WATER RESOURCES RESEARCH, VOL. 33, NO. 4, PAGES 877–889, APRIL 1997

Stochastic modeling of pool-to-pool structure in small Nevada rangeland streams

Thomas J. Myers and Sherman Swanson
University of Nevada, Reno

Abstract. We developed, calibrated, and verified a compound Poisson process model of pool-to-pool spacing and size using an exponential distribution for spacing and gamma distributions for length and width on 12 rangeland streams in Nevada. Neither distribution parameter varied with simple stream morphologic or vegetation characteristics. We verified the model by comparing the first three moments and distributions of stream simulations with observed streams using two transect-based sampling schemes. Very small errors stemmed from an inability to reproduce autocorrelation of width at short distances, pool cyclicity, and additional density at the tails. We conclude that the presented model is accurate for small, Nevada, rangeland streams and for pools located randomly on small streams with forced pool-riffle or step-pool sequences and regularly on larger, pool-riffle systems. Simulated streams may be used for testing stream survey procedures and hypotheses regarding pool habitat, spacing, and length.

Introduction

The spacing of pools along a stream is often reported as five to seven channel widths for alluvial riffle-pool streams [*Keller*, 1972; *Keller and Melhorn*, 1978] and one to four channel widths for steeper, step-pool streams [*Chin*, 1989; *Grant et al.*, 1990]. Pool spacing and area have been linked to pool or stream type [*Myers and Swanson*, 1991; *Montgomery et al.*, 1995] and formative features [*Keller and Swanson*, 1979; *Marston*, 1982; *Robison and Beschta*, 1990]. Neither various types of development nor substantially different structural geology has led to differences in pool spacing [*Keller*, 1978; *Keller and Melhorn*, 1978; *Gregory et al.*, 1994]. *Grant et al.* [1990] and *Keller and Melhorn* [1978] found much variability in pool spacing. *Keller and Melhorn* [1978] presented histograms of pool spacing but did not consider the concept of frequency distribution.

Pool spacing includes the length of the pool and the intervening nonpool geomorphic unit. *Wohl et al.* [1993] and *Hubert and Kozel* [1993] found substantial variation of the pool/riffle area ratio with gradient but did not consider spacing. Indirectly, many authors considered the length of steps between pools by finding a linkage with the energy dissipated [e.g., *Marston*, 1982; *Chin*, 1989; *Thompson*, 1995]. However, we found no literature combining frequency distributions of pool and nonpool lengths.

The purpose of this paper is to present a stochastic model of the occurrence of pools and nonpools along a stream. We modeled the length of the nonpool reach with an exponential distribution and the length of pools and widths of all units with a two-parameter gamma distribution. Cumulative pool length on a stream reach is a compound Poisson process. This approach allows us to simulate stochastically homogeneous stream reaches specified by stochastic model parameters which have a physical basis. Stochastic homogeneity of a stream reach requires that all measured parameters be drawn from the same population. Simulated streams may be used for testing stream survey procedures and hypotheses regarding pool habitat, spacing, and length. Stochastically homogeneous physical stream reaches are too short for adequate simulation experiments of sampling [*Myers*, 1996].

Paper number 96WR03975.
0043-1397/97/96WR-03975$09.00

Background

Stochastic modeling and simulation has ample precedence in geomorphology [*Leopold and Langbein*, 1962; *Price*, 1974; *Shreve*, 1974; *Kirchner*, 1993]. Poisson process modeling, whereby an exponential distribution describes the spacing, is useful for spatially or temporally random events [*Law and Kelton*, 1991] such as thunderstorm [*Rodriguez-Iturbe et al.*, 1987], winter storm [*Duckstein et al.*, 1975; *Bonser et al.*, 1985], and flood arrival [*Kavvas*, 1982; *Nachtnebel and Konecny*, 1987; *Caissie and El-Jabi*, 1991; *Clarke*, 1991] or spatial locations of thunderstorms [*Rodriguez-Iturbe et al.*, 1986; *Jacobs et al.*, 1988]. In fluvial hydrology, several authors considered the movement of individual sediment particles [*Troutman*, 1980] or bed load transport events [*Carling and Hurley*, 1987; *Hurley*, 1992] as a Poisson process. Compound Poisson process modeling has the added characteristic that the size (time, length, or area) of the event is also considered such that the model represents with length or time a cumulative value such as contaminant infiltration breakthroughs [*Pegram*, 1980], effective precipitation [*Pegram*, 1980], or the longitudinal profile of a stream [*Nordin and Richardson*, 1967].

Methods

A distinct habitat unit (pools and nonpools to avoid distinctions among other habitat types) was a feature that spanned the stream at some point along its length. Beginning at the upstream end of a chosen reach, we measured the length of each habitat unit and water widths at each end and in the middle according to *Hankin and Reeves* [1988]. We surveyed at base flow when streamflow consists almost entirely of groundwater return flow [*Mosley and McKerchar*, 1993], which we assumed was occurring when spring runoff had ceased and flow rates had become essentially constant. Repeatability of the

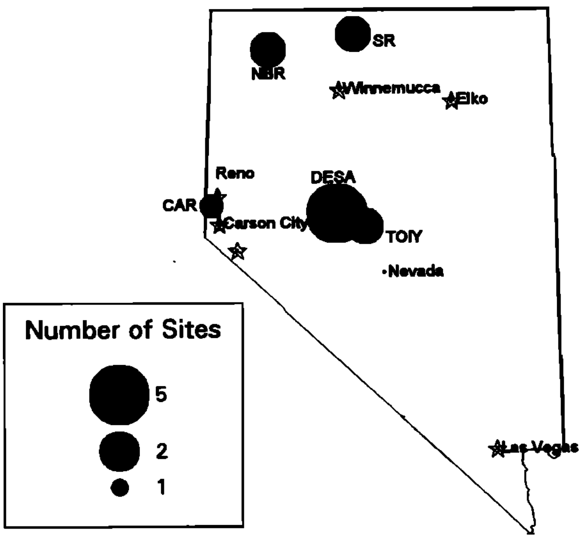

Figure 1. Location Map: SR, Santa Rose Mountains; NBR, North Black Rock Mountains; DESA, Desatoya Mountains; TOIY, Toiyabe Mountains; and CAR, the Carson Range. The scale of symbols indicate the number of sites in a specific mountain range. See Table 1 for which site is located in each mountain range.

identification of basic units is high [*Roper and Scarnecchia*, 1995]. Following *Grant et al.* [1990], we consider a pool to be a distinct habitat unit with gradient less than average reach gradient and subcritical flow over at least 85% of the surface area of the unit. This definition allows supercritical inflow chutes or plunges to be included in the measurement of pool area.

For many units, precise beginning points are nebulous [*Montgomery et al.*, 1995]. We determined lengths of units between points where the fraction of water width occupied by the unit equalled one half of the total width. Occasionally, the downstream end of a pool flows into another pool with only a very short, irregular nonpool unit separating them. Having measured many hundreds of units, we determined that the minimum length we could accurately measure was 0.25 m; therefore the length of some very short nonpool units were rounded to zero. The impact of this roundoff on descriptive statistics is minimal because average length usually exceeded three widths, which is at least 3 m. There were no very short pools (<0.25 m) that spanned the stream. Pocket pools and other small pools were not individual units. As suggested by *Montgomery et al.* [1995], these definitions may not apply to cascades, but none of our sites had many cascades.

All length and width measurements were rounded to the nearest 0.05 m. Therefore, while actual unit lengths and widths are continuous variables, our measurements are discrete. For example, a range of 2 m has 40 possible discrete values. For comparison among streams of any size, all length and width measurements were standardized, with the average water width determined from systematically spaced transects (cross sections perpendicular to the channel centerline) [*Myers*, 1996].

Study Area

We chose 12 long (>67 channel widths, most > 125 widths) stream segments in five mountain ranges of central and northwestern Nevada (Figure 1) to evaluate our model. They were chosen to represent stream types found in Nevada by mimicking a distribution of types found previously [*Myers and Swanson*, 1991]. All are within the basin and range geologic province [*Stewart and Carlson*, 1978]. Dominant watershed vegetation types range from sagebrush steppe to pinyon-juniper woodlands. Riparian vegetation includes shrubs, trees, forbs, and graminoids. Dominant land management is primarily livestock grazing. Table 1 lists general characteristics of the study reaches, including categories of ungulate damage, soil type, and dominant vegetation.

We classified our study sites with two widely used classification systems [*Montgomery and Buffington*, 1993; *Rosgen*, 1994] to aid in description and interpretation and because of their common use in land management agencies. Three *Rosgen* [1994] types were represented in our reaches. The active channel of B4 streams is moderately entrenched and sinuous with a moderate width/depth ratio, gradient (2–4%) and a gravel-

Table 1. Characteristics of Study Sites

Stream Name	Pools	L, m	Channel Width, m	Water Width, m	Rosgen Stream Type*	MB Stream Type†	Dominant Soil‡	Dominant Geology§	Dominant Vegetation	Ungulate Damage‖	Pool Area (Fraction)	Pool Spacing (Widths)
Smith U	40	500	1.96	1.24	B4	SP	CGr	Tt2	aspen	heavy	0.26	7.85
Smith D	53	398	2.09	1.23	C4	PR	GrS	Tt2	bare	heavy	0.47	7.53
Reese R	18	500	4.92	3.04	C4	PR	S	Qa	grass	light	0.50	11.97
Big Den D	22	300	1.38	0.69	C4	PR	GrS	Tt2	sedge	light	0.18	18.60
Big Den U	42	300	1.53	1.08	B4	SP	CS	Tt2	aspen	light	0.30	6.26
Big Mead	74	500	1.15	0.81	E4	PR	SSi	Tmi	sedge	light	0.20	8.80
Cabin D	51	309	2.34	1.40	C4	PR	SSi	Tr3	sedge	light	0.76	5.35
Cabin U	61	388	1.34	0.86	B4	fPR	SiGr	Tr2	will.	light	0.45	7.25
Mahogany	59	504	2.62	1.60	C4	fPR	GrS	Tr2	aspen	none	0.40	5.34
Summer C	62	501	1.94	1.44	B4	fPR	SGr	Tr2	aspen	none	0.23	5.59
Washington	44	441	2.41	1.97	B4	fPR	CGr	CZq	will.	light	0.36	5.11
Willow	63	400	1.63	1.14	B4	fPR	CGr	Tt2	W.Rose.	none	0.33	5.49

**Rosgen* (1994); see text for descriptions.

†*Montgomery and Buffington* (1993); PR is pool-riffle; fPR is forced pool-riffle; SP is a stepped pool system.

‡Dominant soil of the channel banks; C is cobbles; Gr is gravel; S is sand; Si is silt/clay.

§Dominant geology of the watershed [*Stewart and Carlson*, 1978]: Qa is alluvial deposits; Tt2 is welded and nonwelded silicic ash flow; Tr2, Tr3 are rhyolitic flows and shallow intrusive rocks; Czq is quartzite; Tmi is intrusive rock of mafic and intermediate composition.

‖Level of damage by ungulates, primarily domestic livestock. Based on a rating from 0 to 5 where 0 represents completely trampled and no vegetation ungrazed and 5 represents no damage. For this analysis, ungulate damage was categorized as none, light, or heavy.

dominated substrate (2–64 mm). C4 streams are slightly entrenched and very sinuous, have a high width/depth ratio (>12), low gradient (<2%) and a gravel substrate. E4 streams are similar to C4 streams except that they have a narrow channel (low width/depth ratio, <12). The low entrenchment of C4 and E4 streams suggests that floodwaters easily access their floodplain. Three *Montgomery and Buffington* [1993] types were noted as well. Pool-riffle channels exhibit regularly spaced bars (riffles) and free-formed pools. A free-formed pool is not forced by structural elements such as debris or boulders and may result from scour and deposition in conjunction with the tendency for meandering [*Yang*, 1971; *Keller*, 1972; *Keller and Melhorn*, 1978]. Forced pool-riffle channels generally have pools scoured as a result of directional currents from structural elements [e.g., *Robison and Beschta*, 1990]. Step-pool channels have pools formed by plunges over channel-spanning structural elements.

Model Development

The length of pools and of intervening nonpools both affect pool spacing. Pool length ranges from near 0 to many widths (our minimum field-measured length is 0.25 m, which ranges from 0.05 to 0.3 widths depending on the stream). We theorized, on the basis of observed histogram shapes, that a gamma distribution would describe pool length. The two-parameter gamma distribution is bounded on the left by 0 and ranges to infinity on the right. It models the right skewness caused by left bounding and has great flexibility in its shape. Specifically, based on texts [*Law and Kelton*, 1991] and experience, the gamma distribution fits best when there is little density near 0. Because nonpool lengths may equal 0 but have no upper limit, we hypothesized that pool locations are random along a homogeneous stream and can be represented by an exponential distribution.

Considered together, our hypothesis is that the cumulative length of pool along a stream reach is a compound Poisson process [*Ross*, 1982]. A Poisson process is a counting process with three requirements. First, the count N at the beginning, $N(0)$, equals 0. This states that no pools have occurred at the beginning of counting. Second, the process has independent increments in space or time. This states that the number of pools in an increment of time or space is independent from any other increment. Third, the number of pools in any interval of length l is Poisson distributed with mean λl. That is, for all s, $l \geq 0$,

$$P[N(l+s) - N(s) = n] = e^{-\lambda l}\frac{(\lambda l)^n}{n!} \qquad n = 0, 1, \cdots \tag{1}$$

where s represents the location at the beginning of a reach. Then, a stochastic process $\{X(l),\ l \geq 0\}$ is a compound Poisson process if

$$X(l) = \sum_{i=1}^{N(l)} Y_i \qquad t \geq 0 \tag{2}$$

where $(N(l),\ l \geq 0)$ is a Poisson process and $\{Y_i,\ i = 1, 2, \ldots\}$ is a family of independent, identically distributed (IID) random variables (which we hypothesized to be gamma distributed). The process $\{N(l),\ l \geq 0\}$ and the sequence $\{Y_i,\ i \geq 1\}$ are assumed to be independent. This means there is no systematic relation between pool length and location along the reach.

In accord with *Harvey* [1975] and *Richards* [1976], we found that widths differ between pools and riffles and that the two-parameter gamma distribution described widths at random locations within a pool [*Myers*, 1996]. However, different pool-forming processes lead to differing widths along a pool [*Keller and Swanson*, 1979; *Robison and Beschta*, 1990]; therefore distributions of width at random locations within a pool found by *Myers* [1996] do not apply to widths at systematic locations (middle, upstream, and downstream) used in this model. The properties of the two-parameter gamma distribution discussed above, plus the fact that it can have a mode very close to 1, led us to theorize that the two-parameter gamma distribution would describe standardized pool widths. There is no reason that widths at random locations along a nonpool reach should differ from the middle of the reach; therefore we used the same distributions fit for nonpools in *Myers* [1996].

Table 2. Exponential Distribution Parameter, λ, and Goodness-of-Fit Comparison With Empirical Distributions by χ^2 Test for the Standardized Distance Between the Downstream End of One Pool and the Upstream End of the Next Pool (Nonpool Lengths)

Reach	n	λ	K	χ^2	p
Smith U	40	6.61	8	8.00	0.333
Smith D	54	4.04	8	6.03	0.536
Reese R	17	6.34	4	8.18	0.042
Big Den D	22	17.5	4	4.91	0.178
Big Den U	43	5.11	8	6.00	0.540
Big Meadow	74	3.42	10	9.24	0.415
Cabin D	51	1.26	8	7.51	0.378
Cabin U	62	4.08	10	6.70	0.669
Mahogany	59	3.37	10	10.7	0.300
Summer Camp	62	4.56	10	18.6	0.029
Washington	44	3.94	8	5.82	0.561
Willow	63	4.09	10	12.4	0.192

Here n is the number of pools, K is the number of categories in the χ^2 test, and p is significance probability.

Distribution of Nonpool Lengths

The density function of the exponential distribution is

$$f(\mathrm{RL}) = \frac{1}{\lambda}e^{-\mathrm{RL}/\lambda} \qquad \text{if RL} \geq 0 \tag{3a}$$

$$f(\mathrm{RL}) = 0 \qquad \text{otherwise} \tag{3b}$$

where RL is the standardized distance from the downstream end of a pool to the upstream end of the next pool. By the method of moments, the parameter, λ, is the mean of the sample. We tested the fit with a χ^2 goodness-of-fit test for H_0: the data are IID random variables with distribution function exp (λ). Rejecting H_0 when $\chi^2 > \chi^2_{k-1,1-p}$ ($p = 0.10$) and using equiprobable categories based on minimum expected values equal to 5 [*Law and Kelton*, 1991], we accepted the chosen distribution on 10 of 12 study reaches (Table 2). For 12 tests we expect to reject H_0 once with $p \leq 0.1$ by chance alone (that is, commit a type 1 error [*Sokal and Rohlf*, 1981]). Acceptance of H_0 suggests that pools locate randomly on these streams. This may be especially true on streams with forced scour or step pools formed by randomly spaced structural elements.

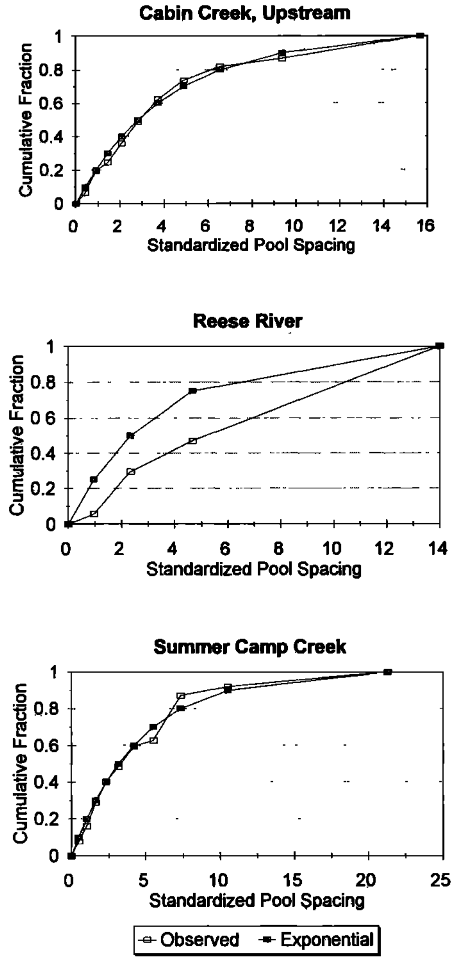

Figure 2. Comparison of observed with exponential pool spacing for select streams.

Cabin Creek U is typical (Figure 2). More pools had short spacings, resulting in the category of longest spacings being very wide in comparison with other categories. On Cabin Creek U, approximately 20% of pool spacings were less than 1.0 width, while just 10% ranged from 9 to 16 widths. The Reese River and Summer Camp Creek were not fit by the exponential distribution (Table 2, Figure 2). There is little similarity between these two streams in size, stream type, pool area, vegetation, soils, substrate or ungulate damage (Table 1). The Reese River is flat with riffles separating most pools leading to no measurements near 0 where the exponential distribution has the most density. Many researchers [*Keller and Melhorn*, 1978; *Montgomery et al.*, 1995] have noted the presence of riffles between pools on this type of stream, which corresponds to descriptions of pool formation due to changing flow directions and velocities [*Keller*, 1971, 1972] on streams that do not have forced pools. Apparently, large pool-riffle streams have regular, rather than random, pool spacings. The rejection of Summer Camp Creek is due to different counts in categories between five and eight spacings, which likely does not have a physical explanation and is random. When $p \leq 0.1$, we expect rejection of at least one test in 11. Thus we accept the overall hypothesis that the distance between pools on streams with primarily forced pools is exponentially distributed.

Table 3. Gamma Distribution Parameters (α, β) Estimated by the Method of Moments and Goodness-of-Fit Comparison by χ^2 Test With Empirical Distributions for the Standardized Length of Pools

Reach	n	α	β	χ^2	P
Smith U	40	3.77	0.330	8.02	0.532
Smith D	54	6.32	0.552	5.30	0.811
Reese R	17	1.89	2.98	3.88*	0.422
Big Den D	22	5.18	0.212	0.73*	0.945
Big Den U	43	2.88	0.398	14.9	0.094
Big Meadow	74	0.787	6.84	26.3	0.002
Cabin D	51	3.75	1.09	8.80	0.456
Cabin U	62	4.12	0.770	13.2	0.155
Mahogany	59	2.91	0.678	7.95	0.539
Summer Camp	62	3.33	0.309	23.5	0.005
Washington	44	4.65	0.251	5.09	0.826
Willow	63	3.01	0.466	21.9	0.009

Number of categories in the χ^2 test, $K = 10$, except as noted; n is the number of pools, P is significance probability.
*$K = 5$.

Using one-way analysis of variance, we tested for and rejected differences in λ among ungulate damage levels, *Montgomery and Buffington* [1993] stream types, and dominant soil and vegetation types ($F = 0.2$, $p = 0.818$; $F = 0.65$, $p = 0.544$; $F = 1.23$, $p = 0.338$; and $F = 0.34$, $p = 0.801$, respectively; all categories are described in Table 1). Testing for differences between *Rosgen* [1994] stream types B4 and C4 (there was only one E4 type) with two sample t tests, we rejected the hypothesis that λ was different between types ($t = -0.67$, $p = 0.517$). This suggests that geomorphic and vegetative differences as represented by the two stream-type procedures, soil and vegetation types, and ungulate damage levels do not explain the differences in the exponential distribution as represented by λ among streams.

Distribution of Pool Lengths

The density of the two-parameter gamma distribution is:

$$f(\text{PL}) = \frac{\beta^{-\alpha}\text{PL}^{\alpha-1}e^{-\text{PL}/\beta}}{\Gamma(\alpha)} \qquad \text{if PL} > 0 \qquad (4a)$$

$$f(\text{PL}) = 0 \qquad \text{otherwise} \qquad (4b)$$

where PL is standardized pool length and α and β are parameters. Parameter estimation is by the method of moments [*Bobée and Ashkar*, 1991].

We tested H_0: the data are IID random variables with distribution function gamma (α, β) with a χ^2 goodness of fit test. Rejecting H_0 when $\chi^2 > \chi^2_{k-1,1-p}$ ($p \leq 0.10$) and using $k = 10$ categories chosen to be equiprobable [*Law and Kelton*, 1991], we accepted the chosen distribution on 8 of 12 study reaches (Table 3).

Typical accepted fits occurred on Smith Creek D and Washington Creek (Figure 3). The flatter Smith Creek D had a well-defined distribution with most pools between 2.0 and 5.5 widths. The steeper, debris- and boulder-influenced, forced pool-riffle Washington Creek had most pool lengths well distributed between 0.5 and 2.0 widths.

The number of rejected fits suggests that the gamma distribution may not be the best descriptor for the pool lengths of all streams. The rejection of Willow Creek appears due to random fluctuations between one and two widths (Figure 3). Distributions of the other three rejected streams (Figure 3) indicate

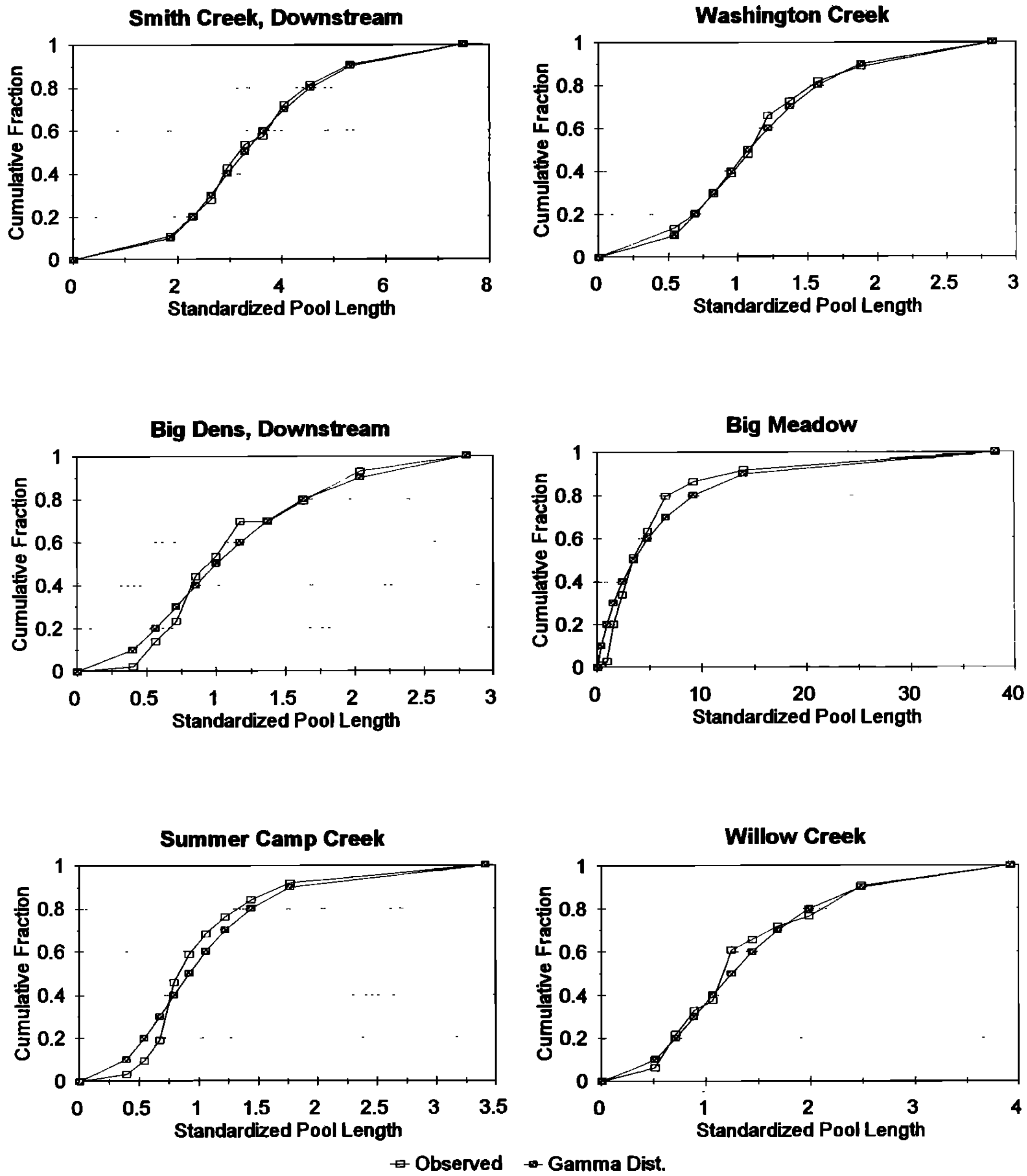

Figure 3. Comparison of observed with gamma fit pool length for select streams. Smith Creek, Downstream, and Washington Creek are accepted; the others are rejected.

fewer pools at shorter lengths than modeled by the distribution. Big Den U, which was barely rejected (Table 3), had almost no pools shorter than 0.5 widths, which caused its rejection. The other two (Big Meadow and Summer Camp Creek) show a definite central tendency. Big Meadow had high right skewness and $\alpha \ll \beta$ due to the occurrence of several very long pools. The longer 10% of pools exceeded 13 widths. In fact, about 45% of the stream consisted of these long pools. On Summer Camp Creek, all pool lengths are less than 3.5 widths. Its rejection was due to a lack of pool lengths in the upper tail of the distribution.

Although a few distributions are rejected, such rejection appears to be controlled by variation in the short end of the range; therefore we accepted the gamma distribution as a descriptor of pool length. The model may have a few too many short pools which have little effect on pool area (PA), the simulation of which is the objective of the model. Big Meadow, with many lengths in the range [1, 5] but also high right skew, is probably not fit by any distribution.

We rejected the hypothesis of difference among groups for α ($F = 1.37, p = 0.303$; $F = 0.02, p = 0.977$; $F = 0.91$, $p = 0.438$; and $F = 2.04$, $p = 0.187$, respectively, for ungulate damage, *Montgomery and Buffington* [1993] type, soil type, and vegetation type). There were also no differences between Rosgen types B4 and C4 ($t = -0.49, p = 0.634$); β did not vary among ungulate damage, *Montgomery and Buffington* [1993] types or vegetation ($F = 0.65, p = 0.544$; $F = 1.54$, $p = 0.266$; and $F = 1.45$, $p = 0.299$) or between Rosgen types B4 and C4 ($t = -1.51, p = 0.164$). It did vary among soil type ($F = 3.81, p = 0.063$) primarily because β on Big Meadow equaled 6.84 and just one other reach was in the silt/clay category. This suggested that simple geomorphology and vegetation characteristics as represented by the two stream type procedures, soil and vegetation types, and ungu-

Table 4. Gamma Distribution Parameters (α, β) Estimated by the Method of Moments and Goodness-of-Fit Comparison by χ^2 Test With Empirical Distributions for the Standardized Water Width at Different Sections of the Pools

Pool Location	α	β	χ^2	P	$r_{PL, ww}$
		Smith U; n = 40			
US	6.98	0.139	8.51	0.483	−0.374
DS	12.8	0.0814	6.50	0.689	−0.131
MID	11.4	0.0865	2.17	0.988	−0.359
		Smith D; n = 54			
US	21.8	0.0407	8.22	0.512	−0.266
DS	20.9	0.0551	19.3	0.022	0.293
MID	26.9	0.0357	7.11	0.626	−0.185
		Reese R; n = 17			
US	20.0	0.0477	2.00*	0.736	−0.079
DS	31.2	0.0320	2.65*	0.618	0.346
MID	15.3	0.0686	9.18*	0.057	0.438
		Big Den D; n = 22			
US	6.71	0.144	0.272*	0.992	0.300
DS	7.52	0.135	10.7	0.220	−0.180
MID	7.05	0.144	5.73*	0.221	−0.056
		Big Den U; n = 43			
US	5.88	0.163	9.79	0.368	−0.082
DS	12.3	0.0831	12.6	0.182	0.096
MID	17.0	0.0607	8.40	0.495	−0.105
		Big Meadow; n = 74			
US	4.83	0.217	7.80	0.554	0.025
DS	9.85	0.101	15.2	0.086	0.102
MID	7.36	0.130	18.4	0.030	0.156
		Cabin D; n = 51			
US	6.42	0.145	9.92	0.357	−0.059
DS	9.85	0.111	7.63	0.572	0.346
MID	11.9	0.0822	8.42	0.493	0.062
		Cabin U; n = 62			
US	6.58	0.141	12.2	0.203	0.088
DS	12.3	0.0854	8.97	0.440	0.363
MID	7.97	0.128	9.29	0.411	0.205
		Mahogany; n = 59			
US	8.17	0.123	10.7	0.300	0.141
DS	9.28	0.109	9.98	0.352	0.327
MID	11.3	0.0869	3.54	0.939	0.204
		Summer C; n = 62			
US	9.86	0.0951	10.2	0.337	−0.130
DS	13.8	0.0786	8.97	0.440	0.014
MID	11.8	0.0824	6.05	0.735	−0.213
		Washington; n = 44			
US	9.43	0.100	13.7	0.133	−0.123
DS	9.60	0.104	3.73	0.928	−0.059
MID	12.2	0.0864	5.09	0.826	−0.049
		Willow; n = 63			
US	7.19	0.138	10.1	0.346	0.073
DS	8.22	0.123	8.27	0.507	0.113
MID	14.3	0.0693	9.12	0.426	0.071

US, upstream; DS, downstream; MID, middle; n, number of pools and of χ^2 test categories; P, significance probability; $r_{PL, ww}$, Spearman rank correlation of water width and pool length. $K = 10$, except as noted.
*$K = 5$.

late damage did not explain the differences among pool length stochastic parameters.

Distribution of Pool Widths

We theorized that water widths at the downstream and upstream ends and in the middle of pools were distributed according to (4) with water width, ww, substituting for PL. We tested H_0: the data are IID random variables following gamma (α, β). Rejecting H_0 when $\chi^2 > \chi^2_{k-1,1-p}$ ($p \leq 0.10$) and using $k = 10$ categories chosen to be equiprobable [*Law and Kelton*, 1991], we accepted the fit on 30 of 36 tests (Table 4).

One of the best fits, Smith Creek U, middle of pool, showed

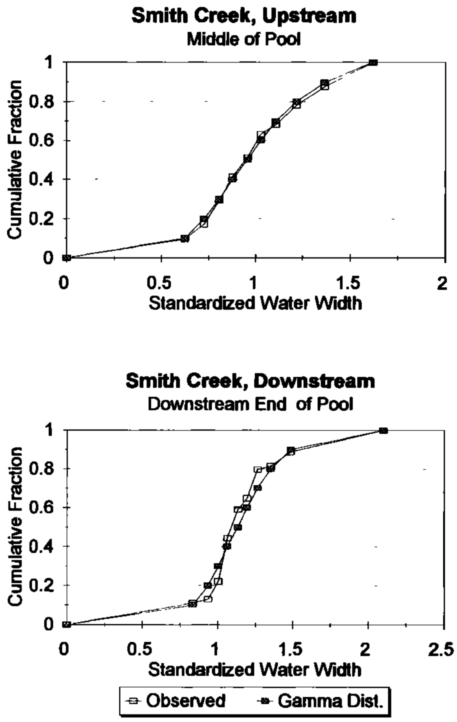

Figure 4. Comparison of observed with gamma fit water widths for select streams and locations in pools.

almost perfect agreement (Figure 4). One of the worst fits, Smith Creek D, downstream end of pool, is mostly random fluctuation due to the roundoff that occurs when measuring width (Figure 4). The gamma distribution is continuous, and near the expected value the categories are very small (<0.1 widths). Our measurements are to the nearest 0.05 m, which is only 0.02 widths. Therefore categories near the mean contain few potential measurements which leads to high cell χ^2 values. Also, with $p = 0.1$, 3.6 of the fits should be rejected. On the basis of this and the randomness of some rejections, we accepted the gamma distribution for describing systematic pool widths.

Relations Among Pool Length and Width

Although there is insufficient data to calibrate a conditional distribution for width based on pool lengths, we tested for correlation of width and pool length (Table 4). The wide scatter of correlation coefficients among streams does not suggest a systematic variation explainable by stream type. The wide scatter indicates that any conditional relation varies among streams. The lack of data and inability to find stochastically homogeneous reaches long enough to collect data from a sufficient number of independent transects precludes inclusion of distributions of width conditioned on the location within a pool.

Simulation Routine

The model simulates a pool-riffle sequence utilizing the distributions described above. We chose the first unit to always be a nonpool because of the memoryless property of the exponential distribution in that [*Ross*, 1982]

$$P(\mathrm{rl} > \mathrm{rl}_2 + \mathrm{rl}_1 | \mathrm{rl} > \mathrm{rl}_1) = P(\mathrm{rl} > \mathrm{rl}_2) \quad (5)$$

where rl is riffle, or nonpool, length. Equation (5) states that the probability that the length remaining in a unit starting at any point exceeds a given value is independent of the length of unit upstream of it. Thus it has no memory and it was unnecessary to assume the starting point is at the upstream end of a unit.

The simulation starts with the length of a nonpool followed by the widths at each end and the middle. Then nonpool widths at either end of the unit are simulated with distributions for the appropriate pool end. Simulation of the middle width in a nonpool is with distributions from *Myers* [1996] for random nonpool locations. Then the length and middle and downstream widths of a pool are simulated. The width of the upstream end of a simulated unit is set equal to the downstream width of the previous unit. Simulated nonpool lengths less than 0.25 widths are rounded to 0 and another pool is simulated. This roundoff corresponds reasonably to our field sampling rules described above. New random numbers are selected for each simulated length or width. We simulated one long (1000 units), stochastically homogeneous series for each stream which we subdivided for comparison.

Verification

Simulations based on stochastic models do not reproduce the deterministic processes from which they were parameterized. Rather, they reproduce basic probabilistic properties of the structure developed by the processes, in this case, pools and widths along a stream. The input distributions should be, and were, reproduced exactly within round-off error. This verifies only that we coded the distributions properly. Note that there is no round-off of measurements, as in the field surveys. We tested the model by comparing moments and histograms of width and PA based on similar independent sampling of widths and pools of the actual and simulated stream. We used a Monte Carlo randomization scheme to subsample widths and PA of the actual and simulated stream [*Myers*, 1996]. The sampling was based on systematic transects with starting location chosen from $U(0, L - L_1)$ where U is the uniform distribution, L is reach length, and L_1 is subreach length (equal to spacing $\times$ $(n - 1)$, where n is the number of transects) in widths. Additional transects were sampled at spacings of $1/(n - L_1)$ widths in the downstream direction. For comparison we used two schemes to represent properties, such as covariance, of the pool-riffle sequence in the transect series. The mean width was also determined for the following survey schemes described for PA.

$$\mathrm{PAGAWS} = \frac{\sum_{i=1}^{5} \mathrm{WW}_{i+4(i-1)}\mathrm{PF}_{i+4(i-1)}}{\sum_{i=1}^{5} \mathrm{WW}_{i+4(i-1)}} \quad (6)$$

This emulates the GAWS sampling procedure (General Aquatic Wildlife System; *USFS*, 1985) by sampling every fourth transect. Here, $n = 5$ and $L_1 = 4 \times (5 - 1) = 16$ widths. The second PA value used adjacent transects to preserve width and unit-to-unit persistence:

$$\mathrm{PA5TR} = \frac{\sum_{i=1}^{5} \mathrm{WW}_i \mathrm{PF}_i}{\sum_{i=1}^{5} \mathrm{WW}_i} \qquad (7)$$

Again, $n = 5$ while $L_1 = 4$ widths.

Based on observed autocorrelation [*Myers*, 1996], (6) should preserve properties of randomness, and (7) should preserve properties of autocorrelation of habitat units along a stream. These schemes were not optimum transect sampling methods because they lead to a high standard error about the mean [*Myers*, 1996]. Additional transects at the same spacings would preserve the same properties but decrease the scatter rendering differences among distributions less obvious.

We divided the 1000-unit simulated stream into 10 equal-length subreaches similar in length to the actual stream. Scatter of moments determined from the 10 subsamples varying more than for the actual streams would indicate shifts or trends due to simulation. Relative accuracy of the simulation of PA moments for each sampling scheme were compared using a sum of squared differences coefficient [*Singh*, 1988].

$$\mathrm{SS} = \sum_{i=1}^{12} [Y_{\mathrm{obs}}(i) - Y_{\mathrm{exp}}(i)]^2 \qquad (8)$$

The mean, standard deviation, or skewness coefficient of PAGAWS or PA5TR is represented by Y, and 12 is the number of stream reaches compared.

Distributions of PA from the actual streams were compared with the simulated using a Kolmogorov-Smirnoff goodness-of-fit test [*Sokal and Rohlf*, 1981]. This comparison tests the null hypothesis; H_0, observed, and simulated PA values are described by the same distributions. H_0 is rejected if the significance probability, p, is less than a chosen value for n equal to 100, the number of PA values chosen from the observed reach. The test statistic, D, is $\mathrm{MAX}|P_{\mathrm{PA}}(\mathrm{PA})\text{-}S_{\mathrm{PA}}(\mathrm{PA})|$ or the maximum deviation between the distribution of the actual stream, P, and the simulated stream, S. We rejected H_0 if D exceeded $D_{0.1}$.

Simulation of Width

Most mean widths range from 0.9 to 1.1 (Figure 5). As also reflected in the standard deviation (sd) (Figure 6), there is more scatter observed in the sampling scheme with one width spacing due to autocorrelation [*Myers*, 1996]. Observed widths scattered about the value 1 because the standardization was based on an average width from systematic transects [*Myers*, 1996] which have random locations within a habitat unit. This suggested that measurement of width only at specific locations within a unit (upstream, middle, and downstream) biases the measurement when reported as an overall reach value. The scatter of average widths for the 10 simulated subreaches around 1.0 for all 12 reaches is very similar to the scatter of actual reaches and is within the range expected from previous sampling experiments [*Myers*, 1996]. This suggests the model reproduced width accurately both at the exact locations of simulation and at intermediate points. Skewness decreased with simulation due to smoothing (not shown).

Simulated width sd did not always agree with observed as some reaches were over or underestimated (Figure 6). Big Den U and Big Meadow (R5 and R6) simulations had an sd consistently less than observed. For example, observed widths on Big Meadow in excess of 3 occurred with a probability of 0.02, while the probability of simulating values in excess of 3 with the gamma distribution is much less (note that the gamma distri-

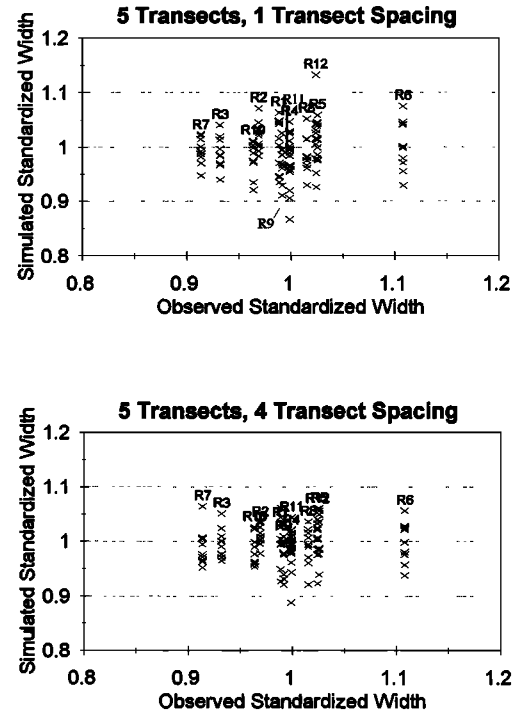

Figure 5. Comparison of mean values of width for both sampling schemes. The expected value is 1. R^* stands for reach number; see Table 1.

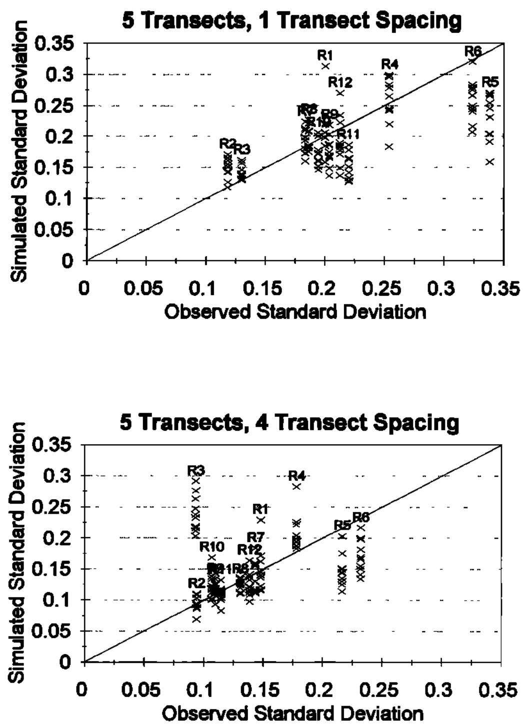

Figure 6. Comparison of sd values of width for both sampling schemes. R^* stands for reach number; see Table 1.

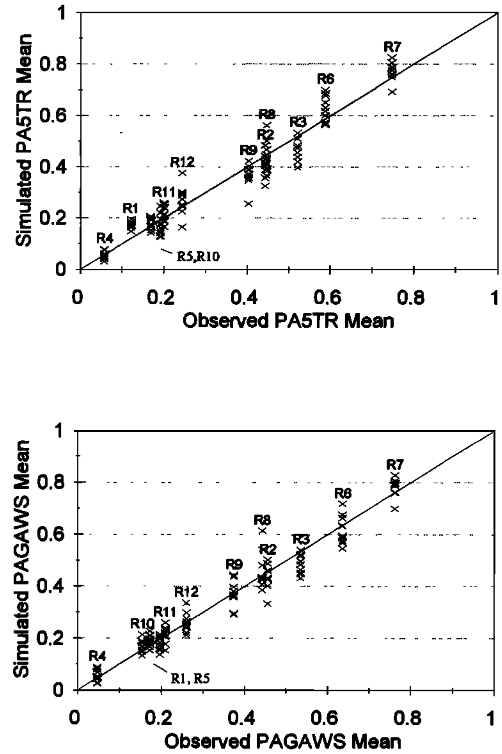

Figure 7. Comparison of observed and simulated pool area means for each sampling scheme. R^* is reach number; see Table 1 for description.

bution did not describe widths for two pool locations on Big Meadow, Table 4). This caused a lower variation around the mean.

The simulated width sd of the Reese River and Big Den D (R3 and R4, Figure 6) increased as sampled spacing increased from one to four widths and no longer agreed with those observed. Both had long pools and short spacings; therefore sampling at short spacings would have sampled the same unit several times, thereby limiting variability. Simulation was more variable at long spacings because different units were sampled, and the model does not preserve correlation among units. Autocorrelation due to short spacings within units decreased variability.

Simulation of Pool Area

Pool area ranges were as much as 0.22 (R8, Cabin U, Figure 7), but most were less than 0.1 which is within expected scatter for these sampling methods [*Myers*, 1996]. PAGAWS sampling was more accurate for the mean value (SS = 0.0045 and 0.017 for PAGAWS and PA5TR, respectively).

Observed PA sd and skewness decreased substantially with increased spacing (Figures 8 and 9) because there is less autocorrelation of pools and width with longer spacing. There was a slight tendency to overestimate sd, mostly at a four-width spacing (Figure 8), which was less accurate than one-width spacing (SS = 0.0055 and 0.0022 for PAGAWS and PA5TR, respectively). Overestimation of sd ranged from 5 to 25% on five reaches (R2, R3, R4, R5, and R8). Four of the five have pool spacings that are multiples of four (Table 1). This indicates that the simulation has less scatter in the spacing, leading to a tendency for pools or nonpools to be repeated at multiples

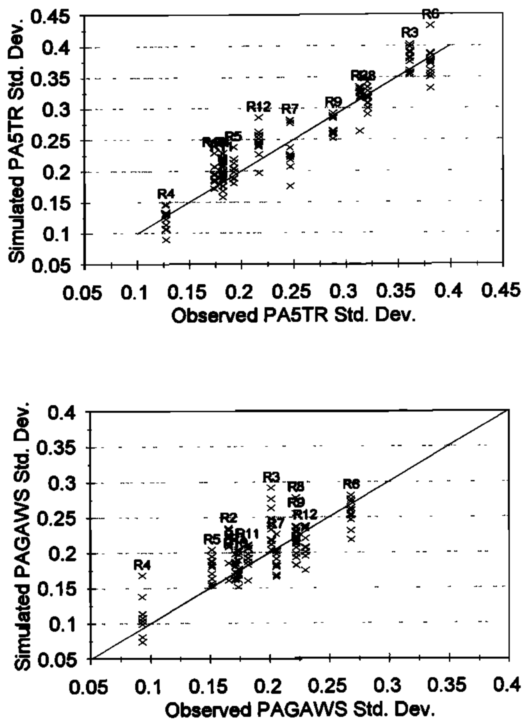

Figure 8. Comparison of observed and simulated pool area sd for each sampling scheme. R^* is reach number; see Table 1 for description.

of four transects. This leads to simulations of both high and low PAGAWS values.

Simulated skew agreed closely with observed for both spacings (SS = 0.50 and 0.888 for PAGAWS and PA5TR, respec-

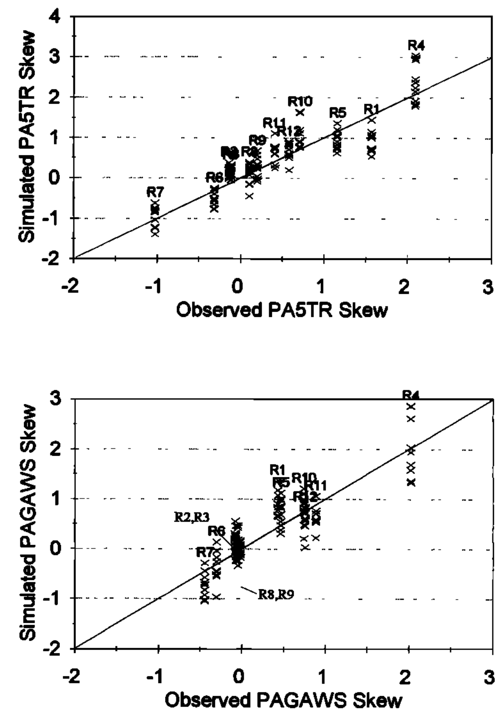

Figure 9. Comparison of observed and simulated pool area skew for each sampling scheme. R^* is reach number; see Table 1 for description.

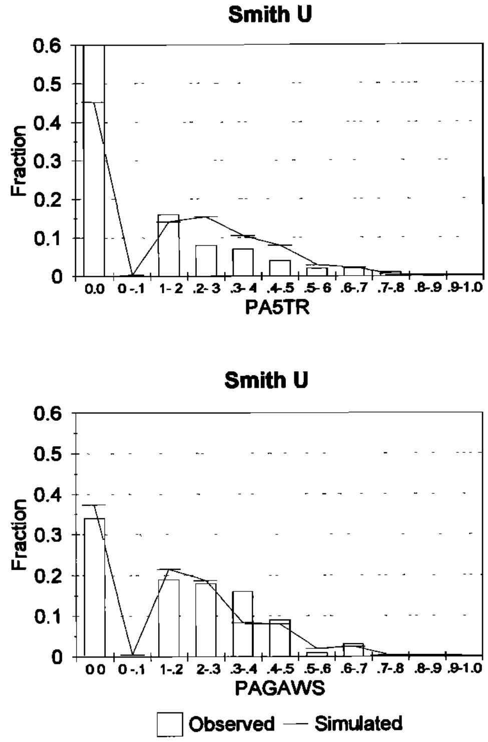

Figure 10. Comparison of observed and simulated distributions of pool area for each sampling scheme for Smith U.

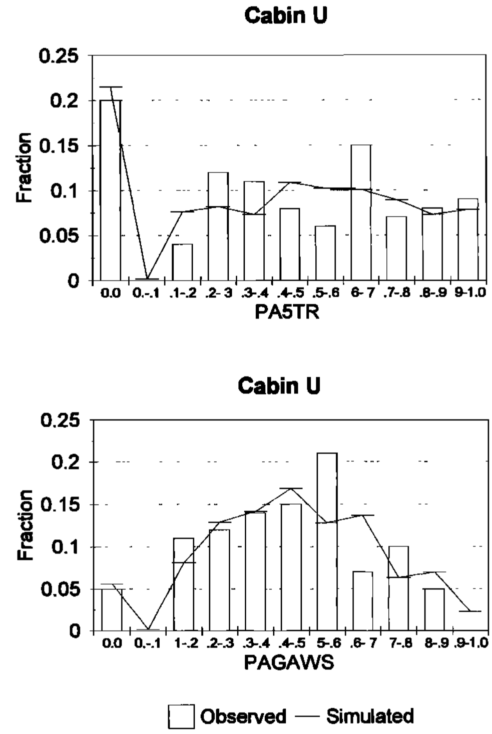

Figure 11. Comparison of observed and simulated distributions of pool area for each sampling scheme for Cabin U.

tively). The only substantial overestimation was for PAGAWS on Smith U resulting from generation of high outliers. Observed values of PA on Smith U did not exceed 0.7, whereas the model simulated 10 values in the range (0.7, 1.0) (Figure 10), which lead to the overestimation of skewness. However, even in a stream with few small pools, it is possible to sample PA = 1.0 with systematic pool and transect spacing. Distributions from the modeled stream may be more realistic than the observed.

Most simulated distributions agreed closely with observed (Table 5) reflecting the close agreement for all moments but especially the skew coefficient. The hypothesis, tested with Kolmogorov-Smirnoff tests, was often rejected due to disagreement in the tails of the distribution, which also leads to different skews.

Although the equations for PA includes width, there were no similar tendencies among PA and width moments. The wide variability and lack of agreement of sd for width did not affect simulation of PA. As noted elsewhere [*Myers*, 1996], the positioning of pools and riffles controls the moments of PA and not the differences in width. Two specific examples should help to clarify differences between observed and modeled.

Table 5. Comparison of Simulated and Observed PA Values Based on the Kolmogorov-Smirnov Test Statistic *D*

Reach	PA5TR *D*	PAGAWS *D*
Smith U	0.163*	0.099
Smith D	0.090	0.151*
Reese R	0.104	0.110
Big Den D	0.037	0.053
Big Den U	0.095	0.079
Big Meadow	0.080	0.062
Cabin D	0.063	0.076
Cabin U	0.053	0.073
Mahogany	0.073	0.071
Summer Camp	0.143*	0.109
Washington	0.057	0.095
Willow	0.057	0.037

PA5TR is pool area based on five transects spaced one transect apart; PAGAWS is pool area based on five transects spaced four transects apart.

$*D > D_{0.1} = 0.122$.

Specific Examples

Smith U has an observed PA distribution with many values equalling 0 (Figure 10). There is a substantial difference between the density for different spacings. Simulation reproduced the general shapes very well but was not sensitive to some fluctuations which led to high-*D* values (Table 5). For PA5TR, for which *D* was significant, the model underestimated the fraction of zero values by 25% and overestimated the small (less than 0.2 of all observations) fractions in the range (0.2, 0.5) by about 75%. For PAGAWS the model underestimated only in (0.3, 0.4) by about 40%.

Cabin U has a much different PA density (Figure 11) than Smith U (Figure 10). The fraction of observed 0 values decreases from 0.2 to 0.05 from PA5TR to PAGAWS. The model simulates the observed uniform density in the range (0.3, 1.0) for one width spacing missing only the nadir at (0.5, 0.6) and spike at (0.6, 0.7). Random fluctuations such as this tend not to follow a probability distribution and are difficult to simulate. For PAGAWS the model follows the rise and fall within the range (0.2, 1.0). However, the model smoothes peaks and valleys in that it underestimates the peak by about 35% and overestimates the large succeeding drop by about 80%.

Discussion

Physical Interpretations

An implicit result is acceptance of the hypothesis that pools on small Nevada rangeland streams locate randomly along stream reaches when formation is due to structural features in the stream. Thus nonpool length ranges from 0, which occurs when one pool spills into the next, to well above the mean value. Features which form pools, such as rocks, roots, or debris, enter the stream at random locations. If these are large enough to resist movement during high flows, they will force pools at the point of entry. If several successive forced pools were followed by longer nonpool reaches, clusters would exist. Histograms of pool spacing on a reach with clustered pools would be bimodal with one peak near 0 and the other peak at higher values, depending on the length of nonpool reaches. This was not manifest for the small streams studied here which confirms the random nature of pool formation on small streams.

However, as streams become larger, annual flood flows increase [*Klein*, 1981], and features which enter the stream at random locations undergo sorting such that pool spacing becomes regular. *Abrahams et al.* [1995], in a series of flume studies, found regularly spaced step pools to optimize energy dissipation as defined by a maximum Darcy-Weisbach friction factor when compared to random and suboptimum spacings. They compared these results to several actual streams and concluded that pool formation is optimum when the friction factor is maximum, as found with regularly spaced pools. *Lisle* [1986], working on a 12-m-wide stream in northern California, found that features, particularly root wads, large woody debris, and bedrock outcrops, controlled pool and bar locations. His figures suggest a regular spacing with at least two channel widths separating pools. *Grant et al.* [1990], on larger streams in the Pacific Northwest, found that spacing of pools was more regular on steep, high-energy reaches where particles representing the 90th or larger percentile size fraction of bed material were sorted by observed flow with high variability due to large boulders and immovable bedrock. They also found that forced channel units formed during events with a return interval of about 50 years suggesting that low-frequency flows are necessary to cause a regular pool spacing. Viewing our results in light of these articles suggests that because of sorting of large substrate, there is an upper limit to the size of stream on which pools are randomly located.

Regarding the Reese River, rejection of the hypothesis suggests that pools are not random, but neither are they clustered. Because the Reese River is a low-gradient, C-type or pool-riffle stream, the rejection suggests pools may not be random on this type of stream. However, Big Den D, Cabin 2, and Smith D are the same stream type, and they tended to have randomly spaced pools without substantial large forcing features. Big Den D is rapidly recovering from abusive grazing and has patchy, dense herbaceous vegetation on stabilizing sand bars that help to form pools. Cabin Creek has patchy clusters of shrubs controlling the bends and therefore has meander-formed pools. Smith D is a recently downcut stream with pools constrained to the locations of boulders that were preexisting in the alluvium through which the stream downcut. Because of their small size, bank vegetation, small-scale bank soil heterogeneities, and boulders control their planform. Meander patterns are irregular; meander bends and the pools which form on them are located randomly. The much larger Reese R has regularly spaced pools with location primarily controlled by the tendency of streams to meander [*Keller*, 1971, 1972]. This suggests there is a stream size or flow rate threshold dividing streams with random and regularly spaced pools. It also suggests a subdivision of both the *Rosgen* [1994] C-type and *Montgomery and Buffington* [1993] pool-riffle classifications based on size. Heterogeneities control planform and pool locations on smaller streams. Natural meandering tendencies control planform and pool locations on larger, unconfined streams. On larger, confined streams, it is likely that features form pools but are sorted to a regular spacing.

Because of the requirement that stream reaches be stochastically homogeneous, it is possible that a reach with clusters would never be observed. Because of an appearance of different reaches, surveyors would subdivide reaches according to pool clusters and the lack thereof. This raises the question of sampling scale. We [*Myers*, 1996] found that stochastic homogeneity decreases after about 30 channel widths and recommended this as an upper limit for transect-based (equations (6) and (7)) pool area sampling. *Frissel et al.* [1986] found that the length of reach to be sampled depended on the desired result.

We did not consider the role of pool-forming features and pool types on the distribution of length or spacing because of insufficient data. Additional research would assist in prediction and design of pool sequences if long homogeneous reaches can be found to calibrate models. Larger streams tend to be dominated by certain pool types [*Grant et al.*, 1990; *Montgomery et al.*, 1995], and it may be possible to calibrate models utilizing probability distributions conditioned on pool types on large streams.

Sampling Analysis

This model may be used for testing the sampling methods represented in (6) and (7) or in other methods. The parameters have physical significance and are readily observable on streams. Thus this model will allow the determination of the variance of any desired sampling scheme based on pool spacing and length. Sampling tests can be performed with this model without concern about inhomogeneities always present along actual streams.

The precision of pool spacing measurements may also be considered with the model by examining the variation of the standard error ($s_{PSP}/\bar{n}^{1/2}$) with the number of pool sequences measured. As the number of pool sequences increases, the standard error approaches 0. We simulated two synthetic streams, named A and B, with pool spacings of 3.5 and 7, respectively, to resemble spacings found commonly in the literature [e.g., *Keller and Melhorn*, 1978; *Grant et al.*, 1990; *Montgomery et al.*, 1995]. We assumed λ equal to 2.5 and 5.5 widths; therefore E (pool length) is 1 and 1.5 widths, respectively, for A and B. For the gamma distribution of pool length we assumed that $\alpha > \beta$ and that α/β resembled values from Table 3. We then simulated two artificial streams with 2000 habitat units (approximately 1000 pool sequences; the number of pools always exceeds the number of nonpools because some pools flow directly into another pool) and randomly chose 10 locations within the synthetic reach to start measuring pool spacing. We subsampled successively longer reaches starting at 5 pool sequences by adding 5 pool sequences to a maximum length of 500.

Standard error at $n = 50$ in B is twice that of A (Figure 12). Standard error decreases as n increases. Optimum reach length for stream survey is that at which additional precision of

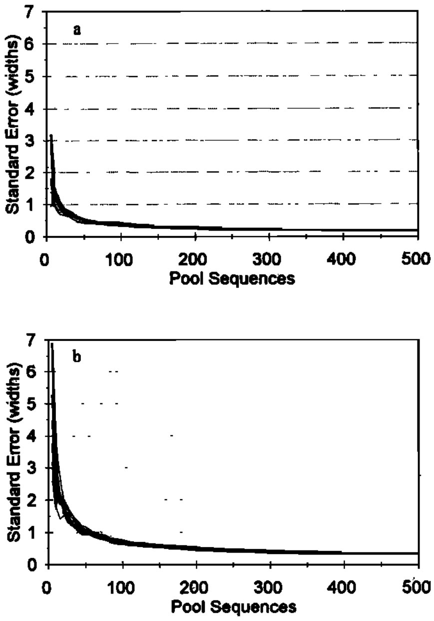

Figure 12. Standard error as a function of the number of pool sequences of a hypothetical stream with (a) 7 and (b) 3.5 width spacings.

a population moment estimate for additional measurements becomes much less. This corresponds to a point of substantially decreased slope on Figure 12. A breakpoint on the curves for A occurs at 35 pool sequences compared with 60 for B. With 35 pool sequences measured, standard error on A is about 0.5 widths. With 60 pool sequences measured, standard error on B is about 0.9 widths. This suggests 95% confidence limits of about 3–4 or 6–8, respectively. Because of the different spacings, the total length in widths required for optimum sampling length for B is much longer than A (420 compared to 122.5). Most studies in the literature, including those referenced above, sampled much shorter reach lengths.

Standard error will vary with model parameters in a predictable way. Assuming no correlation between pools and nonpools, as found by T. J. Myers and S. Swanson (Variability of pool characteristics with pool type and formative feature on small Great Basin rangeland streams, submitted to *Journal of Hydrology*, 1996), the variance of pool spacing,

$$\text{var(pool spacing)} = \text{var(RL)} + \text{var(PL)} = \lambda^2 + \alpha\beta^2 \quad (9)$$

shows that variance increases as the length between pools increases but that it depends on the covariation of the pool length parameters. As α increases with β remaining the same, the gamma distribution becomes flatter and the variance increases. Increasing β increases the density in the right tail, which increases the variance according to the square of β. Nine of 12 streams in this study had a β less than 1; therefore its impact on the variance was small. However, the other three streams, all pool-riffle types, tended to have longer pools. This suggests that pool-riffle streams, or streams with many long, low-gradient pools, have higher variance and require a longer reach to be sampled.

Conclusion

The stochastic model reproduced expected values of width and PA for two different sampling schemes accurately. On reaches for which the observed width (based on sampling described above; the actual is 1.0 because of the standardization) differed from 1, the simulation actually reproduced 1. Observed differences in sd were due to autocorrelation at one-width spacing, which sampled the same unit, and a possible slight correlation in the size of adjacent pools. Rounding by the model did not decrease skewness. In fact, the model produced occasional extremes not observed on actual streams but certainly possible. Because PA ranges from 0 to 1, if a simulated reach is long enough, there will always be extremes not present on the original. This is only a error if density in the tails of the simulated PA distribution are physically unrealistic, which they are not.

The main sources of error in this model are an inability to reproduce autocorrelation at short ranges, slight pool cyclicity on simulated but not on observed reaches, and a tendency to produce outliers not observed in the actual data. The errors are very small, however, and we conclude that the presented compound Poisson process model of pool spacing and size is accurate and applicable to small Nevada rangeland streams and, by extension, to similar streams elsewhere.

Acknowledgments. This research was funded by a Federal Aid in Sport Fish Restoration grant from the Nevada Division of Wildlife and by funds from the Nevada Agricultural Experiment Stations Project 52EU. We thank G. Fred Gifford, Dale F. Ritter, Elizabeth Jacobsen, and John Warwick for review and service on the senior author's Ph.D. committee. We also acknowledge the helpful suggestions of the reviewers Dave Montgomery and Erik Webb.

References

Abrahams, A. D., G. Li, and J. F. Atkinson, Step-pool streams: Adjustment to maximum flow resistance, *Water Resour. Res.*, *31*, 2593–2602, 1995.

Bobée, B., and F. Ashkar, *The Gamma Family and Derived Distributions Applied in Hydrology*, Water Resour., Littleton, Colo., 1991.

Bonser, J. D., T. E. Unny, and K. Singhai, Marked Poisson process model of summer rainfall in southern Ontario, *Can. J. Civ. Eng.*, *12*, 886–898, 1985.

Caissie, D., and N. El-Jabi, Stochastic study of floods in Canada: Frequency analysis and regionalization, *Can. J. Civ. Eng.*, *18*, 225–236, 1991.

Carling, P. A., and M. A. Hurley, Time-varying stochastic model of the frequency and magnitude of bed load transport events in two small trout streams, in *Sediment Transport in Gravel-Bed Rivers*, pp. 897–920, J. Wiley, Ney York, 1987.

Chin, A., Step pools in stream channels, *Prog. Phys. Geogr.*, *13*, 391–407, 1989.

Clarke, R. T., Information transfer with censored data: Some large-sample results, *Water Resour. Res.*, *27*, 1011–1018, 1991.

Duckstein, L., M. Fogel, and D. Davis, Mountainous winter precipitation: A stochastic event-based approach, in *National Symposium on Precipitation Analysis for Hydrologic Modeling*, June, 1975, Davis CA., 1975.

Frissel, C. A., W. J. Liss, C. E. Warren, and M. D. Hurley, A hierarchical framework for stream habitat classification: Viewing streams in a watershed context, *Environ. Manage. N. Y.*, *10*, 199–214, 1986.

Grant, G. E., F. J. Swanson, and M. G. Wolman, Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon, *Geol. Soc. Am. Bull.*, *102*, 340–352, 1990.

Gregory, K. J., A. M. Gurnell, C. T. Hill, and S. Tooth, Stability of the pool-riffle sequence in changing river channels, *Reg. Rivers Res. Manage.*, *9*, 35–43, 1994.

Hankin, D. G., and G. H. Reeves, Estimating total fish abundance and total habitat area in small streams based on visual estimation methods, *Can. J. Fish. Aquat. Sci.*, *45*, 834–844, 1988.

Harvey, A. M., Some aspects of the relations between channel characteristics and riffle spacing in meandering streams, *Am. J. Sci.*, *275*, 470–478, 1975.

Hubert, W. A., and S. J. Kozel, Quantitative relations of physical habitat features to channel slope and discharge in unaltered mountain streams, *J. Freshwater Ecol.*, *8*, 177–183, 1989.

Hurley, M. A., Modeling bedload transport events using an inhomogeneous gamma process, *J. Hydrol.*, *138*, 529–541, 1992.

Jacobs, B. L., I. Rodriguez-Iturbe, and P. S. Eagleson, Evaluation of a homogeneous point process description of Arizona thunderstorm rainfall, *Water Resour. Res.*, *24*, 1174–1186, 1988.

Kavvas, M. L., Stochastic trigger model for flood peaks, 1, Development of the model, *Water Resour. Res.*, *18*, 383–398, 1982.

Keller, E. A., Areal sorting of bed-load material: The hypothesis of velocity reversal, *Geol. Soc. Am. Bull.*, *82*, 753–756, 1971.

Keller, E. A., Development of alluvial stream channels: A five-stage model, *Geol. Soc. Am. Bull.*, *83*, 1531–1536, 1972.

Keller, E. A., and A. N. Melhorn, Rhythmic spacing and origin of pools and riffles, *Geol. Soc. Am. Bull.*, *89*, 723–730, 1978.

Keller, E. A., and F. J. Swanson, Effects of large organic material on channel form and fluvial processes, *Earth Surf. Processes*, *4*, 361–380, 1979.

Kirchner, J. W., Statistical inevitability of Horton's laws and the apparent randomness of stream channel networks, *Geology*, *21*, 591–594, 1993.

Klein, M., Drainage area and the variation of channel geometry downstream, *Earth Surf. Processes, Landforms*, *6*, 589–593, 1981.

Law, A. M., and W. D. Kelton, *Simulation Modeling and Analysis*, 759 pp., McGraw-Hill, New York, 1991.

Leopold, L. B., and W. B. Langbein, The concept of entropy in landscape evolution, *U.S. Geol. Surv. Prof. Pap. 500-A*, 1962.

Lisle, T. E., Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California, *Geol. Soc. Am. Bull.*, *97*, 999–1011, 1986.

Marston, R. A., The geomorphic significance of log steps in forest streams, *Ann. Assoc. Am. Geogr.*, *72*, 99–108, 1982.

Montgomery, D. R., and J. M. Buffington, Channel classification, prediction of channel response, and assessment of channel condition, *Rep. TFW-SH10-93-002*, 84 pp., Wash. State Dep. of Nat. Resour., Olympia, 1993.

Montgomery, D. R., J. M. Buffington, R. D. Smith, K. M. Schmidt, and G. Pess, Pool spacing in forest channels, *Water Resour. Res.*, *31*, 1097–1105, 1995.

Mosley, M. P., and A. I. McKerchar, Streamflow, *Handbook of Hydrology*, chap. 8, edited by D. R. Maidment, McGraw-Hill, New York, 1993.

Myers, T. J., *Stochastic Structure of Rangeland Streams*, Ph.D. dissertation, 200 pp., Univ. of Nev., Reno, 1996.

Myers, T. J., and S. Swanson, Aquatic habitat condition index, stream type, and livestock bank damage in northern Nevada, *Water Resour. Bull.*, *28*, 743–754, 1991.

Nachtnebel, H. P., and F. Konecny, Risk analysis and time-dependent flood models, *J. Hydrol.*, *91*, 295–318, 1987.

Nordin, C. F., and E. V. Richardson, The use of stochastic models in studies of alluvial channel processes, *Intern. Assoc. for Hydr. Res. 12th Congress Proc.*, pages 96–102, 1967.

Pegram, G. G. S., A continuous streamflow model, *J. Hydrol.*, *47*, 65–89, 1980.

Price, W. E., Simulation of alluvial fan deposition by a random walk model, *Water Resour. Res.*, *10*, 263–274, 1974.

Rendell, H., and D. Alexander, Note on some spatial and temporal variations in ephemeral channel form, *Geol. Soc. Am. Bull.*, *90*, 761–772, 1979.

Richards, K. S., Channel width and the riffle-pool sequence, *Geol. Soc. Am. Bull.*, *87*, 883–890, 1976.

Robison, E. G., and R. L. Beschta, Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, U.S.A., *Earth Surf. Processes Landforms*, *15*, 149–156, 1990.

Rodriguez-Iturbe, I., D. R. Cox, and P. S. Eagleson, Spatial modelling of total storm rainfall, *Proc. R. Soc. London A*, *403*, 27–50, 1986.

Rodriguez-Iturbe, I., D. Febres de Power, and J. B. Valdes, Rectangular pulses point process models for rainfall: Analysis of empirical data, *J. Geophys. Res.*, *92*, 9645–9656, 1987.

Roper, B. B., and D. L. Scarnecchia, Observer variability in classifying habitat types in stream surveys, *N. Am. J. Fish. Manage.*, *15*, 49–53, 1995.

Rosgen, D. L., A classification of natural rivers, *Catena*, *22*, 169–199, 1994.

Ross, S. M., *Stochastic Processes*, 308 pp., John Wiley, New York, 1982.

Shreve, R. L., Variation of mainstream length with basin area in river networks, *Water Resour. Res.*, *10*, 1167–1177, 1974.

Singh, V. P., *Hydrologic Systems: Rainfall-Runoff Modeling*, vol. 1, 480 pp., Prentice-Hall, Englewood Cliffs, N. J., 1988.

Sokal, R. R., and F. J. Rohlf, *Biometry: The Principles and Practice of Statistics in Biological Research*, 859 pp., W. H. Freeman, New York, 1981.

Stewart, J. H., and J. E. Carlson, Geologic map of Nevada, U.S. Geol. Surv., Carson City, Nev., 1978.

Thompson, D. M., The effects of large organic debris on sediment processes and stream morphology in Vermont, *Geomorphology*, *11*, 235–244, 1995.

Troutman, B. M., A stochastic model for particle sorting and related phenomena, *Water Resour. Res.*, *16*, 65–76, 1980.

U.S. Forest Service, Fisheries habitat survey handbook, *USFS Intermountain Region (94)-FSH 2609-23*, Ogden, Utah, 1985.

Wohl, E. E., K. R. Vincent, and D. J. Merritts, Pool and riffle characteristics in relations to channel gradient, *Geomorphology*, *6*, 99–110, 1993.

Yang, C. T., Formation of riffles and pools, *Water Resour. Res.*, *7*, 1567–1574, 1971.

T. J. Myers and S. Swanson, University of Nevada, 1000 Valley Rd., Reno, NV 89512. (e-mail: tjmyers@equinox.unr.edu)

(Received October 21, 1996; revised December 23, 1996; accepted December 23, 1996.)