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EXTENSION OF RATING CURVES BY FIELD SURVEYS

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SYNOPSIS

Certain aspects of modern river forecasting are described. These demonstrate the need for station rating curves that extend above the previous maximum flood. The relationship among stage, discharge, and channel dimensions is examined.

Two methods of extending ratings are presented and compared. These are the "Stevens Method" and the direct application of the Manning formula, sometimes referred to as the "Slope-Conveyance Method."

Emphasis is given to the basic differences between the extension of existing ratings and the development of entirely synthetic ratings or the solution of slope-area measurements. These differences justify, in part, the conclusion that the simpler Stevens method is as adequate for this work as the more complex slope-conveyance method.

The Stevens method was intended by its originator to be applicable only in approximately trapezoidal flood plains. The "Offset Technique," developed by the writer, is presented. It permits use of the Stevens method in extending a rating curve over a previously un-wetted flood plain and greatly increases the usefulness of the method.

The mechanics of the field survey are described herein. Criteria are given for the selection of the cross section, and recommendations are made regarding the instrumentation and survey procedure. The possibility of basing the computations on aerial photographs rather than on actual field surveys is considered and discouraged.

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An example of a rating extension is given. The situation existing on the Naugatuck River at Beacon Falls, Conn., during the record breaking flood of August, 1955, is described. It is shown that a Stevens extension made before the event would have reduced the forecast error to approximately one sixth of that resulting from a logarithmic extension.

The point is made that a program of rating extensions based on field surveys is a vital and necessary part of any modern river and flood forecasting program.

INTRODUCTION

Modern methods of river forecasting produce an estimate of the discharge that will occur at a particular point and time. In the case of flood forecasting, the recipient is usually interested in maximum stage rather than maximum discharge, and the forecaster must therefore convert the discharge to stage before issuing his forecast. Usually, this is a simple matter and involves the use of a station rating curve that has been previously defined for the purpose of producing streamflow records. Such ratings, of course, extend no higher than the maximum flood of record. A serious problem occurs when a major storm yields a discharge forecast that greatly exceeds the previous maximum. Under these conditions, the forecaster must extend the rating. Working under severe time limitations, and without data on the physical shape of the channel, this is a difficult procedure, and can lead to gross error in the stage forecast.

The forecaster would be in a much more firm position if an extension had been made before the occurrence of the record-breaking flood. Most ratings in use by Weather Bureau river forecasters are furnished by the United States Geological Survey (USGS), but since extensions of this type are not necessary for the production of discharge records, the USGS has not done much in this field for its own needs. The United States Weather Bureau (USWB) has, using its own personnel, conducted a small amount of this work, and will probably continue to do so as time and funds permit.

RELATION BETWEEN DISCHARGE AND CHANNEL DIMENSIONS

Although at low stages the ratings at most gaging stations exhibit the general form of a weir formula and result from a weir-type control in the channel, this control usually becomes submerged at high stages and the hydraulic characteristics of an open channel are present. If follows that if certain coefficients for the channel in question can be obtained from the upper limb of the existing rating, the rating can be extended on the basis of channel dimensions.

The factors usually involved in open channel work are as follows:

1. Discharge;

2. velocity;
3. cross-sectional area;
4. slope of water surface;
5. hydraulic radius; and
6. roughness.

The area and hydraulic radius may be determined for all stages by survey. The slope of the water surface changes with stage, but tends to become constant and to approach the bed slope at high stages. Thus, if the existing rating goes to a reasonably high stage, no serious error will result from the assumption that no further change in slope will occur, through the range of the extension.

Roughness is one of the most elusive quantities in any problem of this type. In a slope-area determination, or in the construction of an entirely synthetic rating, the selection of a proper roughness coefficient is extremely critical. In this problem, however, it is still important, but its selection is easier. The roughness of the channel to the previous maximum stage is already indicated by the existing rating. Although the extension may well involve a discharge several times greater than that previously experienced, only a small percentage of this will pass over previously un-wetted ground. Thus, a large error in roughness coefficient for the new flood plain will not produce a significant error in total discharge. Unless the extension involves a wide flood plain with roughness greatly different from that of the main channel, the assumption of constant roughness through the extension will produce a rating that will be satisfactory for forecasting work. It is interesting to note, at this point, that one of the conditions mentioned previously that may produce a significant error in the computed discharge also tends to mitigate the effect of this error. Where a wide flood plain does exist, the upper limb of the rating will be flat, and show a large increase in discharge for a small increment of stage. From the standpoint of the streamgager, such a rating is "insensitive," and makes the production of accurate streamflow records difficult. To the flood forecaster, however, such conditions permit a rather large error in the discharge forecast with only a small error in the stage forecast. By the same token, the definition of such a rating may have a large error, discharge-wise, and still yield an accurate stage forecast.

One of the types of computation to be described makes no provision for variation of the roughness coefficient. If it is desired to use this method, and if a part of the cross section exhibits vastly different roughness characteristics than does the main channel, the effect may be accounted for by an adjustment to the cross-sectional area. In a wooded section, for instance, a percentage of the area, based on estimate, may be deducted from the cross section. A field, covered with tall vegetation, may be assumed to have an effective ground elevation a fixed distance above the actual elevation. Although such adjustments require a good deal of judgment, the writer believes that the results should compare favorably with those obtained by estimating roughness coefficients.

METHODS OF COMPUTATION

Stevens Method.—This procedure was suggested by J. C. Stevens[2] over 50 yr ago. The intent was to develop and extend a rating curve through the range of actually experienced stages for the purpose of producing streamflow records. It was never widely used because other methods, such as the "Slope-Area" method, which are generally considered to be superior, were developed subsequently. These methods, however, cannot be used to determine the discharge at a stage that has never been reached, and it therefore appears that the Stevens method may be applicable as a tool for the forecaster.

The method is based on the Chezy formula,

$$Q = A\,V = A\,C\,\sqrt{R\,S} \qquad (1)$$

in which Q represents the discharge, A is the cross-sectional area, V represents the mean velocity in the cross-section, R is the hydraulic radius, S denotes slope of the water surface, and C describes the Chezy coefficient, which Kutter defined as follows:

$$C = \frac{\left(41.6 + \frac{0.0028}{S}\right) + \frac{1.81}{n}}{1 + \left(41.6 + \frac{0.0028}{S}\right)\frac{n}{R^{1/2}}} \qquad (2)$$

in which n represents a roughness coefficient. By this definition, C is not a constant, but in the Chezy formula, and in the Stevens application, its variation is neglected. Stevens assumed that $C\sqrt{S}$ is constant throughout the range of stage under consideration. The validity of this assumption has been examined. Stevens also assumed that the mean depth of the cross section, D_m, was a suitable substitute for the hydraulic radius, R. In a river channel, where the ratio of horizontal distances to vertical distances is great, this substitution is obviously satisfactory. Modifying the Chezy formula on the basis of these assumptions results in the working formula for the Stevens method, in which

$$Q = C_1 A \sqrt{D_m} \qquad (3)$$

in which C_1 is assumed constant. To apply the method, the cross section survey is used to compute values of $A\sqrt{D_m}$ for various stages extending as high as desired. The existing rating defines a curve of Q versus $A\sqrt{D_m}$, which usually approximates a straight line and can be extended as such.

Stevens recognized that where considerable quantities of overbank flow were present, no hydraulic formula applied to the entire section would give correct results, and cautioned against the use of his method in these cases. Recent work by the writer has suggested a technique for analyzing such a section. Where overbank flow begins (Fig. 1), values of $A\sqrt{D_m}$ will show a sudden decrease, as values of Q and stage increase slightly. This produces a jog, or offset, in the curve of $A\sqrt{D_m}$ versus Q. If an auxiliary curve of $A\sqrt{D_m}$ versus stage is plotted, it too will have an offset of approximately the

2 "A Method of Estimating Stream Discharge from a Limited Number of Gagings," by J. C. Stevens, Engineering News, Vol. 58, No. 3, July, 1907.

same magnitude. Experience has shown that the auxiliary curve may be used to define the position and size of the offset, and that the upper part of the $A\sqrt{D_m}$ versus Q curve has the same slope as the lower part. Thus, this technique may be used to define a rating over a previously un-wetted flood plain.

Manning Formula.—The problem can also be solved by direct application of the Manning formula, as follows:

$$Q = \frac{1.486}{n} A R^{2/3} S^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

The roughness coefficient, n, is the same as that used by Kutter (Eq. 2); it has been determined for various types of beds, and it can be estimated reasonably accurately by experienced field personnel. All other symbols are as previously defined. In using the Manning formula, the section must be broken down into trapezoidal sections, each one analyzed separately, and the dis-

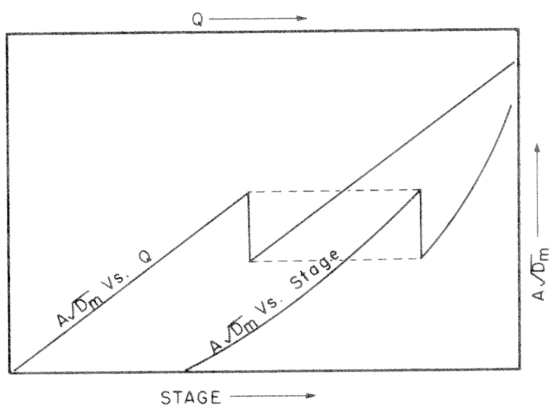

FIG. 1

charge summed. The slope is assumed to be the same throughout the cross section, and may be equated to the measured bed slope without serious error. If the range of the existing rating involves flow in only one trapezoidal section, the formula may be solved for the value of n applicable to this section. Values of n for overflow sections may either be assumed the same or varied, as conditions indicate. If the existing rating involves overflow, the total discharge is the sum of the flow in two or more trapezoidal sections. A simple trial and error solution will produce values of n that will have the proper relative values and that will yield the correct total discharge.

Some users of the Manning formula separate the quantity, $\frac{1.486}{n} AR^{2/3}$, and term this the "conveyance," K. This results in

$$Q = K S^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

This method of use is known as the "Slope-Conveyance Method." It is a mathematical manipulation that tends to simplify computation in some applications, but does not represent a different concept than direct application of the original formula.

Comparison of Methods.—The main practical difference between the two methods is the degree of flexibility. The Stevens method includes certain simplifying assumptions that must be retained throughout the problem. The Manning formula may be used with analagous assumptions, but also permits a more rational approach when needed. It can, therefore, be used to advantage in particularly complicated sections.

If the Manning formula (or Slope-Conveyance Method) is used with the assumption of constant n and S values, the only difference between it and Stevens' formula is the use of $R^{2/3}$ rather than $D^{1/2}$. The use of R instead of D is certainly proper. The true value of the exponent is not really known, but probably lies somewhere between 0.500 and 0.667.

Although use of the Manning formula and subdivision of the cross section appears to be more sophisticated than the Stevens method with the offset technique, experience to date indicates that this is not reflected in the accuracy of the results. The writer believes that for most channels, the Stevens method will yield as good an extension as is practicable.

FIELD SURVEY

In general, the section should be measured at the gage. Situations have been encountered in which obstructions a short distance upstream or downstream from the section would obviously result in a slack water condition in the section. In these cases, such obstructions have been translated upstream or downstream, so that their area was deducted from that of the cross section. In other cases, the cross section itself was taken some distance downstream from the gage, in what it was thought would be the controlling reach of channel at high stages. When this is done, elevations in the section are related to stages at the gage, and this requires that the slope does not change with stage. This, however, has already been assumed.

Normally, a stadia survey across the section produces data that will serve the purpose well. Some consideration has been given to obtaining the basic data from detailed topographic maps or from aerial photographs. The writer believes that this would not be a satisfactory approach. It is questionable whether such material would yield sufficiently accurate results. Aside from this, however, matters such as the evaluation of the effect of variable roughness, selection of the particular section to be used, a decision as to the type of computation indicated by gage conditions, and others all require professional judgment that can hardly be exercised except by a visit to the site. If time is to be taken to travel to the gage for this purpose, not much additional effort is required to run out the line with a transit. Furthermore, the inspection may indicate that a simple logarithmic extension will yield as accurate results as any method, and eliminate the need for any more complicated analysis of that gage.

EXAMPLE

As an example, a rating extension for the Naugatuck River at Beacon Falls, Conn., is computed below. This gaging station was established by the USGS on October 21, 1955. Prior to August 19, 1955, records were collected at a site 2.5 miles upstream at a station known as Naugatuck River at Naugatuck, Conn. The latter station was destroyed in the August, 1955, flood. Had the station been at Beacon Falls continuously, the maximum peak of record prior to August, 1955, would have been 16.6 ft, or 29,500 cfs, which occurred on December 31, 1948. The great flood of August, 1955, produced 26.0 ft (108,00 cfs) at this point. The Hartford, Conn., River Forecast Center of the USWB, which provides flood forecasting service for this area, had not yet been established at the time of this event. The hypothetical problem is then that which would have faced a forecaster in August, 1955, had the service been in operation.

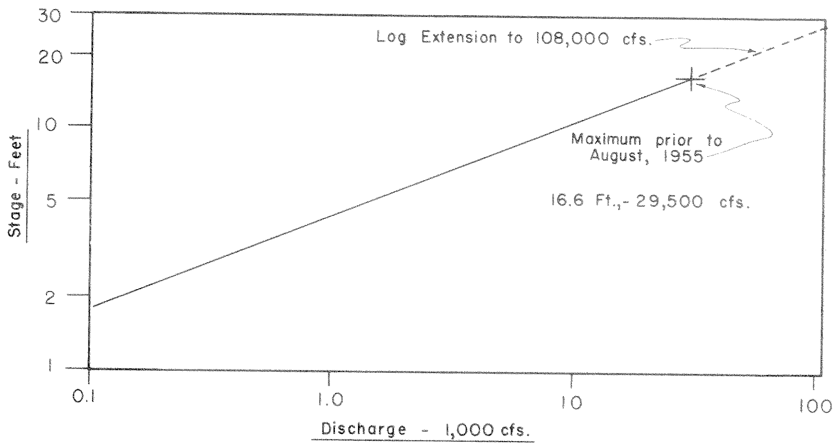

FIG. 2

A discharge of 108,00 cfs would presumably have been correctly forecast, and a rating curve to 29,500 cfs would have been made available.

Without a knowledge of the channel characteristics, he could have done little other than extend the rating logarithmically. This extension of the stage-discharge relationship is shown in Fig. 2, and would have indicated a stage forecast of 27.8 ft, or an error of +1.8 ft.

The channel has been surveyed by the USWB and is shown in Fig. 3 (the cross section of the River shown is at a point 220 ft downstream from the gage). Section properties computed from the cross section are plotted in Fig. 4. The offset in the curve of stage versus $A\sqrt{D_m}$ defines a similar offset in the curve of Q versus $A\sqrt{D_m}$. This curve is then extended, at the same slope, to 108,000 cfs. The corresponding value of $A\sqrt{D_m}$ is 24,500 $ft^{5/2}$. The cross section yields this value at a stage of 26.3 ft. Thus, using this method, the crest

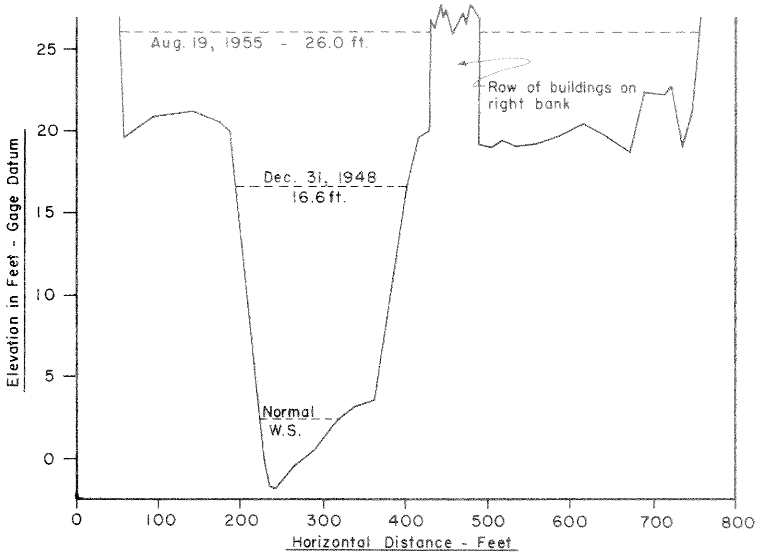
Aug. 19, 1955 - 26.0 ft.
Row of buildings on right bank
Dec. 31, 1948
16.6 ft.
Normal
W.S.
Elevation in Feet - Gage Datum
Horizontal Distance - Feet
0
100
200
300
400
500
600
700
800
25
20
15
10
5
0

FIG. 3

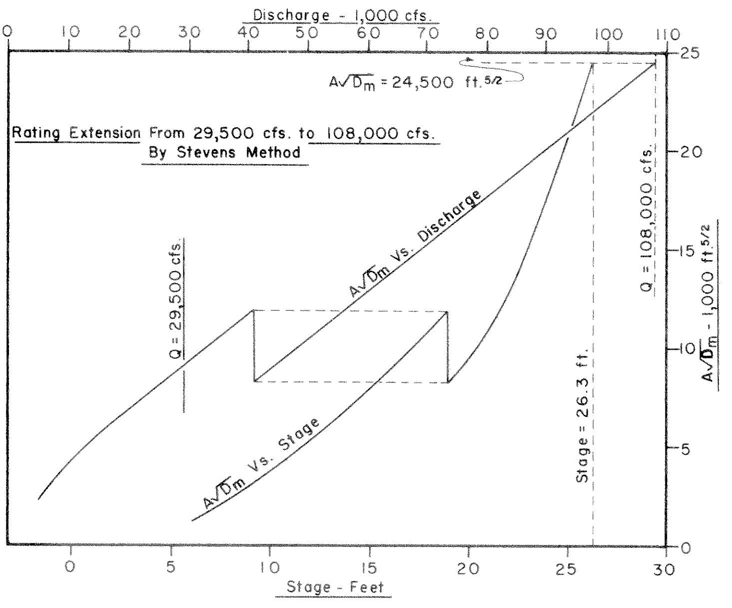
Discharge - 1,000 cfs.
$A\sqrt{D_m}$ = 24,500 ft.$^{5/2}$
Rating Extension From 29,500 cfs. to 108,000 cfs.
By Stevens Method
$A\sqrt{D_m}$ Vs. Discharge
$A\sqrt{D_m}$ Vs. Stage
Q = 29,500 cfs.
Q = 108,000 cfs.
Stage = 26.3 ft.
$A\sqrt{D_m}$ - 1,000 ft.$^{5/2}$
Stage - Feet
0
10
20
30
40
50
60
70
80
90
100
110
0
5
10
15
20
25
30

FIG. 4

stage forecast would have been 26.3 ft, and the error +0.3 ft. This is a considerable improvement over the logarithmic extension.

CONCLUSIONS

1. A program of rating extensions to points above previous maxima is a vital and necessary part of any modern river forecasting program.
2. The extensions should be based on actual field surveys and personal site inspections by experienced hydraulic engineers.
3. The concepts involved in this work are distinct from those in entirely synthetic ratings or indirect streamflow measurements.
4. The Stevens Method is simple and fast, and when combined with the offset technique, will give as good results, at most sites, as more complex methods.

KEY WORDS: curves; floods; water flow; hydraulics

ABSTRACT: The need in modern river forecasting for station rating curves extending above the previous maximum flood is described. Two methods of computing rating extensions, based on field surveys, are given. The first, which is recommended for most sites, is the "Stevens Method," presented by J. C. Stevens in 1907, and modified by the writer through inclusion of the "Offset Technique." The second is the "Slope-Conveyance Method." Basic differences between the extension of existing ratings and the development of entirely synthetic ratings are emphasized. The impact of these differences on the survey and computational methods is examined. An example is given of an actual rating extension by the Stevens Method, and the results are compared with those obtained by extending the same rating logarithmically. The point is made that a program of rating extensions based on field surveys is a vital and necessary part of any modern river forecasting program.

REFERENCE: "Extension of Rating Curves by Field Surveys," by Walter T. Sittner, Journal of the Hydraulics Division, ASCE, Vol. 89, No. HY2, Proc. Paper 3444, March, 1963, pp. 1-9.