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PROBABLE MAXIMUM FLOOD ESTIMATION – EASTERN UNITED STATES[1]

Paul B. Ely and John C. Peters[2]

ABSTRACT: In 1982, the National Weather Service (NWS) published criteria for developing the spatial and temporal precipitation distribution characteristics of Probable Maximum Storms. The criteria, which are intended for use in the United States east of the 105th meridian, involve four variables: (1) location of the storm center, (2) storm-area size, (3) storm orientation, and (4) temporal arrangement of precipitation amounts. A computer program has been developed which applies the NWS criteria to produce hyetographs of spatially-averaged precipitation for a basin, or for each subbasin if the basin is subdivided. The basis and operational characteristics of the program are described, and an application is illustrated in which the program is used in conjunction with a precipitation-runoff simulation program (HEC-1) to compute a Probable Maximum Flood.
(KEY TERMS: Probable Maximum Flood; design storm.)

INTRODUCTION

In 1978, the United States National Weather Service (NWS) published estimates for Probable Maximum Precipitation (PMP) for the eastern part of the country, east of the 105th meridian (NWS, 1978). The estimates apply to areas of 10 to 10,000 sq. mi. and durations of 6 to 72 hours. The National Weather Service has also published applications criteria (NWS, 1982) that can be used with the PMP estimates to develop spatial and temporal characteristics of a Probable Maximum Storm (PMS). A PMS thus developed can be used with a precipitation-runoff simulation model to calculate a Probable Maximum Flood (PMF) hydrograph. The PMF is used in the hydraulic design of project components for which virtually complete security from flood-induced failure is desired; for example, the spillway of a major dam or protection works for a nuclear power plant.

The NWS criteria for defining a PMS require that the magnitude of four variables be established: (1) location of the storm center, (2) storm-area size, (3) storm orientation, and (4) temporal arrangement of precipitation amounts. Additional variables that influence the magnitude of a PMF include antecedent moisture conditions and the initial state of a reservoir or reservoir system. The four PMS variables are generally chosen to produce the maximum peak discharge or runoff volume at the point of interest. It is therefore necessary to calculate runoff as a part of the trial and error process of establishing the magnitude of the PMS variables.

A computer program has been developed (HEC, 1983b) for applying the NWS procedure for defining a PMS. The program, called HMR52, has an optional capability to pass calculated hyetographs to a data storage system for subsequent retrieval by computer program HEC-1 (HEC, 1981), with which runoff is calculated. This paper describes the basis for the new program and describes its application in conjunction with HEC-1.

COMPUTER PROGRAM HMR52

The NWS criteria define the PMS in terms of a set of elliptical isohyets for a series of 'standard' area sizes – 10, 25, 50, 100, etc., up to 60,000 sq. mi. The basis for, and method of, assigning precipitation depths to the isohyets are provided in Hydrometeorological Report No. 52 (NWS, 1982). For runoff determination, a watershed is generally divided into subbasins, and a hyetograph (i.e., time distribution) of average precipitation for each subbasin is required. The output from HMR52 consists essentially of a set of subbasin hyetographs.

The sequence of computations in HMR52 is first to calculate a PMS for the total watershed and then to determine the corresponding subbasin hyetographs. Input items for HMR52 include the following:

1. X-Y coordinates for the total watershed and for each subbasin. These could be obtained with a digitizer.
2. Depth-area-duration PMP data from Hydrometeorological Report No. 51 (NWS, 1978).
3. Preferred storm orientation from Hydrometeorological Report No. 52 (NWS, 1982).
4. X-Y coordinates of the storm center.
5. Storm-area size.
6. Storm orientation.
7. Temporal arrangement of six-hour depths.
8. Time interval for hyetographs.

Although PMS variables are generally based on the production of peak discharge or maximum runoff volume, maximization of the average depth of precipitation over the watershed is, in many cases, a virtually equivalent criterion. The HMR52 program contains an option by which storm area size

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and/or orientation can be optimized with maximization of average depth as an objective function. Although the program does not have capability to optimize the location of the storm center, the program will locate the storm center at the basin centroid if location of the storm center is not specified. The programmed optimization procedure is as follows:

1. The major axis of the storm is oriented such that the moment of inertia (second moment) of the basin area about this axis is a minimum. The depth of basin-average precipitation is determined for an array of storms corresponding to the standard storm-area sizes. The storm-area size which produces the maximum average depth is selected as the critical storm-area size (i.e., see Table 1a).

2. Using the critical storm-area size, the depth of basin-average precipitation is determined for an array of storms for which storm orientation varies in 10-degree increments over the range of possible orientations. The orientation producing the maximum average depth is determined and two additional storms, with orientations of $\pm 5^{\circ}$ from this orientation, are developed. The orientation that produces the maximum average depth is selected as the critical orientation (i.e., see Table 1b).

Six-hour incremental precipitation amounts for each storm identified in the optimization process are arranged in order of decreasing magnitude, as illustrated in Tables 1a and 1b. The time interval for incremental precipitation used for definition of the optimized (or user-specified) storm is selected by the user in the range of five minutes to six hours. Precipitation is assumed to occur with uniform intensity during each six-hour period outside of the 24-hour period of maximum precipitation.

The user can specify the arrangement of six-hour increments throughout the storm or just the position of the maximum six-hour increment, which may occur in any position after the first 24 hours of the storm. If the position of the largest six-hour increment is not specified, it is placed in the seventh position (hours 37-42) by default. Figure 1 illustrates a program-generated hyetograph for which Δt is one hour. Criteria and guidelines for determining the temporal arrangement of precipitation are given in Hydrometeorological Report No. 52 (NWS, 1982).

RUNOFF SIMULATION

The HMR52 program has capability to write subbasin hyetographs to a disk file, or to a special Data Storage System (HEC, 1982), for subsequent runoff simulation with computer program HEC-1 (HEC, 1981). An advantage of using the Data Storage System is that a graphics program called DSPLAY (HEC, 1983a) can be used to plot the precipitation hyetographs as well as hydrographs calculated with HEC-1.

The HEC-1 program can be used to simulate the runoff generation, routing and combining operations required for complex multi-subbasin watersheds. Generally the unit hydrograph approach to runoff simulation is employed, although capability to calculate runoff with kinematic wave methodology is also available (HEC, 1979).

In addition to the subbasin hyetographs, input items for HEC-1 would include:

1. Subbasin areas.
2. Unit hydrograph, loss rate, and base flow parameters for each subbasin.
3. Streamflow routing parameters for each routing reach.
4. Storage-outflow criteria and an initial storage for reservoirs, if reservoir routing is to be performed.

ILLUSTRATION

The joint use of HMR52 and HEC-1 for PMF estimation is illustrated in the following hypothetical example. Figure 2 shows the 288 sq. mi. watershed above Jones Reservoir. HMR52 is used to develop PMS hyetographs for the four subbasins shown in Figure 2, and HEC-1 is used to calculate a PMF inflow hydrograph to the reservoir and to route the PMF through the reservoir.

For this illustration, no values are specified for storm center, storm-area size, orientation, and temporal arrangement. The program therefore places the storm center at the basin centroid and obtains storm-area size and orientation by maximizing the depth of precipitation. A default two-hour temporal distribution is used.

Table 1a is HMR52 output that summarizes storm depths for various storm-area sizes and for a storm orientation that minimizes the moment of inertia of the basin area about the major axis of the elliptical storm pattern. As may be seen from the table, a storm-area size of 300 sq. mi. produces the largest depth.

Table 1b summarizes depths obtained by varying storm orientation in 10° increments and a storm-area size of 300 sq. mi. The last two storms in the table have orientations which are 5° to either side of the best previous orientation. By coincidence, the best previous orientation is 285°, so the last two storms (280° and 290° orientations) are repeats of storms calculated previously.

With PMS variables thus defined, hyetographs are calculated for the four subbasins. Table 2 shows precipitation amounts for Subbasin 1. The four hyetographs, runoff and routing parameters, etc., are used as input to HEC-1, which calculates discharge hydrographs for locations of interest. Table 3 shows HEC-1 summary output resulting from the storm generated by HMR52. Peak discharge and maximum average discharges for durations of 6, 24, and 72 hours are tabulated for each location.

The objective in calculating a PMF is to obtain the largest flood that can reasonably occur. Because of hydrologic characteristics of a watershed, the largest flood may not result from the storm that produces the greatest average depth of precipitation. Results from several trials that were made in calculating the PMF for Jones Reservoir are shown in Table 4. These trials represent a sensitivity analysis with respect to position of the peak six-hour interval, storm area, storm

TABLE 1a. Selection of Storm-Area Size – Varying Storm Area Size and Fixed Orientation.

Storm Area (sq. miles)	Orientation (degrees)	Basin-Averaged Incremental Depths for Six-Hour Periods (inches)												Sum of Depths for Three Peak Six-Hour Periods (inches)
10	285	9.62	1.35	0.71	0.48	0.37	0.30	0.25	0.21	0.19	0.17	0.15	0.14	11.69
25	285	12.06	1.96	1.05	0.71	0.54	0.44	0.37	0.32	0.28	0.25	0.22	0.20	15.07
50	285	13.82	2.40	1.28	0.88	0.67	0.54	0.45	0.39	0.34	0.30	0.27	0.25	17.50
100	285	14.81	2.76	1.48	1.01	0.77	0.62	0.52	0.45	0.39	0.35	0.32	0.29	19.05
175	285	15.23	2.99	1.59	1.09	0.83	0.67	0.56	0.48	0.42	0.39	0.34	0.31	19.82
300	285	15.38	3.21	1.67	1.13	0.86	0.69	0.58	0.50	0.44	0.39	0.35	0.32	20.25
450	285	15.07	3.32	1.68	1.13	0.85	0.69	0.57	0.49	0.43	0.39	0.35	0.32	20.07
700	285	14.40	3.40	1.66	1.11	0.83	0.67	0.56	0.48	0.42	0.37	0.34	0.31	19.46
1,000	285	13.76	3.42	1.63	1.08	0.81	0.67	0.54	0.47	0.41	0.36	0.33	0.30	18.82
1,500	285	13.04	3.33	1.58	1.04	0.78	0.63	0.52	0.45	0.39	0.35	0.32	0.29	17.95
2,150	285	12.23	3.22	1.51	0.99	0.75	0.60	0.50	0.43	0.38	0.33	0.30	0.27	16.95
3,000	285	11.31	3.05	1.42	0.93	0.70	0.56	0.47	0.40	0.35	0.32	0.28	0.26	15.78
4,500	285	10.84	3.05	1.41	0.92	0.70	0.56	0.47	0.40	0.35	0.31	0.28	0.26	15.30
6,500	285	10.45	3.00	1.37	0.89	0.67	0.54	0.45	0.39	0.34	0.30	0.27	0.25	14.82
10,000	285	9.76	2.97	1.31	0.85	0.63	0.51	0.42	0.36	0.32	0.28	0.26	0.23	14.05
15,000	285	9.04	2.86	1.30	0.85	0.64	0.52	0.43	0.37	0.33	0.29	0.26	0.24	13.21
20,000	285	8.34	2.78	1.30	0.85	0.64	0.52	0.44	0.38	0.33	0.29	0.26	0.24	12.41

TABLE 1b. Selection of Storm Orientation – Fixed Storm Area Size and Varying Orientation.

Storm Area (sq. miles)	Orientation (degrees)	Basin-Averaged Incremental Depths for Six-Hour Periods (inches)												Sum of Depths for Three Peak Six-Hour Periods (inches)
300	140	14.85	3.14	1.64	1.11	0.84	0.68	0.57	0.49	0.43	0.38	0.34	0.32	19.62
300	150	14.60	3.10	1.62	1.10	0.83	0.67	0.56	0.48	0.42	0.38	0.34	0.31	19.31
300	160	14.37	3.07	1.60	1.09	0.83	0.66	0.56	0.48	0.42	0.37	0.34	0.31	19.04
300	170	14.18	3.04	1.59	1.08	0.82	0.66	0.55	0.48	0.42	0.37	0.33	0.30	18.81
300	180	14.03	3.02	1.58	1.07	0.81	0.66	0.55	0.47	0.41	0.37	0.33	0.30	18.63
300	190	13.96	3.01	1.58	1.07	0.81	0.65	0.55	0.47	0.41	0.37	0.33	0.30	18.54
300	200	13.96	3.01	1.57	1.07	0.81	0.65	0.55	0.47	0.41	0.37	0.33	0.30	18.54
300	210	14.04	3.02	1.58	1.07	0.81	0.65	0.55	0.47	0.41	0.37	0.33	0.30	18.64
300	220	14.19	3.03	1.59	1.08	0.82	0.66	0.55	0.47	0.42	0.37	0.33	0.30	18.81
300	230	14.40	3.07	1.60	1.09	0.82	0.66	0.56	0.48	0.42	0.37	0.34	0.31	19.06
300	240	14.63	3.10	1.62	1.10	0.83	0.67	0.56	0.48	0.42	0.38	0.34	0.31	19.34
300	250	14.88	3.14	1.63	1.11	0.84	0.68	0.57	0.49	0.43	0.38	0.34	0.31	19.65
300	260	15.11	3.17	1.65	1.12	0.85	0.68	0.57	0.49	0.43	0.38	0.35	0.32	19.93
300	270	15.28	3.19	1.66	1.13	0.85	0.69	0.58	0.50	0.43	0.39	0.35	0.32	20.13
300	280	15.37	3.20	1.66	1.13	0.86	0.69	0.58	0.50	0.44	0.39	0.35	0.32	20.24
300	290	15.37	3.21	1.67	1.13	0.86	0.69	0.58	0.50	0.44	0.39	0.35	0.32	20.25
300	300	15.28	3.19	1.66	1.13	0.86	0.69	0.58	0.50	0.44	0.39	0.35	0.32	20.14
300	310	15.10	3.17	1.65	1.12	0.85	0.68	0.57	0.49	0.43	0.39	0.35	0.32	19.92
300	280	15.37	3.20	1.66	1.13	0.86	0.69	0.58	0.50	0.44	0.39	0.35	0.32	20.24
300	290	15.37	3.21	1.67	1.13	0.86	0.69	0.58	0.50	0.44	0.39	0.35	0.32	20.24

orientation and storm-center location. A sensitivity analysis of this kind should be performed when using the HMR52/ HEC-1 PMF estimation procedure. Characteristics of the trials are as follows:

Trial 1 – Storm center, area size, orientation, and temporal distribution were selected by the program. Figure 3 shows the storm pattern used for Trials 1 and 2.

Trial 2 – Same as Trial 1, except a temporal distribution is used in which the peak six-hour interval is shifted to the 10th position (hours 54-60). This change increased the peak flow slightly and was used for subsequent trials.

Trial 3 – Same as Trial 2, except the isohyetal pattern was manually centered on the watershed.

Trial 4 – Same as Trial 3, except that a storm-area size of 175 sq. mi. was specified.

Trial 5 – A storm center was determined considering only Subbasins 1, 2, and 3. The centering was chosen because these subbasins produce most of the runoff.

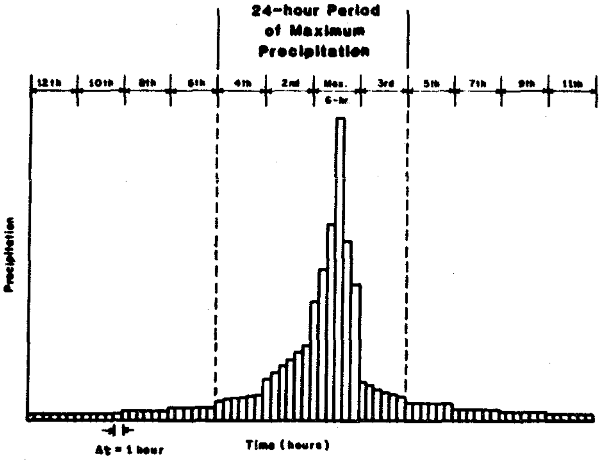

Figure 1. Example One-Hour Distribution of PMS Rainfall.

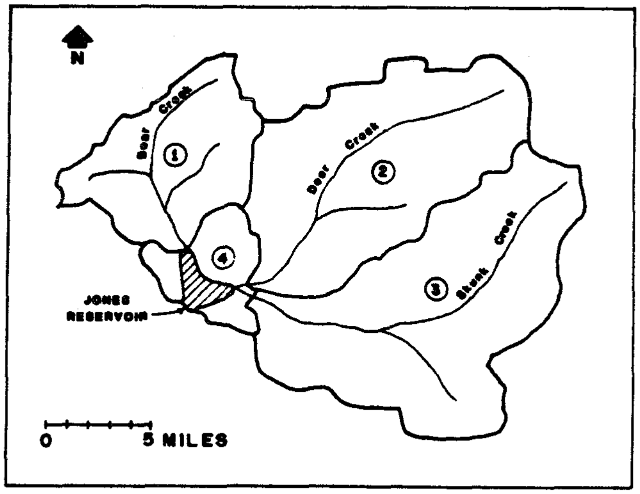

Figure 2. Jones Reservoir Watershed.

As may be noted from Table 4, there is very little difference in results for the five trials. Trial 2 produced the maximum peak inflow and outflow. However the results from Trial 1, using program defaults, could readily be adopted for the PMF, because the difference in peak inflow and outflow differed by only 0.4 percent and 0.7 percent, respectively, from the maximum values.

Although this illustration is hypothetical, studies performed to date indicate that, in most cases, default values in HMR52 will suffice to develop the PMS. However, in the case of a highly unusual basin shape or of a basin with marked spatially heterogeneous runoff characteristics, a number of trials may be warranted.

TABLE 2. Precipitation for Subbasin 1.

		Precipitation (inches)		
	Time	Six-Hour Increment	Two-Hour Increment	Cumulative
Day 1	0000		– –	– –
	0200		0.11	0.11
	0400		0.11	0.22
	0600	0.33	0.11	0.33
	0800		0.13	0.46
	1000		0.13	0.59
	1200	0.40	0.13	0.72
	1400		0.17	0.89
	1600		0.17	1.06
	1800	0.51	0.17	1.23
	2000		0.23	1.46
	2200		0.23	1.70
	2400	0.70	0.23	1.93
Day 2	0200		0.34	2.28
	0400		0.38	2.66
	0600	1.15	0.43	3.09
	0800		0.82	3.91
	1000		1.05	4.95
	1200	3.24	1.37	6.32
	1400		3.94	10.27
	1600		8.99	19.26
	1800	15.51	2.57	21.83
	2000		0.67	22.50
	2200		0.55	23.05
	2400	1.69	0.48	23.53
Day 3	0200		0.29	23.82
	0400		0.29	24.11
	0600	0.87	0.29	24.40
	0800		0.20	24.60
	1000		0.20	24.79
	1200	0.59	0.20	24.99
	1400		0.15	25.14
	1600		0.15	25.29
	1800	0.45	0.15	25.44
	2000		0.12	25.55
	2200		0.12	25.67
	2400	0.36	0.12	25.79

SUMMARY

The National Weather Service has published criteria and procedures for PMS development in the United States east of the 105th meridian. A PMS can be input to a precipitation-runoff simulation program such as HEC1 to develop PMF estimates. A computer program, HMR52, has been developed to facilitate PMS development. The program contains capability to optimize storm-area size and orientation with maximization of average depth as an objective function. In many cases this capability will produce values for storm parameters that are appropriate for PMF development.

TABLE 3. HEC-1 Summary Output for Trial 1
(Runoff Summary – flow in cubic feet per second, time in hours, area in square miles).

Operation	Station	Peak Flow	Time of Peak	Average Flow for Maximum Period			Basin Area
				6-Hour	24-Hour	72-Hour	
Hydrograph at	1	29,528	48.00	28,056	20,818	11,805	51.80
Hydrograph at	4	26,798	42.00	21,758	12,922	8,339	20.30
Two Combined at	1+4	43,374	44.00	42,278	33,231	20,144	72.10
Hydrograph at	2	48,055	50.00	46,176	36,320	20,357	98.60
Hydrograph at	3	44,777	52.00	43,877	36,318	20,591	116.90
Two Combined at	2+3	90,924	52.00	88,749	72,386	40,948	215.50
Two Combined at	Inflow	127,493	50.00	124,553	103,675	61,092	287.60
Routed to	Jones	94,664	60.00	91,656	74,403	42,765	287.60

TABLE 4. Summary of PMF Calculations.

Trial	Position of Peak 6-Hr. Interval	Storm Area (sq. mi.)	Orientation (degrees)	Storm Center (x miles)	Storm Center (y miles)	Total Rainfall (inches)	Peak Inflow (cfs)	Peak Outflow (cfs)
1	7	300	285	32.2	83.8	25.50	127,500	94,650
2	10	300	285	32.2	83.8	25.50	127,800	95,300
3	10	300	285	31.0	83.6	25.44	127,650	95,250
4	10	175	290	31.0	83.6	24.86	125.200	91,650
5	10	300	296	32.7	84.0	25.41	127,200	93,900

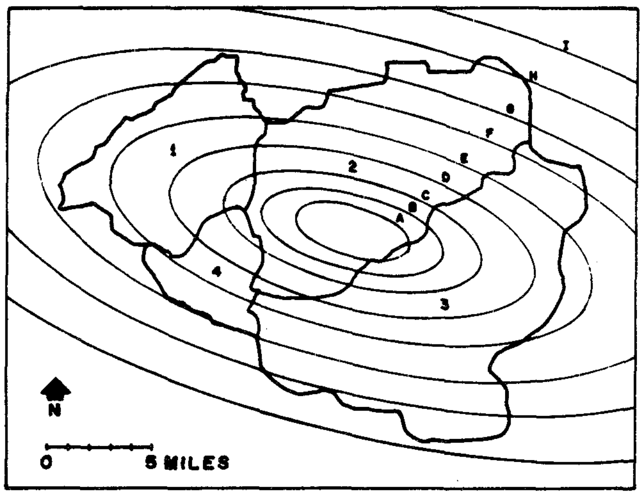

Figure 3. Storm Pattern for Trials 1 and 2.

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