ENGINEERING JUDGMENT AND SMALL AREA FLOOD PEAKS

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ABSTRACT

The knowledge of small basin floods and the state of the art of flood predictions on ungaged basins are such that engineering judgment still plays an important role in the determination of a design flood. An appraisal of the reliability of five current methods of flood prediction is presented as an aid in developing this faculty.

The first phase involved a comparison among flood estimates obtained by applying rainstorms estimated to have return periods of from 2- through 200-years. For each of six such levels of protection applied to fourteen real basins, inconsistencies among five methods produced differences in the magnitude of their estimates as great as 300 per cent.

Since long flood records for small basins were inadequate, it was necessary to insert observed rainfalls into formulae and design methods for a second phase of the study. Design estimates based upon recorded rainstorms were compared to 134 observed floods. These events occurred on forty-five mixed cover agricultural basins ranging in area from 0.12 through 8.16 square miles, within thirteen states of the U. S. A.

Scatter-diagrams, histograms, and statistics suggest some superiority of the "Rational" formula, the Bureau of Public Roads method, and the Tacitly Maximized Peak technique in that they generally overestimate floods from this sample. Although their variability is also less than that of the other two methods, it is sufficient to permit underprediction in about a third of the cases. Comparisons are odious, and it is essential to recognize that the purposes for which some methods were developed were somewhat at variance with restraints imposed by this appraisal. Regional limitations spelled out by their authors were violated expressly here to explore desirable versatility.

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ENGINEERING JUDGMENT AND SMALL AREA FLOOD PEAKS

by Lourens A. V. Hiemstra[1] and Brian M. Reich[2]

CHAPTER I

INTRODUCTION

Practicing engineers, responsible for the task of predicting flood peaks from small basins, cannot rely upon local stream records. For example, within conterminous U. S. A. the 846,000 tributary watersheds with areas between one and two square miles are represented by less than sixty streamgages within that size range [1]. Designers, therefore, lean heavily upon formulae and methods utilizing rainfall data. Unpublished comparisons of applying such estimating techniques are often made by their users. Engineering judgment is called upon to account for anomalies and to select the design flood. Presentation of such a set of data in the first phase of this paper forms a basis upon which such judgment can be developed. Practicing engineers do not normally have the opportunity of including observed floods.

Besides publishing comparative estimates based upon various rainstorm frequencies this paper proceeds, in its second phase, to use 134 flood peaks observed on forty-five basins in the United States of America. The return periods were known for 109 of these floods and ranged from 1.001 through 125 years with an average of 8.46 years. These resulted from rainstorms with return periods from less than 1.001 through 220 years, averaging 11.53 years. Individual comparisons with these real events were made on the basis of average storm rainfall recorded over the experimental basins. Such an approach side-steps the problem that individual storms normally have a different return period, the reciprocal of probability of occurrence in any year, to the return period of the ensuing flood peak. A fundamental argument to the second phase of the paper is that the methods which reproduce recorded flood peaks most satisfactorily from recorded rain also will be most suitable for use in designs involving rainstorm estimates of long return periods.

Flood estimating techniques considered were:

(a) "Rational" Formula [2, 3] or Lloyd-Davis method [4] (RATIONAL)

(b) U. S. Soil Conservation Service Hydrograph Families [5] (SCS)

(c) Bureau of Public Roads method [6] (BPR)

(d) Chow's method [3, 7] (CHOW)

(e) Tacitly Maximized Peaks [8, 9] (TMP)

They will be referred to throughout by the acronyms in parentheses.

Methods are frequently employed outside the bounds originally stipulated by their authors. For example, although Ven Te Chow strictly limited his method to Illinois [7], some modifications have been suggested [10] for applying this method beyond Illinois. BPR was developed for use within the zones marked on fig. 1 almost exclusively east of 105 degrees west. Both the BPR and CHOW methods were not intended for use in the arid Southwest nor in California to which their tests have been extended currently. RATIONAL is often used for larger areas than the five square miles below which its use is usually recommended [11]. It was tested in this study on three experimental areas larger than this. Similarly all tests were not restricted to the exact domain specified by the authors of each particular method. So results of this paper should not be misconstrued as a rechecking of a particular method proposed for a particular set of conditions. Rather, it has been decided to look at all methods across similar wide ranges to examine them for the additional desideratum of generality, or "instant adaptability." Consideration of this feature incidentally will lead engineers to a better understanding of the original restraints imposed by originators of methods.

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CHAPTER II

DATA

Some parameters collected [12] for forty-five experimental areas from topographic maps and other sources are presented in Table 1. Their nineteen localities are marked on fig. 1, mostly according to the Agricultural Research Service [13, 14, 15] reference numbers. This map also reproduces Potter's [6] zones and shows how far outside the applicable BPR regions twelve basins were.

Fourteen basins of which twelve were marked with an asterisk in Table 1 were used in the first phase of this study. Half of these, with ARS numbers: 41.2, 45.4, 47.1, 49.1, 63.3, 63.4, and 63.5, are from arid regions. The others are from relatively humid areas: 26.29, 26.34, 26.36, 37.2, 42.2, 42.3, and 42.4. Both the humid basins and the arid basins were selected to cover a similar spectrum of "basin characteristics," B (previously referred to by others as "time of concentration"). The spread of B's from 0.16 through 3.75 hours involved basins ranging from 0.15 through 8.61 square miles.

The second phase of the study required observed rainfall and runoff data from experimental basins. All nineteen locations listed in Table 1 and fig. 1 were used in providing forty-five basins for this purpose. Their major topographic features are listed in Table 1. Table 2 presents observed conditions for each of the 134 flood events available from these experimental areas. Rainfall amounts listed for both storm and antecedent precipitation were Thiesen averages for all appropriate gages. The soils and additional properties necessary in making flood predictions also appear in Table 2. In addition to the underlined values which were essential to computations performed in this paper, many additional rainfall and soil values have been included. Thus a compendium of observations is presented to engineers in exploring anomalies, and in testing other and new methods which hopefully will be added.

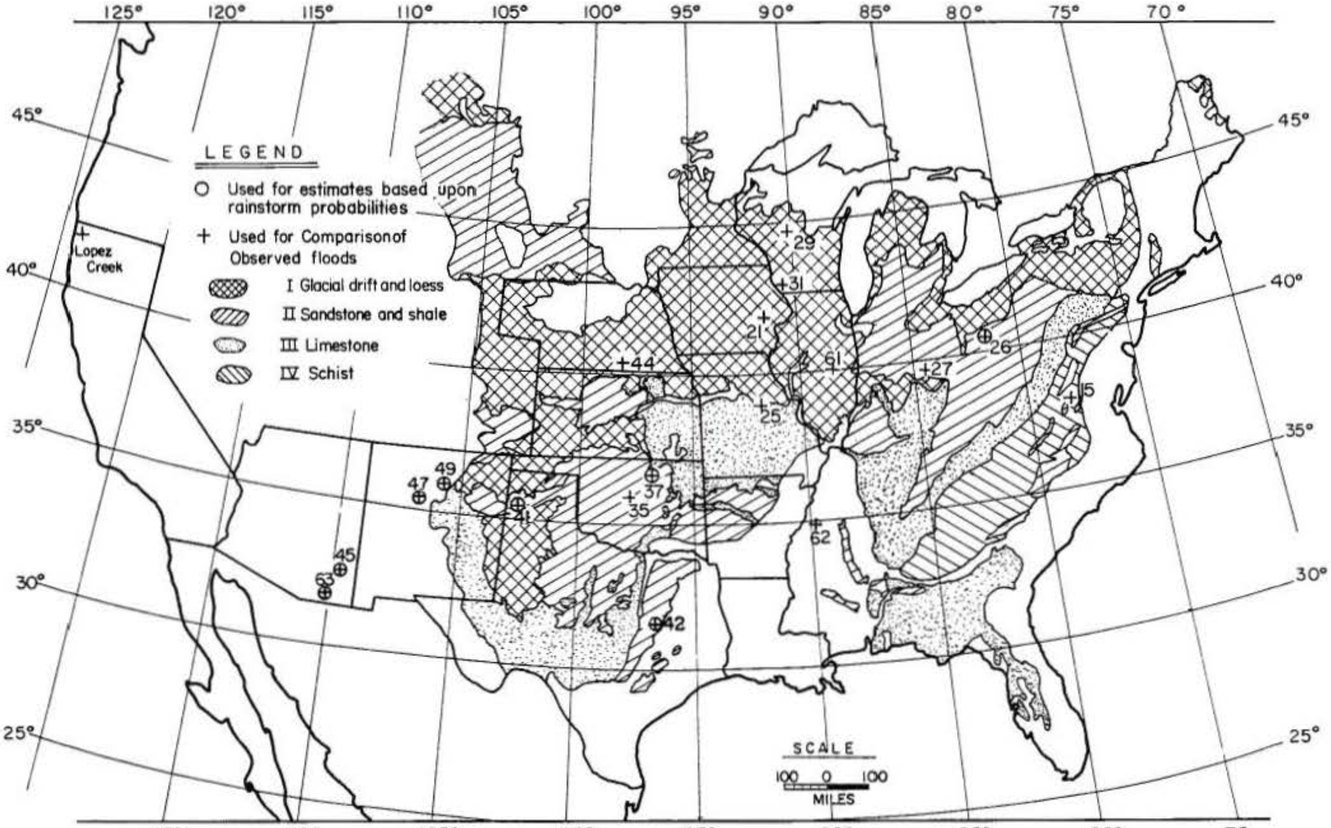

Fig. 1 Map Showing Localities of Watersheds

TABLE 1. TOPOGRAPHIC PARAMETERS

Event Number (1)	Location (2)	A.R.S. No. (3)	Latitude (4)	Longitude (5)	Area (S.M.) (6)	H (ft.) (7)	L (Miles) (8)	S_1 (ft/mi) (9)	S_2 (ft/mi) (10)
1	Staun., Va.	15.1	38°10'01"	78°05'35"	0.61	247	1.54		
2 thru 3	Ral. Cr., Iowa	21.1	41°39'50"	91°30'45"	2.99	149	3.99	62.7	26.5
4	McCred., Mo.	25.1	38°57.3'	91°53.8'	0.24	43	0.95	31.6	51.1
5 thru 8	Cosh., Ohio*	26.29	40°21'29"	81°46'53"	0.12	203	0.61	274.0	358.0
9 thru 13	Cosh., Ohio	26.30	40°21'36"	81°46'04"	0.47	253	0.44		
14 thru 15	Cosh., Ohio	26.31	40°23'33"	81°48'19"	0.19	170	0.67		
16 thru 18	Cosh., Ohio	26.32	40°24'23"	81°48'11"	0.55	203	0.94		
19 thru 20	Cosh., Ohio	26.33	40°24'08"	81°47'41"	1.44	264	1.68		
21 thru 23	Cosh., Ohio*	26.34	40°23'32"	81°48'24"	2.38	330	2.41	277.0	77.2
24 thru 25	Cosh., Ohio	26.35	40°23'03"	81°49'04"	4.30	348	3.23		
26 thru 29	Cosh., Ohio*	26.36	40°21'51"	81°50'20"	7.16	352	5.21	160.0	28.0
30 thru 31	Cosh., Ohio	26.37	40°21'50"	81°51'40"	27.34	363	8.63		
32	Hamilton, Ohio	27.1	39°32'	84°49'	0.17	68	1.01		
33	Colby, Wisconsin	29.1	44°55'	90°14'	0.53	78	1.29		
34 thru 37	Fen., Wisconsin	31.1	43°04'	90°28'	0.51	133	1.09		
38 thru 40	Fen., Wisconsin	31.4	43°04'	90°28'	0.27	90	0.60		
41 thru 43	Guthrie, Okla.	35.11	35°52'	97°25'	0.15	80	0.65	123.0	123.0
44 thru 51	Stilwater, Okla.*	37.2	36°18'	97°03'	0.14	69	0.59	198.0	82.2
52 thru 57	Stilwater, Okla.	37.3	36°18'	97°03'	0.32	93	1.36	118.0	47.3
58	Vega, Texas*	41.2	35°15'	102°25'	0.15	67	0.78	77.0	71.4
59 thru 62	Ries. Wa., Texas*	42.2	31°31'10"	96°53'40"	0.90	51	1.70	39.2	26.0
63 thru 67	Ries. Wa., Texas*	42.3	31°30'38"	96°53'22"	1.74	64	2.66	43.9	15.6
68 thru 69	Ries. Wa., Texas	42.4	31°29'00"	96°52'31"	6.84	108	6.86	26.8	11.1
70 thru 72	Ries. Wa., Texas	42.6	31°27'27"	96°52'46"	0.28	50	1.02		
73 thru 77	Ries. Wa., Texas	42.7	31°27'22"	96°52'53"	0.20	46	0.57		
78 thru 82	Ries. Wa., Texas	42.11	31°28'35"	96°52'35"	0.48	52	0.91	91.6	42.4
83 thru 88	Ries. Wa., Texas	42.12	31°28'28"	96°52'46"	0.21	51	0.66	116.0	60.5
89 thru 94	Ries. Wa., Texas	42.13	31°28'29"	96°52'55"	0.12	45	0.51	117.5	75.6
95 thru 99	Hastings, Neb.	44.1	40°16'	98°16'	0.75	75	1.64	77.3	32.3
100 thru 101	Hastings, Neb.	44.2	40°16'	98°16'	0.64	112	1.45		
102 thru 104	Hastings, Neb.	44.3	40°18'	98°16'	3.23	127	5.66		
105	Hastings, Neb.	44.4			5.45	168	11.68		
106 thru 107	Saff., Arizona	45.1	32°54'54"	109°49'46"	0.81	240	2.70		
108 thru 109	Saff., Arizona*	45.4	32°44'40"	109°35'29"	1.13	520	3.53	212.0	119.0
110	Albq., N. Mexico	47.2	35°16'	106°42'	0.15	192	0.74	719.0	230.0
111 thru 113	Santa Fe, N. Mex.*	49.1	35°42'	105°57'	0.22	113	0.65	215.0	156.0
114 thru 117	Montic, Ill.	61.1	39°59'	88°39'	0.13	18	0.37	63.0	42.5
118	Oxford, Miss.	62.1	34°43'	89°43'	3.10	184	3.46		
119 thru 121	Oxford, Miss.	62.2	34°42'	89°44'	1.75	116	2.21		
122 thru 124	Oxford, Miss.	62.6	34°45'58"	89°34'45"	0.38	130	1.03	145.7	118.0
125	Oxford, Miss.	62.8	34°44'10"	89°27'29"	1.69	118	2.00	66.6	55.7
126 thru 129	Tombst., Ariz.*	63.3	31°45'	110°03'	3.47	585	6.29	127.2	80.0
130 thru 131	Tombst., Ariz.*	63.4	31°44'	110°04'	0.88	200	1.94	147.0	85.0
132 thru 133	Tombst., Ariz.*	63.5	31°42'	110°02'	8.61	362	4.01	83.0	93.0
134	Lopez Cr., Cal.		41°57'36"	124°12'08"	0.93	1202	3.02		

Note: Localities marked with * were used in calculations from "Rainfall Frequency Atlas".

TABLE 2. BASIN AND RAINFALL CHARACTERISTICS USED FOR EACH EVENT

Event No. (1)	A.R.S. No. (2)	Date (3)	A.P.I.$_5$ (4)	I (5)	P6hr (6)	P_{60} (7)	P_{30} (8)	C (9)	Curve No. S.C.S. (10)	B.P.R. Zone (11)	Curve No. Chow (12)	S (13)	q_o (14)
1	15.1	April 13, 1949	1.54	2.2	1.69	1.16	1.06				49	0.81	287
2	21.1	July 21, 1948	0.09	1.1	2.61	1.62	1.00		52			0.46	219
3		July 18, 1956	0.46	1.6	2.94	2.57	1.60	.55		I		0.46	550
4	25.1	Oct. 4, 1941	9.02	2.8	1.45	1.20	0.92	.50		I		0.36	1290
5	26.29	June 16, 1946	1.42	4.7	3.27	2.90	2.10	.60	79	II		0.84	1610
6		Sept. 1, 1950	0.61	3.2	4.37	2.80	1.70	.60	62	II		0.66	1090
7		June 12, 1957	1.36	4.2	2.86	2.70	2.15	.60	79	II		0.61	1560
8		June 28, 1957	2.12		2.25	1.15	0.75		91			0.89	811
9	26.30	Sept. 23, 1945	1.90	3.8	1.46	1.32	0.97				77	0.63	1220
10		June 16, 1946	1.60	4.6	3.20	2.55	1.74				77	0.62	1150
11		Sept. 1, 1950	0.82	4.6	4.39	2.74	1.48				59	0.84	2420
12		June 12, 1957	1.23	6.9	3.27	2.92	2.66				59	0.63	687
13		June 28, 1957	2.62	3.1	2.17	1.08	0.70				93	0.68	900
14	26.31	Sept. 23, 1945	2.20	2.3	1.91	1.30	1.08		90		78	0.61	1110
15		Aug. 21, 1960	0.70	3.9	3.40	1.75	1.05		60		61	0.83	232
16	26.32	Sept. 23, 1945	1.81	3.0	1.86	1.27	1.10				59	0.84	210
17		June 12, 1957	1.18	4.3	2.54	2.13	1.46		59		59	0.85	276
18		Aug. 21, 1960	0.69	2.9	3.74	1.27	0.92		59		59	0.85	614
19	26.33	June 12, 1957	1.18	3.0	2.54	2.10	1.48		59		59	0.55	181
20		Aug. 21, 1960	0.69	2.1	3.91	1.28	0.91		59		59	0.55	348
21	26.34	Sept 23, 1945	1.46	1.7	1.35	1.21	1.01				76	0.55	266
22		June 12, 1957	1.18	2.3	2.54	2.10	1.50		58		58	0.55	59
23		June 28, 1957	2.72	2.6	2.12	2.12	1.44	.55		II		0.55	590
24	26.35	June 12, 1957	1.18	2.2	2.55	2.14	1.45		60		61	0.82	210
25		Aug. 21, 1960	0.90	2.0	3.57	1.85	1.12		60		61	0.64	248
26	26.36	Sept. 23, 1945	1.20	0.9	1.95	1.35	1.10		89		58	0.83	210
27		July 11, 1946	0.00	1.6	2.72	1.70	1.20		58		58	0.65	136
28		June 12, 1957	1.18	1.4	2.40	2.02	1.49	.72	58	II	58	0.46	168
29		Aug. 21, 1960	0.70	1.3	3.11	1.63	0.98		58		58	0.66	175
30	26.37	Sept. 23, 1945	1.92	3.7	2.34	1.30	1.19		77		77	0.80	74
31		Aug. 21, 1960	0.70	3.7	3.78	1.93	1.15		59		59	0.63	90
32	27.1	July 7, 1943	1.56	2.4	1.38	1.38	1.32					0.46	350
33	29.1	June 4, 1958	0.67	2.5	3.23	3.05	1.75		68		84	0.25	370
34	31.1	Aug. 12, 1943	1.25	5.0	2.15	2.15	2.15		57		57	0.45	580
35		June 28, 1945	2.16	2.5	1.09	1.05	0.98				91	0.44	646
36		June 24, 1949	2.90	4.0	2.16	1.90	1.62		88		91	0.46	460
37		Aug. 5, 1951	0.55	3.2	6.98	3.65	1.58		57		91	0.47	1080
38	31.4	Aug. 12, 1943	1.23	6.2	2.05	2.05	2.05		58			0.45	773
39		June 24, 1949	2.87	5.5	2.39	2.08	1.81		89			0.45	639
40		Aug. 5, 1951	0.55	3.3	6.73	3.40	1.75		58			0.43	1124
41	35.11	Sept. 8, 1942	1.37	3.3	1.17	1.15	1.12	.22		II	79	0.34	203
42		June 26, 1945	2.49	4.8	1.30	1.30	1.25	.22		II	79	0.34	384
43		July 5, 1949	1.31	2.6	1.17	1.17	1.00	.22		II	79	0.34	244
44	37.2	May 23, 1955	4.56	1.2	1.30	1.30	0.93	.35	92	II	95	0.09	620
45		April 18, 1957	0.00	3.8	3.91	2.81	2.01	.35	66	II	66	0.09	2990
46		June 10, 1957	0.57	2.3	1.30	1.17	0.87	.35		II	82	0.09	570
47		June 27, 1957	3.45	3.5	1.01	1.01	1.01	.35		II	95	0.09	620
48		Oct. 2, 1959	1.97	2.7	2.91	1.26	1.01	.35	82	II	82	0.16	1160
49	37.2	Oct. 2, 1959	4.92	2.7	1.84	1.24	0.92	.35	92	II	95	0.16	820
50		May 28, 1960	1.14	3.8	2.51	1.97	1.62	.35	66	II	95	0.16	940
51		May 21, 1961	0.48	5.4	2.29	2.25	2.07	.35	66	II	66	0.16	1230
52	37.3	April 18, 1957	0.40	3.2	2.79	2.32	1.64		75		75	0.16	1820
53		June 27, 1957	3.49	1.5	0.92	0.92	0.92				97	0.16	60
54		Oct. 2, 1959	1.77	1.8	3.15	1.30	1.10		83		96	0.28	1060
55		Oct. 2, 1959	5.12	1.7	2.14	1.26	0.95		93		96	0.28	610
56		May 28, 1960	1.00	2.4	2.28	1.76	1.42	.36	67	II	83	0.28	645
57		May 21, 1961	0.20	3.1	1.97	1.96	1.80	.36		II	67	0.28	815
58	41.2	May 30, 1938	0.00	2.6	1.27	1.15	1.12	.55		II	69	0.32	939
59	42.2	April 24, 1957	10.46	3.4	1.64	1.60	1.39				96	0.10	560
60		May 13, 1957	3.83	2.1	1.36	1.15	0.80				96	0.10	360
61		July 9, 1961	0.33	1.3	1.48	1.25	1.09	.50		II	69	0.12	32
62		July 16, 1961	0.09	1.4	1.54	1.43	1.25	.50		II	69	0.12	96
63	42.3	June 10, 1941	2.07	1.0	1.65	1.57	1.15				83	0.11	480
64		June 15, 1942	3.68	0.6	1.01	0.95	0.85				95	0.11	322
65		July 15, 1950	2.46	1.1	1.90	1.28	0.95		92		95	0.12	344
66		April 24, 1957	10.29	1.0	1.72	1.64	1.34		93		96	0.12	510
67		June 23. 1959	1.96	1.3	2.64	1.65	1.40	.50		II		0.12	388

TABLE 2 - continued

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
68	42.4	June 23, 1959	2.69	0.5	1.81	1.74	1.33		93		96	0.11	248
69		July 16, 1961	0.19	0.4	1.50	1.42	1.36	.50		II	67	0.10	44
70	42.6	June 10, 1941	1.39	0.9	2.39	0.75	0.50		90		78	0.12	2150
71		March 26, 1946	1.02	1.2	0.84	0.77	0.70				78	0.10	585
72		April 24, 1957	9.55	2.4	1.85	1.72	1.45		96		98	0.10	1390
73	42.7	April 24, 1957	9.63	2.0	1.97	1.97	1.50		94		97	0.11	1330
74		May 13, 1957	4.91	3.1	1.65	1.40	1.12		94		97	0.16	1009
75		June 23, 1959	1.84	1.5	2.15	2.11	1.14		85		85	0.17	930
76		May 22, 1961	0.00	2.9	1.90	1.43	1.25	.60			70	0.16	30
77		June 25, 1961	0.00	2.3	1.39	1.37	0.87	.60			70	0.16	130
78	42.11	April 24, 1957	9.72	2.6	1.76	1.72	1.33		92		95	0.14	1170
79		June 4, 1957	1.63	2.0	1.85	1.85	1.56				81	0.14	1030
80		June 23, 1959	1.94	1.4	1.99	2.00	1.02		81		81	.0.14	430
81		June 25, 1961	0.02	2.0	1.46	1.40	0.82	.60		II	64	0.16	133
82		July 16, 1961	0.37	2.2	1.20	1.15	1.08	.60		II	64	0.16	39
83	42.12	April 24, 1957	9.90	3.0	1.79	1.74	1.25		93		96	0.13	1060
84		May 13, 1957	4.73	2.3	1.57	1.32	1.15		93		96	0.13	784
85		June 4, 1957	1.54	3.7	1.88	1.60	1.60				84	0.15	1130
86		June 23, 1959	1.14	2.6	2.83	1.50	1.05				66	0.15	500
87		June 25, 1961	0.03	2.0	1.46	1.40	0.76	.60		II	66	0.15	160
88		July 16, 1961	0.48	2.9	1.15	1.13	1.09	.60		II	66	0.15	455
89	42.13	April 24, 1957	10.08	3.0	1.77	1.75	1.30	.60	93	II	96	0.15	1080
90		May 13, 1957	4.70	2.6	1.46	1.36	1.07	.60	93	II	96	0.15	765
91		June 4, 1957	1.48	4.1	1.85	1.83	1.73	.60		II	96	0.15	1070
92		June 23, 1959	1.11	2.6	2.94	1.95	1.00	.60		II	96	0.16	530
93		June 25, 1961	0.03	2.6	1.47	1.42	0.92	.60		II	69	0.14	219
94		July 16, 1961	0.36	2.6	1.16	1.16	1.05	.60		II	69	0.14	42
95	44.1	July 10, 1951	0.00	2.5	2.70	2.17	1.41		63		63	0.38	1120
96		June 7, 1953	0.68	1.5	1.56	1.40	0.93				63		460
97		June 15, 1957	1.64	2.0	1.95	1.80	1.2	.60		I	80	0.47	1190
98		May 15, 1960	0.00	2.4	2.26	2.05	1.4	.60	63	I		0.47	610
99		Aug. 11, 1961	0.00	2.0	1.70	1.68	1.5	.60		I		0.47	88
100	44.2	June 12, 1958	0.00	3.1	2.18	2.00	1.73				57	0.53	210
101		July 3-5, 1959	2.39	2.8	2.10	2.09	1.32		91		91	0.53	750
102	44.3	July 10, 1951	0.01	1.0	2.97	2.34	1.83		62		62	0.40	41
103		August 28, 1957	0.10	1.0	2.25	2.00	1.70	.60				0.47	140
104		May 15, 1960	0.00	0.8	2.35	2.13	1.30		62			0.47	172
105	44.4	May 15, 1960	2.26	0.4	2.46	2.26	1.60		91			0.34	149
106	45.1	July 26, 1957	0.28	0.9	0.85	0.85	0.85				83	0.32	210
107		Aug. 3, 1959	0.48	1.1	1.01	0.95	0.95				83	0.32	157
108	45.4	Aug. 30, 1957	0.32	2.0	1.90	1.83	1.68				78	0.47	231
109		Aug. 20, 1960	0.12	2.1	2.37	2.10	1.63	.25	78	II		0.47	264
110	47.2	Aug. 24, 1957	0.00	6.2	1.78	1.70	1.62	.22		III	83	0.40	1780
111	49.1	Aug. 18, 1944	0.70	2.8	1.55	1.55	1.10	.42		III	81	0.29	582
112		July 25, 1945	0.00	3.6	1.40	1.40	1.25	.42		III	81	0.29	820
113		Aug. 25, 1947	0.62	3.2	0.90	0.90	0.87	.42		III	81	0.29	670
114	61.1	July 9, 1951	0.19	4.1	2.23	2.10	1.45	.50	58	I		0.46	445
115		June 27, 1951	2.10	4.4	1.83	1.75	1.55	.50	89	I		0.46	316
116		Oct. 6, 1955	2.48	2.9	2.85	1.90	1.43	.50	89	I		0.46	158
117		Oct. 6, 1955	5.33	2.9	1.73	1.32	1.10	.50	89	I		0.46	216
118	62.1	Sept. 9, 1959	1.17	1.4	2.15	1.64	0.80				43	0.58	188
119	62.2	June 10, 1959	1.55	1.3	1.30	1.30	1.04				69	0.56	390
120		June 11, 1959	2.75	1.1	1.31	1.10	1.01				86	0.56	322
121		Aug. 31, 1961	0.04	1.5	1.86	1.50	0.87				50	0.56	220
122	62.6	June 4, 1957	0.92	2.3	1.35	1.20	1.00				55	0.70	192
123		Aug. 24, 1959	1.14	2.7	1.12	1.12	1.12	.62		II	54	0.70	94
124		Aug. 31, 1961	0.00	2.7	1.60	1.36	1.20	.62		II	54	0.70	191
125	62.8	Sept. 9, 1959	1.00	2.3	2.76	2.60	2.20	.62		II		0.80	360
126	63.3	July 19, 1955	0.60	1.5	2.57	1.53	1.50	.25	72	II		0.74	840
127		Aug. 14, 1958	0.42	0.9	1.51	1.30	1.27	.25		II		0.74	205
128		Aug. 16, 1958	1.95	0.7	1.35	1.30	1.22				97	0.74	360
129		Aug. 17, 1961	0.22	0.7	1.34	1.30	1.13				72	0.74	200
130	63.4	July 19, 1955	0.62	2.8	2.62	2.35	1.80	.25	72	II	86	0.48	1590
131		Aug. 17, 1961	0.24	2.7	1.82	1.82	1.75	.25		II	72	0.48	403
132	63.5	Oct. 4, 1954	0.00	1.4	1.75	1.75	1.62	.25		II	72	0.44	615
133		Aug. 17, 1957	0.36	1.5	2.00	1.80	1.43	.25	72	II	72	0.44	364
134		Nov. 25, 1962	2.10	4.2	5.00	2.70	2.25					0.50	136

CHAPTER III

PREDICTION METHODS APPLIED

A brief review is given here for each of the five computational methods and how they were applied.

1. "Rational" Formula. This method was proposed [3] in 1889 after collecting eleven years of storm sewer data from a built-up area. It is frequently applied to rural country. Although subjected to severe criticism, it has retained broad usage, presumably because of its simplicity. The peak discharge rate in cfs is obtained from Eq. (1).

$$q = C\,I\,a \qquad (1)$$

where C = runoff coefficient based upon flood-producing characteristics of the basin

I = rainfall intensity averaged over the consecutive duration B which produces the most rain throughout the storm, in inches per hour

a = area of the basin in acres.

Customarily it is stated that "I" should be averaged over the "time of concentration," a duration equal to the time it takes water to travel from the hydraulically most remote point of the basin to the structure site. Accurate calculations of velocities along this path are impossible. The simplification of average velocities for various types of landscapes is a technique which has sometimes been used. A popular nomograph [5] estimates "time of concentration" from the length of the longest collector, L, and the fall, H, from the rim of the basin to the site (not including waterfall or gully heads). The authors [8] prefer to call the output of the H- and L-nomogram the "basin characteristic," B, which was used in this study.

The runoff coefficient, C, is the one factor which the designer has to manipulate in an attempt to account for the host of interrelated factors which impart different flood potential to various basins. C was evaluated from Table 2 of Frevert, et al [11].

2. Soil Conservation Service Hydrograph Families. Curvilinear hydrographs can be prepared from published semi-dimensionless hydrographs [5]. The technique, which is described beginning on page 3.21-11 in the handbook of the above agency, requires primarily a selection from five hydrograph families on the basis of the anticipated six-hour storm rainfall, P_{6h}, and the runoff curve number describing the local flood-producing potential. The time distribution of the rainfall, which also influences hydrograph shape, was considered to be type- B in all these designs. Time to hydrograph peak is assumed to be about 70 per cent of B. Relationships allow an estimate to be made of the duration of rainfall excess. Following the method through to the maximum ordinate, from a table, enables a flood peak to be estimated. The most recent edition [16] of the handbook was used for converting runoff curve numbers when antecedent rainfall required it.

3. Bureau of Public Roads Method. Streamflow records from 96 basins were studied together with rainfall and topographic factors for many more basins during the development of this modern method. This procedure [6] differs most from the other four methods by using flood peaks of known return period. Thereby it claims to overcome the previously unsolved problem of linking flood return period to rainfall return period. Application simply involves reading maps and charts. For tests against observed floods in the present paper, the observed one-hour rainfall, P_{60}, was used in place of the rainfall index read from Potter's maps. BPR design charts were not published for P_{60} less than 1.7 inches. So where observed rainfalls were slightly less than this amount, the flood peak corresponding to the published lower limit was used for the prediction. The Bureau recommends the method for areas smaller than 25 square miles, and the lower area limit on the design charts is 100 acres. Extrapolation of the design charts was necessary to obtain predictions for 24 events on the 4 basins smaller than 0.15 square miles, or 96 acres.

Another slight modification in applying this method involves the length of the longest collector. In the design procedure [6] this was defined as the actual length from the point where the channel begins to the outlet. It stipulates that only the broken and solid lines for streams on USGS maps must be used. The extent of inking varies between sheets according to cartographers' decisions. Many basins were studied on Agricultural Research Service maps, so a more truly repeatable quantity had to be used. The length from the rim of the basin to the outlet was adopted in this study. This length is measured along the longest collector while it is discernable, and in a straight line to the nearest point on the divide, from the end-point of the discernable drainage-way. Predictions of flood peaks obtained using either definition do not generally differ significantly.

4. Chow's Method. Applicability is claimed for areas smaller than 9 1/2 square miles. This method is based upon S-curve separation from unit hydrograph theory and upon the Soil Conservation Service's [5] relationship between rainfall and runoff volumes.

Assignment of a soil to either of the four hydrologic soil groups was done according to its name and published lists. Consideration of the soil-factor and the cover-type was performed here in the same manner as in the SCS determinations. Intermediate curve numbers ascribed to the observed events were modified for the antecedent precipitation index in terms of the original handbook [5], since it was current at the time Chow's method [3] was developed.

Rainfall amounts for various durations were read from hyetographs of each observed storm. This trial-and-error part of the estimation procedure, to find the greatest flood peak from various rainfall durations, would need to be performed by designers

TABLE 3. EVALUATION OF f

A. Texture

1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Sand	loamy sand	sandy loam	loam	silt loam	silt	sandy clay loam	clay loam	silty clay loam	sandy clay	silty clay	clay
0.200	0.150	0.100	0.080	0.050	0.020	0.018	0.006	0.004	0.002	0.001	0.000

Structure

B. Strength of aggregates

1.	2.	3.	4.
structureless	weak	moderate	strong
0.030	0.005	0.002	0.001

C. Size of aggregates

1.	2.	3.	4.	5.
very coarse	coarse	medium	fine	very fine
0.020	0.008	0.004	0.002	0.001

D. Shape of aggregates

1.	2.	3.	4.	5.	6.	7.
crumbs	granular	subangular blocky	angular blocky	columnar	prismatic	platy
0.010	0.015	0.003	0.003	0.003	0.001	0.001

E. Permeability

1.	2.	3.	4.	5.	6.	7.
very rapid	rapid	moderately rapid	moderate	moderately slow	slow	very slow
0.200	0.150	0.100	0.080	0.050	0.020	0.005

F. Internal Soil Drainage

1.	2.	3.	4.	5.	6.
very rapid	rapid	medium	slow	very slow	none
0.200	0.150	0.100	0.050	0.015	0.000

G. Erosion Class

1.	2.	3.	4.	5.
few rills; up to 25% of A-hor. gone	shallow gullies, 25-75% of A-hor. lost	shallow and deep gullies 75-100% of A-hor. lost	intricate pattern of gullies soil profiles destroyed	recent alluvial and colluvial deposits
0.020	0.015	0.008	0.001	0.020-0.001

H. Land Capability

I	II	III	IV	V	VI	VII	VIII
very good for cultivation, nearly level	good for cultivation, gently sloping	moderately good for cultivation, moderate slope	fairly good cultivation, strong slope, shallow	not for cultivation, good for grazing and forestry	moderately good for grazing stony, shallow	fair grazing, steep slope	not suitable for grazing or forestry
0.010	0.008	0.005	0.003	0.001	0.001	0.000	0.000

I. Surface Drainage

1.	2.	3.	4.
excellent	good	fair	imperfect
0.001	0.002	0.003	0.005

J. Slope

1.	2.	3.	4.	5.
0 - 3%	3 - 8%	8 - 15%	15 - 25%	25% +
0.015	0.010	0.005	0.002	0.002

EXAMPLE: Safford, Arizona. A. R. S. No. 45.4.

A.	Stony, sand loam	0.180
B.	Structureless	0.030
C.	Medium size	0.004
D.	Granular, blocky shape	0.007
E.	Moderately slow permeability	0.050
F.	Slow internal drainage	0.050
G.	Erosion class 1.	0.020
H.	Land capability VI-VII	0.001
I.	Surface drainage, good	0.002
J.	Slope, 8 - 15%	0.002
	Hence, f =	0.346

normally on the basis of an assumed time-distribution for storms. Here again, the use of rainfall which actually occurred should produce more favorable estimates than would result normally from applying the method to design situations in which rainfall amounts and distributions are both estimated with error.

Extension of CHOW beyond Illinois strictly speaking requires more than simply replacing the "climatic factor", Y, in terms of one-hour point rainfall amounts. The other essential component of this method is a relationship between time-to-peak and a compound topographic index. Originally this was developed from sixteen gaged basins around Illinois, and four within the state boundary. Ideally, extrapolation of this Illinois method should be preceded by revised time-to-peak relationships for different geomorphologic regions. For reasons stated earlier this was not done in the present tests. Illinois relationships were simply used throughout in full knowledge of a deterministic error component which may be generated at the twenty-nine alien basins out of the thirty-six used in the current evaluation.

5. Tacitly Maximized Peak Method. Various empirical and theoretical considerations were used in the development of this method [8, 9]. Peak runoff rates were obtained from considerations of the triangular approximation to flood hydrograph shapes, making use of an empirical relationship between the total volume of runoff and the most important causative factors. After flood peak optimization for various storm durations and after discarding unimportant factors, a method resulted which is easier to apply than the RATIONAL.

Selection of appropriate infiltration capacities for a basin is the greatest obstacle in the application of this method. The tables presented in an ASCE manual [17] form the basis for these evaluations. Table 3 was developed to decrease the wide margin of possible judgment error, within the extreme limits of 0.01 and 1.0, and the evaluation of the infiltration capacity for bare soil, f. The elements listed in this table can be obtained easily from a physical inspection of the basin and its soil profiles. Once the appropriate elements in Table 3 are known for the basin, simple addition of the contributions toward "f," gives the desired infiltration capacity. It should be noted that a value for each category of elements (A through J) must be included in the addition. The contribution of the cover factor, F, by which f must be multiplied to give the final infiltration capacity, S, for the basin, is relatively small and more stable [18] than f. The table in the ASCE manual for the evaluation of F was used without modification.

Application of TMP involves the use of design charts [18]. The smallest flood in which the technique is concerned is 350 csm. In seven of the sixty events extrapolation to smaller peaks was necessary. This desire to include as many observed events as possible carried with it the opportunity for enhanced errors. This method was proposed for areas smaller than five square miles. The evaluation involved four events from larger basins.

CHAPTER IV

FLOOD ESTIMATES BASED UPON RAINSTORM PROBABILITIES

In small basins the lack of long flood series often preclude the use of those theoretical analyses which engineers consider most appropriate. The primary criterion that should be established in the choice of a design flood is the "desired lifetime" of the structure involved. Careful considerations of the economics of the service as affected by return periods and risk of failing within the desired lifetime of the structure [6, 19] go into the choice of the design return period. Most designers simply use the rainfall return periods as the basis for predictions of floods. They avoid the associated problem that the resulting floods could have much different return periods from the rainstorms.

1. Approximation in Terms of Rainstorm Probability. The first phase of this study adopted the same position of looking at 406 flood peaks estimated from various methods on the basis of a rainstorm of a specified return period, which is the reciprocal of its probability of nonoccurrence. Such flood-peak estimates were based upon expected rainfalls read from the Rainfall Intensity Frequency Atlas [20] at the fourteen locations of which twelve were marked with asterisks in Table 1. These predictions made for real basins throughout both arid and humid climates by inserting rainstorm estimates of 2-, 25-, 50-, and 100-year return periods into each of the five methods are presented in Table 4. The bars for each method in fig. 2 depict the range corresponding to floods estimated from rains of 10- and 200-year return periods in a similar manner to Table 4. It should be noticed that BPR does not attempt predictions for return periods less than 10 years.

The considerable inconsistency between methods is clear from fig. 2. For quite a few basins the flood peaks obtained for a 10-year return period by one method are much larger than the 200-year floods estimated by another method. For example, for the Coshocton basin, no. 26.29, the 200-year flood obtained by means of CHOW is about 800 csm., whereas the 10-year flood obtained by RATIONAL is 1700 csm.

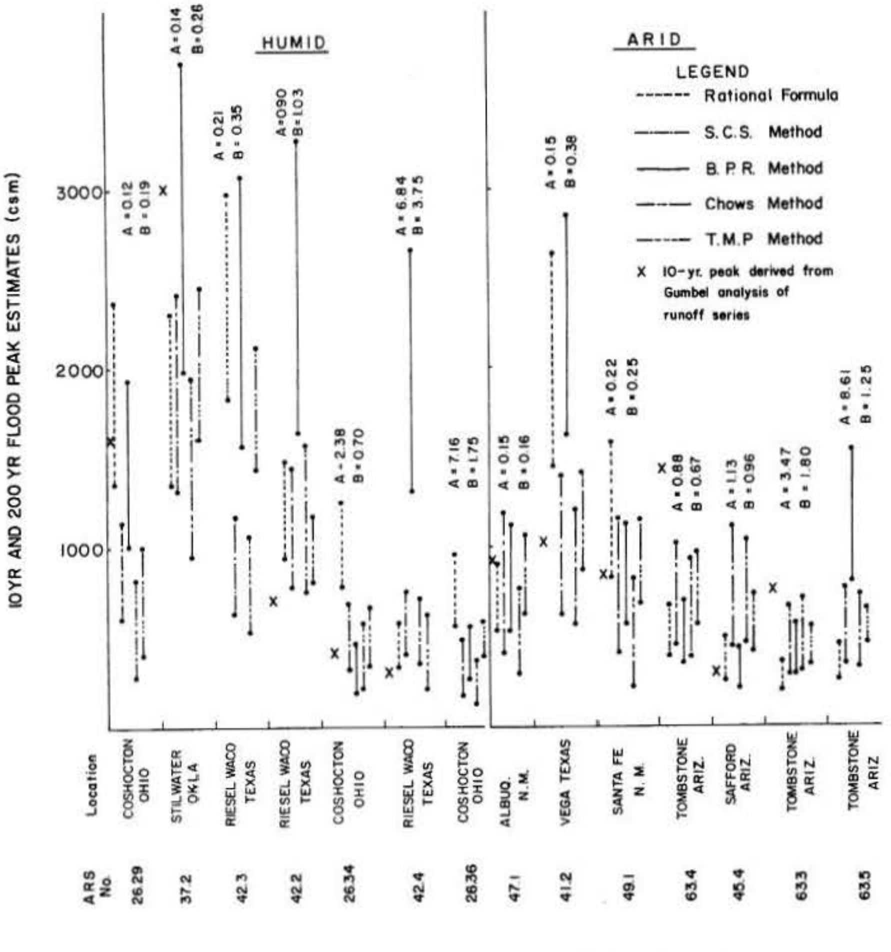

Fig. 2. Ranges and Magnitudes of Predictions Based Upon Rainstorm Probabilities

TABLE 4. FOOD PEAK ESTIMATES, CSM, BY DIFFERENT METHODS, BASED UPON RAINSTORM PROBABILITIES

*ARS	B	A	Rational Formula				Soil Conservation Service				Bureau of Public Roads			Chow				Tacitly Maximized Peak			
No.	hrs	sq.m	2yr	25yr	50yr	100yr	2yr	25yr	50yr	100yr	25yr	50yr	100yr	2yr	25yr	50yr	100yr	2yr	25yr	50yr	100yr
**47.1	0.16	0.15	268	607	730	792	207	760	907	987	725	866	995	71	412	518	637	365	826	938	1019
26.29	0.19	0.12	1128	1985	2260	2480	122	708	829	908	1295	1500	1710	49	396	533	662	182	606	765	900
**49.1	0.25	0.22	450	985	1140	1250	233	795	859	950	800	909	1025	64	443	568	714	350	860	980	1080
37.2	0.26	0.14	900	1596	1850	2020	536	1579	1829	2100	2460	2860	3245	334	1127	1516	1718	1146	1790	2065	2225
42.3	0.35	0.21	1220	2095	2380	2610	319	829	957	1076	2050	2380	2700	263	708	811	930	1064	1624	1855	1994
**41.2	0.38	0.15	900	1670	1860	2110	313	953	1133	1267	2050	2350	2625	212	748	901	1061	627	1121	1211	1365
**63.4	0.67	0.88	238	468	534	600	206	666	773	958	475	546	620	147	569	695	815	338	638	738	850
26.34	0.70	2.38	530	915	1050	1150	63	406	484	533	200	231	263	51	255	344	427	200	435	510	570
**45.4	0.96	1.13	153	351	385	400	242	556	692	1057	292	336	378	184	634	733	804	286	525	588	663
42.2	1.03	0.90	630	1110	1230	1360	391	1044	1212	1362	2180	2560	2925	397	999	1222	1394	614	909	1007	1067
26.36	1.75	7.16	363	623	712	775	54	219	260	336	350	405	460	42	166	225	261	245	405	450	475
**63.3	1.80	3.47	115	230	260	286	111	403	467	580	355	404	452	105	406	495	581	168	356	394	455
**63.5	1.25	8.61	156	309	349	386	130	509	591	733	1075	1160	1320	112	435	530	621	310	504	572	610
42.4	3.75	6.84	212	397	444	490	179	529	614	692	1750	2050	2370	115	413	494	559	344	468	509	544

* Agricultural Research Service

** Arid Watersheds

This type of difference between estimates for average basin conditions should not be confused with the stochastic outcome of individual flood responses. In this first phase of the discussion randomly high antecedent moisture, or unexpectedly bare vegetative cover, are not considered. All that can be considered here are the different ways that various methods predict these "average" stochastic floods.

BPR differs from the other methods in its description of channel slope on the basis of the average slopes over 0.7 and 0.3 of the length of the longest collector, measured sequentially from the gaging site upwards. Present results suggest that the ratio between the uppermost slope of 0.3 of the length of the longest collector and the slope of tne rest of the length, $\frac{S_1}{S_2}$, plays an important role in the magnitudes predicted in Table 4. BPR predictions are much higher than those of other methods when this ratio is less than 1.2 on the arid basins, and less than 3 on the humid basins. With other values of this ratio no such great difference exists.

In the development of the BPR method, use was made of observed flood peaks with known return periods. Crosses have been inserted in fig. 2 for each of its fourteen basins. These represent the 10-year flood read from a Gumbel analysis of measured annual flood peak maxima. It is interesting to note from fig. 2 that in the humid areas for which BPR was developed it predicted far more than other methods. The other methods generally group together with regard to the order of magnitude of their predictions.

2. General Behavior of Five Methods When Applied to Rainfalls of Same Probability. An engineer is fundamentally concerned with formulae which would generally give greater estimates than others and also with differences in pattern between arid and humid zones. Individual events will vary randomly about any such deterministic trend. Flood response is a stochastic process in which individual events represent nature's integration of a particular array, in time and space, of both basin and input features. For economic expedience and for lack of the highly refined synthetic techniques which would demand giant computers, engineers simplify the model by considering average rainfall, average slopes, average infiltration capacities, and many other simplistic features affecting the runoff process. Such simplified parameters may be particularly inept at representing the important hydrologic influences in some instances although normally taking good account of them. It is clear that no practical method can account for all causative factors with deterministic certainty. Situations arise where, on the same basin, one or more methods yield good results for certain events while being unable to describe behavior on other occasions. Use of a different method may correct some of these malpredictions while deteriorating other estimates that had been satisfactory previously. From a similar point of view the estimates from the seven humid basins may be looked upon as a sample whose mean behavior will be freed of much randomness present in its individuals. Similarly the totals of the estimates for the seven arid basins are expected to be more stable than their individual elements.

Prior to an internal study of Table 5, which summarized data from Table 4 in above manner, it appeared desirable to seek evidence which could lend it some credence. After all, it should not be forgotten that the table contains numbers which have been obtained purely from applying estimation techniques which themselves are under consideration. Available flood observations, which will be elaborated upon later, for basins in Table 5 comprised twenty-six and thirteen for the humid and arid zones respectively. Annual flood series were analysed by the Gumbel method for observed flood peaks for each of the humid basins and for six of the arid basins listed in Tables 4 and 5. From these frequency analyses it can be said that return periods of the observed floods for the humid basins ranged from 1.3 through 35-years, and averaged 6.4-years. For the arid data the range from 2.0- through 125-years with an average return period of 15-years. So it may be said that this data was in the range used for inexpensive designs. The average ratio of observed flood peaks in these arid basins to those in humid basins was found to be 0.74. It is interesting to note in Table 5 that the average ratio for all five estimates in arid basins to similar estimates in humid basins of 0.69 is virtually equal to the observed ratio. Thus Table 5 assumes a

TABLE 5. ESTIMATES AVERAGED ACROSS WATERSHEDS OF TABLE 4

		Rational	SCS	BPR	CHOW	TMP	Five Methods
Seven Humid	Average 100-yr. csm	1,550	1,000	1,950	850	1,110	1,290
Watersheds	Ratio to 5-method mean	1.20	0.78	1.51	0.66	0.86	-
Seven Arid	Average 100 yr. csm	830	933	1,060	747	863	885
Watersheds	Ratio to 5-method mean	0.94	1.05	1.20	0.84	0.97	-
Ratio	$\frac{\text{Arid Estimates}}{\text{Humid Estimates}}$	0.53	0.93	0.54	0.88	0.78	0.69

measure of reality at least as far as it reproduces some difference between arid- and humid-floods in the selected fourteen basins.

It remains to consider variability between methods and across climate types upon the basis of Table 5. Only the 100-year estimates have been summarized but Table 4 and fig. 2 provide information for reproducing the analysis for five other return periods. Relative to the five-method mean, certain methods appear to overpredict while others underpredict. Which methods predict higher and which predict lower appears to depend upon whether they are being applied to arid or humid basins. With regard to any one formula having the flexibility required to handle both humid and arid estimates equally well, only one, TMP, appears suitable. This is apparent from the ratio in Table 5 of 0.78 which approximates the observed value of 0.74. It will be interesting to refer back to this table at later stages of this paper.

3. Specific Return Period Floods and Their Estimators. It was mentioned earlier that Table 4 had been produced along the lines of common practice on the basis of rainfall amounts depicted on generalized maps [20] for the specified return periods. In contrast to this Table 6 was prepared on the basis of annual series of observed streamflows. These values should be compared to the corresponding members of Table 4. Ten-year flood peaks expected from this Gumbel analysis have also been entered onto fig. 2 as "x's." They illustrate how radically different flood peak estimates can be according to whether they are based upon runoff probabilities or rainfalls of specified probabilities. These few observations cannot indicate a clear pattern but they do permit the following remarks which serve to caution practitioners. The two Coshocton, Ohio, drainage areas have 10-year floods from runoff records which are larger than most estimates based upon 200-year rainfall. For two Riesel, Texas, areas the 10-year runoff estimates are approximately equal to estimates by any four of the methods, BPR excepted, based upon 10-year rainfall. At Stillwater, Oklahoma, the 10-year runoff estimate is much greater than the rain-based estimates by these four methods. It is slightly greater than the arithmetic mean of BPR's 10-year and 200-year estimates.

A similar spread of results is evidenced in the arid zone. Albuquerque, New Mexico, has a 10-year runoff estimate within the range estimated by five methods using 200-year rainfall. Tombstone, Arizona, has results at both locations greater than any flood estimate based upon a 200-year storm. In contrast Vega, Texas, has a 10-year runoff flood in the midst of the wide range of estimates based upon 10-year rainfall. For Safford, Arizona, the 10-year runoff peak is smaller than SCS, CHOW, and TMP using 10-year rainfall. The other two methods are lower. At Santa Fe, New Mexico, the 10-year runoff estimate equalled the greatest estimate (RATIONAL) based upon 10-year rain.

It can readily be appreciated that the above behavior may have been brought about partly by the smoothing of Isohyets in the Rainfall Intensity Frequency Atlas. Small scale anomolies caused by orographic and other local influences could perhaps be corrected for by performing detailed analyses of rainfall extremes at each experimental watershed

TABLE 6. FLOOD PEAKS PER UNIT AREA FOR ARID AND HUMID WATERSHEDS ESTIMATED BY GUMBEL ANALYSIS OF RECORDED RUNOFF

A. R. S. No.	A Sq. m.	CSM for Various Return Periods in Years					
		q_2	q_{10}	q_{25}	q_{50}	q_{100}	q_{200}
*47.1	0.15	348	928	1236	1450	1655	1900
26.29	0.12	450	1610	2200	2640	3000	3480
*49.1	0.22	232	838	1160	1390	1610	1840
37.2	0.14	980	3000	4000	4750	5460	6300
42.3	0.21		NO PLOT				
*41.2	0.15	252	1025	1410	1700	2000	2280
*63.4	0.88	290	1420	2000	2450	2860	3320
26.34	2.38	155	405	523	620	715	800
*45.4	1.13	122	296	500	580	680	774
42.2	0.90	310	696	878	1030	1160	1290
26.36	7.16		NO PLOT				
*63.3	3.47	194	754	1080	1278	1480	1710
*63.5	8.61		NO PLOT				
42.4	6.84	135	300	388	445	508	570

* Arid Watersheds

TABLE 7. AMOUNTS AND RETURN PERIODS FOR OBSERVED FLOODS AND ASSOCIATED STORM RAINFALL

Event No.	Flood Peak		Max. 30-Min. Rain		Max. 60-Min Rain	
	Inch/Hour	Return Period in Yrs.	P_{30m} Inches	Return Period in Yrs.	P_{1h} Inches	Return Period in Yrs.
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1.	0.445		1.06	2.2	1.16	2.0
2.	0.340	3.4	0.64	1.001	1.50	1.9
3.	0.852	55.0	1.60	5.0	2.57	26.0
4.	2.000	35.0	0.92	1.1	1.20	1.2
5.	2.490	10.0	2.10	110	2.90	260.
6.	1.690	4.6	1.70	25	2.80	190.
7.	2.420	9.6	2.15	120	2.70	120.
8.	1.260	3.3	0.75	1.4	1.20	2.3
9.	1.870	9.0	0.97	2.4	1.32	2.8
10.	1.780	8.5	1.74	28.0	2.55	82.
11.	3.750	120	1.48	11.0	2.74	150.
12.	1.060	3.5	2.66	1.001	2.92	300.
13.	1.390	5.0	0.70	1.25	1.08	1.7
14.	1.720	40	1.08	3.1	1.30	2.6
15.	0.365	2.1	1.05	2.9	1.75	8.5
16.	0.325	2.5	1.10	3.2	1.27	2.5
17.	0.426	3.5	1.46	11.0	2.13	25
18.	0.950	22	0.92	2.0	1.27	2.5
19.	0.280	3.0	1.48	11.0	2.10	23
20.	0.540	14	0.91	2.0	1.28	2.6
21.	0.412	3.7	1.01	2.5	1.21	2.2
22.	0.091	1.3	1.50	12.0	2.10	23
23.	0.910	35	1.44	10.0	2.12	24
24.	0.325	4.0	1.45	10.2	2.14	25
25.	0.384	6.0	1.12	3.5	1.85	11
26.	0.325	4.0	1.10	3.3	1.35	3.0
27.	0.210	2.3	1.20	4.5	1.70	7.5
28.	0.260	2.8	1.49	11.5	2.02	18.0
29.	0.270	2.9	0.98	2.4	1.63	6.2
30.	0.115	2.5	1.19	4.2	1.30	1.7
31.	0.140	3.2	1.15	3.8	1.93	58
32.	0.541	6	1.32	4.7	1.38	2.4
33.	0.573	42	1.75	24	3.05	330
34.	0.589	2.6	2.15	55	2.15	11
35.	1.000	6	0.98	1.3	1.05	1.1
36.	0.711	3.2	1.62	8.2	1.90	5.8
37.	1.670	25	1.58	7.0	3.65	1000
38.	1.20	9.0	2.05	38	2.05	9.0
39.	0.99	6.0	1.81	17	2.08	9.5
40.	1.74	27	1.75	13	3.40	700
41.	0.314	1.7	1.12	1.4	1.15	1.1
42.	0.595	2.2	1.25	1.7	1.30	1.2
43.	0.378	1.8	1.00	1.2	1.17	1.1
44.	0.960	1.7	0.93	1.2	1.30	1.4
45.	4.630	20	2.01	7.0	2.81	10.5
46.	0.882	1.5	0.87	1.1	1.17	1.2
47.	0.960	1.7	1.01	1.3	1.01	1.1
48.	1.800	2.3	1.01	1.3	1.26	1.3
49.	1.270	1.8	0.92	1.2	1.24	1.3
50.	1.460	2.0	1.62	3.2	1.97	2.8
51.	1.900	2.5	2.07	7.2	2.25	4.4
52.	2.82	21	1.64	3.2	2.32	5.0
53.	0.093	1.0	0.92	1.2	0.92	1.1
54.	1.640	4.5	1.10	1.5	1.30	1.4
55.	0.945	1.9	0.95	1.3	1.26	1.3
56.	1.000	2.0	1.42	2.0	1.76	2.3
57.	1.260	2.1	1.80	4.3	1.96	1.9
58.	1.450	8.0	1.12		1.15	
59.	0.866	5.5	1.39	1.4	1.60	1.3
60.	0.556	2.5	0.80	1.0	1.15	1.0
61.	0.050	1.0	1.09	1.1	1.25	1.1
62.	0.150	1.2	1.25	1.3	1.43	1.2
63.	0.744		1.15	1.2	1.57	1.2
64.	0.490		0.85	1.0	0.95	1.0

TABLE 7 - continued

(1)	(2)	(3)	(4)	(5)	(6)	(7)
65.	0.532		0.95	1.0	1.28	1.0
66.	0.790		1.34	1.4	1.64	1.4
67.	0.600		1.40	1.5	1.65	1.4
68.	0.384	6.0	1.33	1.4	1.74	1.5
69.	0.068	1.2	1.36	1.4	1.42	1.1
70.	3.330		0.50	1.001	0.75	1.001
71.	0.905		0.70	1.001	0.77	1.001
72.	2.150		1.45	1.5	1.72	1.5
73.	2.060	3.6	1.50	1.5	1.97	1.8
74.	1.690	3.0	1.12	1.1	1.40	1.1
75.	1.440	2.5	1.14	1.1	2.11	2.4
76.	0.046	1.2	1.25	1.3	1.43	1.2
77.	0.201	3.4	0.87	1.0	1.37	1.1
78.	1.810	6.9	1.33	1.4	1.72	1.5
79.	1.595	5.0	1.56	1.6	1.85	1.6
80.	0.665	1.6	1.02	1.0	2.00	2.0
81.	0.206	1.4	0.82	1.0	1.40	1.1
82.	0.060	1.2	1.08	1.1	1.15	1.0
83.	1.640	3.6	1.25	1.3	1.74	1.5
84.	1.230	2.5	1.15	1.1	1.32	1.1
85.	1.750	3.9	1.60	2.0	1.60	1.3
86.	0.775	1.8	1.05	1.0	1.50	1.2
87.	0.250	1.4	0.76	1.001	1.40	1.1
88.	0.705	1.8	1.09	1.1	1.13	1.0
89.	1.670		1.30	1.3	1.75	1.0
90.	1.190		1.07	1.1	1.36	1.1
91.	1.660		1.73	1.1	1.83	1.6
92.	0.820		1.00	1.0	1.95	1.8
93.	0.340		0.92	1.0	1.42	1.2
94.	0.065		1.05	1.0	1.16	1.0
95.	1.740	14	1.41	3.5	2.17	6.0
96.	1.712	2.4	0.93	1.5	1.40	1.6
97.	1.840	16	1.20	2.3	1.80	2.9
98.	0. 945	3.2	1.40	3.5	2.05	4.6
99.	0.136	1.2	1.50	4.2	1.68	2.4
100.	0.325	1.5	1.73	7.1	2.00	4.2
101.	0.116	1.1	1.32	2.8	2.09	5.0
102.	0.063	1.2	1.83	9.0	2.34	8.1
103.	0.216	2.5	1.70	6.8	2.00	4.2
104.	0.266	3.5	1.30	2.7	2.13	5.5
105.	0.230	4.8	1.60	5.2	2.26	7.1
106.	0.325	3.0	0.85	1.9	0.85	1.2
107.	0.243	2.2	0.95	2.3	0.95	1.3
108.	0.358	3.6	1.68	20.0	1.85	12.0
109.	0.410	4.4	1.63	15.0	2.10	30.0
110.	2.750	125	1.62	200	1.70	38
111.	0.900	4.9	1.10	12	1.55	20
112.	1.270	9.0	1.25	22	1.40	12.5
113.	1.040	6.0	0.87	5	0.90	3.0
114.	0.690	11.0	1.45	4.1	2.10	10
115.	0.490	5.0	1.55	6.0	1.75	3.5
116.	0.245	2.2	1.43	3.9	1.90	5.2
117.	0.335	3.1	1.10	1.5	1.32	1.4
118.	0.291	1.5	0.80	1.0	1.64	1.5
119.	0.605	2.6	1.04	1.2	1.30	1.3
120.	0.500	1.9	1.01	1.2	1.10	1.3
121.	0.340	1.3	0.87	1.0	1.50	1.4
122.	0.298	1.7	1.00	1.2	1.20	1.0
123.	0.145	1.4	1.12	1.4	1.12	1.0
124.	0.396	2.0	1.20	1.5	1.36	1.2
125.	0.556	5.5	2.20	22.0	2.60	14.0
126.	1.300	13.0	1.50	9.4	1.53	4.0
127.	0.318	2.1	1.27	5.0	1.30	2.5
128.	0.557	3.2	1.22	4.3	1.30	2.5
129.	0.310	2.0	1.13	3.4	1.30	2.5
130.	2.460	12.0	1.80	23.0	2.35	27.0
131.	0.625	2.3	1.75	20.0	1.82	7.7
132.	0.950	3.0	1.62	13.5	1.75	6.5
133.	0.564	2.1	1.43	8.0	1.80	7.0
134.	0.211	1.7	1.30	150	2.00	1000

from Agricultural Research Service data. This would, however, have conflicted with the present paper's objective of employing generally used design information.

4. Concurrently Observed Return Periods for Rains and Floods. As will be discussed in the following sections, 134 floods had been observed on forty-five basins including twelve of the fourteen areas referred to in the preceding sections. A return period could be attached to most of these in terms of Gumbel analyses performed on complete series of annual maxima. Correspondingly observed rainfall maxima for both the 30-minute and 60-minute periods were assigned return periods from Hershfield's [20] atlas. The data is presented in Table 7, and plotted in fig. 3. No relationship is apparent between the return period of an individual event and the return period of its associated flood peak. This illustrates how strong the stochastic component is. In other words, it shows how futile it would be to attempt to predict an event of a particular return period on the basis of storm rainfall of the same return period.

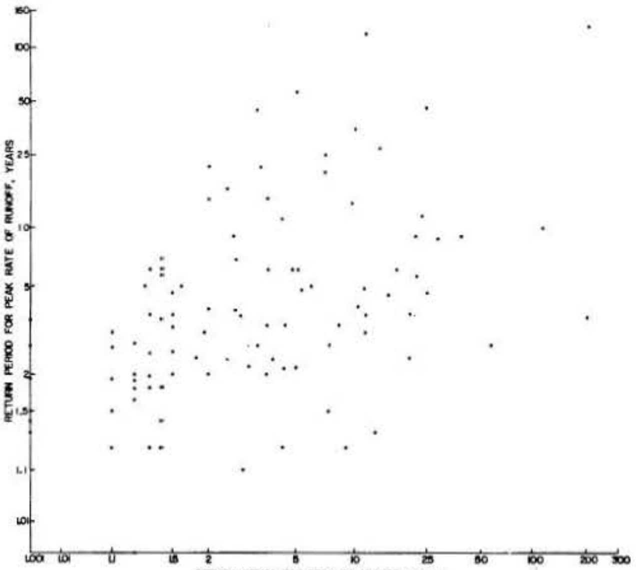

Fig. 3 Return Periods of Flood Peaks and of Their Maximum Associated 30-Minute Rainfalls

CHAPTER V

EVALUATION WITH OBSERVED EVENTS

A test of flood predictions against actually observed flood events may assist in the evaluation of the suitability of each method in real life. To evaluate the reliability of each of the five methods, it will be valuable to test each method against observed flood peaks. Some of the observed events used in this study are of relatively short return period, but fig. 4 shows quite a high percentage of overlap with estimates made from rarer rainstorms. Hence the observed sample covers a range satisfactory to design engineers. Hence in this second phase of the investigation the predictions derived by each method were compared to the observed flood peaks and no longer to predictions by other methods.

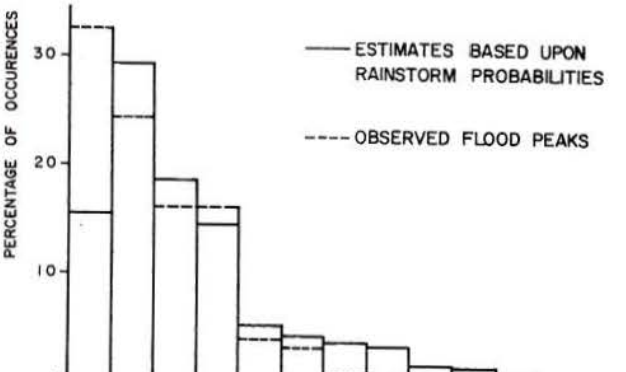

Fig. 4 Comparison of Flood Magnitudes Used in the Two Phases of This Study

The results of applying the five prediction methods are presented in Table 8. It was not possible to use each of the 134 events with every method. The samples for RATIONAL, BPR, and TMP were almost identical. They involved 60 common events except for 4 events omitted from BPR since two of the topographic maps were not available. To avoid bias, this sub-sample omitted 83 events which had been involved in the development of TMP. The total number of events used for SCS and CHOW were 65 and 107 respectively, of which 48 were common to both. Certain events, with very short intense storms, were excluded from the sample used for SCS in view of the relatively long storm duration of six hours that is prescribed for use in this method. For the same reason other events with long rainfall at relatively low intensities which were not used in the other four methods, were included in SCS.

Similar representativeness throughout the range of basin size can be seen from fig. 5 to have been preserved within all samples.

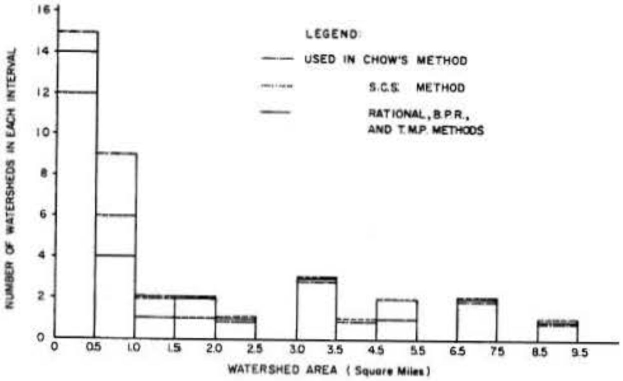

Fig. 5 Comparative Distribution Within Size Range of Watershed Areas Used in Each Method

1. Scatter-diagrams. A scatter-diagram for each method, showing envelope lines with observed floods, 2, 1 1/2, 2/3, and 1/2 times the corresponding estimates, q_p, is shown in fig. 6. Investigation of some events which were overpredicted by all methods except CHOW brought to light that events from Riesel Waco, Texas (A. R. S. No. 42), which were preceded by less than 0.5 inch of rain during five days before the occurrence of the event, were always overpredicted. A physical explanation for these overpredictions can be found in the nature of the soil type of these watersheds, which is a highly swelling clay prone to form wide cracks under dry conditions. A five-day antecedent precipitation totaling more than 0.5 inch generally seems to close the cracks and to improve the predictions of the resulting flood peaks. The events, while cracks likely were present in the soil, have had their numbers circled on the scatter-diagrams and were excluded from all further calculations. It is quite possible that more familiarity with basin conditions elsewhere and rainfall peculiarities may explain further scatter in fig. 6. Engineering judgment will always profit by discussion with local residents during watershed inspection because residents' comments about local peculiarities may indicate possible modifications to prediction methods.

Points marked with crosses on fig. 6 represent events observed on basins in geographic regions for which the methods authors' did not claim applicability, or for basins larger than those for which the method is claimed applicable. These events were not excluded from further calculations because it was decided to evaluate the applicability of all methods over as wide a spectrum of localities as possible; practicing engineers are frequently forced to use methods outside the region or range for which they were developed.

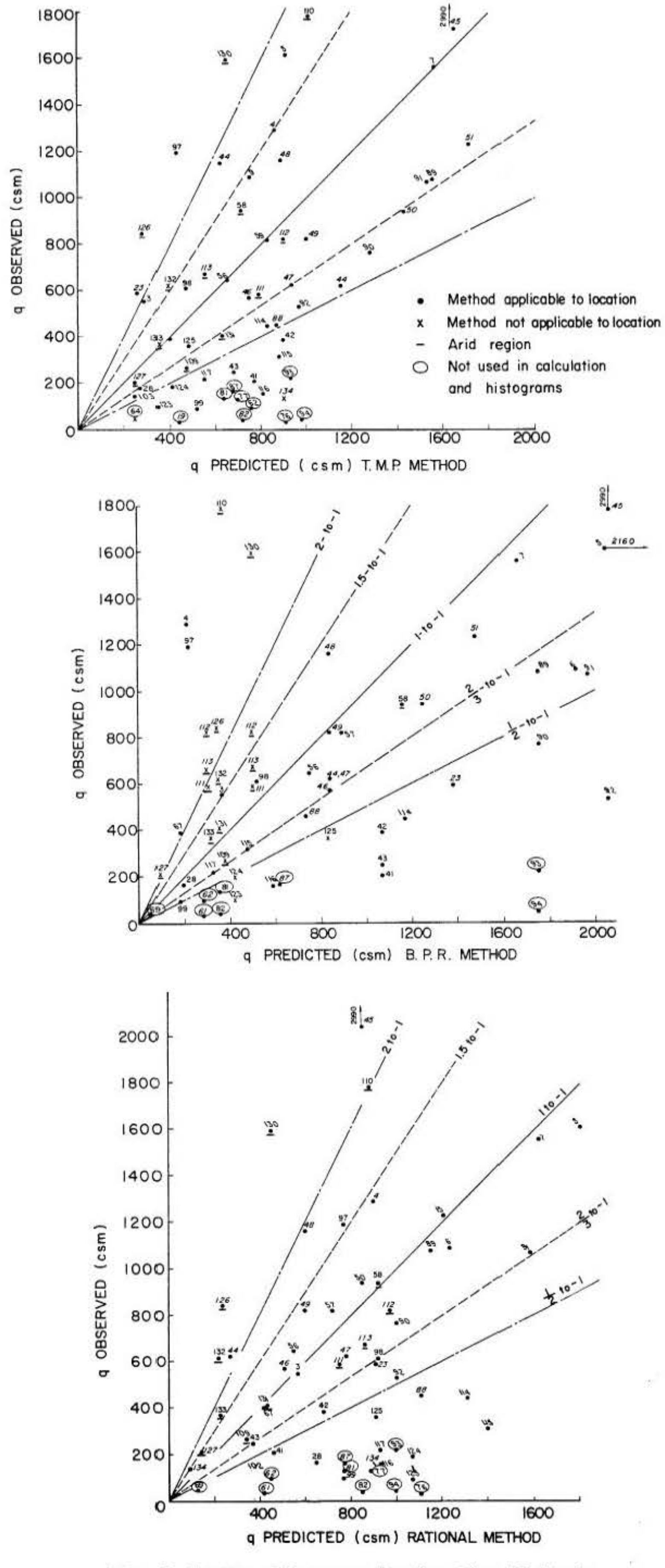

Fig. 6 Scatter-Diagrams for the Five Methods

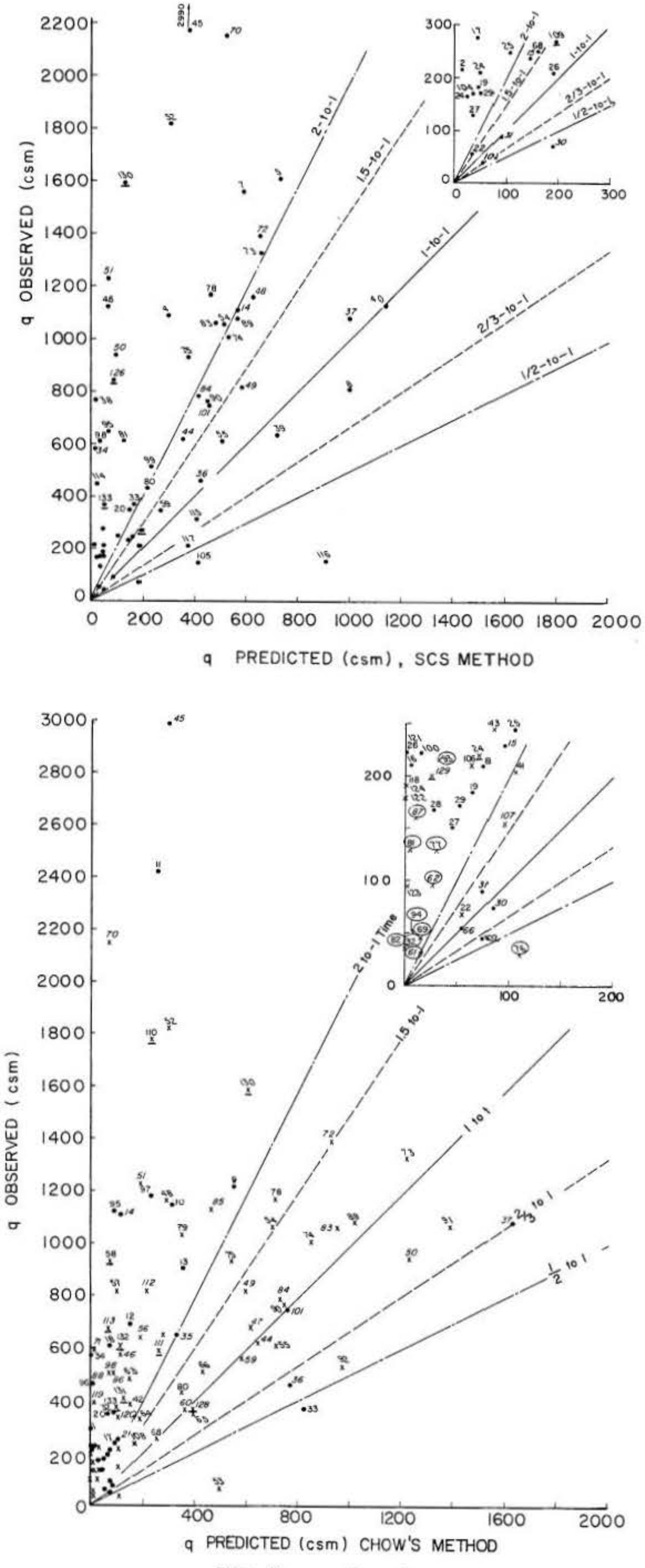

Fig. 6 - continued

TABLE 8. FLOOD ESTIMATES IN CSM MADE WITH FIVE METHODS ON THE BASIS OF OBSERVED RAINFALL

A. R. S. No.	Date	Event No.	q_{obs}	$q_{RATIONAL}$	q_{SCS}	q_{BPR}	q_{CHOW}	q_{TMP}
15.1	Apr. 13, 1949	1	287				x 0	
21.1	July 21, 1948	2	219		13			
	July 18, 1956	3	550	570		366		290
25.1	Oct. 4, 1941	4	1,290	900		217		860
26.29	June 16, 1946	5	1,610	1,800	728	2,160		910
	Sept. 1, 1950	6	1,090	1,230	294	1,915		750
	June 12, 1957	7	1,560	1,620	586	1,665		1,560
	June 28, 1957	8	811		989			
26.30	Sept. 23, 1945	9	1,220				550	
	June 16, 1946	10	1,510				307	
	Sept. 1, 1950	11	2,420				246	
	June 12, 1957	12	687				147	
	June 28, 1957	13	900				352	
26.31	Sept. 23, 1945	14	1,110		564		117	
	Aug. 21, 1960	15	235		142		96	
26.32	Sept. 23, 1945	16	210				4	
	June 12, 1957	17	276		48		63	
	Aug. 21, 1960	18	614		125		71	
26.33	June 12, 1957	19	181		47		62	
	Aug. 21, 1960	20	348		152		70	
26.34	Sept. 23, 1945	21	266				70	
	June 12, 1957	22	59		37		55	
	June 28, 1957	23	590	910		1,385		260
26.35	June 12, 1957	24	210		48		71	
	Aug. 21, 1960	25	248		107		102	
26. 36	Sept. 23, 1945	26	210		198		0	
	July 11, 1946	27	136		38		43	
	June 12, 1957	28	168	650	23	196	32	270
	Aug. 21, 1960	29	175		51		51	
26.37	Sept. 23, 1945	30	74		89		31	
	Aug. 21, 1960	31	90		88		76	
27.1	July 7, 1943	32	350				86	
29.1	June 4, 1958	33	370		164		825	
31.1	Aug. 12, 1943	34	580		15		0	
	June 28, 1945	35	646				330	
	June 24, 1949	36	460		420		770	
	Aug. 5, 1951	37	1,080		1,000		1,630	
31.4	Aug. 12, 1953	38	773		16			
	June 24, 1949	39	639		720			
	Aug. 5, 1951	40	1,124		1,139			
35.11	Sept. 8, 1942	41	203	460		1,070	x 108	770
	June 26, 1945	42	384	680		1,070	x 155	900
	July 5, 1949	43	244	370		1,070	x 89	680
37.2	May 23, 1955	44	620	270	357	840	x 645	1,150
	Apr. 18, 1957	45	2,990	850	289	2,060	x 295	1,650
	June 10, 1957	46	570	510		840	x 120	750
	June 27, 1957	47	620	780		840	x 720	940
	Oct. 2, 1959	48	1,160	600	626	840	x 275	890
	Oct. 2, 1959	49	820	600	582	840	x 600	1,000
	May 28, 1960	50	940	850	97	1,250	x1,230	1,430
	May 21, 1961	51	1,230	1,210	66	1,480	x 185	1,710
37.3	Apr. 18, 1957	52	1,820		303		x 293	
	June 27, 1957	53	60				x 495	
	Oct. 2, 1959	54	1,060		506		x 700	
	Oct. 2, 1959	55	610		506		x 785	
	May 28, 1960	56	645	550	62	750	x 277	650
	May 21, 1961	57	815	720		893	x 100	830

TABLE 8 - continued

A. R. S. No.	Date	Event No.	q_{obs}	$q_{RATIONAL}$	q_{SCS}	q_{BPR}	q_{CHOW}	q_{TMP}
41.2	May 30, 1938	58	939	920		1,160	x 77	710
42.2	Apr. 24, 1957	59	560				x 580	
	May 13, 1957	60	360				x 360	
	July 9, 1961	(61)	32	420		285	x 14	440
	July 16, 1961	(62)	96	450		285	x 28	560
42.3	June 10, 1941	63	480				x 148	
	June 15, 1942	(64)	332				x 183	
	July 15, 1950	65	344		265		x 390	
	Apr. 24, 1957	66	510		229		x 430	
	June 23, 1959	67	388	420		181		400
42.4	June 23, 1959	68	248		160		x 250	
	July 16, 1961	(69)	44	130		55	x 8	250
42.6	June 10, 1941	70	2,150		519		x 69	
	March 26, 1946	71	585				x 11	
	Apr. 24, 1957	72	1,390		651		x 925	
42.7	Apr. 24, 1957	73	1,330		658		x1,220	
	May 13, 1957	74	1,009		528		x 857	
	June 23, 1959	75	930		370		x 540	
	May 22, 1961	(76)	30	1,110			x 109	910
	June 25, 1961	(77)	130	890			x 32	700
42.11	Apr. 24, 1957	78	1,170		460		x 710	
	June 4, 1957	79	1,030				x 345	
	June 23, 1959	80	430		218		x 345	
	June 25, 1961	(81)	133	770		355	x 6	640
	July 16, 1961	(82)	39	850		355	x 0	720
42.12	Apr. 24, 1957	83	1,060		483		x 955	
	May 13, 1957	84	784		409		x 736	
	June 4, 1957	85	1,130				x 460	
	June 23, 1959	86	500				x 70	
	June 25, 1961	(87)	160	770		619	x 13	680
	July 16, 1961	88	455	1,110		738	x 0	870
42.13	Apr. 24, 1957	89	1,080	1,150	562	1,750	x1,020	1,550
	May 13, 1957	90	765	1,000	441	1,750	x 744	1,280
	June 4, 1957	91	1,070	1,580		1,965	x1,390	1,530
	June 23, 1959	92	530	1,000		2,060	x 970	970
	June 25, 1961	(93)	219	1,000		1,750	x 31	930
	July 16, 1961	(94)	42	1,000		1,750	x 13	980
44.1	July 10, 1951	95	1,120		63		83	
	June 7, 1953	96	460				8	
	June 15, 1957	97	1,190	770		219	211	430
	May 15, 1960	98	610	920	34	520		470
	Aug. 11, 1961	99	88	770		178		520
44.2	June 12, 1958	100	210				17	
	July 3, 1959	101	750		459		760	
44.3	July 10, 1951	102	41		57		72	
	Aug. 28, 1957	103	140	380				250
	May 15, 1960	104	172		26			
44.4	May 15, 1960	105	149		413			
45.1	July 26, 1957	106	210				x 63	
	Aug. 3, 1959	107	157				x 92	
45.4	Aug. 30, 1957	108	231				x 181	
	Aug. 20, 1960	109	264	340	198	x 376		470
47.2	Aug. 24, 1957	110	1,780	880		x 367	x 232	1,100
49.1	Aug. 18, 1944	111	582	750		x 300	260	790
	July 25, 1945	112	820	970		x 300	210	900
	Aug. 25, 1947	113	670	860		x 300	67	550
61.1	July 9, 1951	114	445	1,310	24	1,170		830
	June 27, 1951	115	316	1,400	405	462		880
	Oct. 6, 1955	116	158	930	908	592		810
	Oct. 6, 1955	117	216	930	372	323		550
62.1	Sept. 9, 1959	118	188				x 0	

TABLE 8 - continued

A. R. S.. No.	Date	Event No.	q_{obs}	$q_{RATIONAL}$	q_{SCS}	q_{BPR}	q_{CHOW}	q_{TMP}
62.2	June 10, 1959	119	390				x 16	
	June 11, 1959	120	322				x 109	
	Aug. 31, 1961	121	220				x 0	
62.6	June 4, 1957	122	192				x 0	
	Aug. 24, 1959	123	94	1,070		x 420	x 0	350
	Aug. 31, 1961	124	191	1,070		x 420	x 0	410
62.8	Sept. 9, 1959	125	360	910		x 828		480
63.3	July 19, 1955	126	840	$\underline{240}$	$\underline{90}$	x $\underline{346}$		$\underline{280}$
	Aug. 14, 1958	127	205	$\underline{144}$		x $\underline{90}$		$\underline{250}$
	Aug. 16, 1958	128	360				x $\underline{394}$	
	Aug. 17, 1961	129	200				$\underline{24}$	
63.4	July 14, 1955	130	1,590	$\underline{450}$	$\underline{130}$	x $\underline{502}$	x $\underline{600}$	$\underline{650}$
	Aug. 17, 1961	131	403	$\underline{430}$		x $\underline{355}$	x $\underline{128}$	$\underline{630}$
63.5	Oct. 4, 1954	132	615	$\underline{220}$		x $\underline{350}$	x $\underline{85}$	$\underline{390}$
	Aug. 17, 1957	133	364	$\underline{230}$	$\underline{51}$	x $\underline{314}$	x $\underline{94}$	$\underline{370}$
Lopez Creek	Nov. 25, 1962	134	136	940				x 900

Symbols Signify:
x Method originally not intended for that location.
— Underlined peaks are from arid regions.
Events circled were not used in calculations because other evidence supported deterministic influence far outweighing stochastic components.

2. Histograms. Modified histograms, fig. 7, show the percentage of points within each of the six zones formed by the 1-to-1 and other envelope lines on the scatter-diagrams. Shading lines sloping downward from the left show the areas of underprediction. Heavier shading symbolizes closer predictions to observed flood peaks. The dotted uniform-distribution line of 15.5 per cent would have been achieved if points on the scatter-diagram had been obtained by a purely random process. Peakedness of the histogram above this line indicates the deterministic influence of the method. Peakedness to the left of the heavy 1-to-1 verticals in fig. 7 signifies underprediction.

3. Statistics. Some statistics can be introduced in order to aid the engineer to adjudge the highly variable results of applying these five methods. To eliminate the adverse effects of mixing large numbers with much smaller numbers in the same sample of flood peaks, most of the statistics which are presented in Table 9 are in the form of the ratio $\frac{q_p}{q_o}$, where q_p = predicted peak rate of runoff and q_o = observed peak rate of runoff. If the average of this ratio is smaller than unity for a specific method, it means that this method underpredicts on the average by that factor.

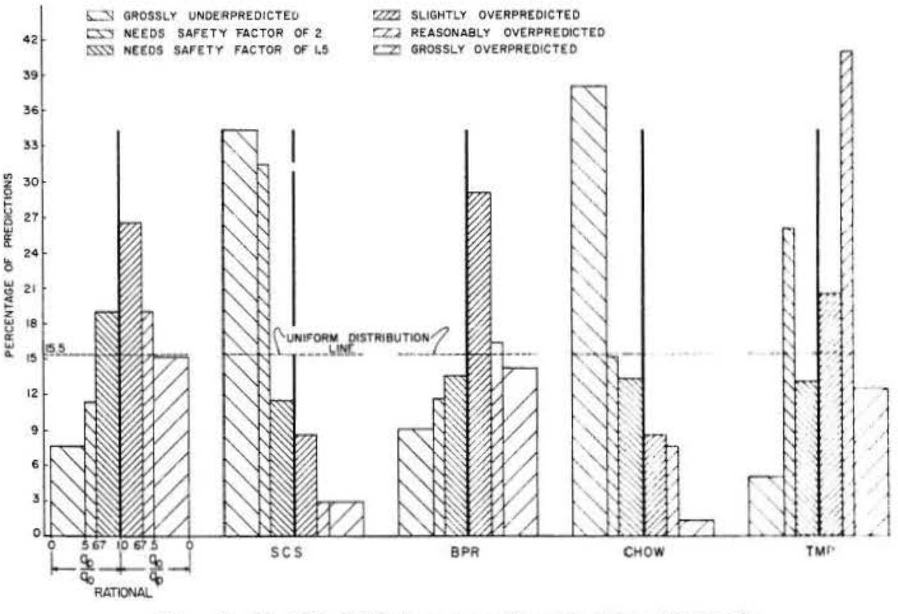

Fig. 7 Modified Histograms for the Five Methods

TABLE 9. STATISTICS BASED ON THE RATIO $\frac{q_p}{q_o}$ FOR EACH METHOD

Method	Sample Size n	Average $\frac{q_p}{q_o}$	Standard Deviation s	95% Confidence interval for $\frac{q_p}{q_o}$	Range of Average $\frac{q_p}{q_o}$	$\frac{\text{Range}}{\text{Mean}}$ of Ratio	Percent of sample over-predicted	Percent of sample under predicted
RATIONAL	50	2.01	2.24	1.37 thru 2.65	1.28	0.64	64	36
SCS	65	0.64	0.64	0.45 thru 0.84	0.39	0.61	12	88
BPR	48	1.54	1.18	1.19 thru 1.88	0.69	0.45	67	33
CHOW	96	0.59	0.92	0.40 thru 0.78	0.38	0.64	16	84
TMP	50	1.65	1.34	1.27 thru 2.03	0.76	0.46	72	28

The 95% confidence intervals were calculated [21] on the assumption of population normality which is not strictly met in this case of observed flood peaks, but this deviation from normality does not materially detract from the usefulness of these numbers as descriptive statistics. The correct interpretation of the confidence intervals is that "if all possible samples of size 'n' are drawn from a normal population, 95% of the samples yield confidence intervals which include the population mean." These confidence intervals can be looked upon as performance ratings of the different methods and they give some indication of the range of ratios within which a specific method can be expected to predict.

The range of this ratio divided by its mean for each corresponding method gives a statistic which can serve to compare the scatter of the methods relative to their mean $\frac{q_p}{q_o}$.

The level which an engineer will set as the threshold for the probable percentage of underprediction will be influenced by economic and other considerations. In the limited sample studied in this paper three of the methods would have produced underprediction one-third of the time. The two other methods would have done so almost nine times out of ten. Reasons for the consistently bad predictions are presented under separate discussions which follow for each method.

4. The "Rational" Formula. The simplicity of this method should not lead to undeserved criticism. In each of the five methods except BPR, engineering judgment must be employed to choose a factor used in the application of the method. The runoff coefficient, C, used in the "Rational" formula, is of such overruling importance and its choice for this study was often based on such vague descriptions that the results obtained in this study were surprisingly good. Engineering judgment can be expected to give even better results if the choice of C is based on a personal inspection of the basin instead of on word descriptions.

Additional consideration was given to the runoff coefficient by computing it as:

$$C_o = \frac{q_o}{Ia} \qquad (2)$$

The intensity I was determined for the duration B, from the observed time-pattern of each storm. Figure 8 shows the observed values of the runoff coefficient, C_o, plotted against the appropriate rainfall intensities and with the five-day antecedent precipitation noted. Firstly, attention is drawn to the extreme variations in C_o itself, from a value of 0.105 to 1.123, for ARS No. 26.32 at Coshocton, Ohio, as an example. This variation draws the attention to the important role of C in this formula. Not only must it account for all the rainfall and basin factors omitted from the formula itself, but also for the joint probabilities of occurrence of certain states of these factors.

Some slight trend can be observed for C_o to increase with increasing rainfall intensity and high five-day antecedent precipitation. The short length of available records on each basin prohibits the establishment of possible underlying relationships. However, it was thought that the relationship between C and rainfall intensities found on small Cochocton watersheds by Horn and Schwab [22] may possibly improve results obtained by the "Rational" method. For estimations of C it was necessary to extrapolate this relationship beyond Cochocton to other localities, to larger basins and for different cover factors. The results obtained by applying these new C's actually were inferior to the results obtained using the C's evaluated originally from the Fervert et al., table [11] as can be seen from the histogram of fig. 9.

5. The SCS Method. The peaks predicted by this method averaged only 0.64 of the observed flood peaks. More than 34 per cent of the estimates were underpredicted more than twice. The basin sizes of this sample are perhaps too small to give credit to this method. Larger basins seem to behave more in accordance with the tenants of this method. For example, both the events observed on the Coshocton basin, No.26.37 of 27.34 square miles, were predicted very well. It is physically understandable why a method based on rainfall of six-hours duration underpredicts flood peaks from basins smaller than approximately ten square miles [23]. A modification involving the effective storm duration was obtained from the segment of the mass rainfall curve for each storm event which contains the most intense and significant part of the storm. Two variations of runoff

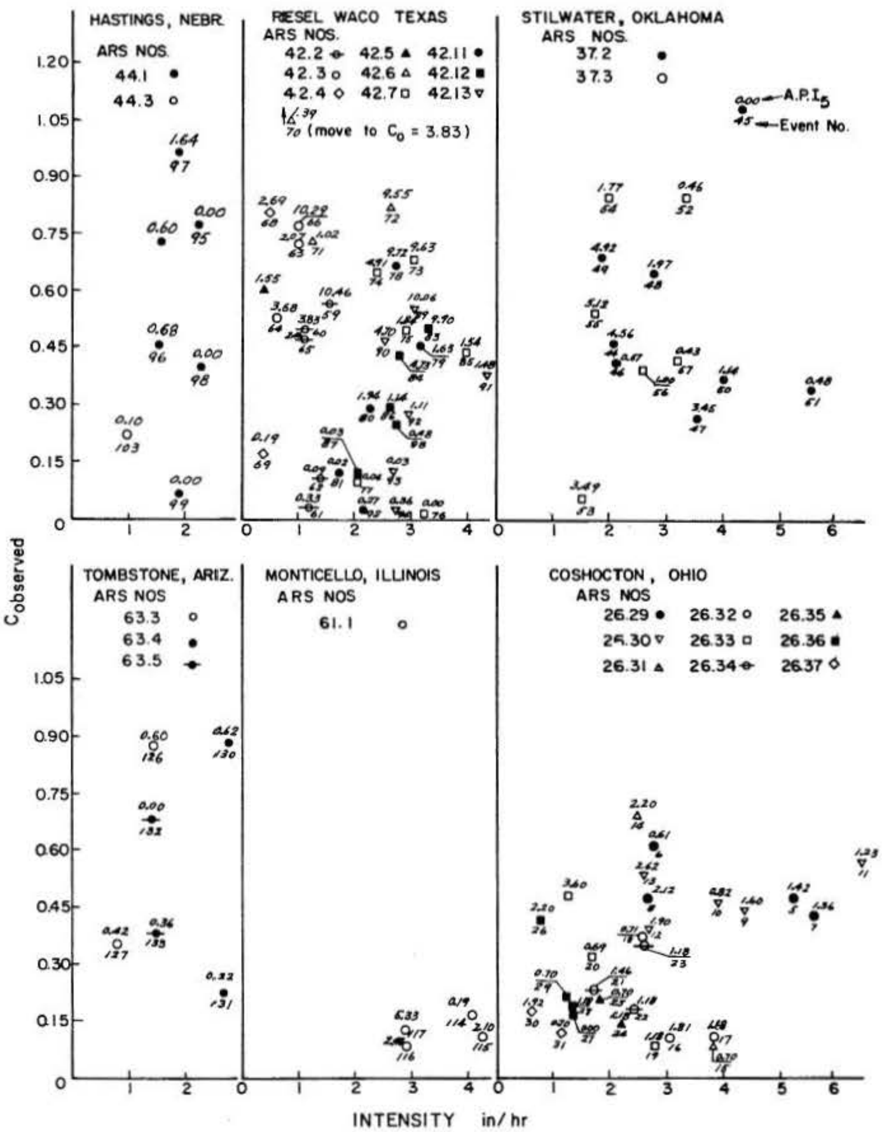

Fig. 8 Variations in C_o with I and A. P. I.$_5$

curve numbers were also considered. Firstly, basin moisture condition II was used for all events and secondly, an average moisture condition halfway between the values given for growing- and dormant seasons [16] was used. The best results were obtained with effective storm duration and moisture Condition II for all events. Figure 10 shows the histogram for these predictions, which is an obvious improvement over the six-hour method. The average

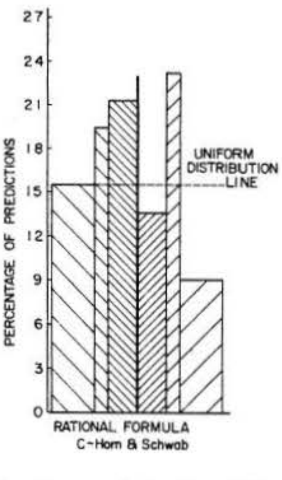

Fig. 9 New Evaluations of C Give Worse Results

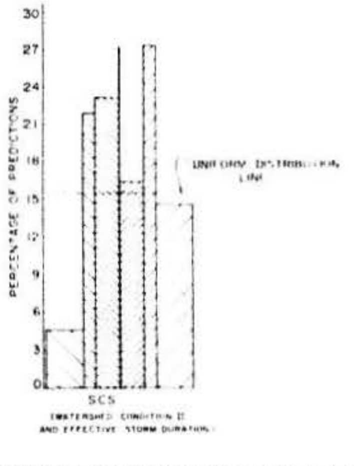

Fig. 10 Modifications Considerably Improve SCS

ratio of $\frac{q_p}{q_o}$ is 1.52 for this variation of the method, with a standard deviation of 1.15 and a 95% confidence interval ranging from 1.24 through 1.79. This range is 0.36 of the mean ratio. So by comparison with Table 9, this variant of the SCS method becomes even more reliable than BPR or TMP. For design purposes the effective storm duration is unknown; hence, this modified SCS is still impracticable. Better criteria for the optimum storm duration will need to be developed. It also remains to determine the basin size, or other basin criteria, at which the six-hour design storm breaks down. Application of shorter storms than six hours to these small basins is merely the application of sound engineering judgment. The inordinately small peaks obtained with P_{6h} should warn against the slavish application of a method primarily intended for larger areas.

Along similar lines it should be noted that the purpose for which SCS was developed was the prediction of a design hydrograph which, in practice, is routed through large flood control reservoirs. The peak rate itself is of little consequence as it is the recession side of the hydrograph that provides the discharge for which a spillway is designed.

This agency frequently performs its designs with the so-called "probable maximum precipitation," which can be as much as 25 inches in six hours, and seldom as low as a 100-year rain. The amounts of six-hour rain causing the observed floods never reached 7 inches. It averaged 2.63 inches and was less than 1.5 inches on two occasions. For such small amounts of rain the method gives runoff to be a small fraction of rainfall dependent largely upon the curve number. Should designs be performed for as much as 20 inches of storm rainfall, runoff volumes approach about 90 per cent almost independently of curve number, in the common range of Table 2. So although no test can be made of it within forseeable time, the SCS method may perform within its agency objectives far better than that which appears in this paper.

6. The BPR Method. BPR's predictions are relatively good. This method is especially attractive because all the factors used are incorporated in the design charts and no evaluations of coefficients, runoff curve numbers, or infiltration capacities are necessary. Hence experience plays a much smaller role in applying this method than in any other. However, sight should not be lost of the fact that the fringe areas between adjacent BPR's zones can lead to severe malprediction in the absence of sound judgment. Potter's maps are of relatively small scale and consequently exhibit marked smoothing. In the folded hills and valleys of the East, geologic changes take place very rapidly. One basin may be in a karst region while another, three miles away (indistinguishable on BPR maps), may have radically different hydrologic characteristics. Supplemental use of large-scale geologic maps will help.

An improvement of predictions on relatively even-sloped basins seems to result from this method's making use of the slope over 0.7 and 0.3 of the length of the longest stream channel. Figure 2 shows that, in the predictions of rare events, this method's range between 10- and 200-year floods is much higher on the relatively even-sloped basins than those of the other methods. Observed flood peaks on these basins were generally predicted better by BPR than by the other methods. The implication is that recognition of topographic peculiarities by the method gives it added realism.

Reference to Table 9 shows that on the average this method overpredicts by a factor of 1.54 which is an acceptable safeguard against underpredictions. The scatter around the mean value as indicated by 0.45 in Table 9 is the smallest. Hence this method is highly acceptable when compared to the others.

7. Chow's Method. Chow's method was tested heavily outside Illinois which may be a reason for the unfavorable results obtained. The great similarity between the results obtained by this method and SCS, as shown on the histograms of fig. 7 and the statistics of Table 9, is interesting, but not surprising, since this method is strongly related to SCS.

The tedious maximization of flood peaks makes this method relatively difficult to apply and the poor results obtained are thus even more disappointing. Chow's predictions averaged 0.59 times the corresponding observations. Wide scatter is also present around this average value. About 38% of the sample was underpredicted by factors greater than two. On the basis of the distributions of dots and crosses on the scatter-diagram of fig. 6 it seems as if the scatter could be reduced if the method were tested only in and immediately around Illinois, but this would also increase the unfavorable underprediction ratio.

This method is based on some sound hydrological reasoning and offers interesting possibilities for improvement.

8. TMP Method. Ease of application and reasonably good predictions make this method attractive. It overpredicts the observed flood peaks on an average of 1.65 times and the scatter about this value is reasonably small. Overprediction for this limited test sample can be explained as development of this method pivoted on an attempt to use the optimum storm duration for various types of basins. It can be expected that such optimum storm durations made up a very small part of the observed sample. The observed events will therefore be smaller than the conservative design peaks yielded by TMP.

This method had been tested previously against another set of 79 observed events [17] which were excluded from this new evaluation. The histogram for the earlier test, fig. 11, shows a great similarity with the histogram obtained in this study, fig. 7, and may serve to give more confidence in this method.

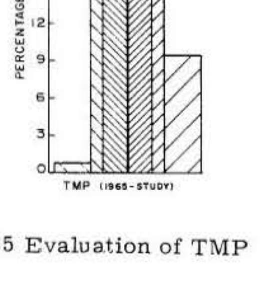

Fig. 11 1965 Evaluation of TMP

CHAPTER VI

APPRAISAL OF FINDINGS

Recognition of residual gaps in the knowledge on small basin floods and the state of the art of flood predictions is the cornerstone to engineering judgment in this field. The wisest practice may be to simultaneously apply three of the better methods before deciding on a design flood peak. Statistics, like those presented in Table 9 can serve as some kind of performance rating for each method. Relative performance between methods applied in either arid or humid zones can be weighted from Table 5.

When the lower side of the confidence interval in Table 9 is greater than unity, underprediction by the method is unlikely. This is valid for RATIONAL, BPR, and TMP. It should be noted, however, that underpredictions may still occur. For example, although the lower side of the confidence interval is 1.37, 1.19, and 1.27 for RATIONAL, BPR, and TMP, underpredictions occur in 36-, 33-, and 38-per cent respectively of the samples used. The greatest underpredictions occur on event no. 130, Tombstone, Arizona, which was underpredicted 3.5, 3.2, and 2.5 times respectively by these three methods.

The upper side of the confidence interval must also be considered in terms of overprediction that may occur. These ratios of 1.88 for BPR and 2.03 for TMP suggest that overpredictions by a factor of more than 2 is highly unlikely for these methods.

The range of ratios covered by the confidence interval divided by the average ratio of $\frac{q_p}{q_o}$ gives an indication of the relative variability around this average ratio. BPR and TMP with values of 0.45 and 0.46 respectively show the least variability. Both these methods appear to be highly acceptable. The wider suitability and easier applicability of TMP compensate for the slightly greater precision of BPR.

RATIONAL has more variability than the above two methods and overpredicts on the average of 2.01 times. The upper side of the confidence interval represents floods 2.15 times the observed values. It is interesting to recall the results of a study [24] in Great Britain which found that on an average the "Rational method" overpredicted 2.6 times. This tendency to overpredict by a large ratio of $\frac{q_p}{q_o}$ should not give undue faith in the conservatism of this method as shown by the fact that 36% of the events used in this study were underpredicted.

The SCS hydrograph families, based upon the six-hour rain, produce peaks with nearly as much relative variability as RATIONAL. The former is, however, seriously in error, since predicted peaks are on the average only 64% as great as observed events. In terms of the upper confidence limit of 0.84, it is seen that a correct prediction by this method would have an extremely small chance of occurring.

Faith in the basic premises of the SCS method, except for the restrictions of six-hour duration and the B-type time distribution of it, is restored since the modification with respect to effective storm duration resulted in the least relative variability of any method. By the use of this modification the average SCS peak was overpredicted by 52% rather than the previously mentioned underprediction. This improvement will need research into small area flood producing rainstorms before it can be used on designs for ungaged basins. The overruling superiority of the modified Soil Conservation Service method illustrates how successful engineering judgment can be applied to bend a technique for use beyond the restrictions for which it was primarily intended.

Use of the published procedure based on six-hour rainfall has clearly shown that a lower limit to drainage area, or possibly B, should be set to its application. In practice shorter rainfall durations would be used for these small areas. The optimum storm duration could be found by trying several durations until the maximum discharge is discovered. This would, however, superimpose further difficulty upon the establishment of a return period for such an event.

The results obtained by means of Chow's method closely resemble the results obtained by using SCS with a 6-hour duration. Its underprediction cannot be rectified simply by dividing results by 0.59. Such adjusted predictions would like between 0.68 and 1.32 times the observed events and still contain much underprediction. This method also shows great relative variability.

Floods on the arid regions were generally underpredicted. Out of the twelve events considered, RATIONAL, BPR, and TMP underpredicted 58-, 83-, and 50-per cent, respectively, which indicates that special care must be exercised by designers in these regions. From Table 5 it can be seen that relative to each other, average estimates only deviate about ±20% for arid predictions. For humid estimates the same range is from -35% to 51%.

Summarizing the findings of this study it can be said that:

1. The most reliable method is BPR, but it is slightly complicated to use. Furthermore, its use is as present limited to only certain localities of the U. S. A. Extrapolation to other localities and to other parts of the world is difficult. It does not predict small floods, as the design charts are limited to a minimum 60-minute rainfall of 1.7 inches.

2. TMP is nearly as reliable as BPR and is much easier to apply. Less topographic data is needed and it can easily be obtained from maps or with a transit or even an altimeter in the field. This method is applicable over most of the U. S. A. [8] and extrapolation to other parts of the world [9] where small area floods are caused by short convective storms is relatively easy.

3. RATIONAL is nearly as easy to apply as TMP. If C is estimated well, it gives reasonable results.

4. CHOW needs considerable improvement and simplification before it can compare with the above three methods. Its extension to different hydrologic regions than Illinois should not be undertaken without the development of additional relationships for time-to-peak.

5. SCS, based upon a six-hour storm, was not developed for and does not suit conditions prevailing in the present study. Its application to small basins could be made superior to any of these methods with improved knowledge of short duration rainfall. Sight should not be lost, however, of the potential of protracted rainfall-based methods in high rainfall regions like the Northwestern United States, some Appalachian regions typified by Coweeta Experimental Forest, or areas in New South Wales, Australia [25].

6. Predictions of events by all methods were worse for arid regions than for other locations. These events were generally underpredicted.

7. Much remains for the researcher to do to assist his practicing colleagues in this common engineering problem.

8. For some time to come judicious judgment will continue to play a vital role in small area floods.

CHAPTER VII

CONCLUSIONS

Individual engineers must select prediction methods or adjust them according to whether their design criteria permits over and underprediction, or whether they seldom wish to underpredict, or to whatever criteria they have to meet.

Comparing predicted flood peaks with those of observed events on this sample of mixed cover agricultural basins ranging in area from 0.12 through 8.61 square miles showed that not one method out of the five considered can always predict floods with commonly desired precision.

Extension of methods beyond regions and size ranges for which they were developed, when necessary, must be done with extreme caution.

Finally, the assumption often made in design computations that rainfalls of certain return periods will always result in floods with roughly the same return periods is false. Only when the stochastic processes affecting rainfall before it emerges as runoff have return periods of such magnitudes that together they make the assumption true, can rainfall return periods be used as indicators of flood return periods. The chance for such an occurrence of magnitudes seems to be very small.

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APPENDIX

The following symbols have been adopted for use in this paper:

A = area of basin in square miles;

a = area of basin in acres;

$A.P.I._5$ = five-day antecedent precipitation

B = basin characteristic, a function of H and L;

C = runoff coefficient, for the "Rational" formula, based upon flood-producing characteristics of the basin;

C_o = runoff coefficient, computed from the observed peak rate of runoff;

cfs. = cubic feet per second;

csm = cubic feet per second per square mile;

F = cover factor, modifying f;

f = infiltration capacity for bare soil after one hour from the beginning of excess rainfall, in inches per hour;

H = fall over watershed from rim to outlet, omitting waterfalls and gully-head, in feet;

I = rainfall intensity averaged over the consecutive duration, B, which produces the most rain throughout the storm, in inches per hour;

L = length of longest collector, from watershed outlet to rim, in miles;

n = size of sample;

P_{6h} = maximum total rainfall over 6 consecutive hours;

P_{60} = maximum total rainfall over 60 consecutive minutes;

P_{30} = maximum total rainfall over 30 consecutive minutes;

q = peak rate of runoff in cfs. ;

q_o = observed peak rate of runoff in csm;

q_p = predicted peak rate of runoff in csm;

S = infiltration capacity of watershed in inches per hour;

S_1 = average slope over the uppermost 0.3 times the length of the longest collector in feet per mile;

S_2 = average slope over lower 0.7 times the length of the longest collector in feet per mile;

s = standard deviation

Key Words: Floods, Predictions; Engineering judgment, Appraisal, Small basins, Hydraulics Rainfall intensities.

Abstract: The knowledge of small basin floods and the state of the art of flood predictions on ungaged basins are such that engineering judgment still plays an important role in the determination of a design flood. An appraisal of the reliability of five current methods of flood prediction is presented as an aid in developing this faculty. The first phase involved a comparison among flood estimates obtained by applying rainstorms estimated to have return periods of from 2- through 200-years. For each of six such levels of protection applied to fourteen real basins, inconsistencies among five methods produced differences in the magnitude of their estimates as great as 300 per cent. Since long flood records for small basins were inadequate, it was necessary to insert observed rainfalls into formulae and design methods for a second phase of the study. Design estimates based upon recorded rainstorms were compared to 134 observed floods. These events occurred on forty-five mixed cover agricultural basins ranging in area from 0.12 through 8.16 square miles, within thirteen states of the U. S. A. Scatter-diagrams, histograms, and statistics suggest some superiority of the "Rational" formula, the Bureau of Public Roads method, and the Tacitly Maximized Peak technique in that they generally overestimate floods from this sample. Although their variability is also less than that of the other two methods, it is sufficient to permit underprediction in about a third of the cases. Comparisons are odious, and it is essential to recognize that the purposes for which some methods were developed were somewhat at variance with restraints imposed by this appraisal. Regional limitations spelled out by their authors were violated expressly here to explore desirable versatility.

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