1992

Loop Rating Curves from Goodwin Creek

Roger A. Kuhnle
USDA National Sedimentation Laboratory

Andrew J. Bowie
USDA National Sedimentation Laboratory

Published in Hydraulic Engineering: Saving a Threatened Resource—In Search of Solutions: Proceedings of the Hydraulic Engineering sessions at Water Forum '92.
Baltimore, Maryland, August 2–6, 1992. Published by American Society of Civil Engineers.

Loop Rating Curves from Goodwin Creek

Roger A. Kuhnle and Andrew J. Bowie[1]

Abstract

Two types of hysteresis loops have been observed on Goodwin Creek: those with a greater flow depth for a given discharge on the falling limb of the hydrograph (type 1) and those with a greater flow depth for a given discharge on the rising limb of the hydrograph (type 2). Causes of these 2 loop types are investigated in this paper.

Introduction

Determining the flow discharge of a stream accurately is essential for hydraulic and hydrological studies. Yet relationships between the depth of flow and flow discharge on streams are not unique. Loop rating curves have been described by many authors (e.g. Carey and Keller, 1957; Colby, 1960; Simons, Richardson, and Haushild, 1962; Combs and Flowers, 1977; Combs, 1991) usually with the depth of flow for a given discharge greater on the falling than on the rising limb of the hydrograph. In this study two types of hysteresis loops were identified for Goodwin Creek and the causes of these loops were investigated.

Study Area

The study site was at station 2 of the Goodwin Creek Research Watershed in north central Mississippi. The channel has a mean bed slope of 0.003, bed sediment with D_{50} = 8.3 mm (range 0.1 - 64 mm), and a drainage area of 17.9 km^2. At the site is a concrete supercritical flow flume which was designed to have a unique relationship between flow depth in the flume and flow discharge (Bowie and Sansom, 1986). Depth of flow in the channel was measured using four USGS bubble gages in a 91 m long straight reach of channel 63 m upstream of the flume. The bubble gages were connected to pressure transducers from which data were collected every minute by the remote

[1]Research Geologist and Research Hydraulic Engineer, respectively, USDA National Sedimentation Laboratory, P.O. Box 1157, Oxford, MS 38655

telemetry system of the watershed. Flow depths from the bubble gages were related to flow discharges calculated from the recorded depth in the supercritical flow flume.

Background

It is generally agreed that there are two main causes of hysteresis loops in depth discharge relations. These are the dynamics of the flood wave and lags in the formation and destruction of bed forms (or other bed roughness elements) with the changing flow in the channel.

The dynamics of the unsteady flow during a runoff event can be shown to result in a loop curve between depth and discharge. For a wide channel in which the vertical components of acceleration in the flow are small the following equation can be written:

$$Q = CA\sqrt{y\left(S_0 - \frac{\delta y}{\delta x} - \frac{v}{g}\frac{\delta v}{\delta x} - \frac{1}{g}\frac{\delta v}{\delta t}\right)} \tag{1}$$

(Henderson, 1966) where Q-flow discharge, A-flow area, C-Chezy coefficient, y-flow depth, S_0-slope of the bed, v-flow velocity, g-acceleration of gravity, x-flow parallel coordinate, and t-time coordinate. For Goodwin Creek the velocity slopes in (1) can be assumed to be small allowing

$$Q = CA\sqrt{y\left(S_0 - \frac{\delta y}{\delta x}\right)} \tag{2}$$

to be written. If the Chezy C is taken to be constant (2) can be divided by its uniform flow equivalent to yield:

$$\frac{Q}{Q_0} = \sqrt{1 - \frac{1}{S_0}\frac{\delta y}{\delta x}} \tag{3}$$

where Q_0 is the flow discharge for uniform flow (Henderson, 1966). Q/Q_0 in (3) represents the effect of the dynamics of the flood wave on the depth-discharge relationship. Only Q/Q_0 can be calculated unless an independent measure of the roughness is available.

The effect of bed roughness changes on depth-discharge relations has been studied by Simons et al.

(1962). Simons et al. demonstrated with a series of simulated hydrographs in a laboratory flume that a variety of types of hysteresis loops could be generated. The cause of these loops was attributed to the formation and destruction of bed forms in a sand bedded channel. Simons et al. found that type 1 loops could be generated by keeping the whole hydrograph in the lower flow regime, while type 2 loops could be generated by starting with lower flow regime dunes, increasing the flow to form an upper flow regime plane bed and then forming lower flow regime dunes again as the flow decreases.

<u>Hysteresis Loops on Goodwin Creek</u>

Flow depth versus flow discharge curves for 47 runoff events with peak discharges greater than 14 $m^3 s^{-1}$ for the period 1985-1989 were plotted and examined. Of the 47 events plotted 43 had identifiable hysteresis loops with 79% being type 1 and the rest type 2. The variation in discharge for a given depth resulting from a given loop

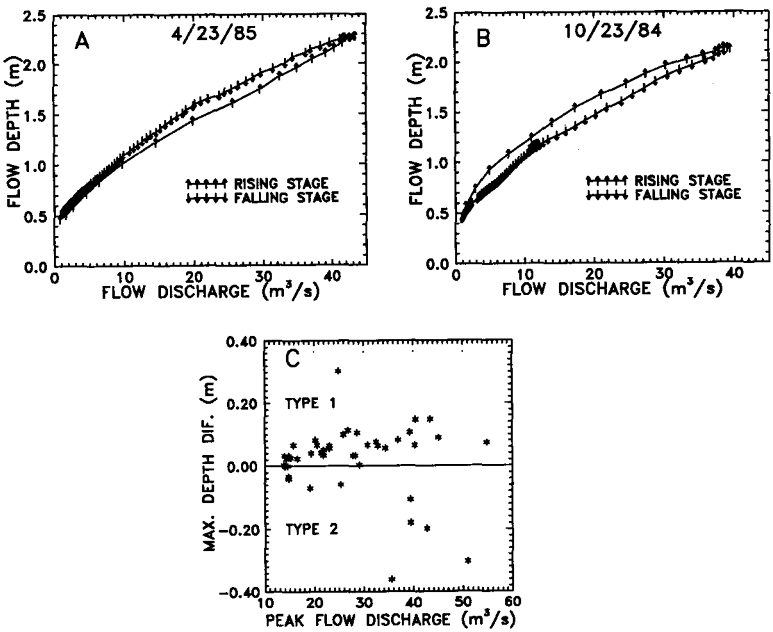

Fig. 1- Examples of type 1 (A), type 2 (B) loops, and (C) MDD versus peak discharge. Negative values refer to type 2 loops.

varied by a factor of as much as 1.7. Examples of the 2 loop types and the range of maximum depth differences (MDD) for a given discharge are shown in Figure 1.

Causes of the Loops

The separation of the dynamic effects from the roughness effects on the depth-discharge relations could not be accomplished explicitly in this study because of the lack of an independent measure of the boundary roughness. Boundary roughnesses on sediment beds with a mixture of sand and gravel are difficult to predict. To approximate the effect of the dynamics of the flow on the depth-discharge relation, equation (3) was used with the collected slope data to calculate the maximum Q ratio ($(Q_r/Q_0)/(Q_f/Q_0) = Q_r/Q_f$ for a given flow depth, with r - rising stage, f - falling stage) for the 27 runoff events with MDD's greater than 0.05 m. This was compared to the maximum Q ratio measured graphically from digitized plots of the depth-discharge relations. The results of this comparison were varied. In 11 cases a significant portion (mean of the 11 = 62%) of the Q ratio could be explained by the calculated dynamic effects of the flow, while in the rest of the 27 (including all of the type 2 loops) none of the Q ratio could be explained.

For the cases when the dynamics of the flow could not explain the observed loops in the depth-discharge relations, the bed roughness was believed to be the cause. Lags in the formation and destruction of bed forms in sand have been shown to cause hysteresis loops similar to the two types identified in this study (Simons et al., 1962). However, the type of bed forms that form in a gravel bed channel and the flow strengths at which they form is poorly known. Simons et al. (1962) created a depth-discharge curve very similar to the type 2 curves identified here, however, lower flow regime dunes and upper flow regime plane bed configurations were required to produce it. While the types of the bed forms on the bed of Goodwin Creek during runoff are generally unknown, indirect evidence suggests that upper flow regime conditions are not present. The coarseness of the bed sediment, and maximum Froude numbers at the study site of 0.4, seem to preclude the formation of an upper regime plane bed similar to the ones generated in Simons et al.'s (1962) experiments. In several instances large dune-like bed forms have been observed on the bed of Goodwin Creek after large runoff events. Heights and lengths of the bed forms observed were generally about 0.4 - 0.8 m and 18 - 22 m, respectively (Fig. 2). Documentation of a type 2 depth-discharge loop after observation of large bed forms on the bed after a runoff event has been elusive, probably because of the high probability that low flows would plane off the bed forms before a flow of sufficient magnitude occurs. Possibly the inherited roughness is more subtle than the large dunes that have been observed after large runoff events.

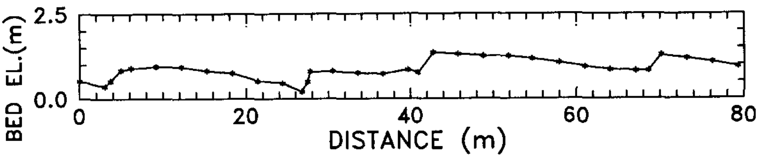

Fig. 2.- Flow parallel transect of bed surface taken after 5/9/89 runoff event at Goodwin Creek, station 2. Downstream is to the left, vertical axis is exaggerated by a factor of 4.

The mechanism that we believe causes the type 2 loops on Goodwin Creek is the presence of a relatively high bed roughness, inherited from a previous runoff event, on the bed at the beginning of a runoff event. The initial high bed roughness on the rising limb of the hydrograph causes the flow depth to be relatively high for a given discharge. By the time of the peak flow most of the inherited roughness has been destroyed and the falling limb of the hydrograph has lower flow depths than were present on the rising limb.

In the cases when the type 1 loops cannot be explained by the dynamics of the flow, a sequence of lags in the formation and destruction of the bed forms (or bed roughness elements) is hypothesized. This sequence would be analogous to the one observed by Simons et al. (1962).

Discussion

While the above analysis using equation (3) was instructive, it also raises questions about the dynamics of the system operating on Goodwin Creek. Figure 3 is a plot of equation (3) for the 5/9/89 event. The sloping trend of the data in Figure 3 is typical for all of the 26 others. Our expectation was that the trend of these plots

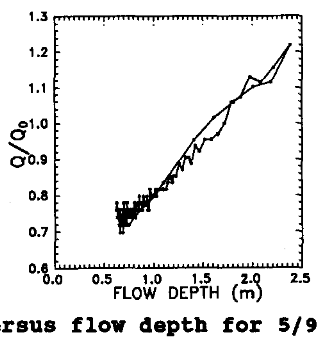

Fig. 3.- Q/Q_0 versus flow depth for 5/9/89 runoff event.

would be horizontal about the line of $Q/Q_0 = 1$. The slope of the data shown in Figure 3 indicates that the straight reach of channel selected for this study is probably not as simple as desired. Our best hypothesis is that the cross section may be changing over the study reach yielding the observed sloping trend in Figure 3.

Conclusions

It appears that for Goodwin Creek the causes of the type 1 hysteresis curves are about evenly split between the dynamics of the flood wave and lags in the formation and destruction of bed roughness elements. It is not known what form these roughness elements take. For the type 2 hysteresis curves the dynamics of the flood flow do not appear to explain any of the curves. A relatively high initial bed roughness from a previous runoff event that is progressively destroyed as the flow increases is thought to be the most likely cause of the type 2 curves. More study on bed forms in streams with gravel and sand beds is needed.

APPENDIX I.-- References

Bowie, A. J. and Sansom, O. W. (1986). "Innovative techniques for collecting hydrologic data", Proceedings of the 4th Federal Interagency Sedimentation Conference, 1-59 - 1-69.

Carey, W. C., and Keller, M. D. (1957). "Systematic changes in the beds of alluvial rivers", *J. Hydr. Div.*, ASCE, 83(4), 1331-1 - 1331-24.

Colby, B. R. (1960). "Discontinuous rating curves for Pigeon Roost and Cuffawa Creeks in northern Mississippi", U.S. Department of Agriculture, Agricultural Research Service, *ARS 41-36*, 31 p.

Combs, P. G. and Flowers, D. (1977). "A study of the dynamic rating curve of the Mississippi River", Proceedings Mississippi Water Resources Conference, Mississippi State, MS, 57-75.

Combs, P. G. (1991). "Examination of Red River dynamic loop rating curve", Proceedings of the 5th Federal Interagency Sedimentation Conference, 4-24 -4-31.

Henderson, F. M. (1966). *Open Channel Flow*. Macmillan Publishing Company, Inc., New York, NY, 522 p.

Simons, D. B., Richardson, E. V., and Haushild, W. L. (1962). "Depth-discharge relations in alluvial channels", *J. Hydr. Div.*, ASCE, 88(5), 57-72.