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PRECISION OF CHANNEL WIDTH AND POOL AREA MEASUREMENTS[1]

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ABSTRACT: The precision of width and pool area measurements has rarely been considered in relation to downstream or at section hydraulic geometry, fisheries studies, long-term or along a continuum research studies, or agency monitoring techniques. We assessed this precision and related it to other stream morphologic characteristics. Confidence limits (95 percent) around mean estimates with four transects (cross-sections perpendicular to the channel centerline) ranged from ± 0.4 to 1.8 m on streams with a width of only 2.2 m. To avoid autocorrelation, transects should be spaced about three channel widths apart. To avoid stochastic inhomogeneity, reach length should be about 30 channel widths or ten transects to optimize sampling efficiency. Precision of width measurements decreased with decreased depth and increased with stream size. Both observations reflect variability caused by features such as boulders or coarse woody debris. Pool area precision increased with pool area reflecting increased precision for flat, wide streams with regular pool-riffle sequences. The least precision occurred on small, steep streams with random, boulder or coarse woody debris formed pools.

(KEY TERMS: stream morphology; aquatic habitat; stream surveys; survey design.)

INTRODUCTION

The variation of stream channel width with flow, basin area, habitat unit type, vegetation and soil type has been considered by many (e.g., Zimmerman *et al.*, 1967; Leopold and Maddock, 1953; Murgatroyd and Ternan, 1983; Touysinhthiphonexay and Gardner, 1984). Studies of pools included spacing (Keller, 1978; Keller and Melhorn, 1978; Grant *et al.*, 1990; Montgomery *et al.*, 1995), variation of pool area (Lanka *et al.*, 1987; Kozel *et al.*, 1989; Myers and Swanson, 1991), mechanisms (Robison and Beschta, 1990), formation, formative features and resiliency of the pool-riffle sequence (Tinkler, 1970; Gregory *et al.*, 1994; Myers and Swanson, 1994). Studies of the impact of land management on streams often compare changes in width or pool area (PA) or spacing with time (Heede, 1981 and 1986; Ryan and Grant, 1991; Gregory *et al.*, 1994; Myers and Swanson, 1996a, b), among streams receiving different treatments (Myers and Swanson, 1994, 1995), or along stream reach continuums that experienced different treatments (Gunderson, 1968; Kondolf, 1993).

Variability at a site affects width or PA studies. Wolman (1955) and Knighton (1975) found that width measurements varied substantially along short reaches and caused scatter around downstream hydraulic geometry relationships. Hydraulic exponents may vary substantially within short reaches where the flow is constant (Knighton, 1975; Richards, 1976a; Phillips and Harlin, 1984). Myers and Swanson (1991) found that the high variance, or low precision, of measurements limited the value of stream measurements of PA.

Precision is the degree to which an estimate represents the appropriate population value (Thompson, 1992) and is expressed as a confidence limit or coefficient of variation. Although measurement precision affects the design of monitoring studies and comparisons among treatments (Thompson, 1992), and many studies cited above found that variability decreased the value of their results, we found no published studies of the precision of width or PA measurements.

Our objective is to improve future studies and provide a better understanding of previous studies of the variation of stream width and pool area with location or time by considering the precision of transect-based width and PA estimates. We make recommendations for transect numbers and spacings that optimize

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measurement precision and survey time. Our study relates to the pool-riffle scale of Frissel *et al.* (1986). Because randomly located features such as boulders and coarse woody debris vary among watersheds (Robison and Beschta, 1990; Myers, 1996), some streams may be inherently more variable. This potentially affects survey strategies. Therefore, we also analyzed the variation of precision estimates with stream morphology to assist in the selection of survey methods based on the type of stream.

BACKGROUND

Channel and Water Width

The ability to detect width changes with time, $w = b(t)Q^{n(t)}$ depends on measurement precision which depends on in-stream structural features and the selection of reach lengths. Surveyors should select stochastically homogeneous reaches to minimize measurement variance. Stochastic homogeneity is the condition that randomly chosen measurements are drawn from the same probability distribution such that expected value and variance for any measurement y, E(y x) and Var(y | x), is constant for any location x on the reach. For example, a survey reach combining reaches with scour pools and reaches with step-pools would be inhomogeneous yielding descriptive statistics not representative of either reach.

Confidence limits are higher for correlated observations because of decreased effective n (where n is sample size). Although spatial autocorrelation of channel width is generally insignificant after two widths (Furbish,1985; Robison and Beschta, 1990) some studies have found cyclic variations in width along a channel in relation to the spacing of pools and riffles (Harvey, 1975, Richards, 1976a, b). Our transects were spaced to measure the phenomenon of autocorrelation.

Water width, measured at baseflow, represents the lowflow channel which may be a stable indicator of basin conditions (Richards, 1982). The baseflow channel coincides within a few centimeters with various vegetative indicators (Hupp and Osterkamp, 1985), has been useful in analyzing long-term changes due to land management (Dose and Roper, 1994; Myers and Swanson, 1996a) and is essential in definitions of pool area (BLM, 1978; USFS, 1985, 1992; Andrus *et al.*, 1988; Hankin and Reeves, 1988; Myers and Swanson, 1991). Thus, many types of studies and surveys depend on the precision of water width which we analyzed herein.

Pool Area

Many studies showing the importance of pools as fish cover (Baltz *et al.*, 1991; Heggenes *et al.* 1991) and indicators of habitat quality (Andrus *et al.* 1988; Myers and Swanson, 1995) estimated PA using systematically spaced transects along a reach. If regularly spaced pools coincide with the transect spacing (i.e., Richards 1976a, b), it is possible to miss all pools or to sample every pool and no riffles. Thus, the estimate varies based on the correspondence of transects and pool location.

STUDY AREA

We used 47 stream segments in six mountain ranges of central and northwestern Nevada (Figure 1). All sites are within the basin and range geologic province (Stewart and Carlson, 1978). Sagebrush steppe to pinyon-juniper woodlands dominated the upland vegetation. Riparian vegetation included grasses, sedges, shrubs, and trees. Based on the distribution of stream types found by Myers and Swanson (1991), we chose sites attempting to represent small streams in Nevada rangelands. There were three primary stream types with a variety of subtypes based on substrate (Rosgen, 1994). Table 1 presents site characteristics. Table 2 describes Rosgen stream types used herein to describe the stream cross-section.

METHODS

At baseflow, we surveyed transects, cross-sections perpendicular to the stream centerline, at spacings of 1 to 1.5 active channel widths. The spacing was chosen based on the lack of autocorrelation found by other authors on similar small streams (e.g., Furbish, 1985; Robison and Beschta, 1990). Baseflow exists when streamflow consists almost entirely of ground water discharge (Mosley and McKerchar, 1993). We assumed that baseflow occurred when spring runoff had ceased and flow rates had become essentially constant. A sampling unit is a reach sampled with 25 transects.

The active channel is the point where an area-width curve would substantially change slope (Williams, 1978) as estimated in the field. Vegetation, scour marks, and bar height aided delineation (Leopold, 1994). At each transect, we measured water width (WW), channel width (CHW), fraction of the water width that is a pool (PF), maximum channel depth (CDEP) and interbank width at twice CDEP, water depth at the quarter points ($d_{1/4}$, $d_{1/2}$, $d_{3/4}$), both banks and the maximum depth (d_l, d_r, and d_{max}), substrate fractions [silt/clay, < 0.062 mm; sand, 0.062< sand < 2 mm; gravel, 2 mm < gravel < 64 mm; cobble, 64 mm < cobble < 256 mm; and boulders, > 256 mm, CWD (woody debris with diameter greater than 25 mm)]. We combined CWD and BLD into CWDBLD because of many zero values in each category and similar pool-forming function (Myers and Swanson, 1994).

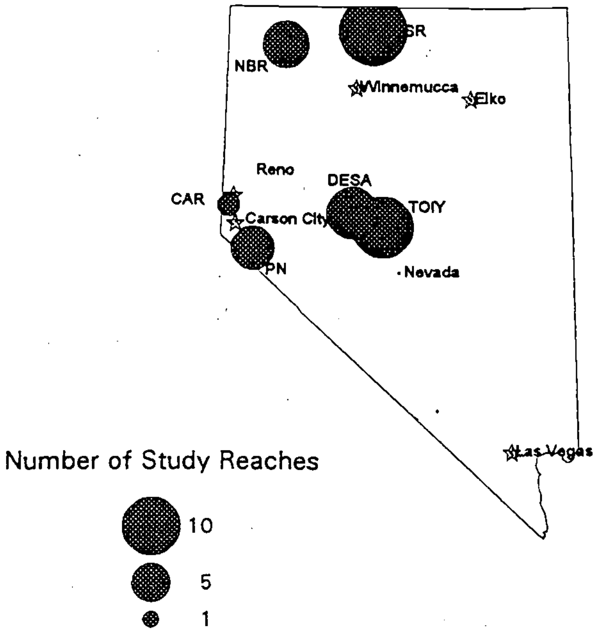

Figure 1. Location Map of Mountain Ranges Containing Study Sites. PN is Pine Nut Mountain; SR is Santa Rose Mountains; NBR is North Black Rock Mountains; DESA is Desatoya Mountains; TOIY is Toiyabe Mountains; CAR is the Carson Range. See Table 1 to see which site is located in each mountain range. Circle diameter represents the number of sites in each range.

We estimated average water depth as:

$$\bar{d} = \frac{d_{1/4} + d_{1/2} + d_{3/4}}{4} + \frac{d_l + d_r}{8} \tag{1}$$

Water width/depth ratio is the quotient of WW and $\bar{d}$. Channel width/depth ratio (CHWD) is the quotient of CHW and (CDEP - d_{max} + $\bar{d}$). Pool area, PA, is the fraction of stream surface area classified as a pool:

$$PA = \frac{\sum_{i=1}^{i=n} PF_i \times WW_i}{\sum_{i=1}^{i=n} WW_i} = \frac{\sum_{i=1}^{i=n} PF_i \times WW_i}{n \times \overline{WW}} \tag{2}$$

where n is the number of transects. Pools are distinct habitat units with hydraulic gradient less than the stream average and subcritical flow conditions except for an entry jet which may affect up to 15 percent of the surface (Grant *et al.,* 1990). Table 3 presents the definition of variables calculated from transect and plan measurements and their simple correlation.

We also measured the length and water width at each end and in the middle of each habitat unit according to Hankin and Reeves (1988). All length and width measurements were standardized by dividing by the average water width. Thus, the expected value of water width is always 1. Repeatability of the identification of basic units (pools and nonpools) is high (Roper and Scarnecchia, 1995). However, for many units, end points are nebulous (Montgomery *et al.,* 1995). We identified ends of units as the points where their width expressed as a fraction of water width reached 0.5. Pocket pools, edgewater and other small units were not identified as separate units. Any unit not a pool is considered a nonpool to avoid differences of rapids, riffles, cascades and other nonpool units.

SAMPLING PRECISION

General Concepts

As measures of precision, we considered confidence limits about the mean and the coefficient of variation CV:

$$CV = \frac{\sqrt{\sigma_x^2}}{\bar{x}} \tag{3}$$

The numerator is the sample standard deviation (sd) and, for a given mean value, the precision increases as the dispersion around the mean decreases.

To evaluate the information lost due to close spacing of transects in a sample, we considered spatial autocorrelation of channel and water width among transects, defined as:

$$\rho(W)_\tau = \frac{Cov(W_t, W_{t-\tau})}{Var(W_t)} \tag{4}$$

TABLE 1. Descriptive Statistics for the Study Reaches. Stream type is described in Table 2. sd is standard deviation. 95 percent conf. limits (CL), upper (u) and lower (l) for five transects. $\rho(\,)_1$ is first order autocorrelation for water or channel width. PN is Pine Nut Mountain; SR is Santa Rose Mountains; NBR is North Black Rock Mountains; DESA is Desatoya Mountains; TOIY is Toiyabe Mountains; CAR is the Carson Range.

No.	Reach	Channel Width Mean (sd)	Water Width Mean (sd)	95 Percent CL		Transect Spacing		$\rho(cw)_1$	$\rho(ww)_1$	Str. Type	Str. Order	Drng. Area (km^2)	Mtn. Range
				u	l	(m)	Widths						
						Short Reaches (25 transects)							
1	Abel Ck.	2.62 (.86)	1.62 (.41)	.82	1.20	3.0	1.14	0.460^1	-0.073	B3	2	9.82	SR
2	NF Abel Ck.	1.54 (.35)	0.93 (.40)	.82	1.28	2.0	1.30	0.004	0.470^1	B3	2	3.52	SR
3	Singas Ck.	3.32 (1.07)	2.42 (.92)	.59	1.27	3.0	0.90	m	m	C3	3	7.47	SR
4	Siard Ck.	1.98 (.93)	1.03 (.40)	.72	1.44	3.0	1.52	0.448^1	0.342	B5	2	9.66	SR
5	Martin C 1	2.91 (.44)	1.80 (.43)	.67	1.41	4.0	1.37	0.265	-0.163	B4	3	13.56	SR
6	Martin C 2	3.15 (.99)	1.89 (.63)	.74	1.16	4.0	1.27	0.712^1	0.418^1	B4	3	10.76	SR
7	Cabin C 1	1.93 (.38)	1.45 (.38)	.81	1.30	3.0	1.55	0.461^1	-0.152	B4	3	23.06	SR
8	Cabin C 2	2.15 (.63)	1.51 (.45)	.76	1.24	3.0	1.40	0.064	0.282	C4	3	17.11	SR
9	Cabin C 3	1.37 (.39)	0.90 (.27)	.72	1.31	2.0	1.46	0.258	0.349	B4	2	6.44	SR
10	Dutch John	4.00 (1.08)	2.58 (.82)	.72	1.30	4.0	1.00	0.419	0.442	C4	3	24.13	SR
11	NF L Humb 1	4.07 (2.06)	2.36 (.87)	.75	1.17	5.0	1.23	0.496^1	0.382	C4	3	48.90	SR
12	NF L Humb 2	6.82 (1.86)	3.72 (1.1)	.76	1.35	8.0	1.17	0.184	0.251	B4	4	89.03	SR
13	Big Den 1	1.24 (.55)	0.72 (.22)	.69	1.34	1.5	1.21	0.520^1	0.459^1	B6	2	5.59	DESA
14	Big Den 2	1.56 (.47)	0.82 (.33)	.76	1.30	1.5	0.96	0.640^1	0.421^1	B6	2	5.59	DESA
15	Big Den 3	1.14 (.24)	0.75 (.23)	.64	1.38	2.0	1.75	-0.137	-0.083	C4	2	2.27	DESA
16	Big Den 4	1.47 (.50)	1.08 (.39)	.76	1.14	2.0	1.36	0.386	0.378	A4	2	0.73	DESA
17	Edwards	1.47 (.46)	0.81 (.32)	.74	1.24	2.0	1.36	0.151	0.139	C4	2	5.30	DESA
18	Smith C 1	1.90 (.45)	1.34 (.36)	.78	1.24	3.0	1.58	0.190	-0.021	A4	2	7.46	DESA
19	Smith C 2	2.58 (.79)	1.68 (.43)	.78	1.29	3.0	1.16	0.595^1	0.240	B4	3	47.98	DESA
20	Wash. 1	2.39 (.43)	1.98 (.43)	.81	1.14	3.0	1.26	0.209	0.152	B4	3	19.26	TOIY
21	Wash. 5	1.07 (.27)	0.78 (.25)	.83	1.20	1.5	1.40	0.239	0.092	B4	3	2.02	TOIY
22	Wash. 6	0.82 (.31)	0.50 (.18)	.76	1.37	1.5	1.83	0.028	-0.001	B4	2	0.55	TOIY
23	Wash. 4	2.37 (.40)	1.94 (.41)	.81	1.24	3.0	1.26	0.294	-0.061	B4	3	13.52	TOIY
24	Tierney 1	2.12 (.99)	1.12 (.41)	.82	1.28	3.0	1.42	0.548^1	0.153	B4	3	13.49	TOIY
25	Tierney 2	1.47 (.28)	0.87 (.23)	.69	1.31	3.0	2.04	0.079	0.058	B4	3	12.74	TOIY
26	Tierney 3	1.52 (.27)	1.06 (.19)	.80	1.29	3.0	1.97	0.095	0.037	A4	4	36.39	TOIY
27	Cottonw. 1	2.31 (.51)	1.69 (.53)	.76	1.40	3.0	1.30	0.380	0.202	A4	3	20.28	TOIY
28	Cottonw. 2	2.52 (.49)	1.88 (.50)	.80	1.32	3.0	1.19	0.356	-0.027	C4	3	18.33	TOIY
29	San Juan 1	2.28 (.62)	1.43 (.45)	.67	1.40	3.0	1.32	0.180	0.146	B4	4	73.73	TOIY
30	San Juan 2	2.44 (.87)	1.42 (.48)	.81	1.21	3.0	1.23	0.387	0.009	B4	4	62.11	TOIY
31	Red Can. 1	1.63 (.48)	0.97 (.30)	.73	1.25	1.5	0.92	-0.001	-0.104	B4	2	6.18	PN
32	Red Can. 1A	0.83 (.34)	0.58 (.24)	.64	1.28	1.0	1.20	0.318	0.216	B5	2	2.04	PN
33	Red Can. 2	1.52 (.29)	1.14 (.32)	.70	1.43	1.5	0.99	-0.174	0.002	B4	3	25.28	PN
34	Red Can. 3	1.40 (.38)	0.92 (.27)	.73	1.30	1.5	1.07	0.413	0.176	C4	3	26.12	PN
35	Redf Can. 4	1.12 (.29)	0.76 (.19)	.72	1.19	1.5	1.34	0.157	0.006	B4	3	6.77	PN
36	Red Can. 5	1.54 (.36)	1.19 (.32)	.80	1.17	2.0	1.30	0.072	0.212	B4	4	19.28	PN
37	Mahogany 1	2.56 (.96)	1.90 (.68)	.75	1.38	3.0	1.17	0.568^1	0.469^1	C4	4	33.89	NBR

TABLE 1. Descriptive Statistics for the Study Reaches. Stream type is described in Table 2. sd is standard deviation. 95 percent conf. limits (CL), upper (u) and lower (l) for five transects. $\rho(\ )_1$ is first order autocorrelation for water or channel width. PN is Pine Nut Mountain; SR is Santa Rosa Mountains; NBR is North Black Rock Mountains; DESA is Desatoya Mountains; TOIY is Toiyabe Mountains; CAR is the Carson Range (cont'd.)

No.	Reach	Channel Width Mean (sd)	Water Width Mean (sd)	95 Percent CL u	95 Percent CL l	Transect Spacing (m)	Transect Spacing Widths	$\rho(cw)_1$	$\rho(ww)_1$	Str. Type	Str. Order	Drng. Area (km²)	Mtn. Range
					Short Reaches (25 transects)								
38	Mahogany 2	2.44 (.46)	1.96 (.45)	.73	1.37	3.0	1.23	0.164	0.414	A4	4	28.34	NBR
39	Summer Cp 4	2.10 (.42)	1.84 (.33)	.87	1.26	3.0	1.43	0.469[1]	0.367	B4	3	7.23	NBR
40	Summer Cp 5	1.96 (.34)	1.52 (.34)	.85	1.16	3.0	1.53	-0.076	0.087	B4	3	3.83	NBR
41	Mahogany 6	1.49 (.36)	1.06 (.26)	.75	1.24	3.0	2.01	0.191	0.037	B4	3	15.17	NBR
42	Mahogany 7	1.27 (.44)	0.98 (.22)	.83	1.21	3.0	2.36	-0.085	0.297	B4	3	11.91	NBR
43	Mahogany 8	1.74 (.47)	1.46 (.45)	.80	1.22	3.0	1.72	0.108	0.168	B4	3	5.27	NBR
44	Willow	1.55 (.44)	1.13 (.33)	m	m	2.0	1.29	0.104	-0.079	C4	2	4.21	NBR
45	Reese	4.90 (.96)	2.89 (.51)	.70	1.25	8.0	1.63	0.382	-0.242	C4	5	872.5	TOIY
49	Big Mead 1	0.95 (.37)	0.72 (.22)	.83	1.24	2.0	2.10	0.560[1]	0.463[1]	E4	2	2.27	CAR
50	Big Mead 2	1.32 (.30)	0.89 (.31)	.88	1.25	2.0	1.52	0.094	0.019	E4	1	2.23	CAR

[1] Autocorrelation is significant at $p = 0.05$.

where τ is lag, w is either CHW or WW, and the numerator is covariance. The sample estimate is calculated as in Salas *et al.* (1980).

TABLE 2. Characteristics of the General Rosgen (1994) Stream Types Represented in this Study. All variable ranges reported represent the major ranges of the classification. The subtypes 3, 4, 5 and 6 in Table 1 represent a dominant substrate class of cobble, gravel, sand or silt/clay, respectively.

Type	Entr. Ratio	Channel W/D	Sinuosity	Gradient
A	< 1.4	< 12	< 1.2	> .04
B	1.4-2.2	> 12	> 1.2	.02-.04
C	> 2.2	> 12	> 1.4	.001-.02
E	> 2.2	< 12	> 1.5	.001-.02

Channel and Water Width

Precision. The expected value estimator for width, E(w), is the mean, $\bar{w}$ determined from n transects. The variance of $\bar{w}$ is (Thompson, 1992):

$$Var(\overline{W}) = \left(\frac{N-n}{N}\right)\frac{\sigma_w^2}{n} \tag{5}$$

where N is population size. When n and N-n are large, by the Central Limit Theorem, the estimators of $\bar{w}$ are normally distributed (Thompson, 1992), and it is not necessary to assume the raw data are normally distributed to calculate confidence limits. However, our interests include the precision of width estimates with n of only 4 or 5 for which the normality assumption may be inappropriate. Therefore, assuming independence among transects, we randomly sampled 100 times without replacement the 25 width measurements to determine confidence limits about the mean for several different n. Because we estimated the mean using n transects, the $100(1-\alpha)$ confidence limits, where α is significance probability, are the range in the subsampled means containing the middle $100(1-\alpha)$ observations.

Table 1 illustrates that the 95 percent confidence limits for water width are not symmetric around the standardized mean of 1. Summer Camp 5 has the narrowest range (.85-1.16) and Big Den 3 has the widest range (.64-1.38) suggesting that confidence limits range from about 31 to 74 percent of the mean width. Expressed in meters, the width estimate on Summer Camp 5 and Big Den 3 ranges from 1.3 to 1.76 and from 0.48 to 1.04 meters, respectively.

TABLE 3. Correlation Matrix for Various Stream Cross-Section and Plan Variables Pooled Across all Short Reaches. Variables are measures or averages over an entire study site; n = 47.

Variable	PA	PACV	CHWCV	WWCV	CHWD	ENTR	SIN	GRAV	RUBL	CHW	CWDBLD	TRSP
PACV	-0.54											
CHWCV	0.15	0.31										
WWCV	0.04	0.25	0.70									
CHWD	0.37	-0.26	0.01	0.13								
ENTR	0.39	-0.29	0.36	0.19	0.15							
SIN	0.13	-0.31	-0.08	-0.13	-0.06	-0.05						
GRAV	-0.04	-0.21	-0.11	-0.07	0.31	0.18	0.33					
RUBL	-0.04	0.22	-0.14	-0.07	-0.16	-0.10	-0.47	-0.23				
CHW	0.47	-0.36	0.03	0.05	0.86	0.42	0.08	0.38	-0.19			
CWDBLD	-0.24	0.17	-0.11	-0.16	-0.32	-0.13	-0.12	-0.37	0.36	-0.24		
TRSP	-0.09	0.01	-0.04	-0.31	-0.35	-0.15	-0.01	0.15	0.06	-0.36	-0.21	
CHWIST	0.32	-0.05	0.38	0.38	0.39	0.28	-0.13	-0.18	-0.04	0.24	-0.20	-0.50

Variable Definitions

PA = pool area
PACV = coefficient of variation of PA
CHWCV = coefficient of variation of channel width
WWCV = coefficient of variation of water width
CHWD = channel width/depth
ENTR = entrenchment ratio, ratio of bank width at twice the maximum depth to the channel width
SIN = sinuosity
GRAV = fraction of channel bottom covered with gravel
RUBL = fraction of channel bottom covered with cobble
CHW = channel width
CWDBLD = fraction of channel bottom covered with CWD or boulders
TRSP = transect spacing in channel widths
CHW1ST = Lag 1 correlation of channel width

Precision improves with additional transects. Figure 2 contains graphs of the 95 and 90 percent confidence limits for the most variable (Big Den 3) and least variable (Summer Camp 5) sites as a function of n. To test H_0: $\mu_1 = \mu_2$, where μ is the expected value and the subscript represents a sample, for changes from year-to-year or site-to-site, a test statistic t* is calculated that corresponds to the calculation of confidence limits (Neter *et al.*, 1985). Thus, a comparable comparison is to determine whether the mean of one sample lies within the confidence limits of the sample it is being compared with for a significant difference to occur. From Figure 2, for 95 percent confidence on Big Den 3 with 4 and 5 transects, the difference must be .44 and .35 widths, respectively. On Summer Camp 5, there must be differences of .17 and .15 widths, respectively. The difference decreased by about 15 percent for 90 percent confidence. The difficulty in monitoring width changes is apparent. The minimum detectable difference decreases by up to 50 percent by doubling transects from five to ten.

Autocorrelation. Autocorrelation for first order lag of channel and water width was significant for 12 and 6 of 47 reaches (Table 1). Only two reaches had significant autocorrelation beyond lag 1(reaches 6 and 14, $\rho(cw)_2 = 0.529$ and 0.525, respectively; reach 14, $\rho(ww)_2 = 0.458$). From Dawdy and Matalas (1964), assuming that widths follow a first-order Markov process, variance is:

$$\hat{\sigma}^2 = \frac{n'}{n'-1} sd^2 = \left[1 - \frac{1-\rho_1^2}{n(1-\rho_1)^2} + \frac{2\rho_1\left(1-\rho_1^n\right)}{n^2(1-\rho_1)^2}\right]^{-1} sd^2 \quad (6)$$

where n and n′ is actual and effective sample size, respectively, and ρ_1 is lag 1 autocorrelation. For estimation with n = 25, n′ decreases as shown in

Figure 3. Based on autocorrelation and n′, a spacing of three channel widths appears to be the minimum for these streams.

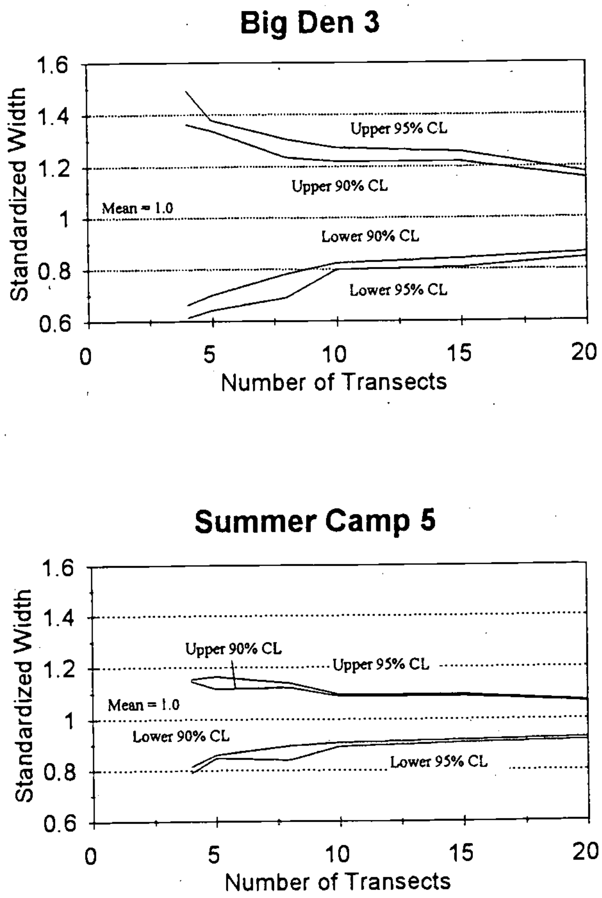

Figure 2. Confidence Limits Around the Mean for Standardized Width as a Function of Transect Numbers for Selected Stream Reaches.

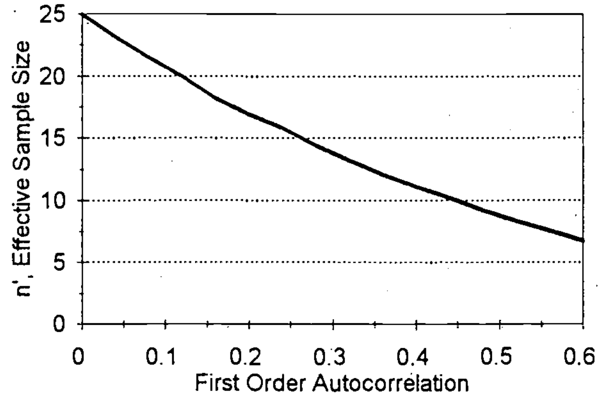

Figure 3. Effective Sample Size as a Function of First Order Autocorrelation.

Pool Area

Estimation of Observed Pool Area Variance. It is not possible to calculate Var(PA) by subsampling the transects because they represent only one estimate of PA. Yet, Var(PA) is the variance of the population of PA values that may be calculated from the infinite number of samples that could have been measured in a study reach. There was an infinite number of samples because the starting point is randomly chosen and there is an equal probability that transect measurement started at any location within the reach.

We digitized the habitat unit measurements of each reach, including standardized lengths and widths at the upstream, middle and downstream points of each habitat, to estimate Var(PA) (Figure 4). Using Monte Carlo methods to subsample PA for each chosen combination of spacings and number of transects, we started at random transects chosen from U(0,L-l). Here, U is the uniform distribution, L is reach length and l is subreach length (equal to spacing × (n-1), where n is the number of transects). Additional transects were sampled at spacings of l/(n-1) in the downstream direction. We chose to subsample 400 times which, on average, represents a spacing between starting locations of less than 0.1 water widths, should adequately describe the histogram.

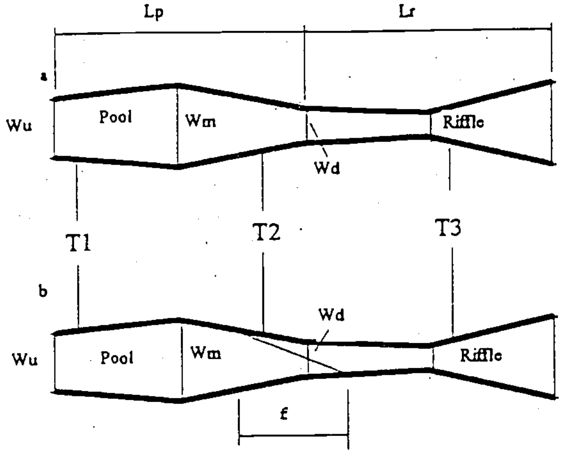

Figure 4. Digital Representation of Sampling Methods. In (a), where partial pools are not considered, transects are either pool (T1 and T2) or nonpool (T3). In (b) there is a length of stream which is a partial pool in which transects (T2) will have PF between 0 and 1. The proportion, f, of the total length Lp+Lr, containing partial pools, equals the proportion of total transects with partial pools. PF ranges from 0 to 1 linearly as shown on b. Wu, Wm and Wd are the upstream, middle and downstream widths of the pool. Wd for the pool equals Wu for the riffle. Spacing between transects depends on the sampling method.

We subsampled with and without consideration of partial pools (Figure 4). At low PA coefficients of variation (PACV), there was little difference (Figure 5). As PACV increased, consideration of partial pools improved the precision (decreased CV, Figure 5). Discrepancies between sampling procedures did not coincide with reaches having the most partial pools. Rather, the precision decreased as pool number increased and the subsamples contained a wide range of values. Inclusion of partial pools decreased the range.

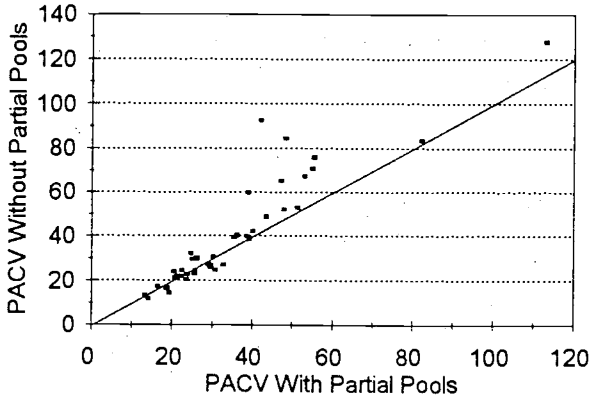

Figure 5. Comparison of PA Coefficient of Variation from the Two Different Monte Carlo Sampling Schemes. Sampling without partial pools assumes that all transects are either pools or nonpools; sampling with partial pools accounts for the proportion of transects that have both pools and nonpools.

For simplicity, we used the sampling scheme without partial pools to determine the relation of precision and numbers of transects or spacing. We determined PA for combinations of 4 (BLM, 1978), 5 (USFS, 1985), 8, 10, 15, 20 and 25 transects and 1, 2, 3, 5, 10 and 15 width spacings for all reaches. Subreaches with length exceeding 80 percent of the complete reach length [(L-l) > 0.8L] were not used because the variation would be artificially low.

The variance of PA decreased with increasing transects (n), but improvement (relative decrease in variance/added transect) decreased at high n (Figure 6). PACV frequently increased at higher spacing and sometimes with greater n. One width spacing resulted in the highest CV. The autocorrelation of closely spaced transects probably caused high and low estimates. Five width spacing often resulted in the second highest PACV for subsampled reaches which were 1.67 to 5 times (depending on n) longer than other reaches. On several reaches (i.e., Figure 6, Cabin Creek 2 and Big Den 4), PACV increased for many transects at a five width spacing. The presumption that increasing observations decreases the variance only holds for stationary conditions. These contrary observations suggest that long reaches are not stochastically homogeneous at the study reach scale.

To balance precision with cost, we considered the optimum n to be that where PACV decreased less than 3 percent/transect because it represents substantial flattening of curves on Figure 6. Comparisons with 2 and 4 percent varied the results slightly in expected directions. At that point, we determined the spacing responsible for the minimum PACV. The results (Table 4) show that either 8, 10, or 15 transects spaced at 2 or 3 widths are most desirable. Based on χ^2 tests, there was no significant association between n and spacing ($\chi^2 = 3.85$, p = 0.427, df = 4), n and stream type ($\chi^2 = 3.10$, p = 0.541, df = 4), or spacing and stream type ($\chi^2 = 4.59$, p = 0.332, df = 4) for selected n or spacing. Thus, there is no set rule for the best sampling scheme based on type.

TABLE 4. Optimal Transect Number and Spacing for the Determination of Pool Area Variance. Optimal transect number is the point at which the step to the next higher value resulted in less than a 10 percent reduction in the pool area coefficient of variation (PACV). Optimal spacing is that which resulted in the lowest PACV at the optimal number of transects. Frequency is the number of sites for which the specified number of transects or spacing was optimal.

Transects	Frequency	Percent
8	14	38.9
10	12	33.3
15	9	25.0
20	1	2.8
Total	36[1]	100.0
Spacing	**Frequency**	**Percent**
1	1	2.6
2	13	33.3
3	18	46.2
5	7	17.9
Total	39[1]	100.0

[1] For some streams, it was impossible to determine one or both of the optimal values tabulated here.

VARIATION WITH GEOMORPHOLOGY

To supplement the sampling recommendations discussed above and presented below, we assessed the influence of stream type and certain stream morphologic variables on measurement precision and autocorrelation.

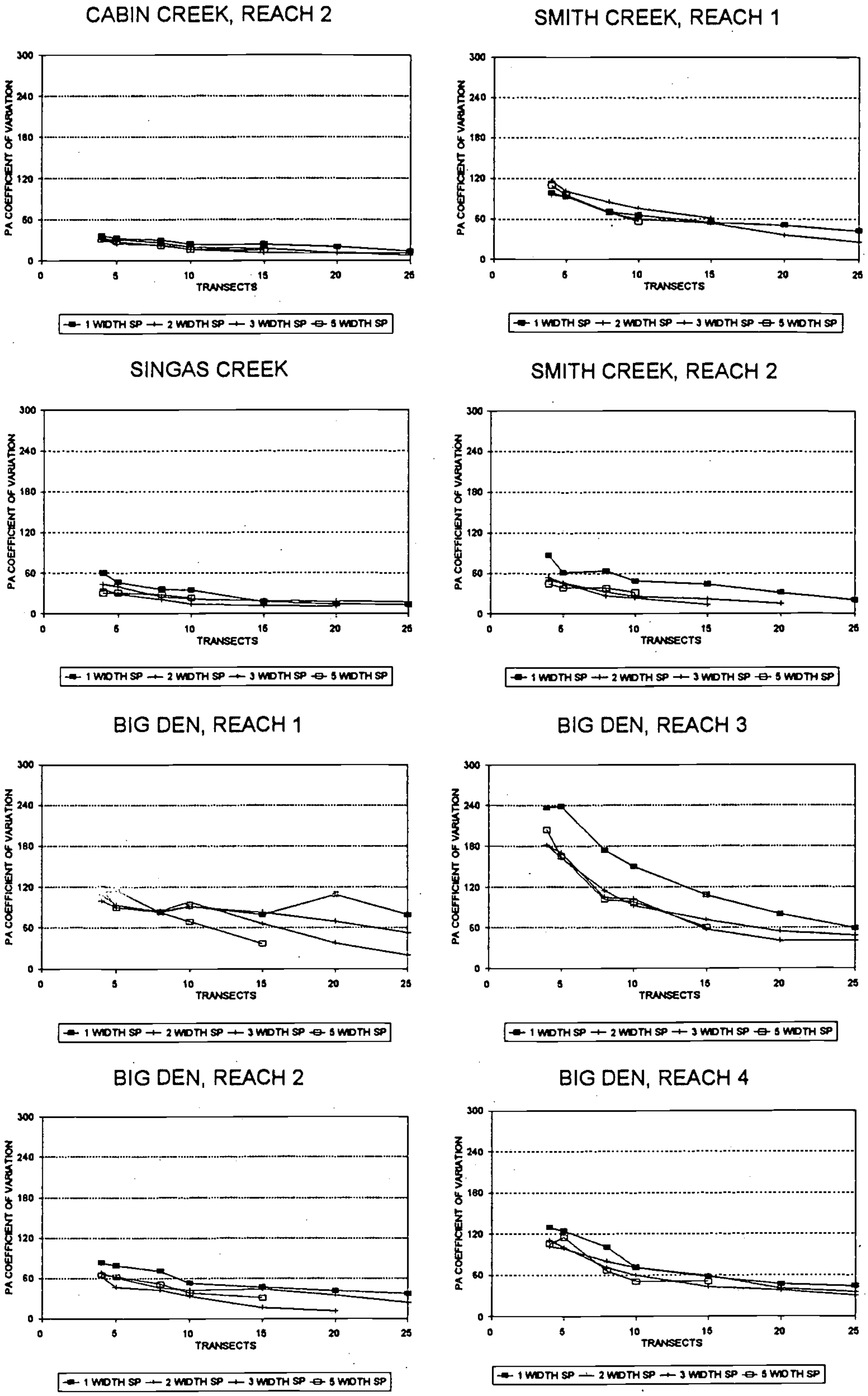

Figure 6. Variation of PA Coefficient of Variation (PACV) with the Number of Sampled Transects and the Spacing.

Channel and Water Width

Based on one-way analysis of variance (ANOVA), neither CHWCV or WWCV varied among stream type. We therefore examined stream type, size, substrate or spacing variables with a best subsets regression model:

$$CV = f(CHWD, ENTR, SIN, GRAV, RUBL, CHW, CWDBLD, TRSP) \tag{7}$$

where CV is coefficient of variation of either width measure and TRSP is the transect spacing in channel widths. We selected the best combination of independent variables by maximizing adjusted R^2. By both definition and observation, some of the independent variables in Equation (7) are correlated (Table 3). As suggested by Neter *et al.* (1985), we assured the variance inflation factor (VIF) never exceeded 10 to minimize the effects of multicollinearity and standard error of the coefficients. Also, within the given range of data, effects of potential multicollinearity are minimal (Neter *et al.*, 1985).

For CHWCV, none of the individual variables explained more than 2.8 percent of the variance and no combination explained a significant amount of variation. For WWCV, the analysis yielded (R^2=0.271, p = 0.008, VIF_{max} = 2.7, n = 41):

$$WWCV = 41.5 + 0.735\ CHWD - 5.93\ CW - 7.56\ TRSP \tag{8}$$

Although substantial variability remains unexplained, Equation (8) indicates several useful physical trends. As CHWD increased, width became more variable. As CHW increased, it became less variable. Simple correlation between WWCV and either CHWD and CHW is very low, but, by definition, is high between CHWD and CHW (Table 3). Partial correlations between WWCV and either CHWD or CHW controlling for the other variables are 0.28 and -0.36, respectively. Thus, decreasing depth or width corresponds to decreased precision, probably because boulders or CWD cause more variability in width on small and/or shallow streams.

Autocorrelation of Widths. Based on one-way ANOVA, neither water nor channel width lag 1 autocorrelation varied among stream type. Best subsets regression:

$$CW1ST = f(CHWD, ENTR, SIN, CHW1D, GRAV, RUBL, CWDBLD, PR, TRSP) \tag{9}$$

resulted in the following relation for lag 1 autocorrelation of channel width selected as described for Equations (7) and (8) (R^2 = 0.340, p = 0.003, VIF_{max} = 1.5, n = 42):

$$CW1ST = 0.655 + 0.0117\ CHWD - 0.317\ GRAV - 0.753\ CWDBLD - 0.228\ TRSP \tag{10}$$

Selection of CHWD indicated increased autocorrelation on wider, shallower streams where random features are less important. The negative coefficient of and high negative correlation with TRSP (Table 3) supported results from above that significant lag 1 autocorrelation is limited to very small spacings. That CWDBLD has a low simple correlation with CHW1ST (Table 3), yet is present in Equation (10), indicates that controlling for TRSP reveals decreased variability due to CWDBLD at shorter distances.

Pool Area Variance

We used the observed partial pool PACV (Figure 4) based on 10 transects at 3 width spacing over the short reaches for additional analyses. A best subset regression model:

$$PACV = f(CHWD, CHWDCV, ENTR, ENTRCV, SIN, GRAV, RUBL, CWCV, CWDBD, PA, PSP, PLNGT) \tag{11}$$

where PSP is pool spacing and PLNGT is pool length resulted in selection of PA as the only useful explanatory variable (R^2 = 0.274, p = 0.018, n = 41).

$$PACV = 59.8 - 56.1\ PA. \tag{12}$$

As PA increased by 0.1, PACV decreased by 5.6 percent. The decrease of PACV is much less than expected from the definition of CV indicating that sd_{PA} decreases as PA increases.

These results suggest that optimum transect number and spacing depends mostly on the stochastic homogeneity of the pool-riffle sequence. However significant the regressions, stream morphologic parameters explained only small percentages (< 35 percent) of overall variability of the CV or autocorrelation terms. Because of the high variability of both WW and PF, the least precise PA estimate occurs on small streams with few pools. Precision increases with n as long as the reach remains homogeneous and autocorrelation remains low.

Pool Fraction

Water width CV varied with geomorphic variables while PACV did not suggesting that PF may vary independently from WW. Understanding the physical causes for variability in PF should help explain the variability of PA.

Pool fraction varies from 0 to 1 inclusively. Values between 0 and 1 are from transects which intersect either end of a stream-spanning pool or intersect pools, such as pocket pools below boulders, that do not span the stream. Heterogeneities, such as substrate or variabilities in cross-sectional shape, should explain much of the variation in PF. Both a χ^2 test for independence between stream type and PF category (no pool, partial pool or full pool) and a Kruskal-Wallis one-way ANOVA for independence of the pool fractions among stream types are rejected ($\chi^2 = 10.9$, $p = 0.092$; $KWS = 9.41$, $p = 0.024$, $n = 1199$) due to a slight prevalence of complete pools on the E-type streams. However, neither elimination of E-type streams nor consideration of just partial pool transects caused rejection of the independence hypothesis. The hypothesis of independence among reaches is strongly rejected ($p = 0.005$) suggesting variation in PF is not explained by stream type.

We tested for variation along a continuum of stream morphologic variables. Because PF varies from 0 to 1 inclusively, we examined variation of PF with logistic regression (Hosmer and Lemeshow, 1989) which solves for the Bs in the following relation

$$E\left(Y \middle| x_1, x_2, \ldots, x_n\right) = \Pi\left(x_1, x_2, \ldots, x_n\right) = \frac{e^{B_0 + B_1 x_1 + B_2 , x_2 + \ldots + B_n x_n}}{1 + e^{B_0 + B_1 x_1 + B_2 x_2 + \ldots + B_n x_n}} \tag{13}$$

where Y is the dependent and x_* represents the independent variables described in Equation (14):

$$PF = f\,(SFR,\ GFR,\ RFR,\ BFR,\ CWDFR,\ CHWD, CHW,\ WW,\ ENTR) \tag{14}$$

Here, *FR is the bottom fraction of sand (SFR), gravel (GFR), cobble (RFR), boulders (BFR) or coarse woody debris (CWDFR). Variables are at a transect and there are 1068 transects from the 47 sites without missing data for any variables.

Using selection methods outlined in Hosmer and Lemeshow (1992), the best logistic regression model (selected from choices in Equation (14), $p \leq 0.1$) included the sand and cobble fraction of substrate and channel width/depth, channel width and entrenchment:

$$PF = \frac{e^{-0.65 + 1.96SFR - 0.82RFR - 0.053CHWD + 0.50CHWID + 0.0060ENTR}}{1 + e^{-0.65 + 1.96SFR - 0.82RFR - 0.05CHWD + 0.50CHWID + 0.0060ENTR}} \cdot \tag{15}$$

Sand accumulated in pools such that an increase in SFR of only 0.1 corresponded with a 7.1 percent increase in PF. An increase in RFR of 0.1 corresponded to a 4.4 percent decrease in PF because of more cobble in nonpools. PF decreased by 5 percent for an increase of 1 in channel width/depth ratio and increased by 1 percent for an increase of 1 in entrenchment ratio. The trends with CHWD and ENTR partially offset each other at the scale of a reach. On the continuum between a Rosgen (1994) B and C shape, both CHWD and ENTR increase. At the transect scale, it suggests PF increases at wider sections on narrow streams or at sections with less entrenchment.

CONCLUSION

Based on this data set, we recommend ten transects per reach at a three channel width spacing for future survey and research studies. This implies a sampling scale of about 30 channel widths per reach which corresponds to a range of three to 20 pool-riffle sequences (dependent on pool spacing). Additional transects within this length will not improve the estimate because spacing closer than three widths will cause autocorrelation between transects. Channel lengths of 30 widths are generally stochastically homogeneous. Additional length only combines adjacent, inhomogeneous reaches leading to decreased measurement precision. Transect locations should not correspond to specific locations within the pool-riffle sequence because of potential cyclic tendencies from pool to pool (Knighton, 1975) on reaches with regularly spaced pools (Myers, 1996).

Stream sizes and the pool formative features of the streams studied herein affect the measurement precision. Pools formed by structural features on small streams tend to be randomly located (Myers, 1996). Regular spacing of transects randomly samples features on these streams which is essential for accurate estimates of pool area. Different recommendations may pertain to larger streams with well-developed unforced pool-riffle sequences with regularly spaced pools. For example, transect spacing that corresponds to the pool spacing may result in repeated sampling of just pools or riffles leading to inaccurate pool area estimates. Spacing transects systematically to alternately sample riffles and pools will not accurately estimate pool area if pool and riffle lengths are different.

In light of our recommendations, consideration of agency monitoring methods is instructive. BLM (1978) prescribes four transects at 30.5 m spacings and USFS (1985) prescribes five transects at 15.2 m spacings without regard to stream size. On a 2 m wide stream, the 122 m reach length and 31 m spacing of the BLM method is two and five times as long as we recommend. The BLM method samples a proper length only on streams wider than 4 m and has proper spacing on 10 m wide streams. The 61 m length of the USFS method is about correct for a 2 m stream, but the 15.2 m spacing is 2.5 times too long. Precision of each method would improve by doubling transects within the same reach.

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