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Variability of pool characteristics with pool type and formative feature on small Great Basin rangeland streams

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Abstract

Land managers and stream restorationists often set goals or complete designs including specifications for pools that are unrealistic because of a lack of knowledge of the potential conditions of the stream. Using 36 study sites on 17 rangeland streams in Nevada in the western United States, we determined relationships among pool and nonpool length, gradient, pool spacing, pool type and formative feature and stream type. Step pools primarily were formed by boulders while backwater pools were formed by coarse woody debris. This led to most pools being randomly located because structural pool-forming features are too large to move by the flows on these small streams. Montgomery and Buffington (1993) stream type associated with pool type and feature because of the direct linkage between the stream type definitions and pool features. Pool spacing varied only with Montgomery–Buffington stream type presumably because of its linkage with pool type and formative feature. Pool length varied with both Rosgen (1994) and Montgomery–Buffington stream type because of the relations between stream type and pool type and feature. Meander bend pools tended to be deeper because they form in erosive, fine substrate and because the spacing of forced pools may not be optimal which leads to sedimentation. Pool area did not vary with stream type but did with various formative features and pool and nonpool length. Variation of pool area with gradient and ln(gradient) was significant but explained much less variation than did other parameters. Meander bend dominated reaches had the highest pool area. The variability of results and the dependence of pool measures on pool type and formative feature indicates that strict adherence to published equations or expectations due to stream type should be avoided. Land managers should set goals for pool measures based on site specific conditions rather than perceived aquatic species needs or stream type. © 1997 Elsevier Science B.V.

Keywords: Pool characteristics; Pool type; Formative features; Streams; Land management

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1. 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 includes the length of the pool and the intervening nonpool geomorphic unit. It tends to remain constant through various development schemes (Keller, 1978; Gregory et al., 1994) and among substantially different geologic bases (Keller and Melhorn, 1978). Some suggest the primary control of spacing is gradient (Wohl et al., 1993; Abrahams et al., 1995). However, pools tend to be spaced randomly in small streams where boulder and coarse woody debris (CWD) structures form pools and regularly in larger, meandering streams (Myers, 1996).

Pool–riffle sequences form for numerous reasons. On fluvial streams without substantial boulders or woody debris structure, pool–riffle sequences result from cross-channel oscillating flow that may be due to a variety of reasons (Yang, 1971; Keller, 1972; Milne, 1982; Dietrich and Smith, 1983). On streams with forced pools, the type and formative feature of pools affects energy dissipation (Heede, 1981; Chin, 1989; Wohl et al., 1993). Marston (1982) linked energy dissipation to the formative feature and suggested that removal of features such as logs frequently leads to incision. Step-pool sequences are important energy dissipators even in bedrock channels (Duckson and Duckson, 1995). Removal of structural features, such as woody debris, often leads to high sediment yields resulting from bank erosion (Smith et al., 1993; Lisle, 1995; Thompson, 1995) and loss of sediment stored behind debris dams (Beschta, 1979). In a review paper, Gregory and Davis (1992) found that woody debris management was an important determinant of channel morphology.

Agencies and stream restorationists frequently include prescriptions in their management plans or designs for a desirable frequency or area of pools. Some stream survey techniques assume that pool area equal to 0.5 (or 50% of the wetted stream area is a pool) is desirable for all streams (US Bureau of Land Management, BLM, 1978; US Forest Service, USFS, 1985) based on perceived desirable conditions for salmonids. Management prescriptions may prescribe this ratio as a recovery goal without considering a specific stream's potential to reach this value (for example, French et al., 1996). However, an agency guide determined frequencies of pools on pristine streams in Idaho as a function of Rosgen (1994) general level stream type, but did not specify concomitant pool areas or pool:riffle ratios (Overton et al., 1995). These pristine streams were 'natural' implying a lack of anthropogenic influences (Scherer, 1994). Many managers and restorationists perceive natural conditions to be optimal and therefore the goal of their plans or designs (Reeves et al., 1991; National Research Council, NRC, 1992). Using relations of pool spacing or area to pool or stream type (Myers and Swanson, 1991; Montgomery et al., 1995) or formative features (Keller and Swanson, 1979; Robison and Beschta, 1990), restoration designs often include pool spacing (Hasfurther, 1985; Reeves et al., 1991) and specific structural measures. Designs rarely consider the length or appropriate pool type based on specific stream morphologic conditions.

This paper determines the existence, nature and deterministic causes of relationships among pool and interpool length, pool spacing, pool depth, the type and formative feature of pools, stream type and gradient on small rangeland streams in Nevada. Statistical expression of these relationships should assist the land manager in the determination of pool conditions, including type, length, spacing and area, that may be expected on similar streams and the restorationist in designing projects that emulate conditions that may exist on streams on which the primary human impact is livestock grazing.

2. Study area

We studied 36 stream segments up to 50 channel widths in length on 17 streams in six mountain ranges of central and northwestern Nevada (Fig. 1). Study sites were chosen to represent the distribution of small streams found in Nevada rangelands (Myers and Swanson, 1991). All sites are within the basin and range geologic province (Stewart

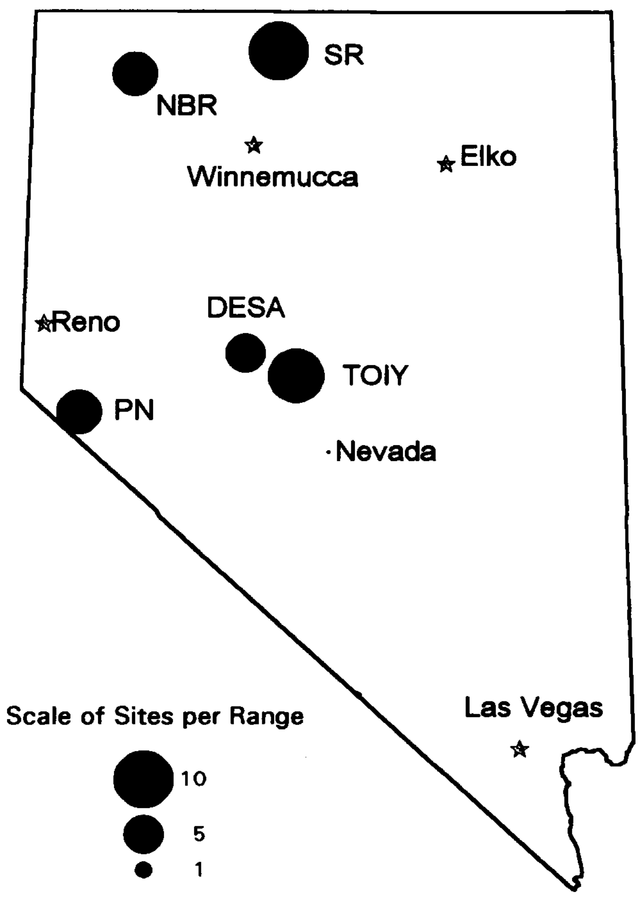

Fig. 1. Location map. PN, Pine Nut Mountain; SR, Santa Rosa Mtns; NBR, North Black Rock Mtns; DESA, Desatoya Mtns; TOIY, Toiyabe Mtns. See Table 1 for which site is located in each mountain range.

and Carlson, 1978) with upland vegetation dominated by sagebrush steppe to pinyon–juniper woodlands and riparian vegetation consisting of grasses, sedges, shrubs and trees. There are three general Rosgen (1994) stream type categories and five Montgomery and Buffington (1993) stream types represented with a variety of substrate. Channel width varies from less than 1.0 to almost 8 m. Stream order is either 2, 3 or 4 and drainage area above the sampling site varies from 0.5 to 89 km^2. Precipitation varies from 15 to 75 cm $year^{-1}$ depending on location and elevation (Houghton et al., 1975). Even in small drainages, it is possible that precipitation at upper elevations is twice that at lower elevations. Table 1 presents basic site characteristics.

Surveys were completed in summer, 1993, following the runoff period of a wet winter that had followed 6 years of very low snowpack (Myers and Swanson, 1996). The winter preceding the survey season provided snowpack equalling 150–200% of the 30-year normal throughout the area of these sites. All of these sites have perennial flow, but summertime baseflow on these streams is less than 0.15 $m^3 s^{-1}$.

The primary land use in watersheds tributary to the study sites, except for Mahogany Creek, is domestic livestock grazing. Almost all of the Mahogany Creek watershed has been a livestock exclosure since 1976 (Myers and Swanson, 1996). Except for the two Smith Creek sites, management of all other sites has been changed in recent years to improve riparian conditions. Many sites have roads in the riparian area which cross the stream. None of the watersheds have substantial mining activity. Some sites have apparently incised to some degree in the last century, but due to receding banks and riparian vegetation regrowth, are recovering (Swanson and Myers, 1994). Based on observed rates of bank retreat on similar stream of about 35 mm $year^{-1}$ in a drought year (Zonge et al., 1996), incision on these sites probably occurred between 1930 and 1970. Based on our observations, these sites represent Nevada rangelands streams with generally improving, but not pristine, conditions.

3. Methods

3.1. Field methods

During baseflow conditions, after snowmelt streamflow recession had ended in the late summer, we measured the length and water width of all habitat units (pools and nonpools) and the maximum depth of each pool along reach lengths of at least 25 channel widths. This survey methodology is similar to Hankin and Reeves (1988) and is similar to the basinwide survey of the USFS (Overton et al., 1995). We also measured the water and channel width at 25 transects spaced an average of 1–1.5 channel widths. We standardized all length measurements by dividing by the average water width, based on the 25 transects. We used water width for several reasons. Measured during baseflow, the water width represents the lowflow channel which is a stable indicator of basin conditions (Richards, 1982) and coincides within a few centimeters with various vegetative indicators (Hupp and Osterkamp, 1985). Myers and Swanson (1997b) found that water width was less variable than channel width due to the impact of large structural features on the channel and that baseflow channels are fit by a flow which occurs for over 300 days in Nevada.

Table 1
Descriptive statistics and parameters type for the study sites. All widths are in meters. General Montgomery and Buffington (1993) (MB) and Rosgen (1994) stream types are described in Table 3. Subtypes 3, 4, 5 and 6 in the Rosgen system represent a cobble, gravel, sand and silt/clay substrate, respectively

Reach	Channel width mean (SD)	Water width mean (SD)	Rosgen stream type	MB stream type	Drainage area (km^2)	Mtn range	Grad. (mm^{-1})
Abel Ck	2.62 (0.86)	1.62 (0.41)	B3	SP	9.82	SR	0.084
NF Abel Ck	1.54 (0.35)	0.93 (0.40)	B3	SP	3.52	SR	0.125 +
Siard Ck	1.98 (0.93)	1.03 (0.40)	B5	PR	9.66	SR	0.022
Martin Ck 1	2.91 (0.44)	1.80 (0.43)	B4	PIB	13.56	SR	0.004
Martin Ck 2	3.15 (0.99)	1.89 (0.63)	B4	PIB	10.76	SR	0.003
Cabin Ck 1	1.93 (0.38)	1.45 (0.38)	B4	fPR	23.06	SR	0.015
Cabin Ck 3	1.37 (0.39)	0.90 (0.27)	B4	fPR	6.44	SR	0.031
Dutch John Ck	4.00 (1.08)	2.58 (0.82)	C4	fPR	24.13	SR	0.016
NF Little Humboldt Riv. 1	4.07 (2.06)	2.36 (0.87)	C4	fPR	48.90	SR	0.004
NF Little Humboldt Riv. 2	6.82 (1.86)	3.72 (1.1)	B4	fPR	89.03	SR	0.012
Big Den Ck 1	1.24 (0.55)	0.72 (0.22)	B6	PIB	5.59	DESA	0.047
Big Den Ck 2	1.56 (0.47)	0.82 (0.33)	B6	PIB	5.59	DESA	0.054
Edwards Ck	1.47 (0.46)	0.81 (0.32)	C4	fPR	5.30	DESA	0.061 +
Smith Ck 1	1.90 (0.45)	1.34 (0.36)	A4	SP	7.46	DESA	0.070
Smith Ck 2	2.58 (0.79)	1.68 (0.43)	B4	PR	47.98	DESA	0.010
Washington Ck 1	2.39 (0.43)	1.93 (0.43)	B4	fPR	19.26	TOIY	0.018
Washington Ck 5	1.07 (0.27)	0.78 (0.25)	B4	Casc.	2.02	TOIY	0.126 +
Washington Ck 6	0.82 (0.31)	0.50 (0.18)	B4	Casc.	0.55	TOIY	0.118 +
Tierney Ck 1	2.12 (0.99)	1.12 (0.41)	B4	fPR	13.49	TOIY	0.034
Tierney Ck 3	1.52 (0.27)	1.06 (0.19)	A4	fPR	36.39	TOIY	0.033 +
Cottonwood Ck 1	2.31 (0.51)	1.69 (0.53)	A4	fPR	20.28	TOIY	0.037 +
Cottonwood Ck 2	2.52 (0.49)	1.88 (0.50)	C4	fPR	18.33	TOIY	0.031
San Juan Ck 1	2.28 (0.62)	1.43 (0.45)	B4	fPR	73.73	TOIY	0.026
San Juan Ck 2	2.44 (0.87)	1.42 (0.48)	B4	fPR	62.11	TOIY	0.057
Red Canyon Ck 1	1.63 (0.48)	0.97 (0.30)	B4	fPR	6.18	PN	0.193 +
Red Canyon Ck 2	1.52 (0.29)	1.14 (0.32)	B4	fPR	25.28	PN	0.171 +
Red Canyon Ck 3	1.40 (0.38)	0.92 (0.27)	C4	PR	26.12	PN	0.045 +
Red Canyon Ck 4	1.12 (0.29)	0.76 (0.19)	B4	fPR	6.77	PN	0.035
Red Canyon Ck 5	1.54 (0.36)	1.19 (0.32)	B4	fPR	19.28	PN	0.087
Mahogany Ck 1	2.56 (0.96)	1.90 (0.68)	C4	fPR	33.89	NBR	0.019
Mahogany Ck 2	2.44 (0.46)	1.96 (0.45)	A4	fPR	28.34	NBR	0.025 –
Summer Camp Ck 4	2.10 (0.42)	1.84 (0.33)	B4	fPR	7.23	NBR	0.015
Summer Camp Ck 5	1.96 (0.34)	1.52 (0.34)	B4	fPR	3.83	NBR	0.055
Mahogany Ck 6	1.49 (0.36)	1.06 (0.26)	B4	fPR	15.17	NBR	0.060
Mahogany Ck 7	1.27 (0.44)	0.98 (0.22)	B4	fPR	11.91	NBR	0.015
Mahogany Ck 8	1.74 (0.47)	1.46 (0.45)	B4	fPR	5.27	NBR	0.040

SD, standard deviation; PN, Pine Nut Mountain; SR, Santa Rose Mtns; NBR, North Black Rock Mtns; DESA, Desatoya Mtns; TOIY, Toiyabe Mtns.
A + or – next to a gradient value indicates the value is greater or less than the published Rosgen (1994) range.

Thus, estimates of pool and nonpool length are more precise when standardized by water width. Average channel width was about 150% of water width with a standard deviation of 10% for the streams in this study.

Following Grant et al. (1990), a pool is a distinct habitat unit with hydraulic gradient

Table 2
Pool types and primary formative features. Primary means the most important feature

	Description
Pool types	
Dam	Pool consists of backwater from a feature at the downstream end
Plunge	Pool formed by a plunge over a feature at the upstream end
Scour	Pool formed by scour from diverting around a feature
Glide	Long, shallow unit formed by general low gradient of stream bottom. No obvious feature. Generally glides are shallow with faster velocity than expected in most pools
Backwater	Pool is flatwater caused by damming of a riffle, rapid or cascade
Underflow	Scour pool underneath a feature
Formative features	
Mid-channel bar	Depositional unit occurring in the middle of the channel
Boulder/cobble	Large particles, or stochastic features in the stream
Free-formed	Pools formed in fine material by scouring due to oscillations in the flow direction in generally straight stream reaches
Meander bend	Pool formed by natural meandering of stream
Roots	Tree or shrubs only
Coarse woody debris	Any type of woody debris which leads to formation
Vegetation	Herbaceous vegetation, includes stems, leaves and roots

less than the stream average. Pools exhibit subcritical flow conditions except for an entry jet which may cause up to 15% of the surface to be supercritical. An identified pool must span the stream at some point along its length, thus small pocket pools and similar habitat units associated with small features within a nonpool reach are not identified as pools. We classified each pool according to six types and seven primary formative features (Table 2) similar to Robison and Beschta (1990). Examples of combinations in Table 2 are scour pools with boulder features concentrating flow and causing deepening or plunge pools with boulder features having flow over boulders falling onto and eroding finer substrate into a pool. Pools scoured into gravel substrate without an obvious formative feature are referred as free-formed.

3.2. Stream classification

We completed Rosgen (1994) stream classification by measuring the channel width/depth ratio and entrenchment ratio ((width between banks at twice the maximum channel depth)/channel width) at representative locations within the site and sinuosity of the entire reach. Classification was only to the general level (A, B or C, Table 3) so that it represents cross-sectional shape only. We determined gradient from a profile survey at 25 evenly spaced locations. The gradient of ten sites was outside of the range expected by Rosgen (1994) and was, therefore, considered separately in statistical analysis of reach-scale pool area.

Montgomery and Buffington (1993) stream types were determined based on dominant pool type. The category forced pool–riffle was added based on Montgomery et al. (1995). These are reaches with a scour pool–riffle sequence but with pools caused and positioned

Table 3
Characteristics of the Rosgen (1994) and Montgomery and Buffington (1993) stream types represented in this study. All variable ranges reported represent the major ranges of the classification. Entrenchment ratio is width between banks at twice the maximum channel depth divided by channel width
(a) Rosgen stream types

Type	Entrenchment ratio	Channel W/D[a]	Sinuosity	Gradient[b]
A	< 1.4	< 12	< 1.2	> 0.04
B	1.4–2.2	> 12	> 1.2.	0.02–0.1
C	> 2.2	> 12	> 1.4	0.001–0.04

(b) Montgomery–Buffington stream types

Type	Description
PR	Pool–riffle: channel with undulating bed having a sequence of free-formed bars, pools and riffles
fPR	Forced pool–riffle: channel with undulating bed but with pools formed in association with structural features such as rocks and coarse woody debris
SP	Step-pool: channel with large clasts organized into discrete channel-spanning accumulations that for a series of steps separating pools with fine material
PlB	Plane bed: channel lacking well-defined bedforms and typically lacking pools
Casc.	Cascade: steep channel characterized by longitudinally and laterally disorganized bed material consisting of cobble and boulders

[a] Channel width/depth ratio.
[b] Gradient as expected by Rosgen (1994). Gradient is generally considered a subtype; the values presented here are subtype ranges.

by a structural feature. The gradient of 18 of these sites exceeds that expected by Montgomery and Buffington (1993). However, 17 of them are forced pool–riffle streams whereby structural features have caused scour pools on reaches that may otherwise have been plane bed or step pool. Differences between step pool and forced pool–riffle streams include the presence of vertical steps on the step pool stream. Cascades generally consist of steep reaches with tumbling flow and only small pocket pools behind and below the features. Based on slope expectations in Montgomery and Buffington (1993), steep reaches herein should be cascades. However, several of these reaches were pool–riffle because they had free-formed, channel spanning pools without steps. This contradiction in channel classification suggests that stream size be considered. In other words, small streams at a steep slope may classify based on pool type and bedform as streams expected for flatter gradients. This study was not designed to test hypotheses of stream type and gradient, therefore these results should be treated as observations which may affect the results of analyses as discussed below.

3.3. Statistical methods

Categorical comparisons for association among categories of pool type, formative feature and stream type were made using chi-square tests for independence (Sokal and Rohlf, 1981). Pool spacing and length are not normally distributed (Myers, 1996), therefore, we used Kruskal–Wallis one-way nonparametric analysis of variance (Sokal and Rohlf, 1981) to determine differences in distributions among categories of pool type, feature and stream type. After eliminating pools with types or features represented by less than ten observations, there were 358 pools used for categorical and Kruskal–Wallis analyses.

We tested the maximum pool depth for variation with categories of pool type and feature using a multiple regression analysis of variance with indicator variable design (Neter et al., 1985). An indicator variable (0, 1) indicates whether a given pool has a specific pool type or feature. Consideration of the sum of squares and f-statistic for any group of indicator variables allows determination of whether that group explains significant variation. We controlled for differences among streams including size, geology and climate by using an indicator variable for each reach. This control prevented testing for differences in maximum pool depth among stream type because stream indicators are perfectly correlated with indicators of stream type. There were only 326 pools available for this analysis due to missing depth data.

Pool area is the fraction of stream surface classified as a pool using methods of Grant et al. (1990). We analyzed among reach variance of pool area with stream type, dominant pool type and feature and gradient, average pool spacing and length using a multiple regression indicator variable model. Indicator variables for stream type and dominant pool type and feature were created. Dominant pool type and feature was the most frequent for the specific reach. Analyzing for each stream type methodology separately, we then removed from the model groups of variables (stream type, pool type or feature) that did not explain significant amounts of variation. A final model included pool and nonpool length and the groups of indicator variables not removed for lack of significance. The model was then used to explain the controls of pool area.

4. Results and discussion

4.1. Pool properties and stream type

Any combination of pool type and formative feature is possible, but several combinations dominate the type and feature association. The null hypothesis of independence was strongly rejected ($\chi^2 = 83.7$, $P = 0.000$). For example, plunges were predominantly formed by boulders, although there was also a slight tendency toward formation by CWD and roots. Observed scour features were similar to that expected except for a strong tendency for scour pools to associate with meanders. Scour pools associated with the free-formed feature suggests pool formation by substrate sorting (Milne, 1982) in reaches without pool-forcing features. Backwater pools associated strongly with CWD indicating a tendency for backwater behind debris jams.

There was no association between pool type and Rosgen (1994) general stream type ($\chi^2 = 4.69$, $P = 0.587$). However, both pool type and feature varied by Montgomery and Buffington (1993) stream type ($\chi^2 = 119.4$ and 41.6, respectively; $P = 0.000$). There was slight association between formative feature and Rosgen general stream type ($\chi^2 = 16.5$, $P = 0.0856$) presumably resulting from associations of stream type and riparian vegetation or substrate (Robison and Beschta, 1990; Myers and Swanson, 1991; Myers and Swanson, 1994; Myers and Swanson, 1996). Streams with well-developed riparian forests have more

CWD input (e.g. Fetherston et al., 1995) which leads to more variable pool types and channel cross-sections (Robison and Beschta, 1990). The lack of associations suggests that Rosgen stream type alone should not be used to predict pool types that will be found or should be found in a restored reach.

Scour pools dominated 30 of 36 sites with boulder/cobble being the dominant pool-forming feature on 21 of the 30. Thus, there were too few observations in other categories to perform categorical association tests. The stream type distribution for either dominant pool type or feature did not vary substantially within the complete set of streams. This suggests that small, Nevada rangeland streams, of several stream types, have scour pools formed by structural features such as boulders and CWD. Boulders predominate because of the lack of trees and the domination by willows or early seral shrubs (such as wild rose, *Rosa woodsii*, or currant, *Ribes* spp.) in riparian zone. Scour pools that form on meander bends are exceptions because, even on small streams of low gradient and C-type shape (Rosgen, 1994), there are structural features to form pools. In the absence of structural features, the natural meandering process yields meander formed scour pools (Keller and Melhorn, 1978). Another exception is the occasional plunge pools that form on steep, cascade streams (Chin, 1989; Abrahams et al., 1995). Possibly, high gradient leads to a requirement for plunge pools to dissipate energy. Boulders and CWD often form these pools and lead to random spacing on small streams that cannot move the large features.

4.2. Pool length, spacing and pool properties

Pool length varied significantly with formative feature, pool type, Rosgen (1994) general stream type and Montgomery and Buffington (1993) stream type (Kruskal–Wallis test statistic (KWS) = 35.3, 14.3, 7.4, 31.7, $P = 0.000$, 0.003, 0.024 and 0.000, respectively) (Fig. 2). The weaker association with Rosgen general stream type reflects the lack of association between stream type and pool type or feature and potentially the ten reaches for which gradient takes on values outside the expected range defined by Rosgen (1994) for streams of this cross-sectional shape (Table 3). However, its significance also indicates that cross-sectional shape influences pool length. The strong association with Montgomery and Buffington (1993) stream type reflects the use of pool forming features as primary classification variables and a strong relation with gradient. Plunge and scour pools were shorter than glides or backwaters (Fig. 2(B)). Boulders were the predominate formative feature for both (Fig. 3). However, many scour pools were either free-formed or resulted from meander bends (Fig. 3) which were two of the three features resulting in the longest pools (Fig. 2(A)). Yet, scour pools formed by boulders, roots or CWD were short enough (Fig. 2(A)) to lower the mean length and increase the skewness of scour pools (Fig. 2(B)). These features also predominate pool formation in step-pool and forced pool–riffle streams causing them to be shorter than other Montgomery and Buffington (1993) types. Scour pools are therefore quite variable depending on their formative feature.

The length of nonpools varied significantly only with formative feature of the downstream pool (KWS = 11.7, $P = 0.039$, Fig. 4(A)). There was weak association with downstream pool type (KWS = 7.3, $P = 0.062$, Fig. 4(B)), but no variation with upstream pool types or features (KWS = 1.1 and 0.9, $P = 0.590$ and 0.750, respectively). Variation with Rosgen and Montgomery and Buffington stream type was insignificant and significant,

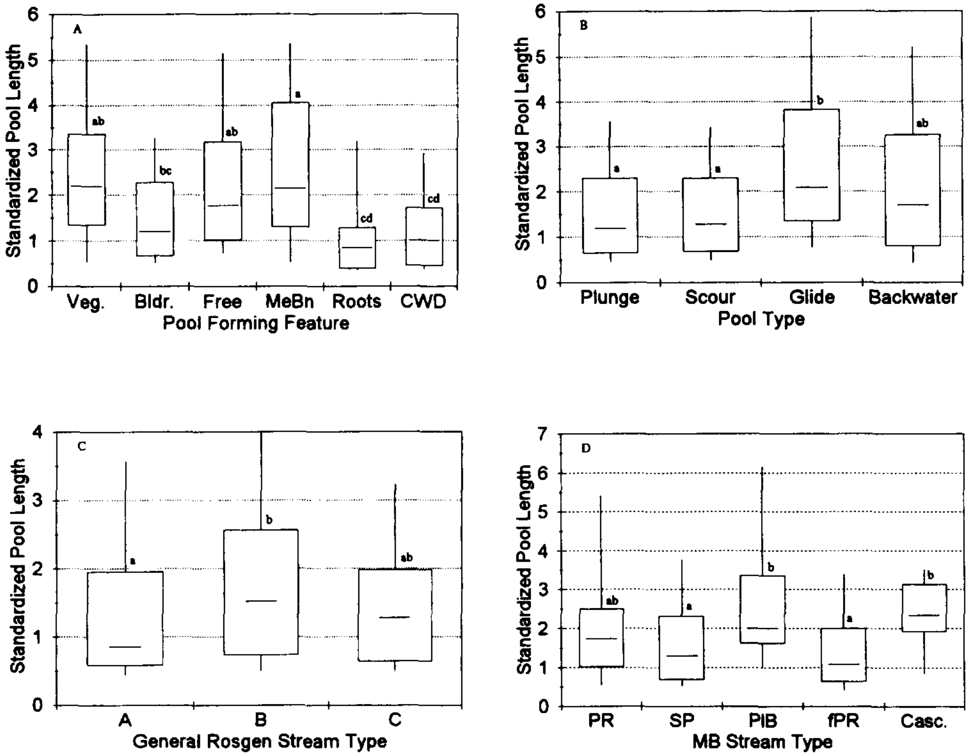

Fig. 2. Variation of standardized pool length with pool formative feature (A), pool type (B), general Rosgen (1994) stream type (C) and Montgomery and Buffington (1993) stream type (D). Similar letters represent groups for which the distribution of length is the same ($P < 0.05$) according to Kruskal–Wallis one-way ANOVA. The vertical line is the range, the box represents the upper and lower quartile and the horizontal mark is the mean. See Table 2 for definition of pool type and features and Table 3 for definition of stream type.

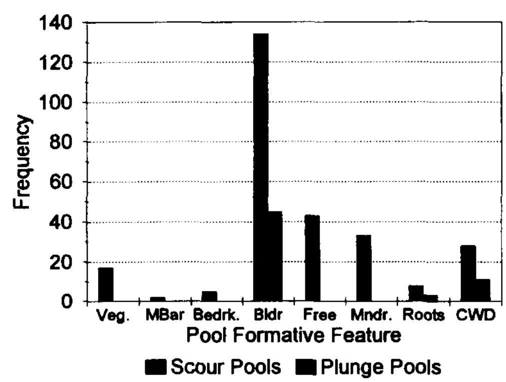

Fig. 3. Frequency of formative feature for scour and plunge pools.

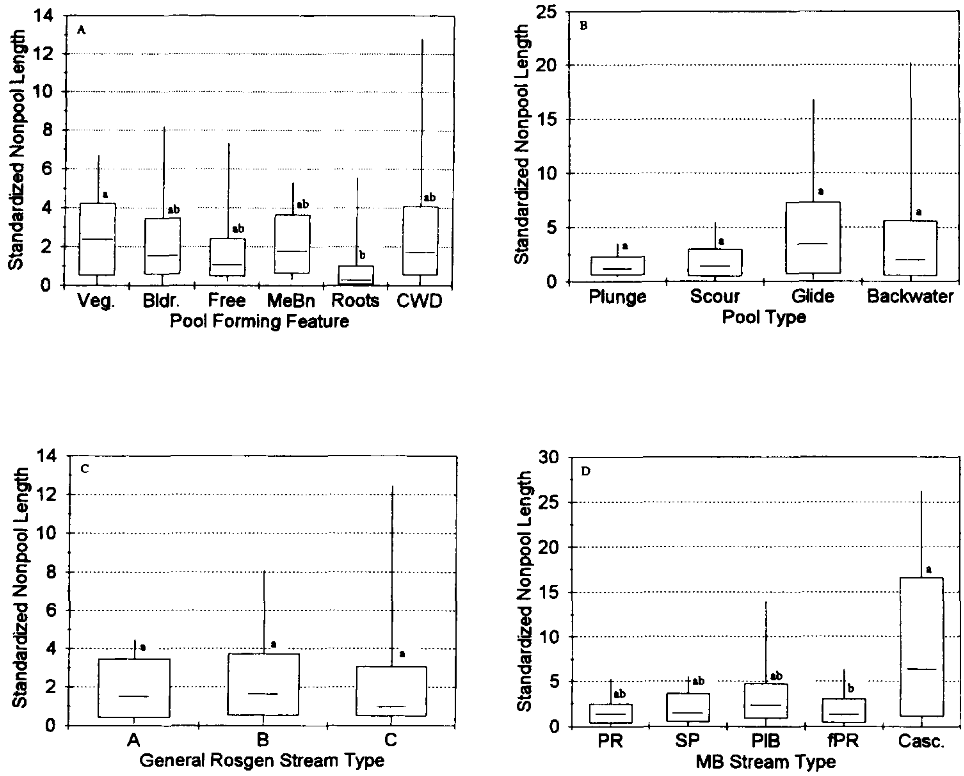

Fig. 4. Variation of standardized nonpool length with downstream pool formative feature (A), downstream pool type (B), general Rosgen stream type (C) and Montgomery and Buffington (1993) stream type (D). Similar letters represent groups for which the distribution of length is the same ($P < 0.05$) according to Kruskal–Wallis one-way ANOVA. The vertical line is the range, the box represents the upper and lower quartile and the horizontal mark is the mean. See Table 2 for definition of pool type and features and Table 3 for definition of stream type.

respectively (KWS = 1.3 and 13.9, $P = 0.519$ and 0.008, respectively) (Fig. 4(C) and (D)). Only A channels that are also cascades differ markedly from other stream types. Boulders and CWD did not cause shortened spacings in most streams, indicating that they substitute for meander-formed or substrate sorted scour pools.

Pool spacing is the sum of pool and nonpool lengths. Both pool feature and type explain variation in spacing (KWS = 13.8 and 15.8, $P = 0.017$ and 0.001, respectively, Fig. 5(A) and (B)). The significance levels, being between those for pool and nonpool lengths, suggest that a blending of effects controls pool spacing. Duckson and Duckson (1995) found that the type of bedrock step determined the length of pools but explained much less of the overall spacing. The shape of the pool spacing relationship with feature (Fig. 5(A)) resembles nonpool (Fig. 4(A)) more than pool (Fig. 2(A)) length. Nonpool length exceeds pool length and therefore controls pool spacing. The skewness of pool spacing for CWD and boulders suggests that pool spacing formed by these features follows an exponential

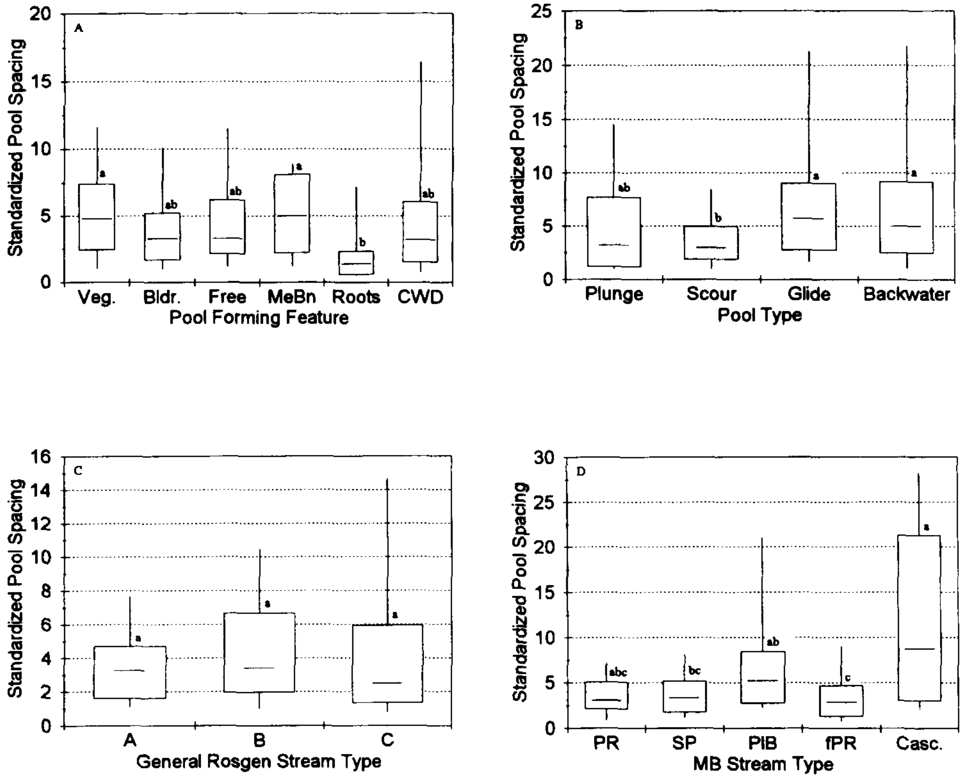

Fig. 5. Variation of standardized pool spacing with pool formative feature (A), pool type (B), general Rosgen (1994) stream type (C) and Montgomery and Buffington (1993) stream type (D). Similar letters represent groups for which the distribution of length is the same ($P < 0.05$) according to Kruskal–Wallis one-way ANOVA. The vertical line is the range, the box represents the upper and lower quartile and the horizontal mark is the mean. See Table 2 for definition of pool type and features and Table 3 for definition of stream type.

distribution. The coefficient of variation is 1.32, which approximates the value 1.0 expected for an exponential distribution. A histogram of pool spacing for these features resembles an exponential distribution except that few spacings are less than 2 (Fig. 6). This implies random locations of these pools and therefore of these features and agrees with previous work (Myers and Swanson, 1997a) that used much longer reaches of similar streams.

Pool spacing does not vary with Rosgen general stream types but does vary with Montgomery and Buffington (1993) types (KWS = 3.6, 28.9; $P = 0.163$ and 0.000, respectively). This should not be surprising in that the general level Rosgen (1994) stream classification used here depends on cross-sectional properties rather than gradient or bed form, a primary classification variable for the Montgomery and Buffington (1993) system. Gradient influences pool–riffle relations (Hubert and Kozel, 1989; Wohl et al., 1993) and the Montgomery and Buffington (1993) classification more specifically separates

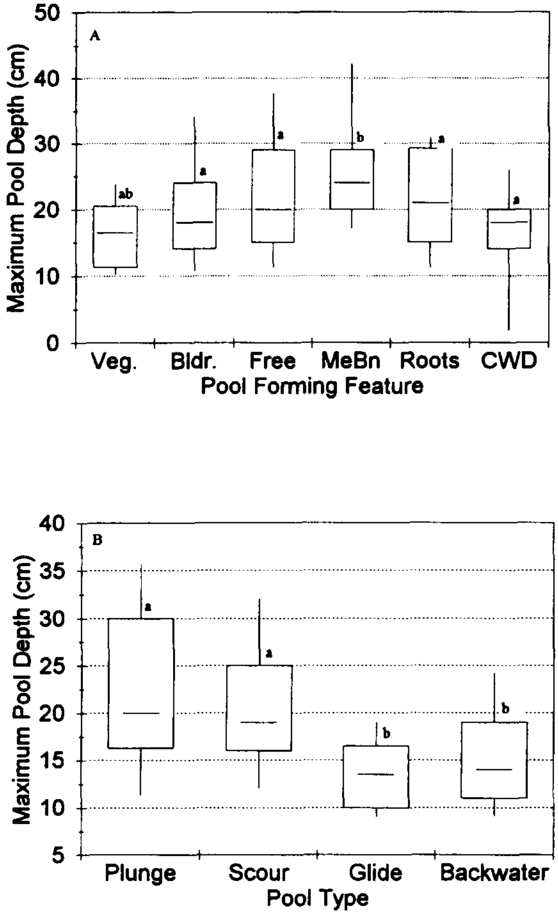

Fig. 6. Frequency of standardized pool spacing for pools formed by boulders or CWD only.

high- and low-energy fluvial streams. High-energy streams will likely classify as either cascade or step-pool and low-energy streams will likely classify as pool–riffle or plane-bed. A forced pool–riffle stream may be either high or low energy, as suggested above, in which the frequency of formative features controls the spacing (Montgomery et al., 1995; Myers, 1996). Differences in feature among Montgomery and Buffington (1993) types explain the significant variation of pool spacing with these types.

Cascades (Montgomery and Buffington, 1993) differ substantially from the other stream types in pool spacing (Fig. 5(D)). This is primarily due to the long distance between pools (Fig. 4(D)). However, the definition of pools used herein may partially cause this distinction. Pools must span the stream to be designated as a pool whereas cascades may contain many small, non-spanning pools below boulders (pocket pools). Formation of pools may be due to the presence of boulders which increases energy dissipation by increasing turbulence.

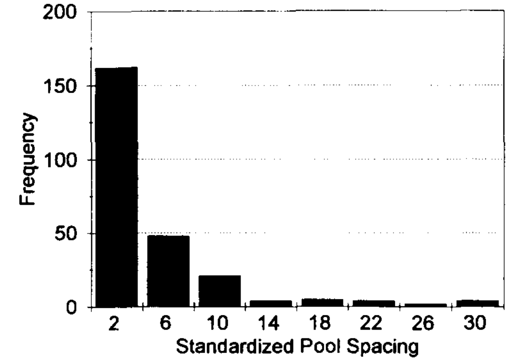

Fig. 7. Variation of maximum pool depth for formative feature (A) and pool type (B) controlling for stream reach. Similar letters represent groups for which the mean maximum pool depth is the same ($P < 0.05$). The vertical line is the range, the box represents the upper and lower quartile and the horizontal mark is the mean. See Table 2 for definition of pool type and features.

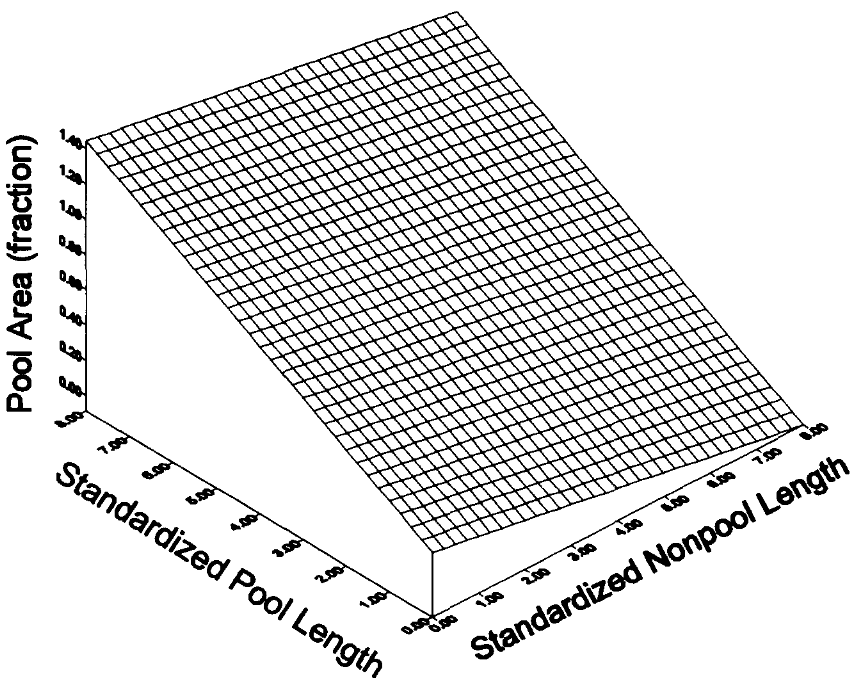

Fig. 8. Variation of pool area with standardized pool and nonpool lengths from 0 to 8 widths controlling for mid-channel bar. Note that the surface extends beyond the range of data in the model.

4.3. Variation of maximum pool depth

Both pool feature and type explained significant portions of the variation of maximum pool depth after accounting for differences in stream size (f statistic (f) = 3.61 and 15.37; P = 0.004 and 0.000, respectively) (Fig. 7). Meander bends generally formed deeper pools (Fig. 7(A)) because they primarily form in erosive gravel or sand-bed channels. However, as mentioned above, these pools form less in streams with pools formed by substantial boulder or CWD. In a meander pool, scour results from natural convergence and divergence of the flow paths (Keller, 1972). In forced pools, immovable objects such as boulders or CWD constrain and disrupt the flow paths leading to zones of faster and slower flow. However, these pools are shallower than free-formed pools suggesting that deposition or less optimal scour flow conditions occur around randomly located features. However, free-formed pools may be transient during years of variable flow (Myers and Swanson, 1996). Although meander-pools are deeper, at least after a year of substantial spring runoff, feature-formed pools may be more stable with more cover (Myers and Swanson, 1994).

Vegetation generally leads to backwater pools or glides. Vegetation also may slow velocities causing sediment deposition which decreases the depth of backwater. Many vegetation formed pools are pools only because of their lower gradient making them, in some cases, glides.

The distribution of CWD formed pools, including a negative skewness (Fig. 7(A)), reflects the variety of CWD-formed pools. Plunge and scour pools were deepest (Fig. 7(B)) suggesting that pool type explains the range for boulder and CWD features. For example, backwater upstream from a CWD jam is shallower than the pool below the plunge. Plunge pools transcend stream size in that a boulder-formed plunge pool on the relatively small Red Canyon 5 is the deepest pool of all these study sites. We could not test for different depths among plunge-forming features because of insufficient observations to include interactions among pool type and feature. Duckson and Duckson (1995) found no differences due to type of bedrock step, but they did not control for stream size.

4.4. Pool area, spacing and length

We initially tested for variation of pool area with reach gradient and nonpool and pool length controlling for stream type, dominant pool feature and type using the multiple regression with indicator variable design discussed above. Neither stream type, pool type nor gradient explained significant variation. However, pool feature and nonpool and pool length explained significant variance in both models (controlling for both stream types separately). After removing stream type and pool type, feature and both nonpool and pool length were still significant (f = 7.53 and 31.8, P = 0.000, respectively) and the final model was (R^2 = 0.91):

$$\mathrm{PA} = 0.282 + 0.049\ \mathrm{BLDR} + 0.020\ \mathrm{FREE} + 0.071\ \mathrm{MnBn} + 0.061\ \mathrm{CWD} - 0.046\ \mathrm{NPL} + 0.145\ \mathrm{PLEN}$$

where PA is pool area expressed as a proportion, BLDR, FREE, MnBn and CWD are indicator variables for reaches with pools dominated by either boulder, free-formed, meander or CWD formative features, respectively, and NPL and PLEN are nonpool and pool length in widths, respectively. The coefficients of the feature terms represent the difference between the mean pool area for that feature and the control, midchannel bar. For the control, Fig. 8 shows the three-dimensional shape of the relationship. Surfaces representing the other features parallel that shown on Fig. 8 but are vertically offset by the value of the coefficient.

Although significant, feature caused a range in PA of only 0.07. Meander-formed, or free-formed, pools caused reaches to have pool:riffle ratios closest to 1:1 (PA = 0.5). The lower pool-area of free-formed pools in confined systems compared with more sinuous meander-bend streams reflects a higher gradient (Wohl et al., 1993). The similar coefficients of boulder-, CWD- and free-formed pools suggests that pool area on non-meandering streams, regardless of formative feature, is an inherent characteristic of non-meandering streams. The pool-forming process apparently results in similar pool–riffle sequences on streams constrained from horizontal meandering with small differences due to feature.

As expected, increased nonpool and pool length had opposite effects on pool area. Pool length is lower and less variable than nonpool length (Figs. 2 and 4). As suggested by the slopes shown on Fig. 8, pool length controls pool area. Small increases in pool length increase pool area about five times as much as similar decreases in pool spacing. Simple regression between PA and width (in m) was significant but spurious and explained little variance ($R^2 = 0.139$, $P = 0.025$). A slight trend toward more pool area for larger streams coincided with a tendency for C-type streams to be larger.

That gradient was removed from Eq. (1) is counter-intuitive and led us to test simple relations with pool area. Linear regression between pool area and gradient was barely significant ($R^2 = 0.145$, $P = 0.024$), but the relation appeared logarithmic. Linear regression of pool area and ln(gradient) improved the relation slightly ($R^2 = 0.227$, $P = 0.004$). The significance of these analyses implies a relation, but the low R^2 reflects high scatter. Linear regression of gradient and ln(gradient) with pool length was significant ($R^2 = 0.194$ and 0.367, $P = 0.008$ and 0.0001, respectively), but with nonpool length was insignificant ($R^2 = 0.011$ and 0.050, $P = 0.543$ and 0.198, respectively). The relative weakness of these relations compared with those for pool type and features suggests that increasing gradient contributes to the tendency for specific pool features and types rather than controlling PA directly. It also suggests the linkage between stream type and pool types and features more directly controls pool area rather than gradient. The tendency for forced pool–riffle streams in this data set to have steeper gradients than expected (Montgomery and Buffington, 1993) also suggests that gradient is less important than available structural features in forming particular types of pool–riffle sequences and channel types.

4.5. Implications for stream restoration

Links among pool area, spacing, length, reach gradient, dominant pool forming feature and type and stream type all suggest that, to be successful, inclusion of pools in restoration projects must consider these relationships. Williams (1986) proposed a set of equations relating meander lengths with many channel properties that are often used for restoration design (Morris, 1995). However, these equations primarily apply to pool–riffle (Montgomery and Buffington, 1993) or C-type (Rosgen, 1994) streams. Use of these equations for the determination of meander length or pool spacing is inappropriate for smaller, nonsinuous streams with randomly spaced pools. Horizontally confined streams have different pool spacing, pool forming features and pool area than those that freely meander.

Abrahams et al. (1995) found that free-formed pools in confined streams are regularly spaced and that forced pools tended toward regular spacing if the stream reach had been stable for long periods. However, Myers and Swanson (1997a) found randomly spaced forced pools in confined streams. Differences were that Abrahams et al. (1995) worked on reaches with very constant gradient in a pristine, humid environment while Myers and Swanson (1997a) did not control small-scale gradient variability and worked on semi-arid streams on which successions of floods and droughts are normal. This suggests a deterministic link with small scale gradient and different designs for different climatic conditions. Restoration designs in semiarid, Nevada rangeland streams should space pools randomly with consideration of local factors.

Frissell and Nawa (1992) found that habitat enhancing structures formed of boulders or woody debris were more successful than other types such as weirs and deflectors. These successful artificial structures influence stream morphology similar to the natural structures studied herein. Combining the structure type with spacing and size guidelines herein should lead to better success.

4.6. *Implications for land management*

The relations developed herein are also necessary for land managers who prescribe management treatments along small rangeland streams. French et al. (1996), in a plan to recover a threatened species, stated that streams should be managed to have a 1:1 pool:riffle ratio. An example based on this management prescription should help to illustrate the usefulness of the relations herein.

Consider a small rangeland stream with predominately a gravel bed and a tree-lined riparian corridor. There is substantial CWD input to the stream, therefore the manager should assume pools will be forced by CWD. The cross-section of the stream is a Rosgen (1994) B-type. Nonpool and pool length for B-type streams ranges around 1.7 and 1.5 widths, respectively (Fig. 2), while CWD leads to nonpool and pool lengths ranging near 1.9 and 1.0 widths, respectively. Averaging expectations for CWD-formed pools and B-type streams suggest nonpool and pool lengths of 1.8 and 1.25 widths, respectively (Fig. 4). Eq. (1) suggests pool area should be near 0.44 indicating that the recovery plan pool area is not optimal, although it may be within an acceptable range. These relations provide a guide for determining possible pool areas for different streams. However, there are limits to Eq. (1). It is unlikely for pool length to increase as gradient increases, so this may not be an option. Thus, most small streams considered in French et al. (1996) are too steep for a 1:1 pool:riffle ratio if the streams studied herein are adequate representations of their streams.

Depth is an important feature of pools in that deeper pools provide more cover. However, certain substrates do not lead to deep pools and writing specifications for cover that would require abnormally deep pools is not appropriate. However, randomly spaced plunge pools may be shallow because the spacing is suboptimal. In reaches that have several clustered pools due to substantial debris input, managers could improve overall flow conditions, leading to deeper pools and pool area closer to optimal, by removing shallow, clustered pools. Managers should be cautious, however, in interpreting these statements as justifying debris removal. Removal of debris jams has led to long time periods of suboptimal pool area and quality on small, rangeland streams (Myers and Swanson, 1996).

5. Conclusion

There are definite linkages between pool properties and stream type. Step pools primarily were formed by boulders while backwater pools were formed by coarse woody debris. Montgomery and Buffington (1993) stream type associated with pool type and feature because of the direct linkage between the stream type definitions and pool features. The small, rangeland streams studied herein had most pools formed by randomly located structural features. Pool length varied with both stream type methods, but pool spacing varied only with Montgomery and Buffington (1993) stream type reflecting the closer linkage of the latter typing with reach gradient and structural features. Gradient appears to be a minor factor with type and feature better explaining tested relations. Pools tended to be deeper on meander bends because they form in erosive, fine substrate and because the spacing of forced pools may not be optimal leading to sedimentation. Pool area did not vary with stream type but did with various formative features and pool and nonpool length. Meander bend dominated reaches had the highest pool area.

These linkages should be understood and utilized by land managers and stream restorationists in their plans or designs. Because of the relation of pool length and site specific features, optimum pool area depends on gradient, substrate and available structural elements to form pools. Managers should specify goals for pool:riffle ratios based on optimums for conditions existing at a specific site and not based on species or stream type specific goals. The analysis herein suggests that broad specifications are inappropriate.

Restorationists should not use stream type alone to specify pool spacing and meander length variables; they should use site specific parameters including dominant pool type and feature, gradient, sinuosity and substrate to establish pools. Also, the pool length, which is a function of feature, is a dominant factor in pool spacing. Stream management and restoration should mimic natural processes and try to direct them as desired.

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