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MULTIHYD

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1. INTRODUCTION

The Northeast River Forecast Center (NERFC) in Hartford, CT, routinely issues forecasts for selected points in the Buffalo Hydrologic Service Area (HSA) such as: streams in the Buffalo area; the Genesee River; and the Black River basin. Analogously, the Ohio River Forecast Center (OHRFC) in Cincinnati, OH, issues forecasts for the Allegheny River at Olean and Salamanca, NY. The stage forecasts produced by these RFCs incorporate quantitative precipitation forecasts (QPF) either from WSFO Buffalo, or from the appropriate Critical Flood Support Office (CFSO). Observed rainfall amounts and river stages (AFOS product BUFRR1BUF) are compiled by WSFO Buffalo. WSFO Buffalo is also responsible for providing forecasts and warnings for headwater basins. These headwater basins respond rapidly to heavy rains.

Events such as mesoscale convective systems, slow moving thunderstorms, and multiple thunderstorms "training" over the same area can produce floods or flash floods. Of course, the workload for the hydrometeorologist substantially increases during such events. Additionally, QPF and rainfall observing networks potentially have their greatest limitations on these occasions, due primarily to the smaller temporal and spatial scales of the events. Time available for decision making, composing statements or warnings, and disseminating the products to the user becomes very limited. It is under these circumstances that on-station hydrologic PC-based software such as MULTIHYD can facilitate HSA-RFC coordination and increase forecast lead time.

On-station, PC-based headwater forecast models are in keeping with the philosophy of NWS Modernization and Restructuring (MAR). Plans call for future integration of meteorologist and hydrologist forecast and warning functions. Future plans also call for the use of on-site hydrologic models, with the issuance of warnings and headwater statements.

PC models such as WSFO Buffalo's MULTIHYD provide a means for accomplishing these goals. This software is a time saving tool for short-fused flood events, a backup to the RFCs, and an excellent hydrometeorological training tool for the forecasting staff.

2. METHODOLOGY AND SOFTWARE STRUCTURE

2.1. Unit Hydrograph Theory and Related Matters

In order to provide the non-hydrologist some idea of what unit hydrograph (UHG) theory is and its applicability to MULTIHYD, a brief review is necessary.

As defined by Sherman (1932): "A unit hydrograph is the hydrograph of runoff (excluding groundwater runoff) on a given basin due to an excess rainfall in a specified unit of time." (Excess rainfall is the total rainfall reaching the ground minus infiltration.) Storms with similar rainfall characteristics (duration, time-intensity pattern, areal distribution, and amount of runoff) are expected to show a considerable similarity in shape of the hydrographs because the physical characteristics of the basin shape, size, slope, etc., are constant. This statement is the essence of the UHG theory. According to Bruce and Clark (1966): "There are three basic assumptions in the UHG concept, none of which are totally fulfilled in nature: a) the ordinates of a UHG are proportional to the total volume of direct runoff from rainfall of uniform intensity and of equal duration, irrespective of the amount of rain; b) the base or time duration of the hydrograph of direct runoff due to an excess rainfall for a given duration is practically constant, regardless of the volume of runoff; and c) the ratio of the volume of runoff during a particular interval of time to the total runoff is the same for all UHGs of direct runoff derived from the same basin." Linsley et al. (1975) view the unit hydrograph as a unit impulse in a linear system, and claim that the principle of superposition applies. Thus, 2 inches of runoff would produce a hydrograph with all ordinates twice as large as those of the unit hydrograph (i.e., the summation of two unit hydrographs).

Since rainfall characteristics often are not similar from one storm to another, variations in the resulting hydrographs are expected. In order to forecast most storms, UHGs derived from several rainstorms that have occurred in the basin are averaged. Over the years, the theory has been refined, and the definition of a UHG has evolved into the flood hydrograph, which is a unit volume of direct runoff in a specified unit of storm duration. In the English system of measurement, the unit volume is 1 inch. The unit of time depends on the drainage area of the basin. Typically, 12- or 24-hour UHGs are used for very large basins, while 6-, 3-, or even 1-hour UHGs for small, headwater basins. However, there is an additional requirement: the unit of time should be less than the time elapsed from the heaviest portion of rainfall to the time of crest, otherwise known as the "lag time." For the Buffalo HSA, the chosen unit of time for most of the local basins is 6 hours and the UHGs are called "6-hour unit hydrographs." Buffalo UHGs satisfy the lag time requirement, and fit well with the data collection times currently used by the NWS (i.e., rainfall and river stage data collection times coincide with 6-hourly stage forecasts). The implementation of new technologies, and the resultant increase in the spatial and temporal resolution of observations, should facilitate the utilization of 1- and 3-hour UHGs.

An example of a UHG is shown in column 2 of Table 1. This UHG has 6-hourly ordinates of 0.5, 8.6, 2.8, 1.1, 0.8, 0.6, 0.5, etc., (in thousands of cubic-feet per second, KCFS). To derive the volume of this UHG: add the ordinates together; convert the sum to CFS; and divide by four (since there are four, 6-hour periods in a day) to get the number of second-feet-days (SFD). To get the volume of runoff in inches, divide the SFD further by the product of the drainage area in square miles (135), and the conversion factor 26.9 (SFD per square mile per inch).

The sum of the ordinates of this 6-hour UHG is 16.8 KCFS or 16800 CFS or 4200 SFD. The volume of the UHG then is 4200 / (135 x 26.9) = 1.16 inches. Why is the volume larger than 1 inch? Many hydrologists increase the peaks of UHGs (which are generally derived from storms of small magnitude) by as much as 20% before using them to forecast floods of extreme magnitude. It is believed that channel velocities rise as flood magnitude increases. (If, however, the floodwaters flow out of river banks into the floodplains, the opposite situation could result.)

2.2. Program Description

MULTIHYD is a user-friendly program that utilizes readily available inputs of 6-hourly basin average rainfall, runoff index, and pre-storm stages. MULTIHYD forecasts river levels based on the input QPF. Moreover, the software has the added feature of producing contingency stage forecasts that are based on 50 to 150% (in 10% increments) of the QPF input. Thus, if the QPF forecast does not predict a flood (i.e., 100% of rainfall input), the program's output would still give an indication of the amount of rainfall that would cause flooding.

The Antecedent Precipitation Index (API) and the Unit Hydrograph Theory (Viessman et al. 1977; Bruce and Clark 1966; and Linsley et al. 1975) were the controlling principles in the development of MULTIHYD. An API program determines the amount of runoff that results from a specified amount of rainfall. Ordinates of unit hydrographs are multiplied by the runoff to produce streamflows. These basic principles were also employed by Blackburn (1981) and by Sweeney (1989). Blackburn's program uses 6-hour UHGs, and four different rainfall-runoff relations. It forecasts rainstorms that last up to 24 hours and outputs 3-hourly stage forecasts. However, it does not consider base flow recession. Sweeney's program uses 6-hour UHGs and outputs a graphical product. MULTIHYD also uses 6-hour UHGs and a consolidated rainfall-runoff relation. It does account for base flow recession, and can forecast rainstorms that last up to 60 hours. The software provides automated contingency forecasts, while the Blackburn and Sweeney programs do not.

2.3. User Input

MULTIHYD is represented by the flow diagram in Figure 1. The first five steps prompt the user to enter the following information:

1) A menu (Figure 2) prompts the user to choose a river basin. Then a message (Figure 3) instructs the user about how to enter data.

2) Input 6-hourly QPF for up to 10 periods (60 hours total).

3) Input the date in an MM-DD-HH format where: MM refers to the month of the year; DD is the day of the month; and HH is the ending time (hour) of the first rainfall entry. HH is based on a 24-hour clock and is entered as 2 digits. HH may either be LST or UTC. MM, DD and HH may be separated by hyphens, commas or any other delimiter. MM-DD-HH is used to compute the valid time for the forecast hydrograph.

4) Input the Runoff Index, RI, for the basin, before the arrival of the storm. An API computer program at WSFO Buffalo computes this value daily from BUFRR1BUF. Briefly, the WSFO Buffalo API software: retrieves the previous day's API for each HSA zone; subtracts 10-16% from these values (to account for evapotranspiration); adds the average amount of rainfall (from BUFRR1BUF) that fell over each zone; adjusts for seasonal influences; and computes the new RI and API for each zone. RI indicates the capability of the soil to produce runoff. It was set to range from 10 (for a very saturated or frozen soil) to 80 (for a very dry soil). RIs can be calculated by the use of many different methods, resulting in different values for similar conditions. To utilize RIs from other sources (e.g., different RFCs), a method of conversion must be derived.

5) Input the pre-storm stage (feet above river gage datum). At WSFO Buffalo, this information is available from BUFRR1BUF.

2.4. Stage Computations

After the user inputs are entered, the program follows the steps depicted in Figure 1, and outputs the forecast (Table 2). In order to describe the computational aspects of MULTIHYD, let us assume a 24-hour storm with the following 6-hourly basin average rainfall amount (inches) to have occurred over the drainage basin of the Cazenovia Creek, above Ebenezer, NY: 0.88; 1.33; 0.28; and 0.20. For RI and pre-storm stage, 43.4 and 3.5 feet were used, respectively. The first rainfall input (0.88) was for the 6-hour period ending at 3 AM, May 30 (05-30-03). Forecast stages based on 100% of rainfall input are computed as follows:

1) The pre-storm stage (3.5 feet) is converted into flow (KCFS) by the use of the rating table, Table 3. (Linear interpolation is used to derive values other

than those in the table). The base flow 6 hours after the storm began is computed by the equation:

$$Q = Q_0 K^t$$

where t = 6 hours; Q_0 = Initial flow (KCFS); and K = Recession constant. Two values of K (one for high flows and another for low flows) are available. MULTIHYD selects the appropriate K value.

To derive the base flow for the next 6 hours, the Q from the previous 6 hours is set as Q_0, and the equation is solved again for Q. The equation is applied repeatedly to derive other future values of Q. This process is known as base flow recession. Receded base flows for this example are shown in column 6 of Table 1.

2) Runoffs for each of the four periods are derived and used as follows:

   a) RI (43.4) and rainfall for the first 6 hours (0.88) are entered in a rainfall-runoff relation (Table 4) to derive the runoff for the first period (0.131). (Linear interpolations between four values in the table are used to derive the runoff). Ordinates of the unit hydrograph for the first period (UH1, Table 1, column 2) are multiplied by the runoff and the result is given in column 7.

   b) RI (43.4) and the sum of the rainfall for the first and second period (2.21) are entered in Table 4 to compute the corresponding runoff (0.690). From this, the runoff from the first period is subtracted. The difference (0.599) represents the runoff for the second period. Ordinates of UH2 (column 3 of Table 1) are multiplied by the runoff for the 2nd period, and the result is shown in column 8.

   c) RI (43.4) and the sum of the rainfall for the 1st, 2nd and 3rd periods (2.49) are input to Table 4, resulting in a runoff of 0.834. The runoff from the previous periods (0.690) is then subtracted. The difference (0.144) is the runoff for the 3rd period. Ordinates of UH3 (column 4, Table 1) are multiplied by the 3rd period runoff, and the result is displayed in column 9.

   d) The 4th period runoff (0.106) is calculated using the RI and the QPF for the first four periods. Ordinates of UH4 (column 5 of Table 1) are multiplied by the 4th period runoff with the result shown in column 10.

   e) For the time intervals indicated in column 1 of Table 1, the base flow (column 6), and the ordinates of the hydrograph for the 1st through the 4th periods (columns 7-10) are added together. The sum is the forecast flow for that position (column 11).

   f) The forecast flows (KCFS) in column 11 are converted into stages (column 12) by the use of the stage-discharge relation, or rating table for Ebenezer (Table 3).

MULTIHYD derives other percentages (50, 60, 70, 80, 90, 110, 120, 130, 140 and 150) of the input QPF and computes forecast stages. Table 2 shows forecast stages corresponding to these QPF contingency forecasts.

The rainfall-runoff relation can handle up to 20 inches of rainfall. The useful range of the rating tables, however, may be exceeded at this rainfall level. To ensure that the program will operate only within proper ranges, the total QPF should not be higher than 12 inches.

MULTIHYD accepts RI values from 0 to 79.9. If a RI lower than 7.0 is entered, which would be the case if an RI from the OHRFC is used, the program multiplies the input by a conversion factor of 12.7 to make the rainfall-runoff relation applicable.

The program was designed to accept ranges of pre-storm stages that are lower than flood stages. This precludes the use of MULTIHYD when a stream is already at or above flood stage. (To use MULTI-

HYD for this situation, base stage and RI before the arrival of the storm and rainfall since the storm began should be used). Input stages that are lower than the range will default to the lowest value of base stage in the rating table. In the Buffalo HSA, the basins are small (with a few exceptions) that 3 or more days after a rainstorm, the runoff have sufficiently drained and stages are low again. In such cases, the default may be invoked by simply hitting the ENTER key.

3. DISCUSSION

Forecasting a river by using the MULTIHYD output (Table 2) can be done by visually matching or comparing actual stage readings (during the streamrise) with the forecast stages. The column that shows similar trends to the actual readings would then be chosen. A better method, but not yet available, might be a plot of observed stage readings on a graphical representation of MULTIHYD output. A smooth curve to connect the plotted points could be drawn, and the forecast hydrograph that most closely resembles the rate of rise would be selected.

Actual rainfall may be used to locate the correct forecast column in Table 2 under the following conditions:

1) When the observed rainfall is the same or nearly the same as the QPF input. In this case, the column to pick is the one under the 100% level.

2) When the observed rainfall is a percentage of the input QPF. For example, the actual rainfall for one period is 120% of the QPF input. For this to qualify as column locator, actual rainfall for other periods should also be 120% of the input.

Sometimes, the rainfall forecast is accurate in a 6-hour period, but displaced in time. This makes column selection by the use of actual rainfall difficult. In such cases, MULTIHYD could be rerun with observed rainfall data as input, and the 100% level used. Also, there may be times when observed rainfall is not available. In these instances, observed stages rather than observed rainfall is the preferred column selector.

If the rainfall input does not forecast a flood at the 100% level, the output could estimate the amount of rainfall needed to cause a flood (e.g., 150% of the QPF is sufficiently high to initiate flooding). For our example, Ebenezer is forecast to crest at 9.0 ft or 1.0 ft below flood stage. Table 2 indicates that 120% of the rainfall input, or a total of 3.2 inches would cause Cazenovia Creek to reach the 10-foot flood stage selected.

MULTIHYD is an example of local PC-based hydrometeorological forecast model. No doubt, additional software, designed to run on-station, will continue to be developed for the current forecast environment, and eventually for use in the AWIPS era.

4. ACKNOWLEDGMENTS

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Time (hrs)	UH1	UH2	UH3	UH4	Base (KCFS)	Runoff x UHG 1st	2nd	3rd	4th	Sum (KCFS)	FCST Ht(ft)
0	0	0	0	0	0.60	0	0	0	0	0.60	3.5
6	.5	0	0	0	0.59	.07	0	0	0	0.66	3.6
12	8.6	.5	0	0	0.57	1.13	.28	0	0	1.98	5.3
18	2.8	8.6	.5	0	0.56	.37	4.81	0.07	0	5.88	9.0
24	1.1	2.8	8.6	.5	0.54	.14	1.56	1.25	0.05	3.54	7.0
30	0.8	1.1	2.8	8.6	0.53	.10	0.61	0.40	0.91	2.57	6.1
36	0.6	0.8	1.1	2.8	0.52	.08	0.45	0.16	0.30	1.50	4.8
42	0.5	0.6	0.8	1.1	0.51	.07	0.34	0.11	0.12	1.14	4.3
48	0.3	0.5	0.6	0.8	0.49	.04	0.28	0.09	0.09	0.98	4.1
54	0.3	0.3	0.5	0.6	0.48	.04	0.17	0.07	0.06	0.83	3.9
60	0.2	0.3	0.3	0.5	0.47	.03	0.17	0.04	0.05	0.76	3.8
66	0.2	0.2	0.3	0.3	0.46	.03	0.11	0.04	0.03	0.67	3.6
72	0.2	0.2	0.2	0.3	0.45	.03	0.11	0.03	0.03	0.65	3.6
78	0.2	0.2	0.2	0.2	0.44	.03	0.11	0.03	0.02	0.63	3.5
84	0.1	0.2	0.2	0.2	0.43	.01	0.11	0.03	0.02	0.60	3.5
90	0.1	0.1	0.2	0.2	0.42	.01	0.06	0.03	0.02	0.54	3.4
96	0.1	0.1	0.1	0.2	0.41	.01	0.06	0.01	0.02	0.51	3.4
102	0.1	0.1	0.1	0.1	0.40	.01	0.06	0.01	0.01	0.49	3.3
108	0.1	0.1	0.1	0.1	0.39	.01	0.06	0.01	0.01	0.48	3.3
114	0.0	0.1	0.1	0.1	0.38	.00	0.06	0.01	0.01	0.46	3.3

Legend:
- Col. 1 = Hours after the storm began.
- Col. 2 = 6-hr UHG for the 1st period of storm, UH1.
- Col. 3 = 6-hr UHG for the 2nd period of storm, UH2.
- Col. 4 = 6-hr UHG for the 3rd period of storm, UH3.
- Col. 5 = 6-hr UHG for the 4th period of storm, UH4.
- Col. 6 = Base flows.
- Col. 7 = Runoff of 1st period (.131) times UH1 (col. 2).
- Col. 8 = Runoff of 2nd period (.559) times UH2 (col. 3).
- Col. 9 = Runoff of 3rd period (.144) times UH3 (col. 4).
- Col.10 = Runoff of 4th period (.106) times UH4 (col. 5).
- Col.11 = col.6 + col.7 + col.8 + col.9 + col.10 = forecast flows (KCFS).
- Col.12 = Forecast stages in feet above gage datum, derived by entering values of column 11 in a rating table.

Table 1. Example of the computations involved in forecasting for the Cazenovia Creek at Ebenezer, NY, by using: 100% of the 6-hourly rainfall amounts of 0.88, 1.33, 0.28, and 0.20; base stage of 3.5 feet; and RI = 43.4.

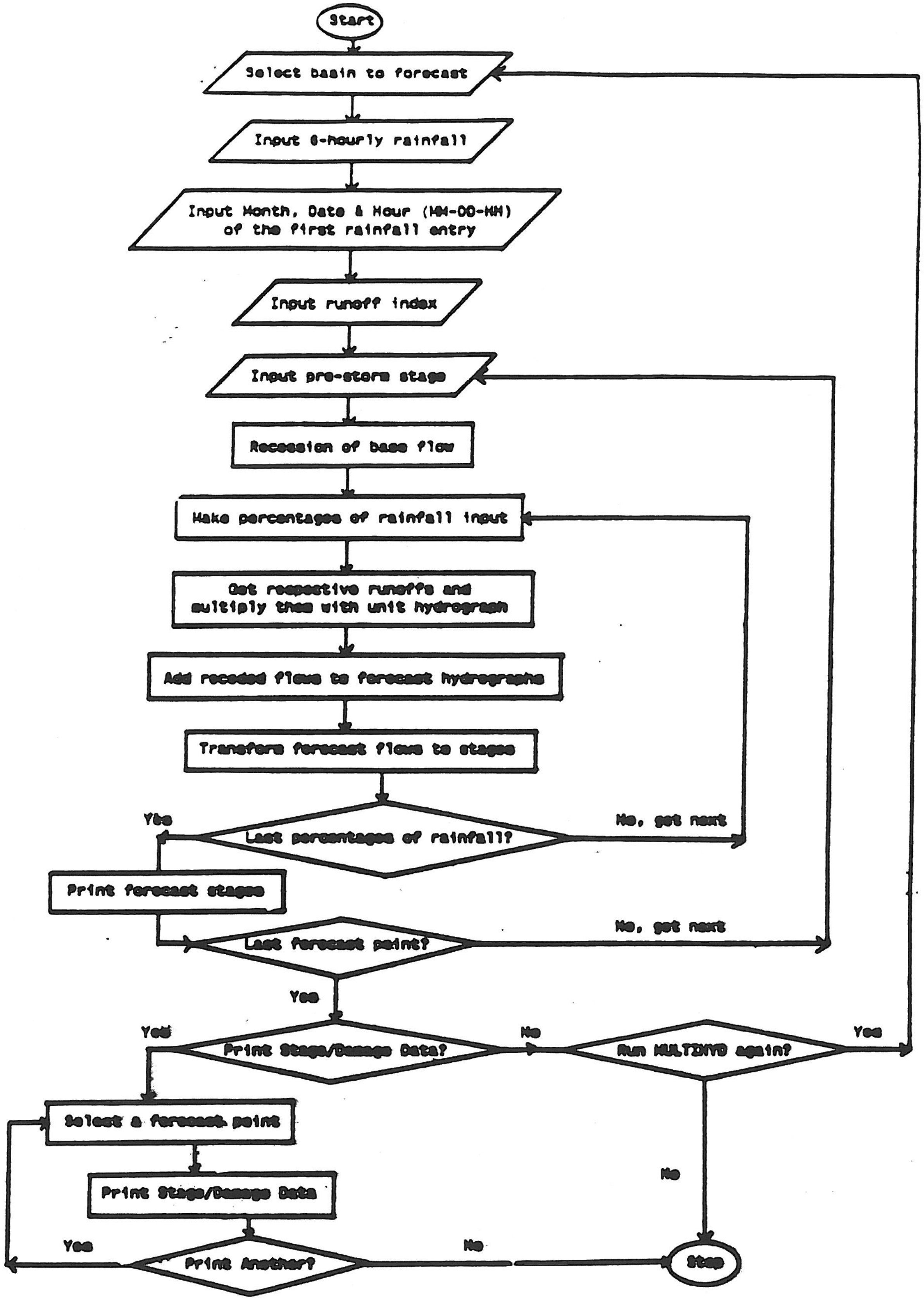

Figure 1. MULTIHYD flow diagram.

Which basin do you want to forecast?

1 - Allegheny River Basin Forecast Points

2 - Black River Basin Forecast Points

3 - Upper Genesee River Forecast Points

4 - Lower Genesee River and Tributaries

5 - Buffalo Area Creeks

(Please select a number. Hit ENTER. Thank you)

Figure 2. MULTIHYD basin selector menu.

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This is a computer program in FORTRAN. For inputs, please use real numbers (with decimals). Before entering data, please check that "CAPS LOCK" light on keyboard is on and printer is ready and "ON LINE". Enter rainfall data separated by commas. If you have questions, please see A. F. Lazo.

Thank you.

Figure 3. MULTIHYD on-line data entry instructions.

Forecast for Ebenezer in the BUFFALO Basin

Col. 1	2	3	4	5	6	7	8	9	10	11	12	13
**************Forecast Stages in feet above Gage Zero************												
Percent of RR->		50	60	70	80	90	100	110	120	130	140	150
************at indicated percentages of rainfall input***********												
MM-DD-HH	RR	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
05-30-03	.88	3.5	3.5	3.5	3.5	3.6	3.6	3.6	3.6	3.7	3.7	3.7
-09	1.33	3.9	4.1	4.4	4.7	5.0	5.3	5.7	6.0	6.4	6.7	7.0
-15	.28	5.7	6.4	7.0	7.7	8.3	9.0	9.6	10.3	10.9	11.4	12.0
-21	.20	4.8	5.2	5.8	6.2	6.6	7.0	7.4	7.8	8.2	8.6	9.2
05-31-03	.00	4.4	4.7	5.0	5.4	5.7	6.1	6.3	6.6	6.9	7.5	7.9
-09	.00	3.9	4.1	4.2	4.4	4.6	4.8	4.9	5.1	5.3	5.6	5.9
-15	.00	3.7	3.8	3.9	4.1	4.2	4.3	4.4	4.5	4.7	4.8	5.0
-21	.00	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6
06-01-03	.00	3.5	3.6	3.6	3.7	3.8	3.9	4.0	4.0	4.1	4.2	4.3
-09	.00	3.4	3.5	3.6	3.6	3.7	3.8	3.8	3.9	4.0	4.1	4.1
-15	.00	3.4	3.4	3.5	3.5	3.6	3.6	3.7	3.7	3.8	3.9	3.9
-21	.00	3.4	3.4	3.4	3.5	3.5	3.6	3.6	3.7	3.7	3.8	3.9
06-02-03	.00	3.3	3.4	3.4	3.5	3.5	3.5	3.6	3.6	3.7	3.8	3.8
-09	.00	3.3	3.3	3.4	3.4	3.5	3.5	3.5	3.6	3.6	3.7	3.8
-15	.00	3.3	3.3	3.3	3.3	3.4	3.4	3.4	3.5	3.5	3.5	3.6
-21	.00	3.2	3.3	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.5	3.5
06-03-03	.00	3.2	3.2	3.3	3.3	3.3	3.3	3.3	3.4	3.4	3.4	3.5
-09	.00	3.2	3.2	3.2	3.3	3.3	3.3	3.3	3.4	3.4	3.4	3.4
-15	.00	3.2	3.2	3.2	3.2	3.2	3.3	3.3	3.3	3.3	3.4	3.4
-21	.00	3.1	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.2	3.2	3.2
**												
Tot. RR		1.4	1.6	1.9	2.2	2.4	2.7	3.0	3.2	3.5	3.8	4.0
**												

R Index = 43.40

Legend:
- Col. 1 = Month, Date & Hour (MM-DD-HH)
- Col. 2 = Rainfall input.
- Cols. 3 - 13 = Forecast stages using 50, 60, 70, 80, 90, 100, 110, 120, 130, 140 & 150 % of rainfall input, respectively.
- Tot. RR = Sum of the rainfall amount used to forecast the corresponding column.

Table 2. MULTIHYD output depicting the forecast stages by using indicated percentages of rainfall input.

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Stage - Discharge Rating Table for Cazenovia Creek at Ebenezer
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Stage (ft)	Discharge (KCFS)	Stage (ft)	Discharge (KCFS)
2.0	0.016	10.0	7.100
3.0	0.300	11.0	8.490
4.0	0.910	12.0	10.000
5.0	1.670	13.0	11.500
6.0	2.540	14.0	13.100
7.0	3.530	15.0	14.700
8.0	4.580	16.0	16.300
9.0	5.760	17.0	18.000

****

Table 3. Rating Table for Cazenovia Creek at Ebenezer.

	TOTAL RAINFALL, INCHES								
	.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5
RI	(Runoff in Inches)								
0	.35	1.15	2.10	3.00	3.97	5.03	6.00	7.00	8.00
10	.23	0.95	1.78	2.63	3.55	4.55	5.50	6.50	7.50
20	.15	0.75	1.48	2.25	3.10	4.08	5.00	6.00	7.00
30	.05	0.57	1.18	1.87	2.68	3.58	4.50	5.50	6.50
40	.03	0.40	0.92	1.50	2.25	3.10	4.00	5.00	6.00
50	.00	0.27	0.68	1.15	1.80	2.60	3.50	4.50	5.50
60	.00	0.15	0.45	0.83	1.37	2.13	3.00	4.00	5.00
70	.00	0.05	0.28	0.56	0.98	1.68	2.50	3.50	4.50
80	.00	0.00	0.13	0.35	0.67	1.30	1.98	3.00	4.00

Table 4. A simplified rainfall-runoff relation.