Approaches to In-Situ Calculation of Floodplain Roughness

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In-situ roughness calculations provide a defensible basis for estimating roughness coefficients in designing or maintaining complex, multi-objective floodways. Conventional methods using standard manuals can work well for straight channels containing little vegetation, but are not really amenable to more complicated conditions typical of many floodways or river corridors. For example, the incremental method, described in Chow (1959) and many regional variants, use additive values for surface irregularities, obstruction, and variations in shape and size of channel cross section. These values are picked from a table, not calculated, and are therefore open to interpretation. The methods of Barnes (1967) and Arcement and Schneider (1989), which use photographs of sites where roughness has been calculated, also employ subjective choices; this can be problematic if none of the channels matches exactly. A better option is to calculate the hydraulic roughness in the actual channel of interest. The key to an accurate roughness coefficient lies in calculating roughness based on high-water marks (HWMs) and local conditions (slope and channel geometry).

In this paper, we outline five steps that allow field data to be applied easily and cost-effectively to channel-management decisions. We also present three selected case studies from the San Francisco and Monterey Bay areas where site-specific calculations of roughness proved to be both effective and central in reaching a management decision. Several findings pertinent to all three studies are presented in the final section.

METHOD

We encourage the use of roughness coefficients that have been calculated locally based on HWMs. We input known values for all parameters into the Manning equation and then solve for the roughness coefficient ('n'). The calculation of roughness can be easily done for low- or medium-flow conditions, because the actual water level can be recorded and the discharge measured. However, roughness often decreases as stage increases, so values obtained at low- or medium-flow conditions must be carefully applied to the large flows that are of the greatest concern. The local data can most effectively be applied in five steps:

1. (1) Validating—or calculating—peak discharge for storms that correspond to identifiable HWMs.
2. (2) Calculating roughness based on field measurements of wetted perimeter, cross-sectional area, and water surface slopes. These measurements are based on a survey of the channel and HWMs.
3. (3) Estimating roughness for flows at the design levels, using one or more of the accepted techniques of extrapolating roughness values obtained in step 2.
4. (4) Assessing effects of likely changes in the channel or overbank areas.
5. (5) Evaluating whether anticipatable episodic events are likely to fundamentally change the assumptions of the calculations, and adjusting accordingly.

CASE STUDIES

We have applied this approach to three California streams: a leveed river with an inboard riparian-woodland fringe, a naturalized channel established within an over-wide leveed floodway, and a deeply incised natural stream in a narrow riparian corridor.

Case Study 1: Pajaro River near Watsonville, California

Floodplain managers must often choose among alternative approaches to bank protection. Sometimes, such choices have enormous cost, public safety, regulatory, and community planning ramifications. If representative reaches of the stream (or a nearby channel) already have some of the bank-protection measures in place, the actual performance of these measures in that stream can be assessed. We made measurements of this type on the Pajaro River near Watsonville.

A federal flood control project was designed in the late 1940s and constructed in the early 1950s, with a design capacity of 22,000 cfs. Approximately 15 miles of the Pajaro River were leveed. Since the levees were built, a narrow band of riparian woodland had become established along the river, usually occupying about half of the floodplain "bench" within the levees. The involved agencies sought to quantify loss of flood conveyance associated with this fringe of willow, cottonwood, box elder and elderberry woodland.

Our approach was to compare the roughnesses of two consecutive straight reaches, the first with riparian woodland on both banks, and the second with one wooded bank and one cleared bank fully riprapped with angular 6-inch quarry rock. The longitudinal slopes, woodland densities, peak discharges, and bed conditions were observed to be very similar in these two consecutive reaches. We posited that the difference in conveyance could be computed by doubling the difference in measured roughnesses between the fully-wooded and half-riprapped reaches.

We computed the observed hydraulic roughness at the peaks of three events by solving the Manning's equation for 'n.' Peak discharge was obtained from the nearby Chittenden gaging station, with minor adjustments for tributary inflow. Cross-sectional area, hydraulic radius, and hydraulic slope were measured from high-water marks of flood crests corresponding roughly to 75, 33, and 15% of the design capacity.

Results (Table 1) indicate that whole-channel roughness was essentially identical in the two reaches at the highest stages measured in this study, except for one section containing two large snags and rootwads. Roughness of the March 2 crest could be estimated from the March 25 flows, adjusted by the -0.4 power of the peak flow, as would be predicted from the at-a-station hydraulic geometry for relatively wide streams. The wooded reach was distinctly rougher (n=0.068) than the half-riprapped reach (n=0.053 to 0.058) during the March 25 storm. Differences increased at the lower-stage event on April 30, when flows were actually below the riparian woodland.

Table 1. Hydraulic roughness values for Case Study 1, Pajaro River near Watsonville, California.

Method	HWM	HWM	HWM	
Date	2-Mar-83	25-Mar-83	30-Apr-83	
Flow	16,210 cfs	7,000 cfs	3,260 cfs	**Channel Condition**
Station				
4+97	0.046	0.058	0.044	Half-riprapped
8+10	0.043	0.053	0.05	Half-riprapped
10+00	0.039	0.053	0.043	Half-riprapped
15+00	0.042	0.068	0.068	Fully Wooded w/o fallen trees
15+90	0.054	0.095	0.081	Fully Wooded w/ fallen trees

Notes:
Design flow = 22,000 cfs.
Peak discharges assumed be those gaged at Chittenden

The difference between the two reaches at the lower flows is probably attributable more to: (1) leafing out—the deciduous woodland is in bud during early March and comes into full leaf by early April, creating considerably more roughness-generating surface area, and bending lower branches into the flow; and (2) more uncleared woody debris along the lower banks in the fully-wooded area. Nonetheless, density of roughness-producing vegetation along the bank at stages when the main channel is nearly at the design capacity does not seem to appreciably affect channel hydraulics at the higher flows of prime concern for flood protection.

Case Study 2: Wildcat Creek, Contra Costa County, California

The study reach in northern Richmond, California, is a multi-level floodway constructed in the late 1980s by the U.S. Army Corps of Engineers to reduce local urban flooding. The constructed flood control channel is about four times wider and two times deeper than the pre-existing natural channel. Drainage area above the study reach is approximately 8.5 square miles; mean annual precipitation is 24 inches. An unusual feature of the project is in-channel vegetation, planned to reduce roughness by shading out undergrowth. However, the planted vegetation has not yet fully matured and currently causes significant hydraulic resistance. The goal of this case study involved evaluating the flood protection provided, and determining maintenance requirements (vegetation and sediment removal). The key aspect of the evaluation concerned assigning roughness values at cross sections representative of channel reaches. A U.S. Geological Survey gaging station approximately 1.5 miles upstream was our source of information for historic and recent flows.

Orr and Owens (1994) applied numerous methods to estimate roughness, but found the conventional methods (mentioned in the introduction) difficult to apply because of dense vegetation directly in the channel. None of the locations presented in Barnes (1967) or Arcement and Schneider (1989) looked at all like Wildcat Creek. In the fall of 1994 they found HWMs at two of four cross sections, but those marks corresponded to a flow less than 1/7 of the design flow. Flexible vegetation, cattails and young willows, in the channel presented difficulty in extrapolating from the low flow of 303 cfs to the design flow of 2300 cfs. Subsequent high flows of the winter of 1995 left fresh HWMs. Following up on the work Orr and Owens, we identified HWMs corresponding to 1310 cfs (January 1995), and personally marked water levels during a later-season storm at a stage corresponding to 916 cfs (March 1995).

We found that sediment deposition, which occurred significantly at three of the four cross sections, caused a decrease in calculated roughness from January to March 1995 (see Table 2). The fourth cross section (66+00, where little deposition occurred) displayed the normal pattern of decreased roughness at higher flows. Flood flows bent many of the cattails, which then became buried by sediment, reducing roughness. Although roughness values estimated using the incremental method are a reasonable approximation of the calculated values (Table 2), calculations based on measurements are more defensible.

Table 2. Hydraulic roughness values for Case Study 2, Wildcat Creek, Contra Costa County, California.

Method	HWM	HWM	HWM	Incremental Method	"Modified" Incremental Cattails Prone	Vegetation Density	Hall and Freeman
Flow	303 cfs	1310 cfs	916 cfs	design	design	design	design
Station							
66+00	0.03-0.067	0.043	0.054	0.043	0.041	0.048	0.044
83+11	na	0.064	0.043	0.051	0.047	0.062	0.053
93+00	na	0.060	0.047	0.07	0.058	0.227	0.071
96+25	0.185	0.149	0.047	0.088	0.069	0.254	0.100
Channel Condition	willows and thick cattails	willows and bent cattails	willows and no cattails fresh sediment	willows and thick cattails	willows and bent cattails	willows and thick cattails	willows and thick cattails

Notes:
Design flow (Q100) = 2300 cfs.
Flow of 303 cfs occurred Feb. 19, 1994. Channel geometry assumed as surveyed Oct. 1994.
Flow of 1310 cfs occurred Jan. 9, 1995. Channel geometry assumed as surveyed Oct. 1994.
Flow of 916 cfs occurred March 11, 1995. Channel geometry assumed as surveyed Nov. 1995.
Considerable sediment accumulated between the Jan. and March 1995 storms, except at station 66+00.
Range of values at 66+00 indicates the thickness of the HWM (debris jam).

Case Study 3: San Francisquito Creek at Webb Ranch, Stanford, California

We were asked to calculate the level of the 10-year event on San Francisquito Creek to guide design of a service road bridge. The analysis was first done using the conventional incremental method, adjusting for channel irregularity, cross-sectional variability, obstructions, vegetation, and meandering. We used the Aldridge and Garrett (1973) adaptation of Chow's method, developed for streams in Arizona.

Values for four cross sections in a 700-foot reach resulted in an estimated 'n' value of 0.098 for this perennial channel cut into cohesive banks, lined by a riparian woodland with alder, buckeye, cottonwood, willow, and bay laurel. We subsequently returned to develop actual crest-of-event roughnesses based on high-water marks from the January 1982, January 1995, and February 1996 storms. Estimated recurrence intervals for these events are approximately 25, 7, and 2 years, respectively.

Our calculated values of roughness decreased with increasing flow, from an average of 0.067 (2-year event), through 0.053 (7-year event) to 0.047 (25-year event). Roughness calculated from the flows that left the three HWMs varied with the -0.3 power of discharge in this narrow channel. Roughnesses based on the site-specific field data averaged 0.047 (for the highest HWM), or 48% of the 0.098 estimated using the incremental method.

We ascribe much of the difference to the very sparse undergrowth along the channel at stages below the elevation of the 10-year event, because the undergrowth has been shaded out by the tree canopy that extends completely across the channel at most locations. Most variants of the Chow incremental method assume presence of weeds, bushy willows, or shrubs within the area inundated by moderate-recurrence events. Shading out occurs widely in western streams with low to moderate width:depth ratios, but is not recognized by this method. Also, we estimated roughness values while vegetation was fully leafed, and we may have overestimated roughness of flows that occurred before the vegetation was in leaf.

CONCLUSIONS

(1) In-situ measurements of roughness offer a valid, defensible alternative to standard 'cookbook' estimates of Mannings 'n'; measured values are particularly suited for complex multi-objective floodways.

(2) If high-water marks can be identified and assigned to a particular flood crest, the 5-step approach outlined in this paper can speed in-situ roughness calculations and make them more valid and versatile.

(3) Our data suggest that it may be feasible to estimate roughnesses of wooded riparian corridors at stages near design capacity from the ratio of the observed peak discharge to the design flow, raised to an exponent of about -0.3 (narrow channels) or -0.4 (wide channels), consistent with at-a-station hydraulic geometries, provided that the observed peak flows were sufficiently high to be affected by the naturalized woody fringe.

(4) In-situ measurements help adapt for changes in channels or for episodic bed sedimentation.

(5) In-situ measurements of roughness in woodland-lined channels are often lower than might be calculated from manuals, perhaps because peak floods occur when the trees are not in leaf, or because the maturing

woodland has shaded out undergrowth that most standard manuals assume to occur in all channels.

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