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Accuracy and Precision of Stream Reach Water Surface Slopes Estimated in the Field and from Maps

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Abstract.—The accuracy and precision of five tools used to measure stream water surface slope (WSS) were evaluated. Water surface slopes estimated in the field with a clinometer or from topographic maps used in conjunction with a map wheel or geographic information system (GIS) were significantly higher than WSS estimated in the field with a surveying level (biases of 34, 41, and 53%, respectively). Accuracy of WSS estimates obtained with an Abney level did not differ from surveying level estimates, but conclusions regarding the accuracy of Abney levels and clinometers were weakened by intratool variability. The surveying level estimated WSS most precisely (coefficient of variation [CV] = 0.26%), followed by the GIS (CV = 1.87%), map wheel (CV = 6.18%), Abney level (CV = 13.68%), and clinometer (CV = 21.57%). Estimates of WSS measured in the field with an Abney level and estimated for the same reaches with a GIS used in conjunction with 1:24,000-scale topographic maps were significantly correlated (r = 0.86), but there was a tendency for the GIS to overestimate WSS. Detailed accounts of the methods used to measure WSS and recommendations regarding the measurement of WSS are provided.

Water surface slope (WSS) is an important determinant of stream energy (Knighton 1984), and its dissipation by channel roughness elements leads to the formation of fish habitats (Keller and Swanson 1979; Bisson et al. 1982; Grant et al. 1990). As a result, WSS is often measured during stream assessments, and many habitat features (Kozel et al. 1989; Hubert and Kozel 1993) and fish population metrics (Trautman 1942; MacPhee 1966; Hubert et al. 1996) have been related to WSS. Further, WSS can be estimated from topographic maps or generated from digital elevation data (Tribe 1992; Martz and Garbrecht 1993), suggesting that its use will increase as the trend to work at broader spatial scales continues.

Previous work has determined the quality of many stream habitat measures (Hogle et al. 1993; Roper and Scarnecchia 1995; Wang et al. 1996) and standardized methods used in stream habitat evaluations (Platts et al. 1983; Simonson et al. 1994). However, current descriptions of methods used to measure WSS in the field (Platts et al. 1983; Hamilton and Bergersen 1984; Gordon et al. 1992) do not contain enough detail to ensure consistent measurement, and little information exists regarding the quality of data derived with the tools being used. Additionally, the correspondence between WSS measured in the field and estimated from maps has not been examined. Our objectives were to (1) provide a detailed account of methods used to measure WSS, (2) assess the accuracy (proximity of an estimate to the true value) and precision (repeatability of an estimate) of WSS estimates derived with tools commonly used to measure WSS, (3) evaluate the correspondence between WSS measured in the field and estimated from maps, and (4) make recommendations regarding the measurement of WSS.

Methods

Data collection.—Five tools used to measure WSS were compared: (1) a surveying level (AT-G2, Topcon[3], Tokyo, Japan), (2) an Abney level (5× magnification, Peco, Tokyo, Japan), (3) a clinometer (PM-5, Suunto, Espoo, Finland), (4) an electronic map wheel (Run-Mate, Nestler, Holland), and (5) a geographic information system (GIS; ARC/INFO, Environmental Systems Research Institute, Redlands, California) coupled to a digitizing tablet (CalComp 9500, CalComp Technology, Inc., Anaheim, California). The GIS and map wheel were used in conjunction with 1:

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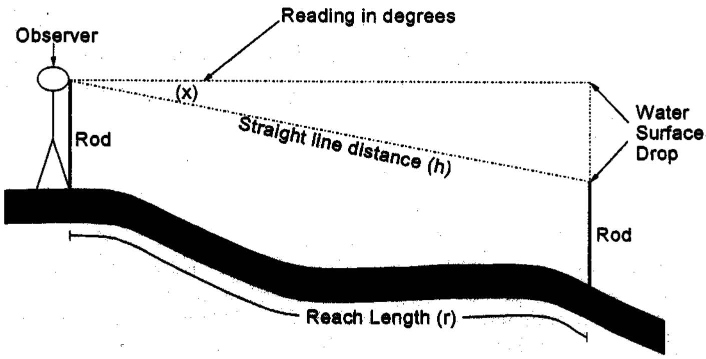

FIGURE 1.—Measures needed to estimate water surface slope in the field with a clinometer or Abney level.

24,000-scale, U.S. Geological Survey (USGS) topographic maps.

A power analysis was conducted before data were collected to estimate the sample sizes needed to compare tool accuracies. Based on formulae provided by Kirk (1982) and the tables of Pearson and Hartley (1951), 24 samples were needed to have an 80% chance of detecting a one-SD difference in tool accuracy using a randomized block design and an α of 0.05. A total of three reaches having lengths approximating those often sampled during stream surveys (75 m) were marked with stakes on two streams in the Laramie Range of southeast Wyoming. Eleven identically trained observers provided estimates of WSS for each of the reaches with a clinometer, Abney level, and GIS (N = 33 for each tool). Nine observers estimated WSS for each reach with the map wheel (N = 27). Logistical constraints limited the number of samples obtained with the surveying level to two per reach (N = 6), but this was not a problem because of the high precision exhibited by this tool (Herubin 1982).

Water surface slopes were measured at the three reaches using a surveying level and stadia rod following standard procedures (Bovee and Milhous 1978). The surveying level was positioned near the midpoint of each reach and leveled. Foresights were taken on a stadia rod placed at the water surface at both ends of the reach. Water surface slope was calculated by dividing the elevational difference between foresights by the mean reach lengths obtained during Abney level and clinometer readings described below. Water surface slopes calculated with the surveying level were assumed to represent true values and were used as baselines for comparison.

Observers measured WSS with the same clinometer and Abney level at each of the three reaches. Each observer worked with a partner and began by taking a measurement in degrees with the clinometer (Figure 1). The clinometer was steadied on top of a leveling rod placed at the water surface and sighted downstream on the top of an identical rod at the other end of the reach. The measurement was silently recorded and the partner then took a reading with the clinometer. The procedure was repeated with the Abney level. Knowledge of the clinometer measurement did not bias the Abney level measurement because the Abney level is read off the side of the tool, and the reading cannot be seen until the measurement is complete. After Abney level and clinometer measurements were complete, each person measured reach length twice with a tape, once along the thalweg and once along the midpoint of the wetted stream width. The number of measurements required to determine reach length using each technique was recorded. The straight-line distance between the ends of each reach was measured once with a tape.

Water surface slope was calculated from the Abney level and clinometer measurements as the drop in water surface elevation between the ends of the reach divided by the length of the reach:

$$\text{WSS} = [\sin(x)\, h/r]100: \qquad (1)$$

WSS = water surface slope (%);
x = clinometer or Abney level reading in degrees (°);
h = straight line distance; and
r = reach length.

Water surface slope calculations were made using the mean length of each reach measured along the midpoint. This was done to isolate the variance of each tool and allowed measures of reach length to be treated separately.

Estimates of WSS at the three reaches were obtained with the electronic map wheel and GIS by highlighting the location of each reach on the topographic maps. Observers traced and digitized the stream length between the two elevation contours that bounded the midpoint of a reach. The stream length was read directly off the map wheel and calculated as the average of three tracings or, in the case of the GIS, calculated in ARC/INFO from a single digitization. The stream length was divided by the elevation increment (12.2 m on most 1:24,000-scale USGS topographic maps) between the elevation contours to calculate WSS.

Inconsistencies detected early in the collection of field data suggested that variability among individual tools and whether readings were taken in an upstream or downstream direction could affect the accuracy of the Abney level and clinometer. Therefore, intratool variability was assessed using identical copies of each tool (two Abney levels, four clinometers) under controlled conditions. Two stable platforms differing in height were used to provide conditions such that a small angle approximating that of a natural stream channel could be measured. Readings in degrees were recorded as all six tools were iteratively placed on the lower platform and sighted on the higher platform. The procedure was repeated with tools placed on the higher platform and sighted on the lower platform. The degree readings were translated to hypothetical WSS values with equation (1).

The correspondence between WSS estimated in the field and GIS estimates of WSS was evaluated with data from 119 stream reaches (WSS range = 0.1–7.2%, mean length = 185 m) across the Salt River watershed of western Wyoming and eastern Idaho. Field estimates of WSS were obtained with an Abney level rather than a surveying level because many reaches were in remote, backcountry areas. The senior author made all measurements with the Abney level and was assisted by a technician in the determination of reach lengths and straight-line distances. All WSS were measured during base flows with the same Abney level, and readings were taken in a downstream direction. Visual obstructions often required that a reach be divided into segments and that WSS be measured on individual segments. When this occurred, a single, weighted average WSS value was calculated based on the proportions of the reach that individual segments constituted. Reaches were located in the field by using available landmarks; their positions were recorded on 1:24,000-scale USGS topographic maps and later were digitized following procedures described above for comparison with Abney level estimates of WSS.

Data analyses.—Tool accuracy was tested with a randomized block analysis of variance (ANOVA). The three reaches were the blocking variable and tool type was the main effect. Both variables were treated as fixed effects, and type III sums of squares were used to construct the error term because of unequal sample sizes (Shaw and Mitchell-Olds 1993). A posteriori pairwise mean comparisons were conducted with Scheffé's *S*-test (Scheffé 1953) and statistical significance was ascribed at $\alpha = 0.05$.

Intertool precision was quantified by calculating the range, SE, and coefficient of variation (CV) for WSS estimates obtained at the three reaches. Intratool precision was quantified by calculating the range of hypothetical WSS values observed with each tool type and by pairwise comparison of the upslope and downslope WSS values obtained with the same tool. Precision of reach length measures was determined by calculating CV.

Simple linear regression and the method of least squares were used to quantify the relationship between WSS measured in the field and WSS estimated with a GIS. Visual inspection of normal probability plots and residual plots suggested that basic assumptions regarding normality and homogeneity of error terms, as well as linearity, were met. Thus, a linear model based on untransformed data was valid.

Results

The accuracy of the five tools differed (F = 56.10; df = 4, 117; $P < 0.01$), but the interaction between tools and reaches was also significant (F = 6.55; df = 8, 117; $P < 0.01$), possibly confounding interpretation of tool accuracy. However, examination of the interaction plot (Figure 2) indicated that tool accuracy could be interpreted directly for two reasons. First, interactions occurred between tools with similar biases. The clinometer, map wheel, and GIS consistently overestimated WSS relative to the surveying level (biases of 34, 41, and 53%, respectively), whereas the Abney level mimicked the surveying level. Second, interactions were not consistent. Differential responses were observed even where WSS were similar (between reaches 2 and 3), suggesting that interactions were due to random error. Pairwise mean comparisons verified what was apparent in Figure 2. Estimates of WSS derived with the Abney and surveying levels did not differ, but the

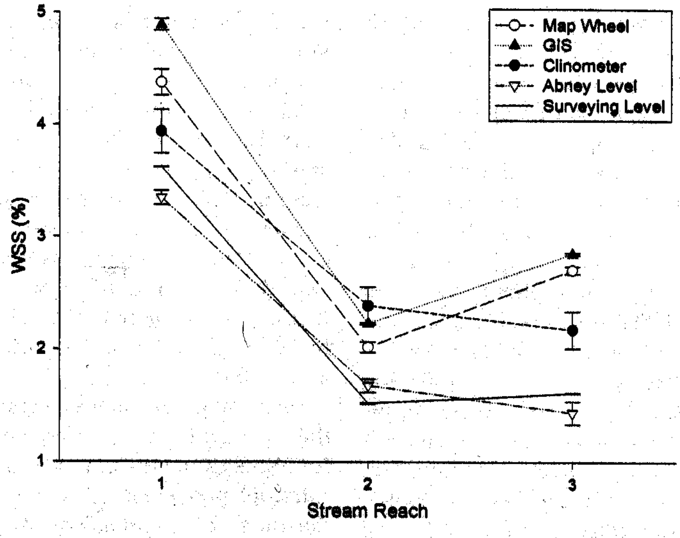

FIGURE 2.—Water surface slopes (WSS) estimated with five tools at three stream reaches. Crossing lines denote interactions; error bars are ±SE.

accuracy of both tools differed significantly from the map wheel, GIS, and clinometer.

The surveying level was the most precise tool, with a SE less than 0.01 and a CV of 0.26% (Table 1). The next most precise tool was the GIS followed, in order, by the map wheel, Abney level, and clinometer. Intratool variability associated with Abney levels and clinometers was substantial. The maximal range for hypothetical WSS values obtained with the two Abney levels was 1.0–1.6% in a downslope direction, and range was 1.0–3.1% for clinometers measuring the same angle in an

TABLE 1.—Statistical summary of water surface slopes (WSS) estimated with five tools at three stream reaches. Topographic maps were used in conjunction with the geographic information system (GIS) and map wheel. Estimates of WSS obtained with the surveying level were used as baselines when calculating the biases of other tools.

Reach and tool	Mean WSS (%)	SE	CV (%)	Range in WSS (%)	*N*	Bias (%)
Reach 1						
Surveying level	3.62	<0.01	0.12	3.62–3.63	2	
Abney level	3.35	0.06	6.31	2.93–3.59	11	−7
Clinometer	3.94	0.19	16.31	3.26–5.37	11	+9
GIS	4.89	0.05	3.60	4.69–5.17	11	+35
Map wheel	4.38	0.11	7.78	4.00–4.92	9	+21
Reach 2						
Surveying level	1.52	<0.01	0.44	1.52–1.52	2	
Abney level	1.68	0.06	11.47	1.27–2.03	11	+11
Clinometer	2.39	0.17	23.36	1.86–3.39	11	+57
GIS	2.23	0.01	0.90	2.19–2.25	11	+47
Map wheel	2.02	0.05	7.01	1.84–2.24	9	+33
Reach 3						
Surveying level	1.61	<0.01	0.23	1.61–1.61	2	
Abney level	1.44	0.10	23.25	0.74–2.08	11	−11
Clinometer	2.17	0.16	25.05	1.49–2.97	11	+35
GIS	2.85	0.01	1.10	2.80–2.90	11	+77
Map wheel	2.70	0.03	3.75	2.54–2.88	9	+68
Mean of all reaches						
Surveying level		<0.01	0.26		6	
Abney level		0.07	13.68		33	−2
Clinometer		0.17	21.57		33	+34
GIS		0.02	1.87		33	+53
Map wheel		0.06	6.18		27	+41

TABLE 2.—Summary of intratool variation within and among clinometers and Abney levels. Measurements were taken under controlled conditions on the same angle in both upslope and downslope directions. Hypothetical water surface slope (WSS) values were calculated from equation (1).

Tool and tool number	Upslope (°)	Downslope (°)	Upslope WSS (%)	Downslope WSS (%)	WSS Difference (%)
Clinometer					
1	0.6	1.4	1.0	2.4	1.4
2	1.8	0.6	3.1	1.0	2.1
3	1.5	0.6	2.6	1.0	1.6
4	0.8	1.4	1.4	2.4	1.0
Abney level					
1	1.0	0.6	1.7	1.0	0.7
2	1.1	0.9	1.9	1.6	0.3

upslope direction (Table 2). Discrepancies between estimates of the same angle measured in upslope and downslope directions with the same tool were 0.3% and 0.7% for the Abney levels and ranged from 1.0% to 2.1% for the clinometers.

Measures of reach length were precise. Coefficients of variation for thalweg and midpoint reach lengths were 2.57% and 2.18%, respectively, across the three reaches. However, measuring the thalweg took observers on average four additional measurements, and remarks made by observers suggested they felt less confident in this endeavor. Thalweg estimates of reach length were 3.19% longer on average than reach lengths estimated along the midpoint.

The slope of the regression line depicting the relation between WSS measured in the field and WSS estimated with the GIS was significantly less than 1 (95% confidence interval = $0.64 \leq \beta_1 \leq 0.79$; SE = 0.04; Figure 3), suggesting a tendency for the GIS to overestimate WSS. The regression accounted for most of the observed variation (r^2 = 0.74), but considerable variation remained unexplained and departures from predicted WSS ranged up to 2.3%.

Discussion

Tool Accuracy and Precision

Information pertaining to the quality of data obtained with different tools can be used to explain the strength of observed relationships or make in-

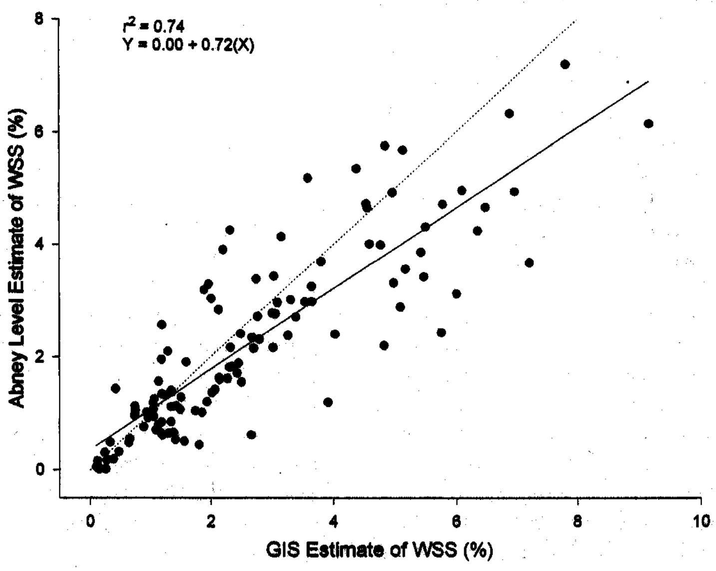

FIGURE 3.—Relationship between water surface slopes (WSS) measured in the field with an Abney level and estimated with a GIS from topographic maps. The solid line depicts least-squares regression, the dashed line represents a 1:1 relationship. The slope of the regression line differs significantly from 1 (95% confidence interval = $0.64 \leq \beta_1 \leq 0.79$).

formed decisions regarding equipment selection. For field studies requiring data of the highest quality, the accuracy and precision exhibited by the surveying level make it the best choice for measuring WSS. In field studies where data requirements are less restrictive, or where other factors preclude the use of a surveying level, a choice must be made between using a clinometer or an Abney level. Clinometers and Abney levels both are inexpensive, portable, and easy to use in the field. However, the intratool variability exhibited by clinometers invalidates inferences regarding the accuracy of these tools. Discrepancies observed among clinometers could result in WSS estimates for the same reach that differed markedly and could alter a stream classification (Knighton 1984; Rosgen 1994), weaken the strength of intrastudy relationships, or cloud interstudy comparisons. Clinometers were also the least precise tool, a troubling fact given that clinometers are frequently used to measure WSS. Thus, the use of clinometers may partially account for discrepancies in WSS-related distributional limits of fish (Fausch 1989) or the inconsistent nature of the relation between WSS and fish biomass (e.g., Lanka et al. 1987; Kozel and Hubert 1989). The Abney level had low intratool variability and moderate precision, and its accuracy did not differ from the surveying level. For these reasons, and given the similar costs and portability of Abney levels and clinometers, the Abney level is a better choice for measuring WSS in the field.

For studies conducted at broad spatial scales, estimating WSS from topographic maps can obviate the time and expense of sending a crew into the field. Water surface slopes calculated with a map wheel or GIS were precise, but some precision was probably an artifact of our methods. In real-world situations, observers must locate their position on the map without assistance, a process mediated by familiarity with a site, available landmarks, and experience level. It would have been unfair to expect this from our observers, given that they were only briefly at each of the three study reaches. Therefore, the precision of WSS estimates derived with the map wheel or GIS is probably lower than that demonstrated in this study.

Estimates of WSS derived from topographic maps were significantly higher than estimates obtained with the surveying level. Overestimation of WSS from maps is best attributed to decreased map resolution and the resultant inability of a map to precisely mimic stream sinuosity. Thus, stream reaches may be depicted as straight on a map, yet possess some sinuosity when observed in the field. This effectively makes streams shown on maps shorter than in reality and partially accounts for the tendency of maps to underestimate stream lengths (Morisawa 1957). Overestimation of WSS occurs when the artificially shortened stream reach length is divided into the elevation change over the same reach length interval.

Several recommendations regarding field methodologies can be made based on our results. Given the intratool variability exhibited by clinometers and Abney levels, these tools should be properly calibrated prior to field measurements. Subsequently, WSS should be measured with the same tool for the duration of a study and consistently in either an upstream or downstream direction. Abney levels and clinometers should be steadied on top of a leveling rod to enhance the precision of measurements. Reach lengths should be measured along the midpoint of the wetted width. Reach lengths measured along both the thalweg and midpoint were precise, but measuring the midpoint required fewer measurements and observers were more confident with the quality of their measurements. Reach lengths measured along the midpoint and thalweg differed slightly, but the size of the difference is inconsequential when used in a WSS calculation.

Scale Correspondence

Estimates of WSS measured in the field and calculated with the GIS were related, but considerable variation remained unexplained. Unexplained variation was probably a function of map resolution and accuracy, measurement error, and errors associated with locating reaches on the map. Maps provide abstractions of the real world and by necessity can include only limited detail. Given this, estimates of WSS from a map are at best approximations because streams exhibit heterogeneity in WSS at relatively small spatial scales (Frissell et al. 1986; Grant et al. 1990). Inaccuracies associated with map depictions of streams and elevation contours will further decrease the accuracy of WSS estimates derived from maps. National map accuracy standards (NMAS) require that easily identified points on maps with scales smaller than 1:20,000 exhibit SD less than 8 m (Bolstad and Smith 1995). Thus, 95% of easily identified points are within 16 m of the true value. However, Thompson and Rosenfield (1971) evaluated USGS 1:24,000-scale maps and found that 17% of the maps did not meet the NMAS.

Other sources of unexplained variation are measurement error stemming from the digitization process and the use of the Abney level. Digitization has errors attributable both to the user (Bolstad et al. 1990) and the digitizing tablet (Warner and Carson 1991), but these errors are small relative to measurement error associated with an Abney level. While the average accuracy of the Abney level did not differ from the surveying level, the Abney level was a less precise tool. As a result, Abney level estimates of WSS obtained in the field would at times have differed from the estimates that a surveying level would have provided.

Locating reaches on maps had the potential to incorporate variation into the relation between WSS measured in the field and estimated with a GIS. Rather than trying to locate each end of a reach on the map, the midpoint of the reach was placed into a stream segment depicted on the map (segments occurred between adjacent intersections of the stream and elevation contours) and this segment was used to calculate WSS. Thus, the length of the segment provided a margin for error, but the ends of the reach measured in the field would rarely coincide with the ends of the stream segment depicted on the map. As a result, the map stream segment can only be viewed as a close approximation to the actual stream reach.

This study evaluated one approach to the estimation of WSS with a GIS, but alternatives exist. Digitizing from maps with scales other than 1:24,000 is one possibility. Use of smaller scale maps (e.g., 1:100,000) will decrease time and money commitments, but sacrifice some accuracy because map standards are less stringent (Bolstad and Smith 1995) and decreased resolution will portray streams more grossly. Digitization from larger scale maps reverses the strengths and weaknesses associated with small scale maps, but large-scale maps do not exist for many areas. Another possibility is presented by procedures that automatically extract stream networks from digital elevation models (DEM) based on user-specified channel maintenance values (Tribe 1992). Automated procedures generate data that can be exported to a GIS whereby WSS can be calculated by using the elevation data associated with the stream network. Automated extractions can reduce time commitments and are an attractive option when data are needed across vast spatial scales, especially given the availability of DEM for virtually all of the United States (USGS 1998). Unfortunately, little information exists regarding the accuracy of automated procedures.

The preceding discussion is not meant to posit one method over another but to highlight the tradeoffs that will occur when choosing a method. Water surface slope is one of a handful of variables relating strongly enough to fish populations across broad spatial scales that it will be used increasingly. Therefore, careful decisions must be made when choosing how a GIS will be used to estimate WSS. Some methods will save time and money at the expense of accuracy and vice versa. In all cases, additional variation will be incorporated as nature is viewed with less resolution. This is a sobering fact given that relationships between WSS and fish populations, like many ecological relations, are rather weak to begin with (Peters 1991). Added variation may thus serve to mask otherwise meaningful relations.

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