Controls on Pool Characteristics along a Resistant-Boundary Channel

Ellen Wohl and Carl J. Legleiter[1]

Department of Earth Resources, Colorado State University, Fort Collins, Colorado 80523, U.S.A.
(*e-mail: ellenw@cnr.colostate.edu*)

ABSTRACT

The North Fork Poudre River in Phantom Canyon has a pool-riffle sequence formed in granitic bedrock. We address two questions: What controls downstream pool spacing? Within a pool, what factors control pool dimensions? We hypothesize that both pool spacing and pool geometry could be governed by available flow energy or by substrate characteristics. These hypotheses were addressed using channel-bed and water-surface gradients surveyed under moderate flow, Selby rock-mass strength at vertical outcrops forming lateral pool constrictions and at other vertical outcrops, and joint density measured from high-resolution digital images of the bedrock outcrop along each of 10 pools. The downstream length between pools is quite variable (mean [m] = 117 m, standard deviation [SD] = 106 m), as is the cumulative drop between pools (mean = 1.3 m, SD = 0.8 m). Total upstream bed gradient and approach bed gradient vary by an order of magnitude. Thus, pools do not have a uniform longitudinal or gradient distribution along the study reach, indicating that the downstream spacing of pools does not reflect systemwide available flow energy. The mean of 10 rock-mass strength measurements at pool constrictions (m = 73), and 10 measurements elsewhere (m = 72), indicate no significant differences in rock strength at pool locations. However, pools are almost always associated with lateral constrictions where the active channel intersects a bedrock ridge. The downstream spacing of these ridges reflects regional patterns of structure and weathering, and the local jointing of each outcrop influences the formation of constrictions. The downstream spacing of pools thus appears to reflect substrate controls. Both flow energy and substrate appear to exert an influence on individual pool geometry. Pools with stronger lateral constrictions are deeper and have a shallower approach gradient. More-constricted pools decrease upstream sediment transport capability through a backwater effect. This decreases approach gradient by promoting coarse-sediment deposition. The stronger constrictions maximize stream power downstream and promote flow separation and bed scour. This leads to longer and deeper pools. Increased joint density on the bedrock walls corresponds to deeper pools. These results indicate that substrate may influence pool geometry via constriction ratio, which in turn influences approach gradient, pool length, and pool depth.

Introduction

Pool-riffle bedform sequences are a widespread form of channel variability along moderate-gradient rivers. These bedforms both reflect and influence downstream variation in sediment transport and sorting, boundary roughness and resistance, hydraulics, and ultimately, flow energy. Flow energy here refers to the forces available to perform work eroding the channel boundaries or transporting sediment. This energy can be symbolized by several variables, including stream power per unit area

$$\omega = \gamma QS/W = \tau V,$$

where ω is stream power per unit area (W/m^2), γ is the specific weight of the transporting fluid (N/m^3), Q is discharge (m^3/s), S is energy slope (m/m), W is bed width (m), τ is boundary shear stress (N/m^2), and V is mean velocity (m/s). Because of the importance of pools and riffles with respect to flow energy, several studies have addressed controls on pool-riffle spacing and geometry along various types of rivers.

Working on a dataset including both alluvial and mixed alluvial-bedrock channels, Keller and Melhorn (1978) found that approximately 70% of the variability in pool spacing can be explained by variability in channel width, with pools generally spaced at five to seven times the channel width. Roy and Abrahams (1980) reanalyzed the combined data as two separate sets (alluvial and bedrock) and

Manuscript received January 29, 2002; accepted June 4, 2002.

[1] Department of Earth Sciences, Montana State University, Bozeman, Montana 59717-0348, U.S.A. Present address: Department of Geography, University of California, Santa Barbara, California 93106-4060, U.S.A.

[The Journal of Geology, 2003, volume 111, p. 103–114] 0022-1376/2003/11101-0007$15.00

concluded that the two populations had significantly different means for pool spacing; 5.6 times channel width for alluvial and 6.7 times channel width for bedrock. Roy and Abrahams (1980) interpreted the slightly greater value for mixed bedrock streams as indicating that bedrock channels are adjusted to discharges of higher magnitude and lower frequency than alluvial channels. However, because the original data set included only mixed alluvial-bedrock rather than completely bedrock channels, Keller and Melhorn (1978) noted only that local bedrock controls may mask the rhythmic downstream pool spacing of alluvial channels

Examining a large bedrock channel, the Colorado River in Grand Canyon, Leopold (1969) concluded that the occurrence of rapids and pools was independent of lithologic variability and represented a quasi-equilibrium state in which downstream spacing of rapids was relatively uniform. This had the effect of equalizing energy loss per unit length of channel. Dolan et al. (1978) countered that rapids and associated pools were located at fracture zones perpendicular to the river, indicating structural controls rather than the autogenic (hydraulic) control that would be expected to produce uniform spacing. Working on 12 canyon rivers of the Colorado Plateau, including the Colorado River in Grand Canyon, Graf (1979) used a Kolmogorov-Smirnov test to demonstrate that rapids were distributed randomly or only slightly more regularly than random and showed little tendency toward equal spacing, rather than the uniform spacing suggested by Leopold (1969). Graf (1979) also tested the applicability to canyon rivers of the idea that riffles and pools are spaced according to discharge. Several investigators (Tinkler 1970; Yang 1971; Richards 1976) found that higher discharges are associated with greater distances between riffles along alluvial channels. Graf found that the spacing of canyon rapids was not related to mean annual discharge, but he did not test for a relation between rapid spacing and maximum discharge. Although Graf found that rapids were not always colocated with debris sources, he concluded that local site conditions are more significant than canyon-long operations of the main river system in controlling the downstream spacing of rapids. Subsequent papers on rapid dynamics in Grand Canyon focused on the role of tributary debris fans in constricting the channel and supplying coarse sediment to rapids (Kieffer 1985, 1989; Webb et al. 1988).

Lisle (1986), O'Connor et al. (1986), and Thompson (2001) also argued for local site controls on pool and riffle spacing. Lisle found that large obstructions such as bedrock outcrops or large, woody debris along the gravel bed of Jacoby Creek in California caused intense secondary circulation that scoured pools, resulting in 85% of the pools along the channel being next to such obstructions or bends. O'Connor et al. found that riffle deposition along Boulder Creek, Utah, occurs where high-discharge stream power minima occur upstream of canyon bends and constrictions and downstream of canyon expansions. Using a simulation model for formation of pools associated with obstructions, Thompson found that a semirhythmic spacing of pools at five to seven times the bankfull channel width could result from a random distribution of obstructions.

Various studies have also examined the controls on the geometry of individual alluvial-channel pools. Pool size has been explained by the characteristics of jets created at channel constrictions (Kieffer 1985; Lisle and Hilton 1992; Schmidt et al. 1993), with stronger jets producing larger pools. Pool depth varies directly with discharge and inversely with sediment-transport rates and average channel gradient (Lisle 1982; Lisle and Hilton 1992; Wohl et al. 1993). Pool length also varies inversely with channel gradient (Wohl et al. 1993) and sediment transport (Lisle 1986). Analyzing a dataset of 145 pools (27 rivers), Thompson and Hoffman (2001) used regression analyses to demonstrate that pool depth is significantly influenced to a decreasing degree by pool exit-slope width, constriction gradient, constriction width, drainage area, upstream channel width, and the exit-slope expansion ratio. Similarly, pool length is influenced by channel gradient, location of the channel constriction, pool width, drainage area, and constriction length. Thompson and Hoffman's (2001) work indicates complex adjustments between different aspects of pool geometry. The various studies of individual pool geometry suggest that basin- or reach-scale controls such as discharge, gradient, and sediment transport influence the geometry of alluvial pools but that pools are also sensitive to local controls such as the degree of channel constriction.

In this article, we summarize an analysis of pool spacing and geometry along a bedrock canyon river. The North Fork Poudre River is similar to many pool-riffle channels in the Rocky Mountains and other high-relief areas where lateral controls of bedrock, large boulders, or large woody debris are associated with pools. For these channels with laterally constricted pools, the North Fork Poudre River forms an end member in that the channel boundaries are mostly bedrock.

The 4.4-km-long study reach on the North Fork Poudre River effectively has constant drainage area, discharge, sediment transport, and gradient. Pools along this reach are mostly associated with lateral constrictions produced by bedrock outcrops. We address two questions: What controls downstream pool spacing? Within a pool, what factors control pool dimensions? We hypothesize that pool spacing could be governed by available flow energy or by substrate characteristics. If flow energy is a strong influence, we expect to see uniform downstream spacing, or uniform cumulative drop in elevation, between pools. If substrate is a strong influence, we expect correlations between pool location and rock-mass strength or joint characteristics. With respect to pool dimensions, we hypothesize that three measures of pool geometry—length, depth, and constriction ratio—could also be governed by flow energy and substrate. If flow energy is a strong influence, we expect pool geometry to correlate with cumulative upstream drop between pools. If substrate is a strong influence, we expect correlations between pool geometry and rock strength or joint characteristics.

Flow energy and substrate are not completely independent variables. To the extent that substrate erodibility influences channel bed gradient, it also influences flow energy as measured by variables such as stream power. What we address in this article is the manner in which substrate correlates with pool characteristics: indirectly via flow energy, or directly via rock-mass strength and joint characteristics.

Study Area

The North Fork Cache la Poudre River has a drainage area of approximately 1470 km^2 at Phantom Canyon. The North Fork continues beyond the canyon to join the Poudre River, a major tributary of the South Platte River in north-central Colorado. In Phantom Canyon, the North Fork Poudre has incised a 140-m deep canyon into Precambrian Silver Plume Granite (Tweto 1979). Valley-bottom width ranges from 30 to 120 m, and preliminary work by Ehlen and Wohl (2002) indicates that wider portions of the valley are associated with a higher joint density than are narrow portions of the valley. Bedrock exposures are common along the streambed and banks, although many of the riffles and runs are partially mantled with cobble and boulder alluvium (mean diameters 100–400 mm). Low alluvial terraces are common along at least one bank.

The channel has a well-developed pool-riffle morphology, with most pools formed at lateral constrictions created by bedrock outcrops. Pools average 32 m long and 15 m wide, may be as deep as 3.5 m, and have a mean downstream spacing of approximately eight times the mean channel width of 14 m.

There is evidence that pools do change location through time. Although confined by the canyon walls, the active channel of the North Fork Poudre has moved laterally across the valley bottom over periods of tens to hundreds of years, as evidenced by relict channels with mature trees growing on infill sediments. Overflow channels in the process of being abandoned also include relict pools now being filled with sediment. In addition, some of the long pools in the canyon appear to be migrating upstream; a deep scour hole and strong lateral constriction in the upstream portion of the pool give way to infill sediments and weaker, apparently relict, lateral constrictions in the downstream portion of the pool.

Unlike many canyon rivers, riffles along the North Fork Poudre are not associated with point sources of coarse sediment such as tributaries or debris fans. Tributaries to the North Fork Poudre in Phantom Canyon are small, ephemeral drainages, and the canyon bottom has no recent (<50 y) mass-movement deposits. Gradient averages 0.011 m/m but steepens locally to 0.04 m/m in some of the riffles.

The North Fork Poudre has a snowmelt-dominated hydrograph modified by flow regulation. Halligan Dam, immediately upstream from the canyon, can release up to 4 m^3/s through an outlet valve. The dam releases higher flows of 4–15 m^3/s during the May–July snowmelt runoff, when water spills over the dam. Flow is reduced to approximately 0.1 m^3/s from October to January. Suspended and bedload sediment transport rates are very low along the North Fork Poudre, and the cobble-boulder bed remains stable during most years (Wohl and Cenderelli 2000).

Phantom Canyon is an ideal location for examining the interactions among hydraulic driving forces and substrate resisting forces in determining pool characteristics. The study reach has essentially the same discharge and sediment supply at each pool. The relatively homogeneity of the granite substrate minimizes the effects of lithologic variations and highlights the effects of structural controls such as joint orientation and density and resulting intact rock strength.

Methods

We conducted a detailed survey of a 4.4-km reach of the North Fork Poudre (fig. 1). During moderate discharge of 3 m^3/s, we visually identified discrete, channel-spanning morphologic units as being riffles, steep segments (bed gradient 0.012–0.04) of the channel characterized by turbulent, shallow flow over a coarse substrate; runs, channel segments with a moderate bed gradient (0.002–0.011) and greater flow depth; and pools, flat-water areas of flow separation, deeper flow, and fine-grained sediment deposition. We used a laser theodolite total station and a Trimble Pathfinder ProXRS GPS receiver to measure 3D position and water depth for the head and tail of each successive channel unit. From these data we determined the length, average flow depth, and bed and water-surface gradients for 23 riffles, 14 runs, and 29 pools. In the pools we also measured both maximum water depth and channel width upstream, at, and downstream from the lateral constriction. Upstream and downstream channel widths were generally measured within 2–5 m from the constriction. The width measurements were used to derive the constriction ratio (the ratio of the channel width upstream of the constriction to that at the constriction) and the expansion ratio (the ratio of width at the constriction to the width downstream). We calculated the rock-mass strength (Selby 1980) for the bedrock outcrop at 10 of the pools and for 10 additional outcrops not associated with a pool.

We used high-resolution digital imagery to characterize joint patterns along the bedrock outcrop at a subset of 10 pools. Seventy-one 1600 × 1200-pixel photographs of bedrock exposures were acquired with a Canon Powershot 5300 ELPH 2.11-megapixel digital camera. Image scale was determined by using a reference object in each image to convert pixels to meters. Images were imported into ArcView GIS 3.2 to serve as a base map of each bedrock exposure, and all joints were then manually digitized as a line theme and put into a grid in which each square represented 0.25 m^2 of the rock surface. These data were used to calculate the mean, median, maximum, and standard deviation of the population of joint density (m/m^2) values across an outcrop (table 1). A log transformation of the outcrop joint density data was applied to satisfy the assumption of normally distributed residuals.

A number of univariate and multivariate statistical techniques were used to analyze the field data. The simplest of these was a two-sample t-test used to compare values of rock-mass strength at constrictions and other outcrops. The pool and rock outcrop data were used to develop a correlation matrix that included 12 variables (table 1). The correlation matrix highlighted which of the variables had the strongest linear association with one another. This served as a starting point for regression analysis. MINITAB's (2000) stepwise regression procedure isolated those predictor variables most strongly related to the channel morphologic response variables (Neter et al. 1990) of pool length and depth, constriction and expansion ratios, and pool approach gradient. Approach gradient is defined as the bed gradient of the channel-unit immediately upstream from a pool; average upstream gradient is here defined as the bed gradient averaged over the length of channel between successive pools. A series of individual regression models were constructed from the results of the stepwise regression. Canonical correlation analysis (CCA) was used to evaluate the strength and nature of the relationship between hydraulic variables measured during the channel-unit survey and the outcrop joint density parameters derived from the digital images. CCA is a multivariate method of measuring the strength of association between two sets of variables by deriving a pair of linear combinations (one linear combination of each of the sets of variables) having the maximum possible correlation.

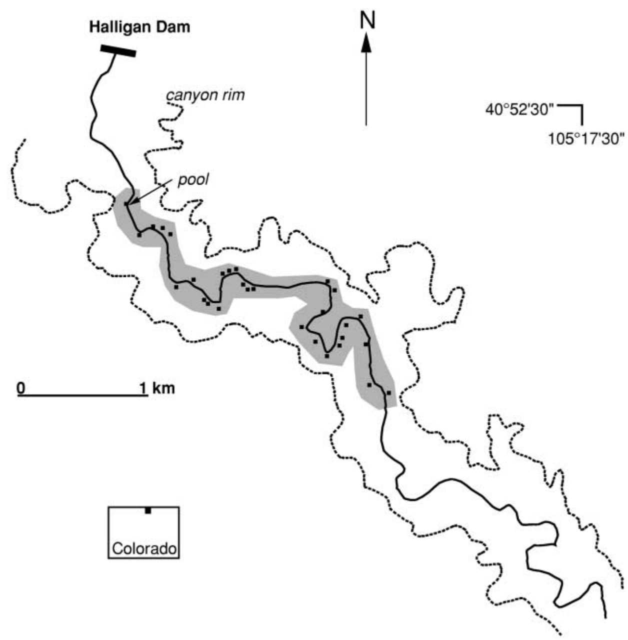

Figure 1. Location map of study area along the North Fork Poudre River, Colorado. Shaded zone indicates study area, dots indicate locations of pools, dashed line is canyon rim. Flow is from upper left to lower right.

Results

Histograms revealed that some of the nontransformed variables, such as pool length and upstream

Table 1. Descriptive Statistics for the Outcrop and Hydraulic Variables for Pools in the Study Area

Variable	Mean	Standard deviation	Range	Type
Pool length (m)	32.5	20.3	14.1–90.5	Response
Pool depth (m)	1.9	.8	.8–2.6	Response
Constriction ratio (m/m)	1.3	.5	.5–2.3	Response
Expansion ratio (m/m)	.8	.2	.4–1.0	Response
Approach gradient (m/m)	.025	.021	.003–.033	Response
Upstream distance (m)	116.8	106.1	18.1–399.6	Control
Cumulative upstream drop (m)	1.3	.8	.13–2.8	Control
Average upstream gradient (m/m)	.014	.008	.002–.025	Control
Mean joint density (m/m^2)	11.9	1.1	10.1–14.2	Control
Median joint density (m/m^2)	10.8	.9	9.6–12.1	Control
Maximum joint density (m/m^2)	45.4	15.7	29.1–82.1	Control
Standard deviation, joint density	8.2	2.2	5.9–12.4	Control

Note. Sample number is 29 for all variables except those involving joint density, for which sample number is 10. Measurement uncertainty for variables other than joint density is ± 0.1 m.

distance, were not normally distributed, but the sample size precluded any inferences about the real distribution of the data. The small sample size and nonnormality might violate certain assumptions implicit in the statistical methods used in this analysis and form a caveat to the interpretations presented here.

The *t*-test revealed no significant differences ($P = 0.761$) between the two populations of constriction-forming and other bedrock outcrops. The linear and stepwise regression analyses indicated several significant relationships among pool control and response variables (table 2). First, higher values of maximum joint density correspond to deeper pools (fig. 2*a*); second, a plot of constriction ratio versus maximum joint density is best fit by a log normal regression such that the maximum constriction ratio occurs at a maximum joint density of approximately 35–45 m/m^2 (fig. 2*b*); third, deeper pools are associated with a shallower approach gradient (fig. 3*a*); fourth, deeper pools have a greater cumulative elevation change from the previous pool (fig. 3*b*); fifth, less constricted pools correspond to a steeper approach gradient (fig. 4); and sixth, more-constricted pools tend to be deeper (fig. 5).

The CCA results support the stepwise regression analyses in suggesting that longer, deeper pools correspond to a greater cumulative elevation change and a steeper average upstream gradient.

Of the 29 pools measured, 25 had a lateral bedrock constriction such that a portion of the channel wall protruded more than a meter into the channel relative to the lateral position of the wall upstream and downstream in the pool (fig. 6). Three of the pools that did not have a lateral constriction had a vertical drop, and one had neither a constriction nor a drop. One pool had a lateral constriction and a vertical drop. Twenty of the 29 pools occurred along a channel bend where the mean downstream flow direction changed course by more than 30°. Although the longitudinal profile of the study reach includes shallower and steeper segments, we did not find any correlations between the gradient of

Table 2. Regression Equations Relating Pool Morphological Response Variables to Upstream Hydraulic Controlling Factors

Response variable (y)	Predictor variable (x)	Regression equation	R^2 (P value)
Pool depth	Cumulative upstream elevation drop	$y = .23x + 1.63$	.06 (1.15×10^{-6})
Expansion ratio	Approach gradient	$y = .53x + .63$	.20 (9.4×10^{-12})
Pool depth	Expansion ratio	$y = -2.21x + 3.65$	.15 (1.65×10^{-4})
Pool depth	Approach gradient	$y = -1.34x + 2.27$	.15 (1.67×10^{-11})
Pool depth	Maximum joint density	$y = -.001x^2 + .09x - 1.03$	.45
Constriction ratio	Maximum joint density	$y = 1.64e^{\{-.5[\ln(x/46.5)/.42]2\}}$	.40

Note. Relationships shown are significant at $\alpha = 0.05$. Definition of variables: pool depth is maximum thalweg depth (m); cumulative upstream elevation drop is elevation loss between successive pools (m); expansion ratio is ratio of width at pool constriction to width downstream (m); approach gradient is gradient of channel unit immediately upstream from pool (m/m); and maximum joint density is maximum value for 0.25 m^2 units of bedrock outcrop at a pool constriction (m/m^2).

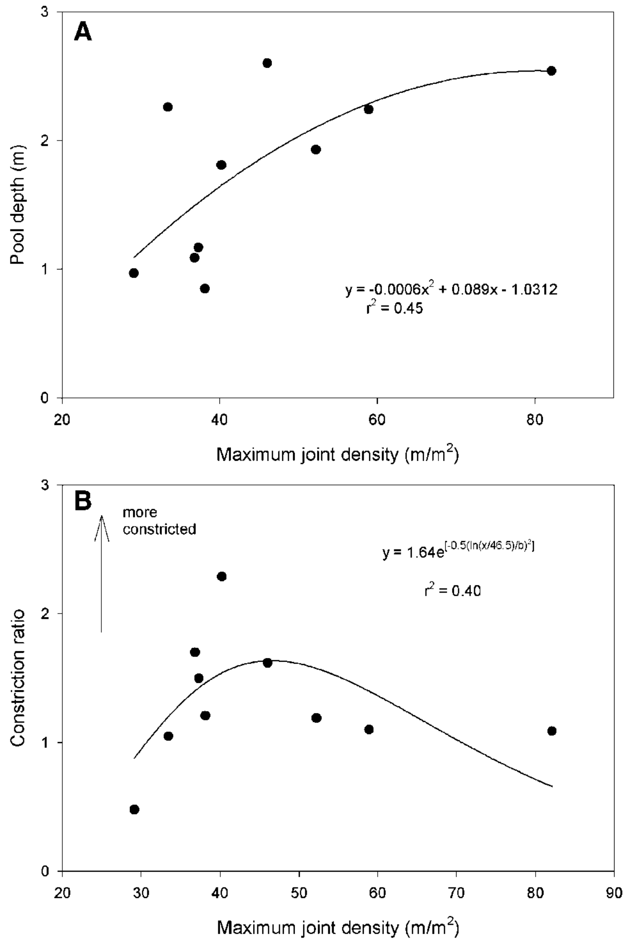

Figure 2. *A*, Plot of pool depth versus maximum joint density for 10 pools along the North Fork Poudre River. *B*, Plot of pool constriction ratio versus maximum joint density for 10 pools.

these subreaches and the downstream spacing of pools, pool dimensions, or number of pools associated with a vertical drop.

Discussion

What Controls Downstream Pool Spacing? As discussed in the introduction, different investigators have correlated pool spacing with several variables. These potential control variables include discharge, channel width, a quasi-equilibrium state that produces uniform downstream spacing, local substrate controls such as fracture zones or debris sources, and downstream variability in stream power per unit area. In the North Fork Poudre River study area, discharge and debris supply are constant. The remaining potential control variables can be distinguished as reflecting either flow energy or substrate resistance.

Flow energy could control the downstream distribution of pools via two mechanisms. First, flow energy creates quasi-equilibrium tendencies in that pools are spaced at regular intervals downstream, with this regularity reflecting an equalization of energy loss along the channel. Segments of stream with high rates of energy directed at the channel boundaries should be erosionally enlarged until rate of energy expenditure declines. Conversely, segments with low rates of energy expenditure would be stable or modified by deposition. In this situation, channel geometry eventually stabilizes in a manner that reflects a balance between available flow energy and boundary resistance. This balance could be expressed by downstream regularity of bedforms such as pools. Second, alternatively, flow

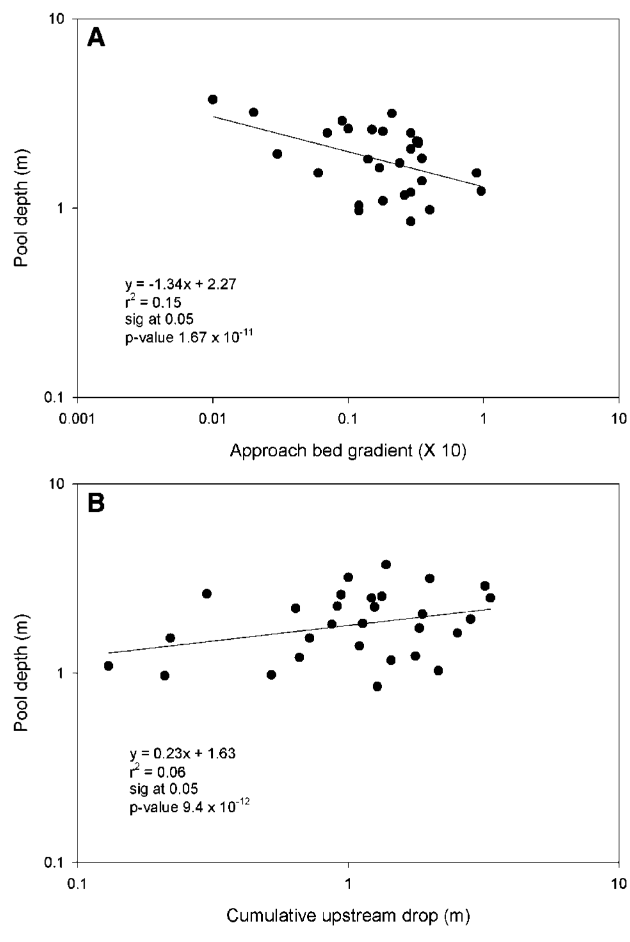

Figure 3. *A*, Plot of pool depth versus approach bed gradient for all 29 pools along the North Fork Poudre River. *B*, Plot of cumulative upstream drop versus pool depth for 29 pools.

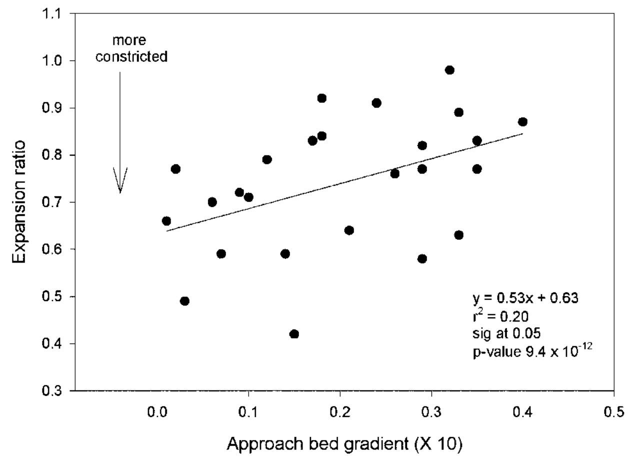

Figure 4. Plot of pool expansion ratio against approach gradient for the 25 pools having lateral constrictions.

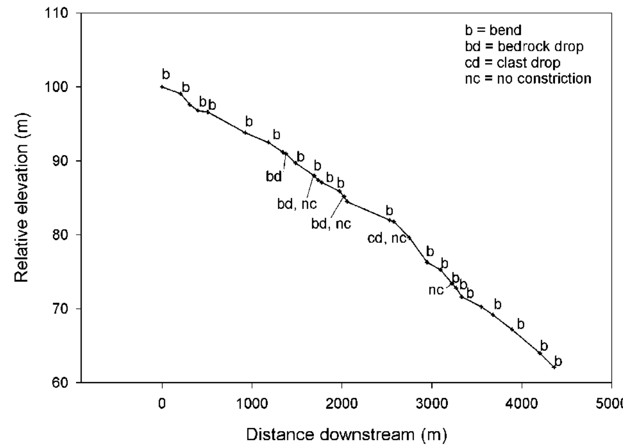

Figure 6. Longitudinal profile of the study reach, indicating the locations of pools (small cross on profile line), channel bends, vertical downsteps in the bedrock channel bed, vertical clast downsteps in the channel bed, and pools with no lateral constriction.

energy controls the downstream distribution of pools in that some minimum energy is necessary to scour the streambed and create a pool. This minimum energy reflects the erosional resistance of the channel boundary.

If pools reflect quasi-equilibrium tendencies, they should be spaced at regular intervals downstream, although other sources of hydraulic resistance such as bends or changes in bed grain size might complicate this relation. The downstream distance between pools along the North Fork Poudre is quite variable, with a mean value of 117 m and a standard deviation of 106 m (fig. 7). This indicates that the pools do not reflect quasi-equilibrium tendencies, particularly as there are no obvious differences in sinuosity or grain size among the channel segments between different pools. Expressed as multiples of channel width, the mean downstream pool spacing is 8.4 times average channel width, with a standard deviation of 7.6. By contrast, Roy and Abrahams's (1980) analysis of the Keller and Melhorn data had a smaller standard deviation for the bedrock channels (mean of 6.7 and standard deviation of 3.4).

If a threshold for minimum energy necessary to create a pool exists, this might be expressed as a consistent cumulative drop in streambed elevation between successive pools or a consistent average

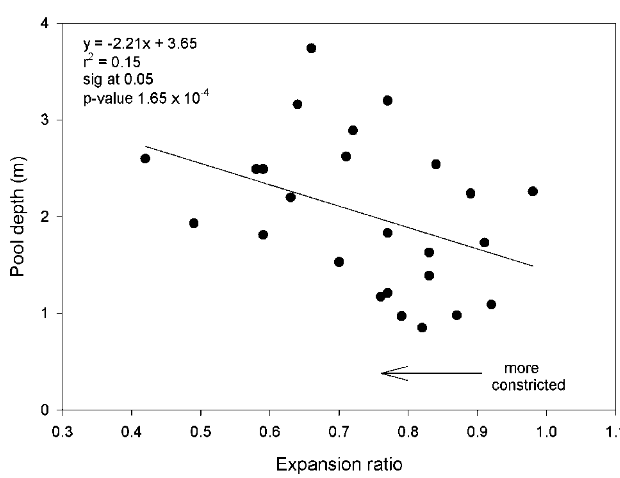

Figure 5. Plot of pool expansion ratio versus pool depth for the 25 pools having lateral constrictions.

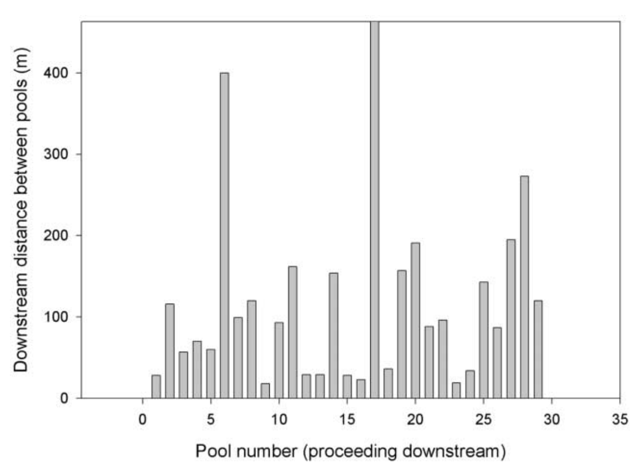

Figure 7. Distribution of downstream distance between pools.

bed gradient upstream, as these influence stream power per unit area. (The threshold might also be expressed in terms of constriction ratio, as discussed later.) The cumulative drop between pools along the North Fork Poudre has a mean value of 1.4 m, with a standard deviation of 0.9. Average upstream bed gradient varies by an order of magnitude. This indicates that if a threshold exists, it is very low, and systemwide energy constraints on pools are negligible.

Thus, we found no evidence to indicate that the downstream spacing of pools reflects systemwide available flow energy along the North Fork Poudre River.

Substrate resistance might control the downstream distribution of pools by creating a less resistant area where the streambed and banks could be readily scoured, or by creating lateral constrictions that localize flow separation and enhanced scour. In the uniform lithology of Phantom Canyon, a change in bedrock substrate resistance would be expressed as different degrees of weathering, or differences in joint characteristics. Bedrock weathering along the active channel margins is very consistent. Joint characteristics, in particular density, vary between outcrops, but these variations are not substantial enough to produce differences between the average rock-mass strength of outcrops forming constrictions and the outcrops elsewhere along the valley bottom.

Aerial photographs of Phantom Canyon reveal a series of bedrock ridges trending east-northeast and west-southwest (fig. 8). Where the active channel of the North Fork Poudre River intersects one of these bedrock ridges, the resulting outcrop may have a fairly uniform face along the river, but it is much more likely to laterally constrict the river with a protrusion created by weathering along prominent joint sets (fig. 9). Examination of air photographs for the entire 12-km-long Phantom Canyon indicates that almost every pool along the Canyon is associated with a bedrock constriction on one or both sides. Like the pools associated with them, the outcrops occur at an average downstream spacing of approximately eight times channel width, with a standard deviation of 7. The downstream spacing of these constricting outcrops, and thus the downstream spacing of pools, is controlled by the regional structure and weathering of the Silver Plume Granite, which produces the bedrock ridges, and by the local jointing of each outcrop, which produces the actual constrictions. The few pools not associated with a bedrock constriction are likely to be associated with a vertical bedrock drop, which is also partly controlled by joint characteristics.

Thompson's (2001) simulation model for pool formation forced by obstacles suggests that pool spacing may range from 10 to 40 times bankfull channel width when the number of pool-forming elements (such as bedrock constrictions) per 100 bankfull widths is less than 10. As the number of elements increases past 20, pool spacing stabilizes at five to seven bankfull widths. The model predicts that, for the North Fork Poudre River study area, which has approximately nine pool-forming elements per 100 bankfull widths, average pool spacing should be approximately eight to 11 bankfull widths. This prediction is in very good agreement with the North Fork Poudre pool data.

Within a Pool, What Factors Control Pool Dimensions? Previous investigators have related pool geometry both to measures of flow energy such as discharge and channel gradient and, indirectly, to measures of substrate such as constriction width. We tested for correlations between the response variables of pool length, depth, amount of constriction, approach gradient, and potential hydraulic and substrate control variables.

Flow energy could influence the geometry of a pool in that greater incoming energy, as indicated by a higher cumulative drop between pools, corresponds to a larger pool. Flow energy could also influence pool geometry through the mediating influence of the lateral constriction: A stronger constriction produces greater flow separation, with higher velocities in the central jet, stronger recirculating flow, and shearing between the central and marginal flow zones, and thus greater potential for bed erosion and pool formation. Pool depth does correlate with cumulative elevation loss between pools (fig. 3), and CCA loadings indicate that longer, deeper pools correlate with greater cumulative upstream drop and steeper average upstream gradient. Correlations are also present between constriction geometry and pool depth (fig. 5). More constricted pools are deeper, as expected. They also have shallower approach gradients (fig. 4). This presumably reflects the backwater effect created by a strong constriction during high discharges. The backwater reduces energy gradient upstream, promoting coarse-sediment deposition and reducing approach gradient. Pool geometry thus appears to reflect flow energy both at the reach and local scale, as governed by elevation loss and gradient at the reach scale, and the degree of development of the lateral bedrock constriction at the local scale.

Substrate resistance could influence pool geometry by facilitating either channel-boundary erosion

Figure 8. Aerial photograph of a portion of the Phantom Canyon study reach, indicating the bedrock ridges trending from east-northeast to west-southwest across the region. Flow is toward the bottom of the photograph; north is up.

or constriction development. The correlation between maximum joint density and pool depth indicates that more highly jointed bedrock is more erodible. This is the strongest relationship among the North Fork Poudre River data; 45% of the variability in pool depth can be explained by variability in maximum joint density. In general, the statistical analyses indicate that joint density

Figure 9. Downstream view of pool about midway along the study reach, indicating the lateral bedrock constriction (middle-left of photo) associated with the pool. This photo, taken during moderately high flow, shows a train of standing waves along the central jet in the pool and flow separation in an eddy upstream from the lateral constriction.

influences both substrate erodibility and the formation of lateral channel constrictions along the North Fork Poudre River.

Conclusions

The field evidence of changes in pool location through time indicates that the North Fork Poudre River in Phantom Canyon adjusts channel geometry in relation to external controls such as discharge or substrate. Downstream pool spacing along the bedrock-controlled channel appears to be strongly influenced by the downstream spacing of lateral bedrock constrictions. These constrictions in turn reflect local jointing and regional structure and weathering patterns. Individual pool geometry is influenced by average upstream gradient and by the degree of lateral constriction, which in turn controls pool length, depth, and approach gradient. The degree of lateral constriction reflects joint density in the bedrock outcrop. The characteristics of pools along the North Fork thus reflect predominantly substrate controls, and secondarily hydraulics such as these are governed by available flow energy and by the degree of lateral constriction. The simulation model of Thompson (2001) accurately predicts average downstream pool spacing along the North Fork Poudre River, indicating that the model's assumptions of obstruction-forced pools and minimum pool- and riffle-length criteria are appropriate.

Where channel boundaries are readily deformable and mostly homogeneous, as in lower gradient alluvial rivers, systemwide tendencies toward uniform energy expenditure may govern pool spacing. In more heterogeneous and resistant substrates such as the granitic bedrock along the North Fork Poudre River, these tendencies may still be present, as suggested by the correlations between elevation losses between pools and pool geometry, but local controls create so much scatter in these relations that it is appropriate to conclude that local controls dominate pool spacing and geometry.

ACKNOWLEDGMENTS

Carl Legleiter's participation in this research was supported by a National Science Foundation Research Experiences for Undergraduates grant to Colorado State University for Water Resources. The Nature Conservancy provided access to their Phantom Canyon Preserve. Greg Springer, Douglas Thompson, Ed Keller, and Frank Pazzaglia provided helpful reviews of this manuscript.

REFERENCES CITED

Dolan, R.; Howard, A.; and Trimble, D. 1978. Structural control of the rapids and pools of the Colorado River in Grand Canyon. Science 202:629–631.

Ehlen, J., and Wohl, E. 2002. Joints and landform evolution in bedrock canyons. Trans. Jpn. Geomorphol. Union 23-2:237–255.

Graf, W. L. 1979. Rapids in canyon rivers. J. Geol. 87: 533–551.

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

Kieffer, S. W. 1985. The 1983 hydraulic jump in Crystal Rapid: implications for river-running and geomorphic evolution in the Grand Canyon. J. Geol. 93:385–406.

———. 1989. Geologic nozzles. Rev. Geophys. 27:3–38.

Leopold, L. B. 1969. The rapids and the pools—Grand Canyon. U.S. Geol. Surv. Prof. Pap. 669-D, 131–145.

Lisle, T. E. 1982. Effects of aggradation and degradation on riffle-pool morphology in natural gravel channels, northwestern California. Water Resour. Res. 18: 1643–1651.

———. 1986. Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwest California. Geol. Soc. Am. Bull. 97: 999–1011.

Lisle, T. E., and Hilton, S. 1992. The volume of fine sediment in pools: an index of sediment supply in gravel-bed streams. Water Resour. Bull. 28:371–383.

MINITAB. 2000. User's guide. State College, Pa., MINITAB Software.

Neter, J.; Wasserman, W.; and Kutner, M. H. 1990. Applied linear statistical models: regression, analysis of variance, and experimental designs. Homewood, Ill., Irwin, 1181 p.

O'Connor, J. E.; Webb, R. H.; and Baker, V. R. 1986. Paleohydrology of pool-and-riffle pattern development: Boulder Creek, Utah. Geol. Soc. Am. Bull. 97:410–420.

Richards, K. S. 1976. The morphology of riffle-pool sequences. Earth Surface Processes Landforms 1:71–88.

Roy, A. G., and Abrahams, A. D. 1980. Rhythmic spacing and origin of pools and riffles: discussion. Geol. Soc. Am. Bull. 91:248–250.

Schmidt, J. C.; Rubin, D. M.; and Ikeda, H. 1993. Flume simulation of recirculating flow and sedimentation. Water Resour. Res. 29:2925–2939.

Selby, M. J. 1980. A rock mass strength classification for geomorphic purposes: with tests from Antarctica and New Zealand. Zeit. Geomorph. 24:31–51.

Thompson, D. M. 2001. Random controls on semi-rhythmic spacing of pools and riffles in constrictiondominated rivers. Earth Surface Processes Landforms 26:1195–1212.

Thompson, D. M., and Hoffman, K. S. 2001. Equilibrium pool dimensions and sediment-sorting patterns in coarse-grained, New England channels. Geomorphology 38:301–316.

Tinkler, K. J. 1970. Pools, riffles and meanders. Geol. Soc. Am. Bull. 81:547–552.

Tweto, O. 1979. Geologic map of Colorado. U.S. Geol. Surv. Misc. Invest. Map G77115, scale 1 : 500,000.

Webb, R. H.; Pringle, P. T.; Reneau, S. L.; and Rink, G. R. 1988. Monument Creek debris flow, 1984: implications for formation of rapids on the Colorado River in Grand Canyon National Park. Geology 16:50–54.

Wohl, E. E., and Cenderelli, D. A. 2000. Sediment deposition and transport patterns following a reservoir sediment release. Water Resour. Res. 36:319–333.

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

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