Nationwide Estimation of Extreme Floods for Bridge-Scour Analysis

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Procedures are described for estimating flood-peak discharges and flood hydrographs for extreme floods, such as the 500-year flood, to evaluate scour at bridges. These procedures are being incorporated (June 1990) in a microcomputer program called "National Flood Frequency" developed by the U.S. Geological Survey in cooperation with the Federal Highway Administration and the Federal Emergency Management Agency. U.S. Geological Survey flood reports typically describe procedures for estimating flood-peak discharges for return periods of 2 to 100 years for rural and urban ungaged watersheds. This paper describes procedures in the National Flood Frequency program for extrapolating design floods with return periods of 2 to 100 years to the 500-year flood.

INTRODUCTION

The planning and design of bridges requires the estimation of extreme flood discharges to facilitate an adequate and safe design. Recent bridge failures, resulting from excessive scour, have prompted the Federal Highway Administration (FHWA) to develop procedures for evaluating scour at bridges. As part of this program, the FHWA advised the State Departments of Transportation (DOT's) nationwide to evaluate the risk of their bridges being subjected to scour damage during floods on the order of a 100- to 500-year or greater average return period. In response, State DOT's are developing and implementing improved procedures for evaluating the magnitude of scour during extreme floods and for designing bridges to minimize scour damage. Essential to these improved procedures is a consistent, unbiased, and easy to apply technique for estimating discharges of floods having return periods on the order of 100 to 500 years.

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The purpose of this paper is to describe a procedure, applicable nationwide, for estimating extreme floods that will meet the design needs of FHWA and State DOT's. The U.S. Geological Survey (USGS), in cooperation with FHWA and the Federal Emergency Management Agency (FEMA), is developing (June 1990) a National Flood Frequency (NFF) microcomputer program for estimating floodpeak magnitudes of T-year events (2 to 500 years) and for estimating a typical hydrograph associated with such events for ungaged rural and urban sites in most areas of the United States. Jennings and Cookmeyer *(1)* provide an overview of the plans for NFF. The flood-peak estimation techniques are a compilation of regional regression equations developed by USGS (primarily in cooperation with State DOT's)) over the last 15 years or so. The flood hydrograph estimation technique is based on unit-hydrograph theory and utilizes a dimensionless hydrograph that is defined by the flood-peak discharge and the watershed lagtime. This paper primarily is concerned with describing an extrapolation procedure for estimating the 500-year flood for bridge-scour evaluation.

ESTIMATING FLOOD DISCHARGES

The USGS has developed regional regression equations for estimating floods with selected recurrence intervals for rural watersheds for every State and Puerto Rico. In some areas of the Nation, however, data are inadequate to define flood-frequency characteristics. Jennings and Cookmeyer *(1)* report that the NFF microcomputer program will include about 1500 equations for 214 flood regions in the United States. USGS reports typically give regression equations for estimating the 2-, 5-, 10-, 25-, 50- and 100-year flood-peak discharges for an average of about four flood regions in each State. Only in a few States has USGS published regression equations for the 500-year flood; hence the need for an extrapolation procedure. The regional regression equations are developed by relating the T-year flood-peak discharges at gaging stations to watershed and climatic characteristics by means of multiple regression equations. (The T-year discharges at gaging stations are determined by following guidelines adopted by the Interagency Advisory Committee on Water Data, *(2)*). Estimates at ungaged sites then can be computed by using the appropriate watershed and climatic characteristics which usually are available from topographic maps and climatic reports.

Regression equations for estimating flood-frequency characteristics for urban watersheds have been published in 18 States. In some instances, these equations are applicable statewide, in other instances, the equations are applicable only for one metropolitan area. These equations are based on watershed and climatic characteristics as well as on urban characteristics, such as the percentage of the watershed that is impervious, or a measure of the state of development of the drainage system, such as the basin development factor described by Sauer and others *(3)*. For those States without urban regression equations, a nationwide technique, developed by Sauer and others *(3)*, is used to adjust the rural frequency curve to urban conditions. Thomas *(4)* provides a listing by State of all USGS published reports (as of December 1986) for estimating rural and urban flood-frequency characteristics.

EXTRAPOLATION FOR EXTREME FLOODS

To date, the USGS has published regression equations for estimating the 500-year flood in only seven States. A procedure will be given in the NFF program for extrapolating the regional regression equations in any State to the 500-year flood. Basically, the extrapolation procedure consists of fitting a log-Pearson Type III curve to the 2- to 100-year flood discharges given by NFF and extrapolating this curve to the 500-year flood discharge. The procedure consists of the following steps for a given watershed:

1. Determine the flood-peak discharges for selected return periods from the appropriate regional regression equations given in NFF. At least three points are needed to define the skew coefficient required in a subsequent step. Use of additional points improves the definition of the frequency curve that is defined by the regional equations and helps to average out any minor irregularities that may exist in the relations among the regional equations. The NFF program will use all available regional equations to define the frequency curve.

2. Fit a quadratic curve to the selected points on log-probability paper using multiple regression analysis. The variables used in the regression analysis are the logarithms of the selected discharges and the standard normal deviates associated with the corresponding probabilities. The purpose of this quadratic curve is to obtain a smooth curve through the selected flood-peak discharges from step 1 above. The quadratic curve is an approximation of the log-Pearson Type III curve that will be computed.

3. Determine the skew coefficient of the log-Pearson Type III frequency curve that passes through the 2-, 10-, and 100-year floods defined by the quadratic curve. The skew coefficient is defined approximately by the formula (IACWD, *2*)

$$G = -2.50 + 3.12 \log (Q_{100}/Q_{10}) / \log (Q_{10}/Q_2).$$

4. Replot (conceptually) the selected discharges and return periods using a Pearson Type III probability scale defined such that a frequency curve with the computed skew plots as a straight line. This scale is defined by plotting probability values p at positions x on the probability axis, where x is defined by the standardized Pearson Type III deviate (K values) for the given skew and probability. A Wilson-Hilferty approximation (Kirby, *5*) is used to compute the K value.

5. Fit a straight line by least squares regression to the points plotted in step 4 and extrapolate this line to the 500-year flood-peak discharge. The variables used in the regression analysis are the logarithms of the selected discharges and the Pearson Type III K values associated with the corresponding probabilities.

Figure 1 is an example of a flood-frequency curve provided by this procedure for the Fenholloway River near Foley, Florida. The solid triangles shown in figure 1 are the regional flood-frequency values as estimated by the equations given in Bridges *(6)*, which will be incorporated in the NFF program. The 500-year value shown as a solid circle in figure 1 (12,800 ft^3/s) is estimated using the extrapolation procedure described above. Note that the extrapolated 500-year value is a reasonable extension (see dotted line) of the regional frequency curve.

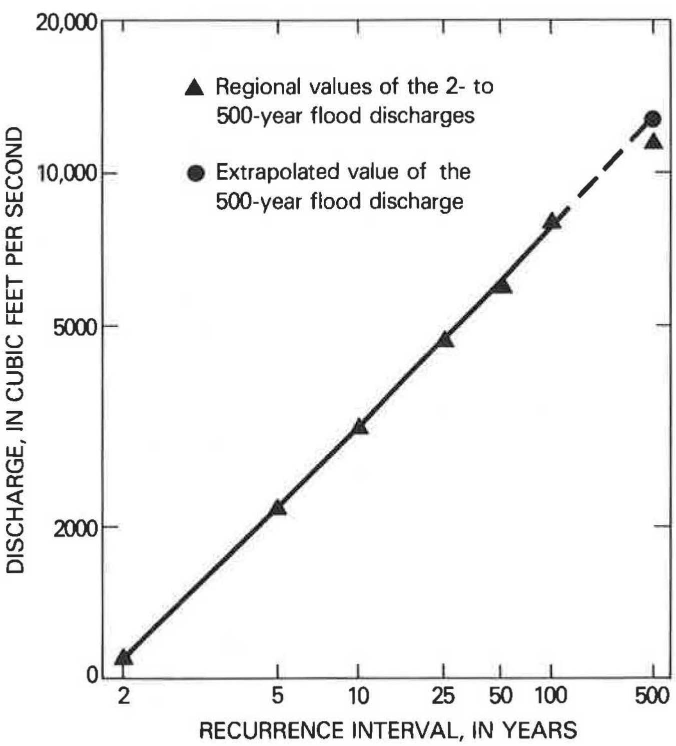

Figure 1. Regional flood-frequency curve for the Fenholloway River near Foley, Florida

The solid triangle shown in figure 1 (11,500 ft^3/s) for the 500-year value is the regional value as obtained directly from the 500-year equation given in Bridges *(6)*. The 500-year flood for the Fenholloway River can be estimated without extrapolation since Florida is one of the seven States for which 500-year regression equations have been published. The difference between the two 500-year values is 11.3 percent. This is typical of several comparisons of extrapolated 500-year floods to published regional equations that have indicated most results agree within plus or minus 15 percent.

Figure 2 is a summary of the input data, questions, and responses that created the frequency curve in figure 1. The information required to compute the regional flood-frequency curve in figure 1 is that the watershed is in Region B with a drainage area of 120 square miles and that 0.37 percent of the watershed area is covered by lakes. Figure 2 shows the regional flood frequency values and their associated standard errors.

For comparison and evaluation, the NFF program will compare each extrapolated 500-year flood-peak discharge with the maximum flood-envelope curves given by Crippen *(7)*. These flood-envelope curves were developed by plotting maximum known flood discharges against drainage areas for 17 flood regions of the United States. Therefore, these flood-envelope curves approximate the maximum flood-peak discharge that has been regionally experienced for a given size watershed. Since there is no frequency of occurrence associated with the envelope-curve estimates, the comparison of these values to the extrapolated 500-year flood is merely a qualitative evaluation. In general, one would expect the extrapolated 500-year flood-peak discharge to be less than the envelope-curve values, assuming that several watersheds in a given region have experienced at least one flood exceeding the 500-year value during the period of data collection. For the Fenholloway River near Foley, Florida, the 500-year flood estimates range from 11,500 to 12,800 ft^3/s. The envelope-curve value from Crippen *(7)* is 101,000 ft^3/s given that the watershed is in region 3 (this information must be provided by the analyst) as defined by Crippen *(7)*.

National Flood Frequency Log Session

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NFF Log session started 07/03/1990 09:04
Enter state id code : FL
Enter name of basin under study: FENHOLLOWAY RIVER NEAR FOLEY, FL.
List of Hydrologic Regions
in Florida
Region
Number Region Name
==============================
   1   Region A
   2   Region B
   3   Region C
Is basin contained in more than one
hydrologic region? (Y/N) N
Hydrologic region? (1-3) : 2
Region B parameters:
Drainage Area (sq mi), DA (13.90-9640.0) : 120.0
Lake Area (%), LK (0.00-13.3) : 0.37
Enter maximum flood region within which the basin is contained (See Report).
Enter 0 if not applicable (e.g. outside of conterminous United States) : 3
Table of rural flood event values
FENHOLLOWAY RIVER NEAR FOLEY, FL.
  Recurrence  Peak,                Eq. Yrs.
| Inter.,yrs   cfs    % Std. Err.  Record
|============================================
| RQ2         1050       60.9         2
| RQ5         2170       59.7         3
| RQ10        3150       59.9         3
| RQ25        4650       60.9         5
| RQ50        5980       61.9         5
| RQ100       8000       63.1         6
| RQ500      12800
============================================
      MAXIMUM FLOOD ENVELOPE = 101000 cfs
  List of Entered Parameters
      Name        Value
==============================
             DA : 120.000
             LK : 0.370
Do you want to calculate a weighted average of observed and regression
estimates? (Y/N) N
Do you want to perform urban calculations? (Y/N) N
Do you want to write a flood frequency plot input file for TELAGRAF? (Y/N) N
Do you want to compute a hydrograph for the rural peak calculated? (Y/N) N
Do you want to do more flood frequency calculations in Florida? (Y/N) N
Do you want to do flood frequency calculations in another state? (Y/N) N
Program terminated.
NFF Log session ended 07/03/1990 09:05
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Figure 2.-- Summary of input data, questions and responses during an interactive session with the National Flood Frequency Program

FLOOD-HYDROGRAPH ESTIMATION

Procedures also will be provided in NFF for computing a flood hydrograph associated with the 500-year flood-peak discharge and floods of other return periods. The flood hydrographs produced by these procedures may be applicable only in certain parts of the country. These computations are based on procedures described by Inman *(8)* and are only briefly summarized here. Using these procedures, a dimensionless hydrograph can be converted to a typical T-year hydrograph by estimating the T-year flood-peak discharge and watershed lagtime (time from centroid of rainfall excess to centroid of runoff). The flood hydrograph that results from this procedure is an average or typical hydrograph that corresponds to a given T-year flood-peak discharge. The volume under the hydrograph may, or may not, have the same recurrence interval as the peak discharge.

Briefly, the procedures for estimating flood hydrographs, as described by Inman *(8)*, involves the following steps. Rainfall-runoff data are used to determine unit hydrographs and watershed lagtimes for selected watersheds in a region. These unit hydrographs are averaged to obtain an average unit hydrograph for the region or State. This average unit hydrograph is converted to an average dimensionless hydrograph by dividing the ordinates by the flood-peak discharge and the abscissa by the watershed lagtime. A typical T-year hydrograph is then obtained by multiplying the ordinates of the dimensionless hydrograph by the T-year peak discharge and multiplying the abscissa by the watershed lagtime. The flood-peak discharge will be estimated by regression equations in the NFF program. The watershed lagtime for urban watersheds will be estimated by regression equations in the NFF program (Sauer and others *(3)*). For rural watersheds, the values for watershed lagtime will be input by the user. The computed T-year flood hydrograph can be used along with the peak discharge to determine bridge scour, flood-hazard risk, and other environmental impacts.

Figure 3 is an example of a typical flood hydrograph for a 500-year peak discharge of 12,800 ft^3/s for the Fenholloway River near Foley, Florida. Flood hydrographs, such as the one shown in figure 3, can be used to determine the duration that flow is above a given discharge. This information should be useful in evaluating scour at bridges.

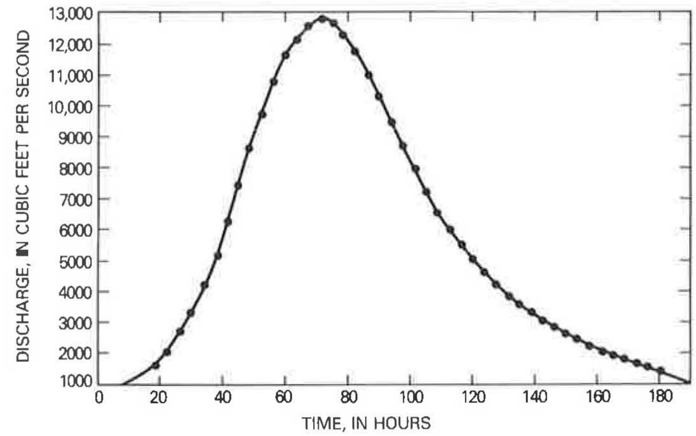

Figure 3. Typical flood hydrograph associated with a 500-year flood-peak discharge for the Fenholloway River near Foley, Florida.

SUMMARY

The procedures to be provided in the NFF microcomputer program give the highway engineer relatively easy and straightforward methods of estimating the flood-peak discharge and flood hydrograph of extreme floods, such as the 500-year flood. The rural flood discharge estimates are based on regression equations that have been developed by the USGS over the last 15 years or so. The equations to be given in the NFF program will be updated periodically as new equations are developed. Procedures will also be available for estimating flood-peak discharges for urban watersheds. If Statewide urban flood-frequency procedures are not available, then nationwide techniques, described by Sauer and others *(3)*, can be used. Finally, a flood hydrograph, associated with the T-year rural or urban flood discharge, can also be computed to aid in the determination of scour during extreme floods.

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