A Proposal to Reduce the Cost of Indirect-Discharge Estimates

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The establishment of peak flood discharges by direct measurement or indirect methods is part of the fundamental mission of the Water Resources Division. These data help identify hazardous areas, establish recurrence intervals of high flows, and define the driving force in sediment-transport and unstable channels. Rapid runoff, remote locations, and dangerous field conditions preclude many direct current-meter measurements of high flows. In these situations, indirect-discharge estimates must be conducted. WRD has done thousands of indirect discharge estimates all over the country, and the slope-area method is the technique most commonly used (at least 2/3 of the time). Over the past few years, there has been inadequate funding for Districts to cover the costs of indirect discharge estimates at gaging stations and miscellaneous sites following widespread major flooding events. I am proposing a simplified method to acquire indirect-discharge estimates for significantly less money than the current average of about $5,000 for each slope-area estimate, while retaining an average of more than 90 percent of the accuracy of a full slope-area procedure. The motivation for the effort is to suggest a method that can significantly reduce the cost of a discharge estimate, and allow the savings to be applied to studies of flood processes, mechanisms, and documentation. I believe more support for these activities will help advance scientific understanding of floods and reduce future losses, and this can be accomplished by streamlining the effort to collect indirect peak-flood data.

The slope-area methodology is fully described in Chow (1959), Dalrymple and Benson (1967), and Herschy (1995). The slope-area method attempts to identify the energy slope of a flood from several cross-sections, high-water profiles, and estimates of flow resistance (Manning's n). The procedure solves the Bernoulli (energy) equation for one-dimensional, gradually-varied, steady flow, then uses a uniform-flow formula (Manning's equation) to solve for discharge. The methodology has been streamlined by development of computer programs to do calculations and iterations (Fulford, 1994), and automated plotting routines from survey instruments (Berenbrock, 19xx). The ideal slope-area reach is straight, with uniform cross-sections or gradually converging flow, and no backwater effects. Problems arise with ambiguous or unclear high-water marks, widely-varied cross-sections, or rapidly expanding flow-fields. The costs of a slope-area measurement are born by the need to flag and survey high-water marks up- and down-stream of the cross-sections, survey cross-sections, plot results, prepare proper documentation, and review and revision of subjective processes such as selection of n-values or location of cross-sections. Other potential problems are described by Jarrett (1987). It is generally believed that a good slope-area measurement can replicate discharge with an error of 10 % or less (Benson and Dalrymple, 1967).

There have been earlier suggestions for ways to simplify or shorten the time and effort required to produce a slope-area discharge estimate (Riggs, 1976), but these methods have not been widely adopted, to say the least. It's time to try again.

Twenty-nine slope-area measurements from the February 1996 floods in Oregon were used to test the hypothesis that a single cross-section slope-conveyance estimate would give nearly as good an estimate of peak discharge as the slope-area because of the following reasons:

1. HWMs are commonly vague and difficult to define for long reaches. It is better to select a place where the HWMs are very clear and well-defined, and run a single cross-section there.

2. The work of defining HWMs in a true slope-area is to help identify the energy slope, which can be different from the channel and water-surface slope. But once that slope is determined, it is used to compute conveyance with a steady, uniform-flow equation (Manning Equation). We pretend it can be used to solve gradually-varied flows but only for convenience or necessity. The assumption in a slope-area solution for peak discharge is thus little different than a single cross-section slope-conveyance estimate, where channel, water, and energy slopes are parallel, and thus equal.

Using bed slope, selecting one of the surveyed cross-sections as a representative section, and using the same n-value used in the slope-area estimate, the Oregon data show that the differences between slope-area results, and slope-conveyance results for the same stations range from +31% to -38% (Fig. 1), with a strong mode in the 0-5% range (Fig. 2), and an over-all average difference of 9.8 %, and a small positive bias of +2.2 %. The slope-conveyance method allows a single representative cross-section to be selected where high-water marks are well-defined, and requires little surveying or data manipulation. Discharge is computed directly from cross-sectional area, n, hydraulic radius, and channel slope. In a study of 173 floods in Wisconsin, using map slope rather than water-surface slope to calculate discharge produced a difference of +50 % and -45 %, with a mean of 4.4 % (Magilligan, 1988); these values are quite similar to the results reported here.

A second test used every-other one of the 50 gaged high-flow sites documented in Barnes (1967). These are actual current-meter measurements, not slope-area measurements, and only the water-surface slope was reported. Using the 25 floods, which were directly measured, the slope-conveyance method results ranged from +43.2 % to -9.2 % of the real discharge (Fig. 3), with a strong mode in the 0-5 % range (Fig. 4), and an overall average difference of 7.9 % and a positive bias of +5.2 %. The small positive bias is assumed to result from site-selection. Discharge-measuring and slope-area sites are commonly selected in gently contracting reaches. In such reaches, the energy slope is less than the channel or water-surface slope, so any calculation using a slope other than the energy slope is likely to produce discharges with a small positive bias.

A log-log plot of slope-conveyance versus known discharge values for the 25 examples used from Barnes (1967) shows the very close agreement between slope-conveyance estimates, and actual discharge, for a range of floods from about 800 cfs to 400,000 cfs.

References

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"Kenneth L Wahl, Reg SW Specialist, Denver, CO" <klwahl@srv2rcolka.cr.usgs.gov>
Subject: Comments on the Slope Conveyance proposal
Date: Tue, 03 Mar 1998 16:16:20 -0700
From: "Kenneth L Wahl, Reg SW Specialist, Denver, CO" <klwahl@srv2rcolka.cr.usgs.gov>

John,

I have given your proposal considerable thought. Indeed, much of that thought has taken place over the last 30 plus years that I have been using the indirect methods. Those years have convinced me that there are instances where slope-conveyance (SK) results are acceptable alternatives to full slope-area (SA) measurements; in my experience, however, the numbers of cases where SK is not a good alternative far outweigh the cases where it is. Even where SK is a good alternative, I believe the cost savings to be fairly small because the costs of getting there to define the cross section and slope are still the principal costs. With that as a preamble, I offer the following comments about the proposal.

Starting at the end and backing up, I question how you came up with only 25 error estimates for 25 WSP1849 sites. In a SA, cross sections are located at breaks in slope. That is required because the energy equation is written over reaches of constant slope. This means that every individual cross section is a potential SK estimate. A 3-section SA would actually produce 4 SK estimates because the interior cross section would have two potential slopes that could be applied -- the slope between it and the upstream section and the slope between it and the downstream section. Even if you decided to use an average slope for the entire reach (and the field survey has generally shown that to be inappropriate), you would have three cross sections and thus three discharge estimates. Therefore, I used 10 sites (western rivers starting from the back and working forward toward lower n values) from WSP1949 to compare SK results to the SA results. Those sites include two that had two verifications so effectively there are 12 sites that produce 76 SK estimates. My Statit frequency distribution for errors follows:

Frequency Distribution for SK errors (percent)

Variable error Interval		Absolute Freq	Relative Freq(Pct)	Cum Freq(Pct)
-40 -	-30	1	1.316	1.316
-30 -	-20	4	5.263	6.579
-20 -	-10	14	18.421	25.000
-10 -	0	15	19.737	44.737
0 -	10	23	30.263	75.000
10 -	20	5	6.579	81.579
20 -	30	5	6.579	88.158
30 -	40	1	1.316	89.474
40 -	50	5	6.579	96.053
50 -	60	2	2.632	98.684
60 -	70	0	0.000	98.684
70 -	80	0	0.000	98.684

80 -	90	1	1.316	100.000
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	Total	76	100.000	

One must look at absolute values of errors because we are not trying to find out what is the average error (some are too large and some are too small, thus cancelling out) -- rather we need to know for an average site, what is our likely error without regard to whether it is positive or negative? The mean of the absolute values of these percentage errors is 14.8 percent with a standard deviation of 15.6 percent. Of course, the errors are not normally distributed as they are bounded by 100 percent on the bottom, but are unbounded on the top.

My Excel spreadsheet for these computations is available by anonymous ftp from srvrcolka.cr.usgs.gov. I have only spot checked my computations; the file is /var/ftp/pub/wahl/wsp1849.xls. A postscript plot of SK errors versus the SK estimate of discharge is also there and is called wsp1849.err.ps.

WSP1849 was done, as we all know, for n verification. Because that was the purpose, the measurements were selected for uniformity in order to reduce the effects of factors other than roughness. Thus, all flows were confined to the channel. That alone makes them more uniform in cross section (and better for SK) than the typical SA.

There are several sentences in your proposal that suggest that SA measurements are really based on uniform flow equations. I do not agree. Uniform flow is defined by Chow and others as the condition where the velocity at an instant in time is constant anywhere along a given streamline. It is true that the SA equation is developed from the energy, continuity, and Manning equations; it is also true that the Manning equation (and SK) is based on uniform flow. However, the energy equation accounts for changes in water-surface slope between individual subreaches within the reach by virtue of the changes in friction slope as reflected in friction loss, hf. For a 4-section SA in which we ignore loss of velocity head in expansions, the energy equation would look something like this, where hv is velocity head at an individual section and hf is friction loss between sections.

h1 + hv1 = h4 + hv4 + hf1.2 + hf2.3 + hf3.4

where hv1 = Q/A1 -- etc. (from continuity),
and hf1.2 = (L1.2)(Q^2)/(K1*K2) -- etc. (from Manning)

Continuity is used to convert hv terms to discharge and Manning's equation is used to convert hf terms to discharge. Discharge is held constant over the reach, but velocity varies from section to section (because area is not constant) and friction loss varies from reach to reach by virtue of changes in conveyance. "When the cross section of flow in an open channel varies gradually along the channel so that the resulting changes in velocity take place very slowly, and thus the accelerative effects are negligible, the flow is known as gradually varied flow" (Albertson and Simons in Chow's Handbook, p. 7-38). Note that only the accelerative effects are neglected; the actual changes in velocity head are not neglected. And while it is true that Manning's equation was defined for uniform flow (and thus constant cross-sectional area), the loss calculation makes no such assumption, recognizing differing properties and giving equal weight to the conveyances at each end of an individual subreach. Effectively, this recognizes that area and conveyance are not constant, but assumes that they vary linearly over the subreach. Multiple subreaches allows the variation to differ between subreaches.

You note that "HWMs are commonly vague and difficult to define for long reaches", concluding that "It is better to select a place where the HWMs are very clear and well-defined, and run a single cross-section there." Assuming by "long reach" we are talking about 5-10 channel widths, I disagree that these are commonly vague and difficult to define if we arrive within a reasonable interval following the flood. But if they are vague, it is improbable that anywhere within that reach we would find clear, well-defined HWMs suitable for a SK. I say that because, in my experience, some of the very best HWMs have signaled the very worse of conditions. Excellent marks are almost always laid down on the inside of bends or at points where the flow has decelerated and is trying to pond. Those are, of course, not ideal sites for SA, but they are totally unsuitable sites for a single cross section SK. In fact, if marks are vague there is all the more reason to extend the reach. Extending the reach extends the fall, thereby reducing the effect of errors in definition of the fall. These are the very reasons why the Surface Water Branch many years ago recommended that all SA's be three or more sections and declared that 2-section SA's would be considered only an estimate, equivalent to a SK.

A move from multisection SA to single section SK would definitely be a move back to the future (or is it forward to the past?). Before "Benson's Manual (late 1950's), which evolved into the July 1964 "white" manual, which in turn evolved into the present TWRIs, SA's were seldom more than 2 cross-sections. Many of the "SA" measurements I have retrieved from archieves for before about 1950 were actually SK (one cross section). Indeed the minutes of the Feb. 1956 meeting of 56 Flood Specialists who worked on the December 1955 - January 1956 floods in the west had this to say about length of SA reaches:

"... a minimum length would be one channel width, with as much as 1.5 to 2 widths desirable. The main criteria, however, should be the amount of fall that is developed in the reach. A shorter reach can be used if there is sufficient fall. The desirability of making several cross sections was also brought out. If we have two 2-section reaches a check between the two sets of figures gives some idea as to the reliability of the determination. When there is a steep-sloped profile immediately upstream from one of flat slope, any reach in the flat slope seems to give too little discharge."

By the 1958 Conference of Flood Specialists, the length of reach criteria had evolved to: "Sections should be located no closer than one to one and one-half times the total width of the channel. Profile should extend far enought to provide for at least 3 cross sections desirably located. In one respect a long reach is better than a short one because, in addition to allowing freer choice of section locations, there is opportunity for more subreaches and consequent checks on internal consistency of computed discharge."

Current practice says a 2-section SA is really not a SA but is just called a "slope-area estimate", essentially equal to a SK; without a second subreach, there is no measure of internal consistency.

Finally, I am not familiar with the Wisconsin study cited, but there is no doubt that on a gross scale, map slope and water-surface slope are similar. Hydraulics are driven by the local scale, and on a local scale there are dramatic differences. This can be seen by looking at the profiles from just about any representative SA. We also know that cross-sectional area varies locally as well; that variation usually relates directly to the variation in slope.

I guess my opposition to going back to SK studies over multi-section SA's could be summarized as follows:

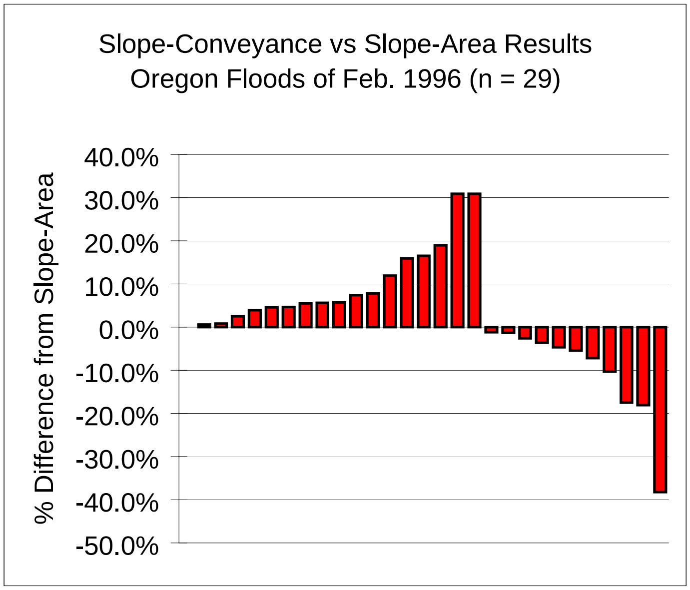
1. Technically, we would knowingly compromise accuracy. The amount of accuracy lost would require evaluation from a much broader data base than WSP1849.

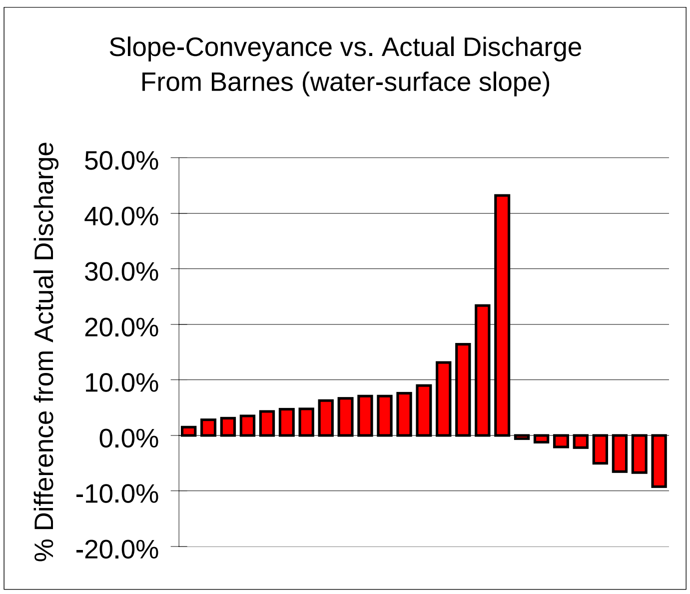
2. I suspect any cost savings from running only one cross section would be minimal. My experience has been that perhaps 85 percent of the effort in running all but the biggest SA was in getting to the site and defining the profiles. Running additional cross section was a piece of cake, generally requiring less than an added hour. And this was in the autoset days -- with EDM's this is probably even more true.

3. With an SK there is basically one answer with no measure or feel for its accuracy. With a SA the variation between subreach discharges gives a measure of the potential range in answers and provides a basis for confidence (or lack thereof) in the answer.

This response has already become much longer than I envisoned. We probably need to continue this discussion, but preferably over a Henry's. I'm sending a copy of this to Mike Nolan as well; he would also enjoy a Henry's -- and one day may find himself the resident historian.

Ken


Slope-Conveyance vs Slope-Area Results
Oregon Floods of Feb. 1996 (n = 29)
% Difference from Slope-Area
40.0%
30.0%
20.0%
10.0%
0.0%
-10.0%
-20.0%
-30.0%
-40.0%
-50.0%


Slope-Conveyance vs. Actual Discharge
From Barnes (water-surface slope)
% Difference from Actual Discharge
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
-10.0%
-20.0%