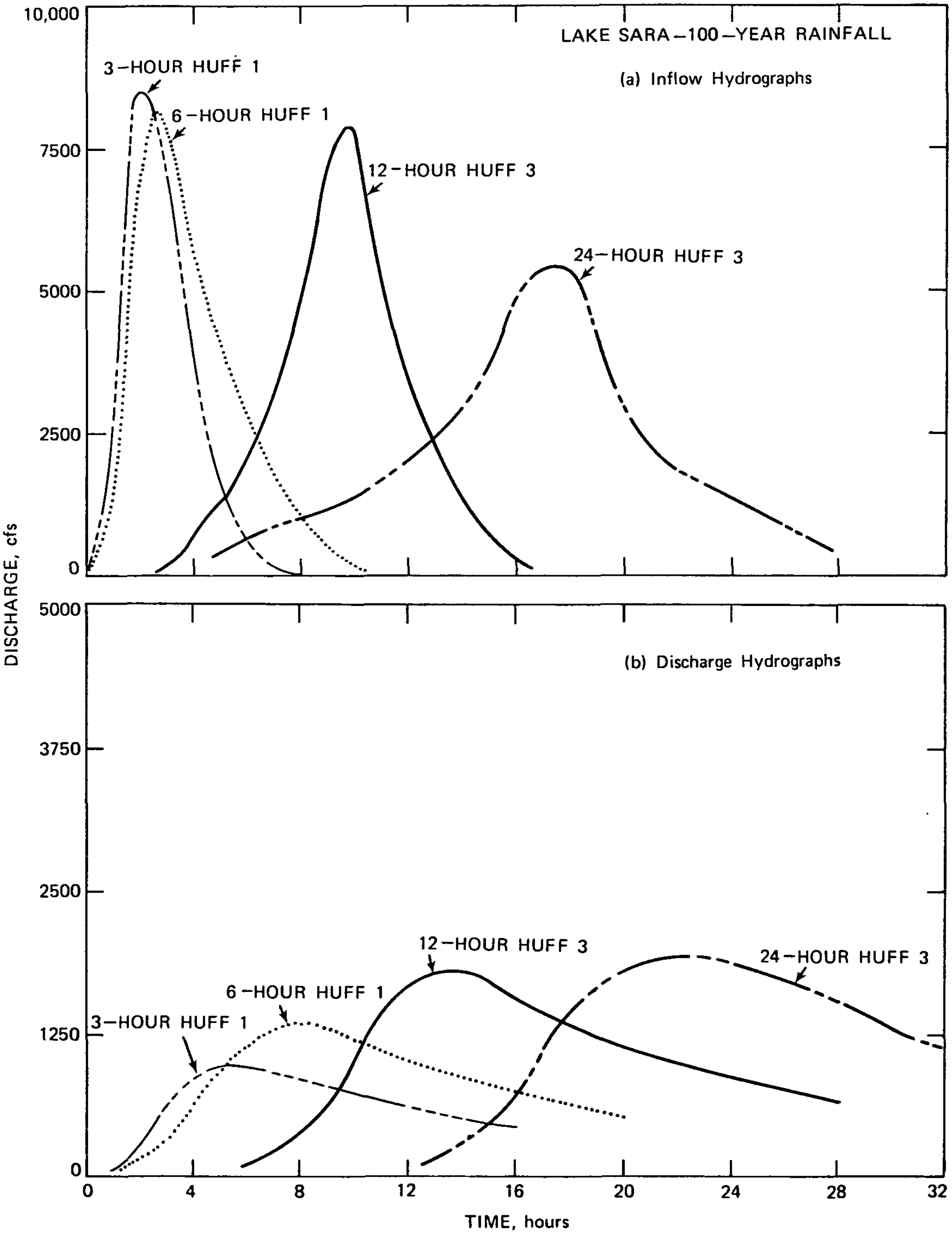

Figure 11. The effects of routing the 100-year flood through a large reservoir on the critical Huff duration; Lake Sara

Prediction of the Conservative Design Storm Duration

The duration of the storm which produces maximum reservoir outflow is dependent upon the critical duration of the hasin runoff storm and the reservoir's storage-outflow relationship. The following procedure attempts to describe the effect of the reservoir storage on the increase in storm duration needed to achieve maximum outflow. The storage index chosen for this analysis measures that volume of rainfall which must be devoted to surcharge storage before a reservoir outflow equal to the peak of the inflow unit hydrograph can be realized. This surcharge storage index, s, is easily computed using the unit hydrograph and the storage-outflow curve (see the section on recommended procedure). Equations 1a and 1b use this storage index to modify the unit hydrograph's W_{50} for use in Table 10, which predicts the storm durations of conservative reservoir outflow. These empirically derived equations are:

$$w' = w_{50}, \text{ for } s \leq .8 \qquad (1a)$$

$$w' = 1.6\, s\, w_{50}^{.8}, \text{ for } s > .8 \qquad (1b)$$

where W_{50} = the width of the unit hydrograph at 50% of peak discharge (hours)

w' = The adjusted W_{50} needed as input to Table 10 to predict the desired duration of the design storm

s = the surcharge storage needed to result in an outflow equal to the peak of the unit hydrograph, expressed as inches of rainfall on the basin

One of the two durations estimated using Equations 1a and 1b and Table 10 predicts the modified duration needed to achieve maximum 25-year, 50-year, and 100-year outflow for all of the reservoirs studied. Of the two durations, the longer duration is more apt to provide the most conservative discharges when a high percentage of early storm rainfall is allocated to infiltration loses. However, both durations should be tested in all situations. An example of the determination of the duration needed for conservative design as described above is presented in the section of this report dealing with recommended procedure.

Table 10. Determination of the Storm Duration of Conservative Design for the Huff Distribution from the Adjusted Width of the Unit Hydrograph, w'

Storm Duration (hrs)	w'(hrs)
1 or 2	< 0.9
2 or 3	0.9 - 1.9
3 or 6	2.0 - 2.6
6 or 12	2.7 - 8.2
12 or 24	8.3 - 16.7
24 or 48	16.8 - 44.0
48	> 44.0

Comparison of the Maximum Discharges from each Distribution

The most conservative estimates of the probable maximum peak inflow and outflow at each of the twenty reservoirs studied are created when using either the HEC-1 or Type-II rainfall distributions, as is shown in Table 11. The Type-II distribution tends to produce peak discharges larger than those experienced with the HEC-1 distribution for basins which are sensitive to rainfall intensity and have a short time of concentration. For several of the smaller reservoirs the Type-II peak inflow exceeds the HEC-1 inflow by over 50%. These higher discharges result from the presumed unrealistic PMP intensities created when using the Type-II distribution. In many smaller basins, the Huff peak runoff is also greater than the HEC-1 peak discharge, generally as a result of the high PMP estimates given by Huff (1980) for short duration storms. However, the HEC-1 hydrographs tend to experience less reduction during the routing of the probable maximum flood than do hydrographs resulting from the Type-II and Huff rainfall. For this reason the HEC-1 distribution results in greater reservoir discharge, even for many reservoirs in small watersheds. For large reservoirs the peak reservoir discharge of the HEC-1 storm exceeds the peak of the Huff and Type-II storms by an average of 5% and 4%, respectively.

The NEH-4 design storm methodology is shown to produce peak inflow which is greater than the inflow from the HEC-1 distribution for basins

Table 11. Maximum Basin Runoff and Reservoir Discharge Resulting from the Various Rainfall Distribution Techniques Using Huff Rainfall Amounts

Peak Basin Runoff (cfs)

	PHP Distributions				100-Year Distributions		
	HEC-1	Huff	Type-II	NEH-4	HEC-1	Huff	Type-II
Northwest Region							
Tara Lake	4011	5729	6074	4878	1063	1092	1599
Lake Summerset	21856	29566	31236	25976	5867	5926	8677
Pierce Lake	29065	28764	32835	30429	7370	5597	8499
Lake Holiday	44002	41424	41511	38893	12072	11181	12641
Wonder Lake	44706	41931	43318	38837	14132	13750	14550
North Central Region							
Hollis Park Lake	5802	8035	10529	7443	1399	1329	2590
Lake Wildwood	11181	10231	10570	9572	2224	1723	2268
Mauvaise Terre Lake	23928	22839	26006	20308	6051	5668	6338
Sangchris Lake	41071	39425	40370	34842	9332	8773	9732
Clinton Lake	126438	123620	124635	88368	26957	28770	26676
Lake Decatur	172512	170632	172535	125141	42695	42465	44634
South Central Region							
Waltonville Lake	2432	3411	3770	3012	582	482	872
Lake Sara	41832	49071	55223	47673	10503	8471	14211
Vandalia City Lake	23177	21746	21950	19845	5878	5426	6062
Lake Taylorville	59091	55836	57632	49734	15683	15027	16083
Lake Vermilion	65295	64314	64146	53514	18080	17770	18617
Southeast Region							
Glen O. Jones Lake	5591	8903	7841	6495	1508	1832	2138
New City Lake	14029	12829	13953	13203	3793	3295	4044
Lake of Egypt	82047	96518	96699	96399	23045	26315	30954
Kinkaid Lake	123858	130223	128537	127209	34990	35952	41545

Peak Reservoir Discharge (cfs)

	PHP Distributions				100-Year Distributions		
	HEC-1	Huff	Type-II	NEH-4	HEC-1	Huff	Type-II
Northwest Region							
Tara Lake	4000	5804	6032	4927	1058	1088	1590
Lake Summerset	18604	17497	19690	16772	686	637	696
Pierce Lake	27027	24933	28444	26696	6201	4887	6672
Lake Holiday	42849	40410	40408	37894	10363	9850	10680
Wonder Lake	43830	41086	42417	38274	12969	12713	13161
North Central Region							
Hollis Park Lake	4837	5528	8596	5619	151	123	199
Lake Wildwood	11161	9216	10128	8355	1026	829	1015
Mauvaise Terre Lake	22674	21411	22328	19698	5611	5332	5831
Sangchris Lake	29296	27936	28657	25403	3680	3445	3757
Clinton Lake	98794	105961	103101	59537	10714	12332	10660
Lake Decatur	162713	162357	162515	115501	37421	37164	39001
South Central Region							
Waltonville Lake	2365	3174	3536	2860	309	246	358
Lake Sara	20714	15291	17153	14736	2174	2150	1895
Vandalia City Lake	20703	18769	19101	17296	3588	3434	3623
Lake Taylorville	56070	53162	54386	46649	14286	13796	14559
Lake Vermilion	64061	63267	62946	53483	17695	17378	18212
Southeast Region							
Glen O. Jones Lake	3207	3002	3215	3278	334	268	333
New City Lake	11586	9997	10873	11061	2865	2552	2892
Lake of Egypt	26861	24858	24921	22309	5478	5224	5467
Kinkaid Lake	41414	38469	38292	41069	8943	8857	8845

which have quick hydrologic response. However, as the response time of the basin increases, the 6-hour NEH-4 storm displays considerably fewer conservative discharges when compared to any of the 24-hour storms. In both large and small watersheds, reservoir routing further favors the use of a 24-hour storm.

Almost all of the twenty basins experience their most conservative 100-year runoff and 100-year reservoir outflow from the use of the Type-II rainfall. For reservoirs with watershed area less than 20 mi^2, the Type-II peak runoff averages 51% greater than the peak runoff using the Huff distribution. Reservoir routing reduces this differential in peak flow to 27%. The 100-year routed hydrographs produced using the HEC-1 rainfall have peak discharges 16% greater than the corresponding Huff discharges in these small basins. For large watersheds the differential in peak outflow between the three distributions is small and averages less than 4%.

The average maximum stage reached at the twenty reservoirs during routing of the probable maximum flood (Table 12) is approximately .2 ft lower using the Huff rainfall distribution than it is using either the HEC-1 or Type-II storms. For several reservoirs the underestimation of the probable maximum stage associated with the Huff distributed rainfall exceeds .4 ft (Lake Taylorville, Lake Sara, and Mauvaise Terre Lake) and, given the probable maximum event, this greatly underrates the risk of overtopping and/or dam breach. The greatest differential occurs for some of the smaller reservoirs in which the greater stages are associated with the unrealistic Type-II and short duration Huff rainfall.

The differentials in stage occurring between floods of the 100-year rainfall are similar, but are even greater than those observed with the probable maximum flood. The HEC-1 and Type-II distributions produce maximum 100-year stages that are on average .25 and .35 ft, respectively, above the stages associated with the Huff distribution. The greatest differences in stage, exceeding 1 ft, are shown to occur with Pierce Lake, Lake Wildwood, and Hollis Park Lake.

Table 12. Maximum Reservoir Stage Resulting from the Various Rainfall Distribution Techniques Using Huff Rainfall Amounts

	Maximum Pool Level (ft above top of dam)						
	PMP Distributions				100-Year Distributions		
	HEC-1	Huff	Type-II	NEH-4	HEC-1	Huff	Type-II
Northwest Region							
Tara Lake	2.0	2.5	2.6	2.3	0.7	0.7	1.0
Lake Summerset	2.2	2.1	2.3	2.0	-2.3	-2.8	-2.2
Pierce Lake	3.2	2.5	3.7	3.1	-4.2	-5.5	-4.4
Lake Holiday	1.5	1.3	1.3	1.0	-6.9	-7.3	-6.8
Wonder Lake	5.2	4.9	5.1	4.6	1.1	1.1	1.2
North Central Region							
Hollis Park Lake	2.7	2.9	3.8	3.0	-0.4	-1.2	0.0
Lake Wildwood	0.4	0.1	0.2	-0.2	-6.5	-7.6	-6.5
Mauvaise Terre Lake	0.4	0.1	0.3	-0.3	-5.8	-7.6	-5.7
Sangchris Lake	-2.6	-2.7	-2.7	-3.0	-6.6	-6.6	-6.6
Clinton Lake	-5.2	-4.8	-5.0	-7.8	-15.2	-4.6	-15.2
Lake Decatur	6.3	6.3	6.3	3.8	-4.2	-4.2	-3.9
South Central Region							
Waltonville Lake	0.9	1.1	1.2	1.0	-0.7	-1.1	-0.4
Lake Sara	0.5	-0.4	0.1	-0.5	-6.0	-6.1	-6.2
Vandalia City Lake	1.3	1.1	1.1	0.9	-5.8	-6.0	-5.8
Lake Taylorville	0.1	-0.3	-0.1	-1.3	-7.7	-7.8	-7.6
Lake Vermilion	-0.2	-0.4	-0.5	-2.3	-5.6	-5.7	-5.5
Southeast Region							
Glen 0. Jones Lake	-1.7	-2.0	-1.7	-1.7	-5.9	-6.2	-5.9
New City Lake	0.5	0.1	0.3	0.3	-4.4	-4.7	-4.4
Lake of Egypt	-3.7	-4.3	-4.2	-5.0	-11.1	-11.2	-11.1
Kinkaid Lake	-1.0	-1.6	-1.7	-1.1	-10.0	-10.0	-10.0

One final consideration in the routing of design floods is the length of time during which the reservoir is at or near peak stage. This is especially important when dealing with the PMP because the peak stages associated with this rainfall are near or above the top of the dams. Even though the SCS Type-II rainfall produces high estimates of maximum stage, its recession from these stages is comparatively fast. In almost all cases the HEC distribution provides the greatest duration of flooding time spent within one or two ft of peak stage. These floods often experience a 20% longer period of high reservoir stage.

EFFECTS OF COMBINED PROCEDURES ON DAM SAFETY HYDROLOGY

Probable Maximum Precipitation

The factors of maximum peak runoff, reservoir discharge, and reservoir stage for some of the PMP methodologies which are likely to be used or which have been used for dam safety evaluations in Illinois are listed for comparison in Tables 13 and 14. The HEC Standard Project Storm distribution, listed in the first column, is suggested for use in distributing the probable maximum rainfall. This distribution, combined with the HMR-51 PMP estimates and the Hopbrook factor, is the methodology commonly used by the Corps of Engineers to describe the probable maximum storm in the dam safety investigations. The floods resulting from this type of rainfall are used as a basis for comparing the floods of the other PMP methodologies listed.

Use of the Huff methodology (Huff PMP and Huff distribution) has the effect of causing the following changes in reservoir hydrology: 1) peak basin runoff for small basins of size less than 20 mi^2 would on average be 20% greater, whereas large basins experience slightly smaller peak runoff; 2) all but the smallest sized reservoirs can expect a 5% average decrease in peak reservoir discharge; and 3) associated with the lower peak discharge is an average .3 ft decrease in

Table 13. Maximum Basin Runoff and Reservoir Discharge Resulting from Various Combinations of Rainfall Magnitude and Distribution Techniques

	Probable Maximum Storm				100-Year Storm		
Rainfall Distribution:	HEC-1	Huff	Type-II	NEH-4	HEC-1	Huff	Type-II
Rainfall Estimate:	HMR-51	Huff	Huff	NEH-ES	TP-40	Huff	TP-40
Hopbrook Factor:	yes	yes	no	no	n/a	n/a	n/a
			Peak Basin Runoff (cfs)				
Northwest Region							
Tara Lake	3989	5729	6244	6143	760	1092	1068
Lake Summerset	22248	29566	33771	32622	3361	5926	6185
Pierce Lake	27139	28764	37907	38427	5286	5597	5590
Lake Holiday	46390	41424	49152	45531	9366	11181	8794
Wonder Lake	46430	41931	50128	44972	10330	13750	10201
North Central Region							
Hollis Park Lake	7279	8035	9780	9321	1277	1329	2291
Lake Wildwood	11831	10231	13333	11986	1944	1723	1865
Mauvaise Terre Lake	25786	22839	28083	24890	6069	5663	6104
Sangchris Lake	43990	39425	47543	40931	9555	8773	9379
Clinton Lake	132609	123620	142053	101185	22288	28770	21787
Lake Decatur	170062	170632	194842	141158	48076	42465	46104
South Central Region							
Waltonville Lake	2535	3411	4199	3852	482	459	645
Lake Sara	43814	49071	63999	60067	8427	8471	10502
Vandalia City Lake	23978	21746	26967	24459	3672	5426	4691
Lake Taylorville	58083	55836	66681	57148	12938	15027	12554
Lake Vermilion	65159	64314	72789	60936	14674	17770	14031
Southeast Region							
Glen 0. Jones Lake	5669	8903	8794	8170	1175	1832	1633
Hew City Lake	14733	12829	17087	16636	3005	3295	3104
Lake of Egypt	86452	96518	116706	116304	19624	26315	24840
Kinkaid Lake	124136	130223	150701	147200	25224	35952	33871
			Peak Reservoir Discharge (cfs)				
Northwest Region							
Tara Lake	3975	5804	6157	6081	756	1088	1061
Lake Summerset	18702	17497	26979	23842	481	637	557
Pierce Lake	25331	24933	33675	33860	4234	4887	4180
Lake Holiday	45410	40410	48417	44870	7873	9850	7264
Wonder Lake	45617	41086	49127	44344	8468	12713	8236
North Central Region							
Hollis Park Lake	6186	5528	8010	7245	127	123	135
Lake Wildwood	11161	9216	12913	11633	886	829	844
Mauvaise Terre Lake	24752	21411	26985	23786	5600	5332	5610
Sangchris Lake	31839	27936	34901	30952	3705	3445	3469
Clinton Lake	105364	105961	116066	72532	8442	12332	8374
Lake Decatur	160846	162357	184259	131575	41913	37164	40247
South Central Region							
Waltonville Lake	2483	3174	4130	3762	245	246	269
Lake Sara	23320	15291	28536	22719	1512	1891	1352
Vandalia City Lake	21784	18769	25306	23045	2790	3434	2717
Lake Taylorville	54885	53162	64486	53466	11374	13796	11028
Lake Vermilion	63965	63267	72008	60211	14360	17378	13735
Southeast Region							
Glen 0. Jones Lake	3291	3002	4178	4376	219	268	211
New City Lake	12334	9997	14562	14682	2212	2552	2173
Lake of Egypt	28640	24858	31430	28266	4184	5224	4002
Kinkaid Lake	42910	38469	47236	52221	6956	8857	6657

Table 14. Maximum Reservoir Stage Resulting from Combinations of Rainfall Magnitude and Distribution Techniques

	Maximum Pool Level (ft above top of dam)						
Rainfall Distribution:	HEC-1	Huff	Type-II	NEH-4	HEC-1	Huff	Type-II
Rainfall Estimate:	HMR-51	Huff	Huff	NEH-ES	TP-40	Huff	TP-40
Hopbrook Factor:	yes	yes	no	no	n/a	n/a	n/a
Northwest Region							
Tara Lake	2.0	2.5	2.6	2.6	0.5	0.7	0.7
Lake Summerset	2.2	2.1	2.8	2.6	-4.4	-2.8	-6.1
Pierce Lake	2.7	2.6	7.4	5.4	-6.1	-5.5	-6.1
Lake Hoiiday	1.7	1.3	2.0	1.7	-8.5	-7.3	-8.9
Wonder Lake	5.4	4.9	5.8	5.3	0.0	1.1	-0.1
North Central Region							
Hollis Park Lake	2.8	2.9	4.2	3.4	-0.8	-1.2	-0.5
Lake Wildwood	0.5	0.1	0.8	0.6	-7.2	-7.6	-7.5
Mauvaise Terre Lake	0.2	0.1	0.7	0.6	-6.3	-6.9	-6.3
Sangchris Lake	-2.4	-2.7	-2.1	-2.4	-6.6	-6.6	-6.6
Clinton Lake	-4.9	-4.8	-4.2	-6.9	-16.1	-14.6	-16.2
Lake Decatur	6.2	6.3	7.4	4.7	-3.5	-4.2	-3.7
South Central Region							
Waltonville Lake	0.9	1.1	1.4	1.3	-1.1	-1.1	-0.9
Lake Sara	0.7	-0.4	1.1	0.7	-7.0	-6.1	-7.2
Vandalia City Lake	1.4	1.1	1.7	1.5	-6.5	-6.0	-6.6
Lake Taylorville	0.0	-0.3	0.9	-0.2	-8.5	-7.8	-8.6
Lake Vermilion	-0.2	-0.4	1.0	-1.2	-6.6	-5.7	-6.7
Southeast Region							
Glen O. Jones Lake	-1.6	-2.0	-0.6	-0.4	-6.6	-6.2	-6.7
New City Lake	0.7	0.1	1.2	1.2	-5.5	-4.7	-5.0
Lake of Egypt	-3.2	-4.3	-3.1	-3.3	-11.7	-11.2	-11.8
Kinkaid Lake	-0.6	-1.6	0.1	0.3	-10.7	-10.0	-10.8

maximum reservoir stage. This comparison is very similar to the comparison made in Table 11 between the Huff methodology and the HEC distribution using Huff PMP rainfall. The similarity between the discharge comparisons using either the HMR-51 or Huff PMP suggests that the choice between either of these estimates is not critical in the design of the probable maximum storm.

The Soil Conservation Service generally uses the NEH-4 Emergency Spillway rainfall and distribution without applying a reduction factor in its reservoir design. The six-hour NEH-4 storm results in basin runoff and reservoir outflow averaging 35% and 26% greater, respectively, than the HEC-HMR probable maximum discharges for watersheds of size less than 20 mi^2. The more intense Type-II distribution, when used for PMP storms, results in the most conservative flood discharges of the four methodologies listed. The reservoir outflow resulting from use of the Type-II distribution averages 22% higher than flows from the HEC-HMR methodology; this differential in reservoir outflow is most commonly 10-15% but ranges to 50% for reservoirs in small watersheds. The median increase in the probable maximum flood stage is .6 ft, but ranges from .3 ft up to 4.7 ft for Pierce Lake. The majority of the increase between the HEC-1 and Type-II methodology, however, is caused by the difference in PMP magnitude caused by the variable concerning use or non-use of the Hopbrook factor.

The hydrology of the probable maximum storm and flood most heavily influences the design capacity of the reservoir emergency spillway. Of the PMP characteristics studied, this design factor is most heavily dependent upon the choice of whether to use the Hopbrook factor. This is unfortunate, as the use of the reduction factor is extremely arbitrary. The second greatest effect, that caused by rainfall distribution, is not generally great except for some of the smaller reservoirs. The choice between available PMP estimates is a minor consideration.

100-Year Precipitation

The most common estimates of 100-year basin rainfall are provided by the TP-40 rainfall estimates and either the HEC-1 or Type-II rainfall distributions. This study recommends the use of the Huff rainfall amounts and distributions. It has been indicated that the use of the Huff family of rainfall distributions tends to result in flood discharges which are low compared with floods of the HEC-1 and Type-II distributions. In contrast, the Huff 100-year rainfall estimates provide for higher flood discharges than do the TP-40 estimates. Because the increase of the Huff rainfall estimate is regionally inconsistent, the effect of an adoption of the Huff methodologies will vary across the state.

For five of the six reservoirs in the North Central region, the peak basin runoff and reservoir outflow associated with the SCS or HEC distributions and TP-40 rainfall exceed those values for the Huff rainfall, with the differential in reservoir outflow being 5%. The only major deviation from this average ratio occurs for the sixth reservoir in this region, Clinton Lake. For the other rainfall regions, the Huff rainfall amounts are much larger than the TP-40 estimates, which causes the Huff basin runoff and reservoir outflow to be much greater than the respective discharges associated with the other two methodologies. The ratios between the Huff and HEC-1 peak reservoir discharges listed in Table 13 average 1.33, 1.18, and 1.23 for the Northwest, South Central, and Southeast regions. For the Type-II distribution these ratios of reservoir outflow are 1.25, 1.18, and 1.27, respectively. These outflow ratios between the HEC-1 and Type-II distributions are similar even though the Type-II inflow peaks are typically much higher than the HEC-1 inflows for most of the smaller basins.

For five of the six reservoirs in the North Central region, both the HEC-1 and Type-II 100-year floods create an average maximum reservoir stage .4 ft greater than the Huff maximum stage. For the other 15 reservoirs studied, the Huff floods result in an average maximum stage .8 ft higher than those stages of the HEC-1 and Type-II floods (Table 14). Of this latter group, the greatest differential in stage is 3.3 ft between the Huff and Type-II floods for Lake Summerset.

The greatest differentials in stage normally occur in the Northwest region.

In summary, the Huff rainfall combined with the Huff distributions provide for maximum reservoir discharges which are an average 20% to 25% greater than either of the more extreme distributions with TP-40 rainfall in all but the North Central region of the state. Therefore, for most of the state, adoption of the suggested methodology will provide for more conservative principal spillway design. In the North Central region the HEC-1 and Type-II distributions generally provide the highest reservoir inflow and outflow for large and small basins, respectively. However, the Huff methodology is still considered preferable for use in the North Central region.

SUMMARY

The sensitivity of the maximum basin inflow, reservoir discharge, and stage of the twenty reservoirs to the choices between available techniques for describing precipitation magnitude, time distribution, and storm duration has been examined. The following conclusions concerning the methodologies of the determination of PMP and 100-year frequency design storms are drawn as a result of this investigation:

1) HMR-51 is recognized as providing the best available PMP estimates; however, little difference exists between these estimates and the HMR-33 and Huff estimates of the PMP. Use of the PMP from any of these sources for durations longer than or equal to six hours is acceptable. The most critical judgment in the estimation of the PMP is that of the use of the Hopbrook factor. Application of the Hopbrook factor is shown to create an average 22% decrease in the maximum reservoir discharge. The continued use of this reduction factor is recommended until HMR-52, which describes a methodology that determines reduction factors for individual basins, is released.
2) Those rainfall distribution techniques which attempt to maximize the depth-duration relationship within a storm are best for use with the PMP. The distributions which best accomplish this maximization for the PMP are the 24-hour HEC-1 Standard Project Storm and the 6-hour NEH-4 Emergency Spillway Storm. Because of its 6-hour duration, the NEH-4 distribution does not produce runoff volume great enough to provide as conservative a discharge as does the HEC-1 distribution, with exceptions occurring only in very small watersheds. Therefore the HEC-1 distribution is recommended as the best rainfall distribution for modeling probable maximum storms. Both the SCS Type-II and Huff distributions create less than maximum discharges for large basins and unrealistically large discharges for very small basins.

3) The Huff estimates of 25-year, 50-year, and 100-year precipitation are favored for use in hydrometeorological studies in Illinois. The 100-year precipitation from Huff exceeds the TP-40 estimates by average amounts of 42%, 11%, 30%, and 29% for the Northwest, North Central, South Central and Southeast regions of the state, respectively.

4) The Huff rainfall distributions are the only rainfall time distributions examined which are based on actual rainfall events. These distributions most closely represent a heavy rainfall and are recommended for use with the 25-year, 50-year, and 100-year rainfall events. The other distributions studied all represent maximal concentrations of rainfall, not indicative of any known event. Use of the Huff rainfall distribution results in basin runoff estimates that average 10% less than floods resulting from the maximal rainfall distributions. However, when used in conjunction with the greater Huff rainfall estimates, this methodology results in higher flood discharges for all areas of the state but the North Central region. In the North Central region the Huff methodology provides for peak reservoir discharge approximately 5% less than when using TP-40 rainfall with either the HEC-1 or Type-II distributions.

5) Peak runoff computed by the Huff rainfall distributions is extremely sensitive to storm duration. For this reason, proper application fo the Huff distributions is more difficult than for other distributions. A technique is provided which approximates the storm duration which will produce the maximum reservoir discharge and/or the peak basin runoff when using the Huff distributions. Small basins and other basins with quick hydrologic response and little reservoir capacity produce greater peak discharges from short duration, high intensity rainfall. Larger basins with greater storage are more sensitive to the total volume of rainfall, and therefore produce greater peak discharge with long duration rainfall.

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RECOMMENDED PROCEDURE

Probable Maximum Precipitation

Rainfall Amount. The HMR-51, HMR-33, and Huff estimates of the PMP are all fairly similar in magnitude, and the use of any of these three is acceptable. The 6-, 12-, and 24-hour PMP estimates given by Huff are shown in Table 15. Two reminders concerning the estimation of the PMP are: 1) All depth-area interpolation should be conducted on semi-log paper, and 2) the PMP value for drainage areas of size less than 10 mi^2 should be estimated from the Huff small basin PMP amounts, or should be computed using the depth-area smoothing procedure described in HMR-51.

The precipitation reduction methodology contained in HMR-52 is to be used with the PMP estimates upon the release of that report. In the interim, the use of the Hopbrook factor should be continued.

Rainfall Distribution. The HEC-1 Standard Project Storm distribution, available as an option in the HEC-1 Flood Hydrograph computer model, is recommended for use as the temporal distribution of the probable maximum storm. The 24-hour duration HEC-1 storm should be used for all basin sizes. For small watersheds of size less than 5 mi^2 the six-hour SCS NEH-4 Emergency Spillway storm distribution is also acceptable.

Table 15. Huff Estimates of the Probable Maximum Precipitation (Hopbrook factor not applied)

Storm Duration (hours)	1	10	25	50	100	200	300
		Northwest Region					
6	25.9	24.9	22.8	21.2	19.5	17.8	16.7
12	28.6	27.8	25.7	23.8	22.0	20.3	19.0
24	31.2	30.5	28.1	26.2	24.3	22.5	21.3
		North Central Region					
6	25.1	24.2	22.1	20.5	19.0	17.4	16.4
12	29.0	28.4	26.2	24.4	22.7	21.0	19.6
24	32.0	31.2	29.0	27.3	25.6	24.0	22.9
		South Central Region					
6	27.2	26.2	23.8	22.3	20.6	19.2	17.9
12	30.7	29.9	27.5	25.8	23.9	22.3	20.7
24	33.5	32.7	30.4	28.7	27.0	25.2	24.0
		Southeast Region					
6	27.8	26.8	24.8	23.2	21.4	19.8	18.6
12	31.7	30.7	28.5	26.8	24.8	22.8	21.6
24	35.1	34.2	31.8	29.8	28.0	26.3	24.8
		Hopbrook Factor					
	.80	.80	.825	.85	.87	.89	.895

100-Year Precipitation

The Huff rainfall distributions and precipitation estimates are suggested for use in representing the 25-year, 50-year, and 100-year design storms. The Huff estimates of precipitation magnitude for these rainfall frequencies are listed in Tables 17, 18, and 19.

Storm Duration. It is imperative that the Huff storm used for these rainfall events be of a duration which possesses qualities which will produce conservative discharges for the watershed in question. The following equations, proposed previously, provide an index by which the storm duration which produces the most conservative estimate of reservoir outflow and stage can be estimated:

$$w' = w_{50} \quad , \text{ for } s \leq .8 \tag{1a}$$

$$w' = 1.6\, s\, w_{50}^{.8} \quad , \text{ for } s > .8 \tag{1b}$$

The product w' is then used in Table 16, from Table 10, to estimate the storm duration which should produce the most conservative estimate of the reservoir outflow. Both of the durations listed in this table should be tested, as either may result in the maximum reservoir outflow.

Table 16. Determination of the Storm Duration of Conservative Design for the Huff Distribution from the Adjusted Width of the Unit Hydrograph, w'

Storm Duration (hrs)	w' (hrs)
1 or 2	< 0.9
2 or 3	0.9 - 1.9
3 or 6	2.0 - 2.6
6 or 12	2.7 - 8.2
12 or 24	8.3 - 16.7
24 or 48	16.8 - 44.0
48	>44.0

Table 17. Huff Estimates of Precipitation Magnitude for 25-Year Rainfall Frequency in Illinois

Storm Duration (hours)	Point Rainfall (in.)	Average Rainfall (in.) for given area (mi^2)					
		10	25	50	100	200	300
				Northwest Section			
0.25	1.4	1.2	1.0	0.9	0.7	0.6	0.5
0.5	1.9	1.8	1.5	1.4	1.2	1.1	1.0
1	2.6	2.4	2.3	2.1	1.9	1.7	1.6
2	3.1	3.0	2.9	2.7	2.5	2.3	2.2
3	3.4	3.3	3.2	3.1	2.9	2.8	2.6
6	4.1	4.0	3.9	3.7	3.6	3.5	3.4
12	4.8	4.7	4.6	4.5	4.4	4.3	4.1
24	5.7	5.6	5.5	5.4	5.3	5.2	5.0
48	6.2	6.1	6.0	5.9	5.8	5.7	5.6
				North Central Section			
0.25	1.2	1.1	0.9	0.8	0.6	0.5	0.4
0.5	1.7	1.6	1.4	1.2	1.1	1.0	0.9
1	2.3	2.1	2.0	1.9	1.7	1.5	1.4
2	2.7	2.6	2.5	2.3	2.2	2.0	1.9
3	3.1	3.0	2.9	2.8	2.7	2.5	2.4
6	3.6	3.5	3.4	3.3	3.2	3.1	3.0
12	4.3	4.2	4.1	4.0	3.9	3.8	3.7
24	5.1	5.0	4.9	4.8	4.7	4.6	4.5
48	5.6	5.5	5.4	5.3	5.2	5.1	5.0
				South Central Section			
0.25	1.3	1.2	1.0	0.8	0.7	0.6	0.5
0.5	1.8	1.7	1.5	1.3	1.2	1.0	0.9
1	2.5	2.3	2.2	2.0	1.9	1.7	1.6
2	2.9	2.8	2.7	2.5	2.4	2.2	2.1
3	3.3	3.2	3.1	3.0	2.8	2.7	2.6
6	4.0	3.9	3.8	3.6	3.5	3.4	3.3
12	4.8	4.7	4.6	4.5	4.4	4.3	4.1
24	5.8	5.7	5.6	5.5	5.4	5.3	5.2
48	6.3	6.2	6.1	6.0	5.9	5.8	5.7
				Southeast Section			
0.25	1.4	1.3	1.1	0.9	0.7	0.6	0.5
0.5	2.0	1.9	1.7	1.4	1.3	1.2	1.1
1	2.7	2.5	2.4	2.2	2.0	1.8	1.7
2	3.3	3.1	3.0	2.8	2.7	2.4	2.3
3	3.6	3.5	3.4	3.2	3.1	2.9	2.8
6	4.4	4.3	4.2	4.0	3.9	3.8	3.6
12	5.2	5.1	5.0	4.9	4.8	4.7	4.5
24	6.3	6.2	6.1	6.0	5.9	5.8	5.7
48	6.8	6.7	6.6	6.5	6.4	6.3	6.1

Table 18. Huff Estimates of Precipitation Magnitude For 50-Year Rainfall Frequency in Illinois

Storm Duration (hours)	Point Rainfall (in.)	Average Rainfall (in.) for given area (mi^2)					
		10	25	50	100	200	300
				Northwest Section			
0.25	1.6	1.5	1.2	1.0	0.8	0.7	0.6
0.5	2.3	2.1	1.9	1.7	1.5	1.3	1.2
1	3.2	3.0	2.8	2.6	2.4	2.1	2.0
2	3.8	3.6	3.5	3.3	3.1	2.8	2.7
3	4.2	4.0	3.9	3.8	3.6	3.5	3.3
6	4.9	4.8	4.7	4.5	4.3	4.2	4.0
12	5.8	5.7	5.6	5.5	5.3	5.2	5.1
24	7.2	7.1	7.0	6.8	6.7	6.6	6.5
48	7.5	7.4	7.3	7.1	7.0	6.9	6.8
				North Central Section			
0.25	1.4	1.3	1.0	0.9	0.7	0.6	0.5
0.5	2.0	1.8	1.6	1.4	1.3	1.1	1.0
1	2.7	2.5	2.4	2.2	2.0	1.8	1.6
2	3.2	3.0	2.9	2.8	2.6	2.4	2.3
3	3.5	3.4	3 3	3.2	3.0	2.8	2.7
6	4.3	4.2	4.1	3.9	3.8	3.7	3.5
12	5.1	5.0	4.9	4.8	4.7	4.6	4.4
24	6.1	6.0	5.9	5.8	5.7	5.6	5.5
48	6.6	6.5	6.4	6.3	6.2	6.1	5.9
				South Central Section			
0.25	1.6	1.5	1.2	1.0	0.8	0.7	0.6
0.5	2.3	2.1	1.9	1.7	1.5	1.3	1.2
1	3.1	2.9	2.7	2.5	2.3	2.1	2.0
2	3.7	3.5	3.4	3.2	3.0	2.7	2.6
3	4.1	3.9	3.8	3.7	3.5	3.3	3.2
6	4.9	4.8	4.7	4.5	4.3	4.2	4.0
12	5.8	5.7	5.6	5.5	5.3	5.2	5.1
24	7.0	6.9	6.8	6.7	6.5	6.4	6.3
48	7.5	7.4	7.3	7.1	7.0	6.9	6.8
				Southeast Section			
0.25	1.8	1.6	1.3	1.1	0.9	0.8	0.7
0.5	2.5	2.3	2.0	1.8	1.6	1.4	1.3
1	3.3	3.1	2.9	2.7	2.4	2.2	2.1
2	3.9	3.7	3.6	3.4	3.2	2.9	2.8
3	4.3	4.1	4.0	3.9	3.7	3.5	3.4
6	5.2	5.1	4.9	4.7	4.6	4.5	4.3
12	6.0	5.9	5.8	5.6	5.5	5.4	5.2
24	7.3	7.2	7.1	6.9	6.8	6.7	6.6
48	7.9	7.8	7.7	7.5	7.4	7.3	7.3

Table 19. Huff Estimates of Precipitation Magnitude for 100-Year Rainfall Frequency in Illinois

Storm Duration (hours)	Point Rainfall (in.)	Average Rainfall (in.) for given area (mi^2)					
		10	25	50	100	200	300
				Northwest Section			
0.25	1.8	1.6	1.3	1.2	0.9	0.8	0.7
0.5	2.6	2.4	2.2	2.0	1.8	1.6	1.5
1	3.6	3.3	3.1	2.9	2.7	2.4	2.3
2	4.4	4.3	4.0	3.8	3.6	3.3	3.2
3	4.9	4.7	4.5	4.3	4.1	3.9	3.7
6	5.8	5.7	5.5	5.3	5.1	5.0	4.9
12	6.9	6.8	6.6	6.5	6.3	6.2	6.0
24	8.3	8.2	8.0	7.9	7.8	7.6	7.6
48	9.2	9.1	9.0	8.9	8.7	8.6	8.5
				North Central Section			
0.25	1.6	1.4	1.2	0.9	0.8	0.6	0.4
0.5	2.3	2.1	1.8	1.6	1.4	1.3	1.2
1	3.1	2.9	2.7	2.5	2.3	2.1	2.0
2	3.7	3.5	3.4	3.2	3.0	2.7	2.6
3	4.2	4.1	4.0	3.8	3.6	3.4	3.3
6	5.1	5.0	4.7	4.6	4.4	4.2	4.1
12	5.9	5.8	5.7	5.5	5.4	5.3	5.2
24	7.2	7.1	7.0	6.8	6.7	6.6	6.5
48	8.0	7.8	7.7	7.5	7.3	7.2	7.1
				South Central Section			
0.25	1.8	1.6	1.3	1.1	1.0	0.9	0.8
0.5	2.7	2.4	2.1	1.9	1.7	1.5	1.4
1	3.6	3.3	3.1	2.9	2.6	2.4	2.3
2	4.5	4.3	4.2	3.9	3.6	3.3	3.2
3	4.9	4.8	4.7	4.4	4.2	3.9	3.8
6	5.9	5.8	5.6	5.4	5.2	5.0	4.8
12	7.0	6.9	6.8	6.6	6.4	6.3	6.0
24	8.4	8.3	8.1	8.0	7.9	7.7	7.5
48	9.2	9.0	8.9	8.7	8.5	8.4	8.2
				Southeast Section			
0.25	2.0	1.7	1.4	1.2	1.0	0.9	0.8
0.5	3.0	2.7	2.4	2.1	1.9	1.7	1.6
1	4.0	3.7	3.5	3.2	2.9	2.7	2.6
2	4.7	4.5	4.3	4.0	3.8	3.5	3.4
3	5.2	5.0	4.9	4.7	4.5	4.2	4.1
6	6.3	6.1	5.9	5.7	5.6	5.4	5.3
12	7.4	7.3	7.1	6.9	6.8	6.6	6.5
24	8.8	8.6	8.5	8.4	8.3	8.1	8.0
48	9.6	9.3	9.2	9.0	8.9	8.8	8.7

The factors W_{50} and s used in Equations la and lb can be provided by the unit hydrograph and the reservoir storage-outflow relationship. For example, Figure 12 shows the basin unit hydrograph and the surcharge storage-outflow relationship for Lake of Egypt in Williamson County. The W_{50} may be read directly from the unit hydrograph. The surcharge storage index, s, is computed by finding the surcharge storage in basin-inches corresponding to a reservoir discharge equal to the magnitude of the peak of the unit hydrograph (6623 cfs). The reservoir storage for Lake of Egypt corresponding to a discharge of 6623 cfs is approximately 10,800 acre-feet, which converts to 6.07 inches of storage. Then, using Equation lb:

$$w' = 1.6\ (3.2)^{0.8}(6.07) = 24.6 \qquad (2)$$

With w' as calculated above, Table 16 suggests that a storm of duration either 24 hours or 48 hours will produce the most conservative estimate of the 25-year, 50-year, or 100-year reservoir outflow.

The design storm which produces maximum outflow is often not of the same duration as the storm which results in maximum reservoir inflow. The critical duration fo the basin runoff storm may be computed by using the W_{50} in place of w' in Table 16, and then choosing the lesser of the two durations listed. For Lake of Egypt the critical storm duration of inflow is six hours, that duration associated with a W_{50} of 3.2 hours.

Rainfall Distribution. Table 20 contains three different curves from the Huff family of distributions. The Huff 1 (first quartile) distribution is used for all storms of duration less than 12 hours. The 12- and 24-hour design storms are best represented by the Huff 3 (third quartile) distribution, whereas the Huff 4 (fourth quartile) curve should be used for 48-hour storms. These curves are the median (50%) rainfall distributions previously recommended by Huff.

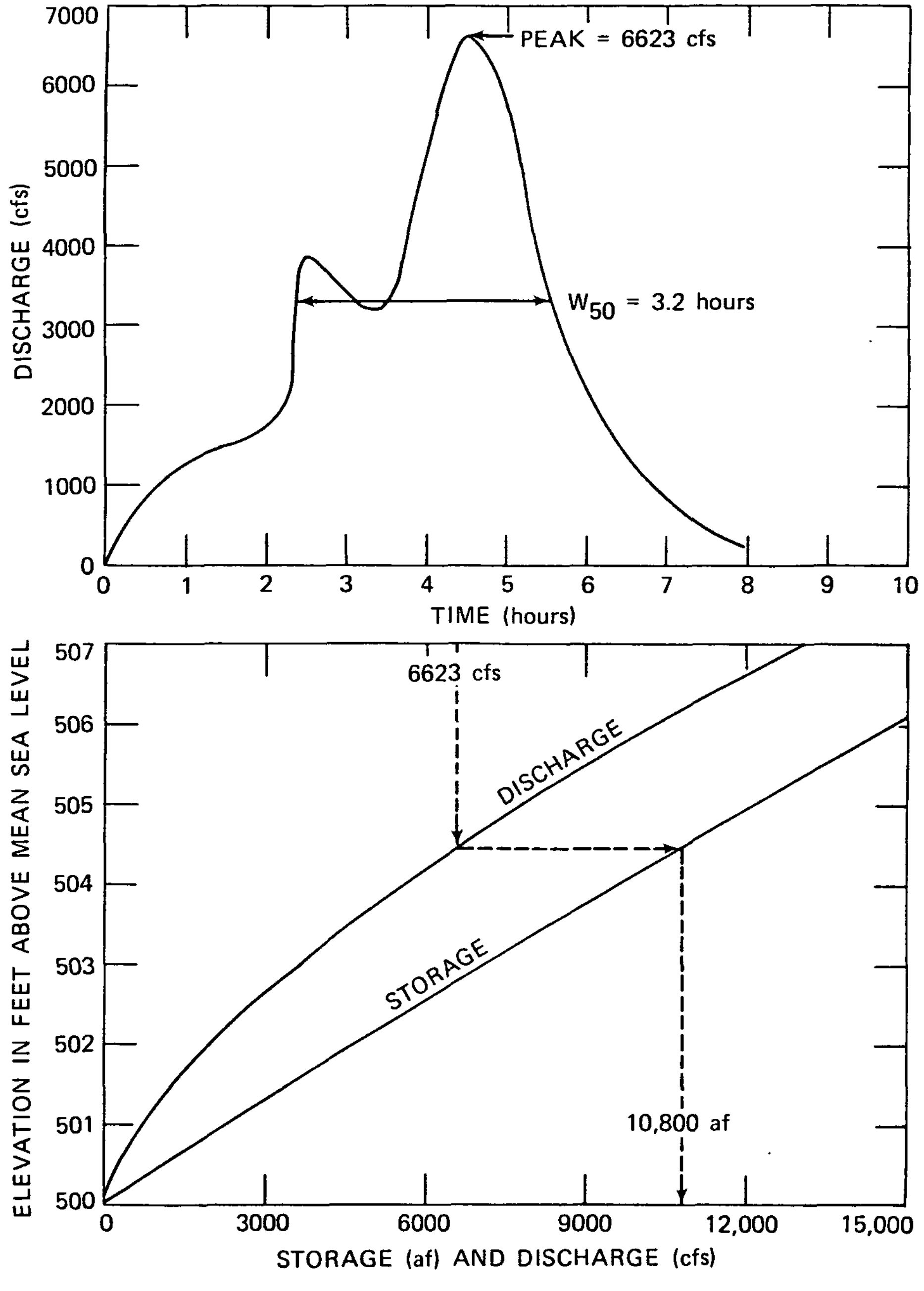

Figure 12. Use of the a) unit hydrography and b) reservoir storage-outflow relationship to determine the design storm duration for Lake of Egypt

Table 20. Time Distribution of Huff Rainfall for First, Third, and Fourth Quartile Storms

Time Units	Percent of Storm Rainfall Occurring in Time Unit		
	Huff 1	Huff 3	Huff 4
1	10.0	2.4	1.6
2	11.4	2.6	2.4
3	11.6	3.0	2.6
4	10.6	2.8	2.2
5	9.0	2.6	2.0
6	6.4	2.6	2.0
7	5.0	3.0	2.2
8	5.0	3.0	2.2
9	4.0	3.0	2.4
10	3.0	4.0	2.4
11	3.0	5.0	2.8
12	3.0	5.0	3.2
13	2.0	6.0	3.4
14	2.0	7.0	3.6
15	2.0	10.0	3.6
16	1.8	9.0	3.6
17	1.6	9.0	4.0
18	1.4	5.0	5.0
19	1.2	3.0	6.0
20	1.0	3.0	8.4
21	1.0	2.6	10.4
22	1.0	2.2	11.6
23	1.4	2.2	8.4
24	1.6	2.0	5.0