Spatial patterns of scour and fill in dryland sand bed streams

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[1] Spatial patterns of scour and fill in two dryland ephemeral stream channels with sandy bed material have been measured with dense arrays of scour chains. Although the depth and areal extent of bed activity increased with discharge, active bed reworking at particular locations within the reaches resulted in downstream patterns of alternate shallower and deeper areas of scour. The variation was such that mean scour depths for individual cross sections varied about the mean for the reach by a factor of 2–4 while the locus of maximum scour traced a sinuous path about the channel centerline. The wavelength of the pattern of scour was about seven times the channel width. During each event, compensating fill returned the streambeds to preflow elevations, indicating that the streams were in approximate steady state over the period of study. Although the patterns of periodically enhanced scour along alternate sides of the channels are consistent with models of periodically reversing helical flow, further work is required to identify the causal relationships between patterns of flow and sediment transport in dryland sand bed channels.

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1. Introduction

[2] The movement of bed material in dryland fluvial systems is closely associated with the process of scour and fill. Scour and fill refer to fluctuations in the vertical position of alluvial streambeds that occur in response to the entrainment, downstream transport and subsequent deposition of bed material during flow events. In as much as they represent the morphological response of the channel to sediment transport, scour and fill processes have been of longstanding interest to geomorphologists and engineers in their quest to understand the morphodynamics of dryland alluvial rivers [e.g., *Lane and Borland*, 1954; *Emmett and Leopold*, 1965].

[3] Before the 1960s, few measurements for the primary purpose of determining the behavior of dryland streambeds under flow conditions had been made. Instead, scientists made adventitious use of data gained from stream-gauging sites where channel cross sections were routinely monitored for the purposes of calculating discharge. Data from large rivers in the drylands of the southwestern United States suggested that graded streambeds are lowered by scour and raised by deposition to approximately their former position on the rising and falling limbs of the hydrograph respectively [*Leopold and Maddock*, 1953]. However, it was also recognized that scour and fill may alternate several times during a flow with different areas of the bed affected at different times [*Culbertson and Dawdy*, 1964] and that the maximum scour depth need not coincide with the peak discharge [*Colby*, 1964].

[4] Scour and fill have subsequently been shown to operate in a wide range of sand- and gravel-bedded dryland streams [*Emmett and Leopold*, 1965; *Leopold et al.*, 1966; *Foley*, 1978; *Schick et al.*, 1987; *Hassan and Shaw*, 1999; *Powell et al.*, 2005]. Most studies, however, are limited to a small number of measurements at isolated cross sections or channel locations rather than extensive lengths of channel. The results therefore are difficult to interpret in the context of wider channel behavior [*Colby*, 1964]. It is generally not known, for example, whether observed changes in bed elevations are representative of either the local cross section or more extensive lengths of channel. A further problem arises in that most methods for determining scour and fill provide information on maximum instantaneous depths of scour and net fill when in fact streambeds may experience multiple cycles of scour and fill.

[5] The problem of inferring streambed behavior from measurements of maximum instantaneous depths of scour and subsequent net fill is difficult to solve without deploying sophisticated (and expensive) monitoring devices. The problem of obtaining more representative measurements and information on the spatial pattern of streambed scour and fill is, however, more tractable and can be addressed using conventional methods if the density of data acquisition is increased. In this study, dense arrays of scour chains were installed in low-order dryland ephemeral stream channels to characterize the spatial pattern of scour and fill. The

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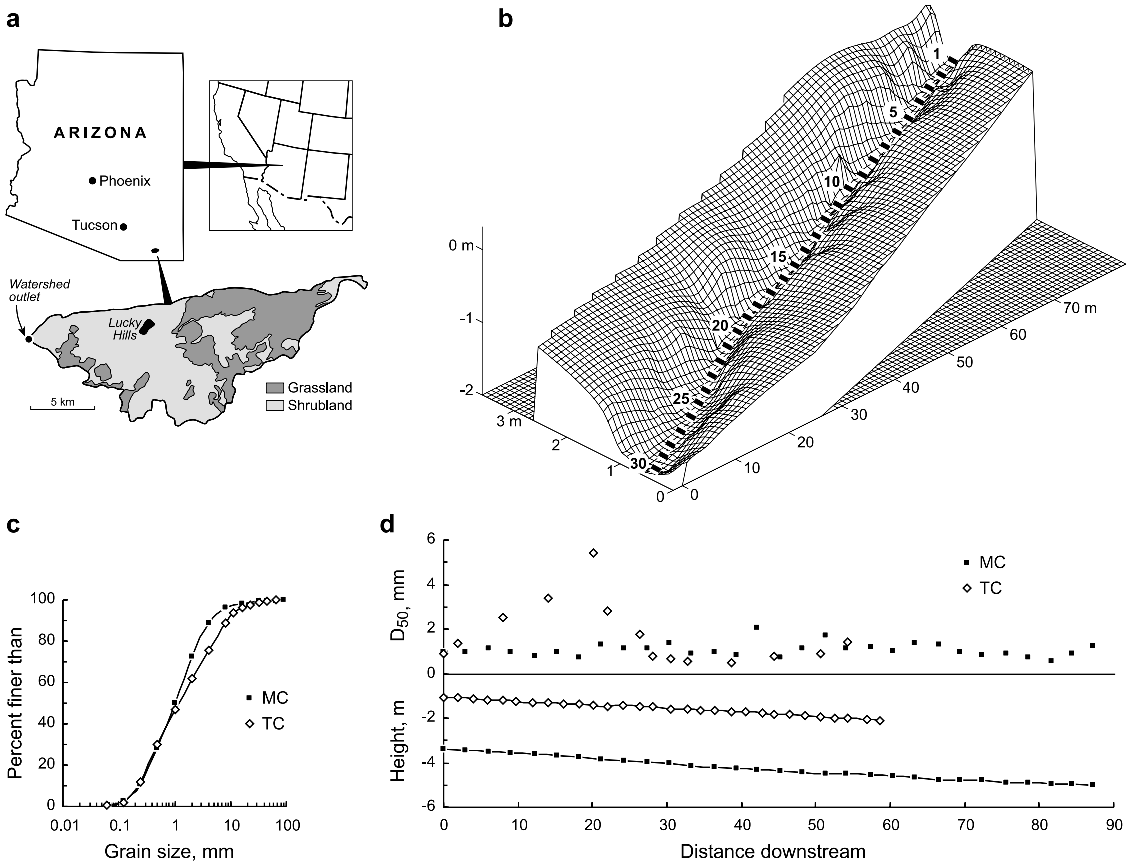

Figure 1. (a) Location of the study within the Lucky Hills subwatershed of Walnut Gulch [after *Lane et al.*, 1997] (with permission from Elsevier), (b) elevation model of the main channel (MC) study reach showing the location of the cross sections, (c) bed material grain size distributions, and (d) channel long profiles and spatial variation in median bed material size (D_{50}) for the main channel and a tributary channel (TC). The bed elevations in Figure 1d are heights below an arbitrary datum.

paper is the first systematic attempt to characterize reach-scale patterns of scour and fill in such channels and to understand the process controls.

2. Field Area and Methods

[6] The study was undertaken at Walnut Gulch (31.43°N, 110.04°W), the Experimental Watershed of the United States Department of Agriculture, Agricultural Research Service in southeastern Arizona (Figure 1a; see http://www.tucson.ars.ag.gov/). The catchment consists of grass- and shrub-covered piedmont sands and gravels. The climate is semiarid with mean annual precipitation and temperatures of 324 mm and 17.6°C, respectively [*Lane et al.*, 1997]. The channels flow ephemerally in response to intense, short-lived and highly localized convective storms during the summer months. Measurement efforts were concentrated in the main channel (MC) of a 43.7 ha subcatchment called Lucky Hills. The study reach was a relatively straight, single thread channel with a 3-m wide planar bed (Figure 1b). The bed material was a spatially undifferentiated and poorly sorted mixture of sands (74%) and fine gravels (26%) (Figures 1c and 1d). The long profile was relatively uniform with an average slope (S) of 1.9% (Figure 1d).

[7] Measurements of scour and fill were collected using lengths of linked metal chain [*Laronne et al.*, 1994]. Since scour chains do not provide information on the temporal scale of scour and fill or the bed elevation changes associated with more than one cycle of scour and fill, data is restricted to the maximum depth of scour and the net depth of fill at each measurement location. Each chain was inserted vertically in the streambed with a length of chain left exposed at the channel surface. After each flow, the elbow (where the chain kinked following maximum scour) of the chain was located. Care was exercised to minimize bed disturbance. The difference in the length of chain above the elbow before and after a flow yielded the depth of scour (x_s) while the distance between the elbow and the postflow bed gave the depth of fill. Once these measurements had been taken, the chain was reset in anticipation of the next flow.

[8] In the absence of any a priori information regarding the spatial variability of streambed activity in sand bed channels, justification of an appropriate strategy for monitoring scour and fill is difficult. However, it is well known that flow in straight channels develops alternating zones of fast accelerating, and slow decelerating flow which, in perennial gravel bed rivers, are thought to be responsible for molding the bed into a sequence of topographic highs (riffles) and lows (pools) with a downstream spacing that scales with channel width [*Robert*, 2003, pp. 115–123]. On the basis that that similar flow patterns and bed topographies may develop during flash flows in sand bed rivers,

scour and fill were sampled at cross sections spaced one channel width (w) apart for a distance of 30w (Figure 1b). Although desirable, selection of a longer study reach was precluded by the presence of tributaries, the inputs from which would have complicated the interpretation of the results substantially. Between three and five chains were installed at equally spaced distances across each cross section. Accordingly, 99 chains were installed giving a chain density of about 0.3 m^{-2}, a value that exceeds those in previous studies by 2–3 orders of magnitude [*Rennie and Millar*, 2000].

[9] Measurements of scour and fill were obtained for ten flow events over three summer flow seasons. In each case, the measurements represent bed elevation changes due to individual events. During each event, flow stage was measured in the centre of the study reach with an ultrasonic depth recorder that logged the elevation of the water surface at 30-s intervals. Stage measurements were converted to flow depths (Y) using the geometry of the local cross section. Since scour chains do not record the time evolution of scour and fill, the conversion incorporates an assumption that the depths of scour recorded at the measurement section coincided with peak stage. Discharge (Q) was estimated using Manning's equation utilizing a roughness coefficient of 0.035 and the reach-average bed gradient. The lowest-flow events had peak depths (Y_p) of about 10 cm (peak discharge $Q_p \approx 0.3$ m^3 s^{-1}) and the highest included two bankfull events (30 July 2000, 10 August 2000; $Y_p \approx 0.4$ m; $Q_p \approx 4$ m^3 s^{-1}) and an overbank flow (4 August 2002; $Y_p \approx 0.7$ m; $Q_p = 11$ m^3 s^{-1}). The rainfall that generated the latter event (34 mm of rainfall in 30 min) has a recurrence interval of between 5–10 years [*Osborn and Renard*, 1988].

3. Spatial Pattern of Streambed Scour

[10] The spatial patterns of streambed scour depths (x_s) for the 10 events are shown in Figure 2. The contours on these maps were constructed using the standard kriging algorithm in the Surfer® software package. A downstream anisotropy ratio of two was chosen to prevent the development of a "bullseye" contour pattern. It was also assumed that the scour declined to zero at the channel margins. As expected, bed activity increased with discharge. For example, scour during the two lowest flows ($Q_p \approx 0.3$ m^3 s^{-1}) was generally less than 3 cm and bed activity did not exceed 8 cm (Figures 2a–2b). In contrast, the highest discharge ($Q_p = 11.4$ m^3 s^{-1}) scoured much of the bed by up to 15 cm with 50 cm of scour observed at some locations (Figure 2j). The amount of scour generated during the event of 30 August 2002 (Figure 2c) is somewhat surprising given the low magnitude of the event ($Q_p = 0.4$ m^3 s^{-1}). The reasons for the anomalous behavior of this event are not known (the event hydrograph was not untypical of other flow events) but they may relate to the legacy of the significant channel disturbance caused by the preceding overbank flow of 4 August 2002 (Figure 2j). *Powell et al.* [2005] showed that the distributions of scour conform to the one-parameter exponential model. In a spatial context, Figure 2 suggests that scour depths are not distributed randomly within the reach. The observation that some areas of the bed experience significantly greater scour of the bed than others suggests a degree of spatial organization in bed activity.

3.1. Downstream Pattern of Streambed Scour

[11] Close inspection of Figure 2 reveals significant downstream variations in scour depths with zones of pronounced scour separating zones of less pronounced scour. The patterns of scour appear unrelated to the slight variations in bed material grain size and channel slope (Figure 1d). Although spatial variability in scour depths is evident at quite low flows (e.g., Figure 2c) the pattern is strongest at moderate to high flows that develop zones of pronounced scour in the vicinity of cross sections 2, 11, and 20 (Figures 2f–2i). The development of these scour zones is evident in Figure 3 which shows the downstream variation in mean cross-section scour depths ($\overline{x_s}$) about the mean for the reach ($\overline{X_s}$). At low to medium flows, scour depths appear to fluctuate randomly about the mean and no downstream pattern is discernible (e.g., Figures 3a and 3b). At higher flows, however, scour depths appear to vary systematically about the mean over a distance of several channel widths (e.g., Figures 3g–3j). Mean cross-section scour depths for the events of 26 July 2002, 10 August, 2000, 30 July 2000 and 4 August 2002 were compared using Spearman's rank correlation coefficient in order to assess the similarity of the patterns of scour that developed at these moderate to high flows ($Q_p \geq 1.45$ m^3 s^{-1}). Values of between 0.47 and 0.69 are statistically significant at the 95% level and indicate a degree of consistency in the patterns of streambed scour generated by the four events.

[12] Figures 2 and 3 suggest the emergence of a reasonably consistent quasi-regular downstream variation in streambed activity at moderate to high flows. In order to test whether the spatial pattern of scour is nonrandom, the sequence of positive and negative deviations of $\overline{x_s}$ from $\overline{X_s}$ were examined statistically for each event. The null hypothesis that variations in the sequence are due to chance is rejected for the events of 30 July 2000 and 4 August 2002 ($p < 0.05$). This implies that the downstream variations in mean cross-section scour depths for the two largest events (Figures 3i and 3j) are not random.

[13] Further examination of the data was undertaken using autocorrelograms. These represent plots of autocorrelation coefficients (R_h) computed for data separated by multiples of the lag distance h against distance. Autocorrelograms are commonly used for checking randomness in data and for identifying appropriate models to fit to nonrandom data [*Box and Jenkins*, 1976; *Davis*, 2002]. Random data are characterized by $R_h \approx 0$ for all multiples of h. If the data are nonrandom, one or more of R_h is significantly different to zero. For the purposes of this study, autocorrelograms were constructed for each event using the cross section averaged data and a lag spacing of 3 m (the downstream spacing of the measurements). Linear regression was used to remove statistically significant trends in the data prior to analysis to ensure that the data were stationary. To ensure that values of R_h were calculated using a reasonable number of pairs of data (>15), the autocorrelograms are truncated at 50% of the maximum distance. Confidence intervals (CI) are calculated as

$$\mathrm{CI} = \pm \frac{z - \alpha/2}{\sqrt{N}} \qquad (1)$$

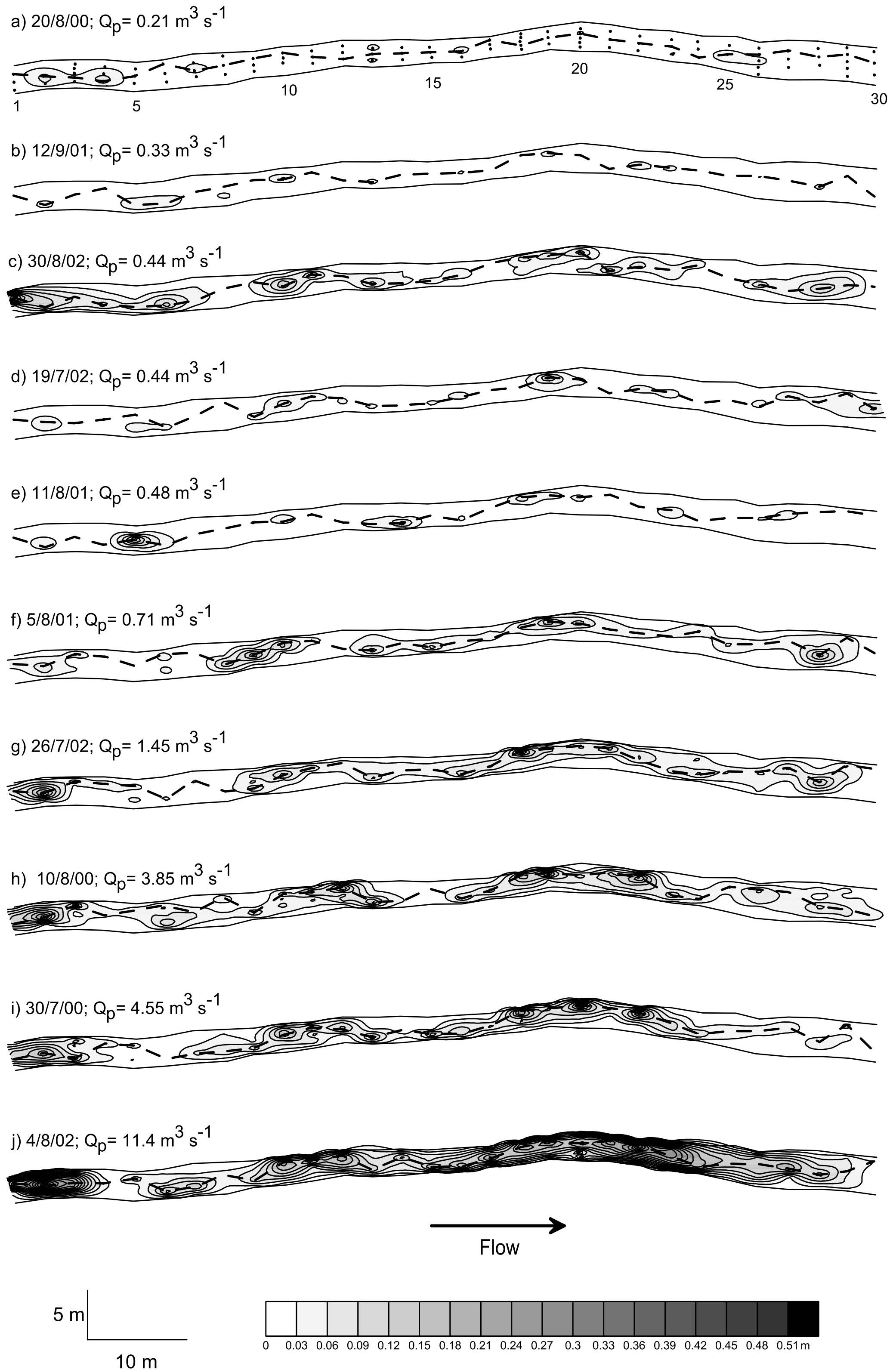

Figure 2. Spatial pattern of streambed scour for the 10 events recorded in the main channel. The events are ordered by peak discharge (Q_p), and the locations of the cross sections and scour chain are shown in Figure 2a. The dashed line plots the locus of the maximum depth of scour. Flow is from left to right.

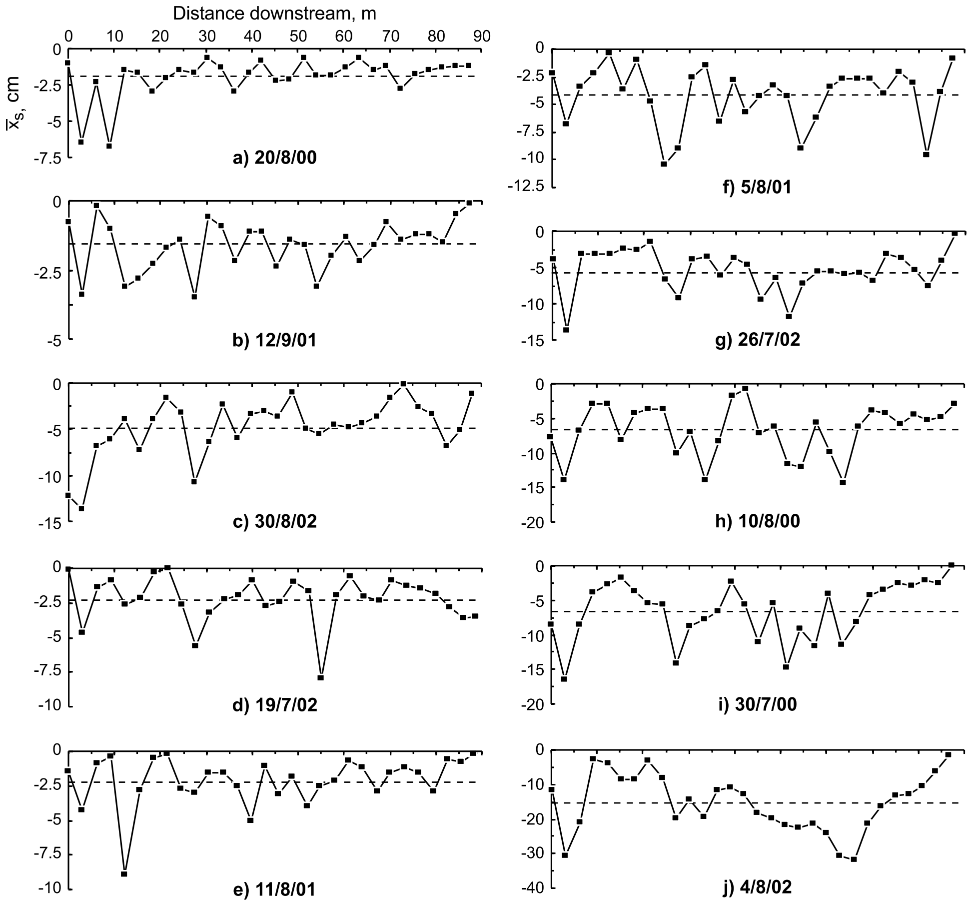

Figure 3. Downstream variation in mean cross-stream scour depths ($\overline{x_s}$) for the 10 events recorded in the main channel. Scour is represented as depths below a zero datum that represents the preflow bed elevation. The events are ordered by peak discharge. For each event, the dashed line represents the mean depth of scour for the reach ($\overline{X_s}$).

where z is the percent point function of the standard normal distribution, α is the significance level and N is the sample size. In showing the 95% confidence intervals, it should be recognized that every value of R_h has a 5% chance of exceeding the confidence limits so that one out of every 20 lags might be expected to be statistically significant even if the data were drawn from a random population [*Chatfield*, 1984, p. 25].

[14] Autocorrelograms for events with a range of discharges up to bankfull are shown in Figure 4. Correlations are, in the main, low and few of the positive and negative peaks exceed the 95% confidence limits. In general, the pattern exhibited by Figure 4 of irregular fluctuations about zero with no clear relationships discernible either between events (e.g., peaks occurring at specific lags) or within events (such as groups of positive autocorrelations followed by groups of negative correlations) is not dissimilar to the autocorrelation plot signature of random data [*Davis*, 2002]). The only data sets to exhibit significant autocorrelation are those of 30 July 2000 and 4 August 2002 which both exhibit significant positive autocorrelation at lag one. This result indicates that adjacent measurements are similar. The autocorrelograms do not give any further information as to the spatial structure of the spatial series. This may reflect the limited length of the data sets.

[15] An alternative statistical technique for assessing the degree of spatial dependence within data is provided by the method of variograms [*Journal and Huijbregts*, 1978]. Semivariograms have been used extensively in the analysis of spatially dependent geomorphic variables including soil properties [*Burgess and Webster*, 1980], alluvial bed forms [*Robert*, 1991] and calcite cements [*Dutton et al.*, 2002]. In this paper, we use the technique to assess the spatial variation in mean cross-section scour depths. Semivariograms were constructed using the software Variowin [*Pannatier*, 1996]. As for the autocorrelograms, the semivariograms are truncated at 50% of the maximum distance. Prior to the computation of the semivariance, the skewed distributions were transformed using the Box-Cox transformation [*Box and Cox*, 1964] so that they follow approximately a normal distribution. The veracity of the transformations was confirmed by constructing normal probability plots and computing correlation coefficients.

[16] Representative semivariograms describing the downstream variability in cross-section average scour depths are shown in Figure 5. Interestingly, none of the semivariograms exhibit the classic shape whereby the semivariance (γ_h) increases with increasing lag distance before stabilizing at a value that approximates the variance (s^2) of the data. In such variograms, the distance at which

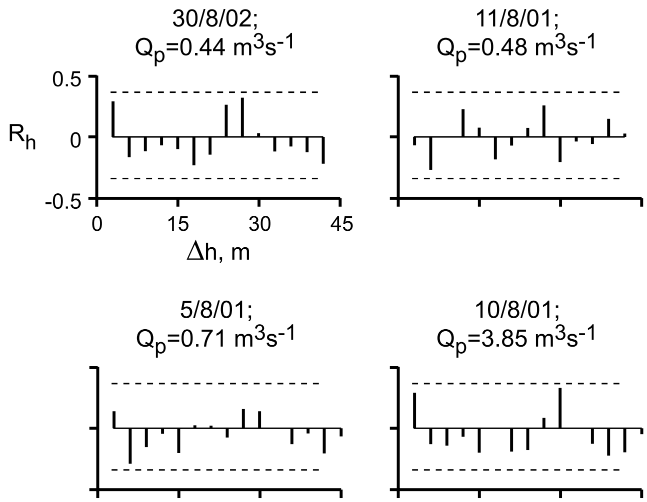

Figure 4. Autocorrelograms for mean cross-section scour depths for a range of discharges up to bankfull in the main channel. Δ is the separation vector, and the dashed horizontal lines represent the 95% confidence intervals of R_h.

all successive pairs of values become independent of each other is termed the range (β) while the value of γ_h at the range is termed the sill (γ_{hs}). Instead, the semivariograms for the majority of the events plot as scatter about a sill (= s^2; Figures 5a and 5b). This pattern indicates an absence of spatial autocorrelation (pure nugget effect) and that the data are random. These results are consistent with the autocorellograms (Figure 4). For the two largest events, however, the semivariance increases from the origin and then varies in a cyclic manner (Figures 5c and 5d). Such variogram structures are termed "hole effect" structures. Since the correlation between data pairs is positive when the semivariogram is less than the sill ($\gamma_h < \gamma_{hs}$) and negative when the semivariogram is greater than the sill ($\gamma_h > \gamma_{hs}$), a hole effect structure indicates that the data vary in a repetitive or cyclic manner with a wavelength (λ) equal to twice the range (2β) and the wavelength of the cyclic component of the variogram (λ_h).

[17] The semivariogram for the event of 30 July 2000 shows a steady increase over a well-defined range of about 12 m (Figure 5c). The degree of spatial correlation therefore decreases over this distance. Thereafter, values of γ_h rise and fall about an apparent sill of γ_{hs} = 1.6. Minima at 24 and possibly 42 m indicate increased spatial correlation (less difference) at these distances. Inspection of Figures 2i and 3i indicates that these distances are associated with greater than average scour depths. A semivariogram range of 12 m implies that the variation in scour depths has a wavelength of 24 m. Although the limited length of the data series restricts the semivariogram to one periodic cycle, this estimate is consistent with a distance between the two peaks of about 21 m. The semivariogram for the event of 4 August 2002 shows a similar, but rather more indeterminate structure (Figure 5d). The curve initially rises, flattens off at about γ_h = 16 and then rises once more to γ_h = 28. Thereafter, the curve falls before increasing again for distances greater than 30 m. Interpretation of such an irregular semivariogram is difficult. Clearly, although the semivariogram for the event of 30 July 2000 has drawn attention to the presence of cyclic variations in the reach-scale pattern of streambed scour, the broader implications of this need to be viewed in the light of additional information about spatial patterns of scour in other streams.

[18] Such information is available for a tributary to the main channel. This channel is 2 m wide and is therefore slightly narrower than the main channel; otherwise, the two channels share similar geomorphic and sedimentological characteristics (Figures 1c and 1d). Streambed scour and

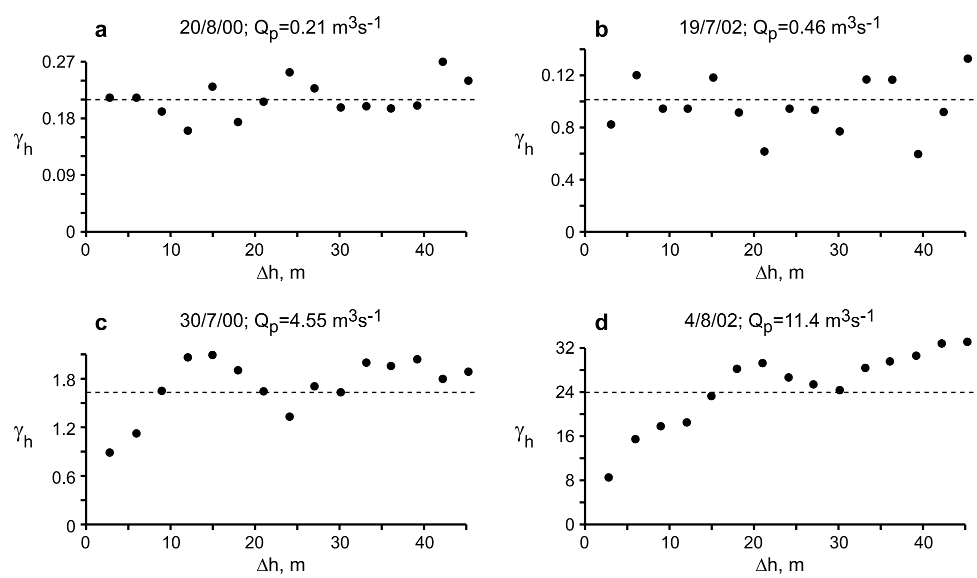

Figure 5. Semivariograms for mean cross-section scour depths typical of (a) low and (b) medium discharge events and for (c and d) the two highest discharge events in the main channel. The dashed line represents the variance of the data and the sill of the semivariogram. Note the cyclical variation about the sill in Figures 5c and 5d.

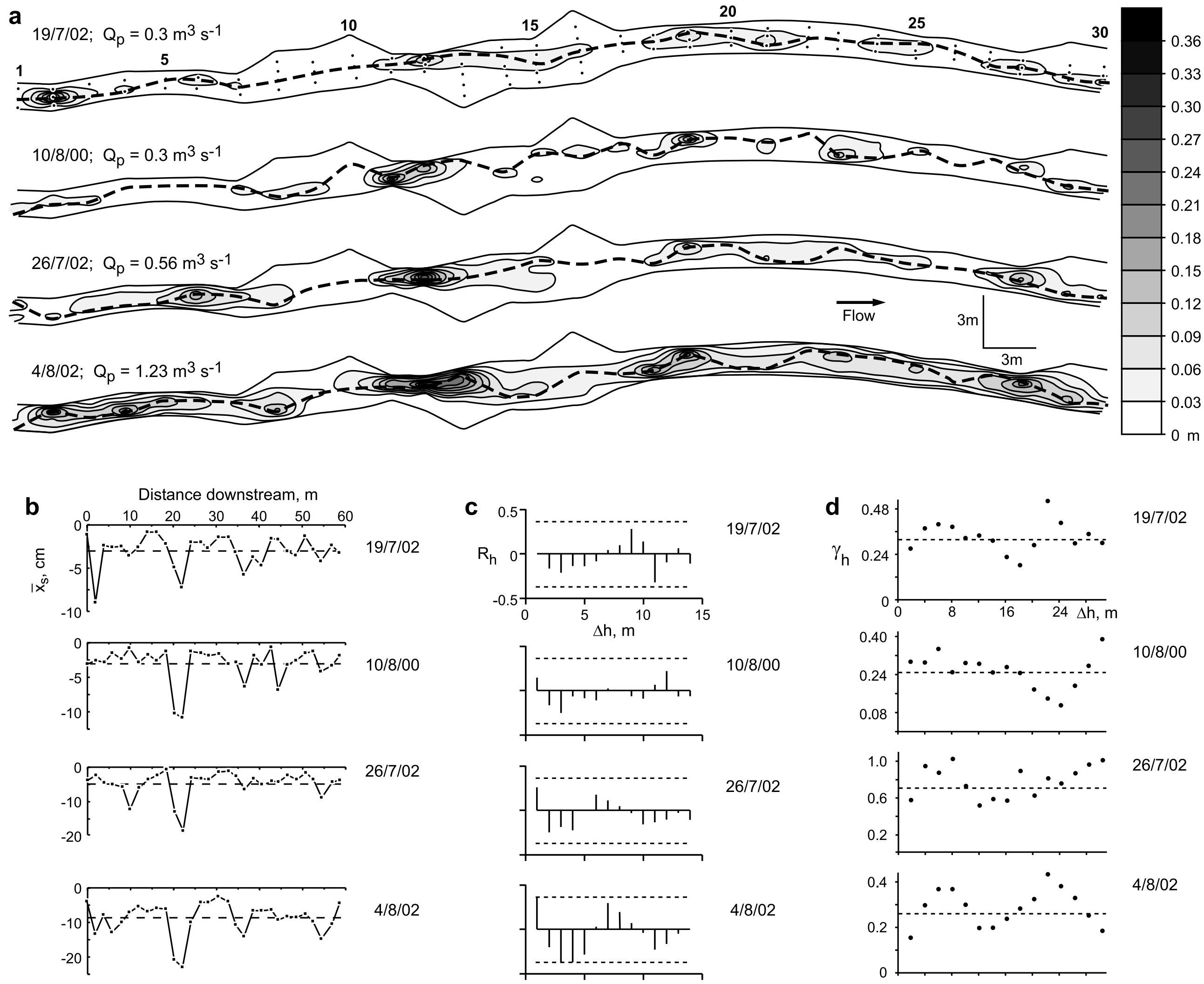

Figure 6. (a) Spatial patterns of streambed scour for the four largest flow events recorded in the tributary channel, (b) downstream variation in mean cross-stream scour depths, (c) autocorrelograms for mean cross-section scour depths, and (d) semivariograms for mean cross-section scour depths. The events are ordered by peak discharge (Q_p). In Figure 6a, the locations of the cross sections and scour chains are shown in the top illustration, and the dashed line shows the locus of the maximum depth of scour. In Figures 6b, 6c, and 6d, the dashed horizontal lines represent the mean depth of scour for the reach, 95% confidence intervals of the autocorrelogram, and the sill of the semivariogram, respectively.

fill in a straight reach of the tributary channel was sampled using scour chains for a downstream distance of 30 channel widths in the same way as in the main channel. Flow, however, was monitored with maximum-stage recorders and as a result, hydraulic information is restricted to peak flow depths. Nine flow events were recorded in this channel. Peak tributary discharges of $0.05–1.2\ m^3\ s^{-1}$ were lower than in the main channel and did not exceed half the bankfull depth. Depths of bed activity were consequently less and significant scour was restricted to the four largest events ($Q_p > 0.3\ m^3\ s^{-1}$).

[19] The spatial patterns of streambed scour for these four events are shown in Figures 6a and 6b. As in the main channel, scour of the channel bed is highly nonuniform and relatively deep areas of scour are confined to certain locations within the reach (Figure 6a). As a result, cross-section averaged scour depths vary about the mean for the reach in a quasi-regular fashion (Figure 6b). Runs tests conducted on deviations of $\overline{x_s}$ from $\overline{X_s}$ provide nonsignificant results ($p > 0.05$) and indicate the absence of nonrandom variation. Lack of spatial dependence within the data is also suggested by the autocorrelograms which, for the events of 19 July 2002, 10 August 2000 and 26 July 2002, exhibit low and nonsignificant values of R_h (Figure 6c). Interestingly, however, the autocorrelograms for the two largest events (26 July 2002 and 4 August 2002) show groups of positive autocorrelations followed by groups of negative correlations, some of which are statistically significant. An alternating sequence of positive and negative correlations is the autocorrelation signature of a sinusoidal model and is indicative of systematic variations in the downstream pattern of streambed scour. Further evidence for cyclical variations in streambed scour is provided by the semivariograms for these two events

(Figure 6d) which exhibit a "hole effect" structure similar to that described above for the event of 30 July 2000 in the main channel (cf. Figure 5c). The pattern is clearest in the semivariogram for the event of 4 August 2002, which has a range of 8 m and a wavelength of 14 m. Both of these semivariogram parameters imply a downstream cyclical variation in scour depths with a wavelength of about 14 m.

[20] The results from the tributary channel provide additional evidence that the spatial pattern of streambed scour in these drylands channels is not random, at least at moderate to high discharges. Further insights were sought from similar analyses undertaken for channel centerline and section maximum scour depths recorded in the main channel. Run tests conducted on the deviations of centerline scour depths from the average for the reach reveal only one nonrandom data set (4 August 2002; $p > 0.05$). This event has a positive peak in the autocorrelogram at lag one that just fails to reach significance at the 95% level. Otherwise, centerline scour depths show no significant autocorrelations. The only nonrandom series of maximum scour depths are associated with the three largest events (30 July 2000, 10 August 2000, and 4 August 2002) and for one of the smallest events (12 September 2001). The autocorrelograms for maximum scour depths indicate that the three largest events have statistically significant positive autocorrelations at lag 1 (10 August 2000 and 4 August 2002) and lag 2 (30 July 2000); all other autocorrelations are not significant at the 95% level. Finally, the only semivariograms to exhibit any structure are those constructed utilizing cross-section maxima for the two largest events (30 July 2000 and 4 August 2002). Semivariograms for these events exhibit similar "hole effect" structures to those generated by the cross-section averaged data for these events (Figures 5c and 5d). Taken as a whole, these results are in general agreement with those generated by using cross-section average data and provide no additional insights regarding the downstream pattern of streambed scour.

3.2. Cross-Stream Pattern of Streambed Scour

[21] Cross-stream variations in scour depths are marked. Figure 7, for example, shows the lateral variation in scour depths recorded at the 30 cross sections during each of the four events of 2002 in the main channel. Maximum and mean cross-section scour depths differ by up to 18 cm with a mean difference of 14 cm for the four events. Systematic variations, however, are not apparent and tie lines between locations cross in opposite directions (Figure 7a). Figure 7b shows that median depths of scour at adjacent locations along the sections are broadly comparable with differences of 5–33% (mean difference = 17%). In nine of the 10 events, median scour depths recorded at left, centre and right sampling locations are not significantly different from each other (Kruskal-Wallis test, $p > 0.05$).

[22] The lack of systematic cross-stream variations in scour depths for individual events is somewhat surprising since several studies have demonstrated regular cross-stream patterns in bed activity that can be related to the influence of sidewall drag and the concomitant lateral decline in shear stress toward channel margins [*Pitlick*, 1988; *Powell et al.*, 1999]. However, there is some consistency in cross-streambed behavior at particular locations between events. For example, scour depths are generally highest toward the left- and right-hand channel margins at cross sections 1, 11, 18, 19, 21, 27 and 29 and 6, 9 and 13 respectively (Figure 2). As a result of these and other changes in the asymmetry of the cross-stream pattern of scour about the channel centerline, the locus of the maximum scour depth forms a sinuous trace down the reach that is reasonably consistent between all but the two lowest flows (some irregularities are to be expected given the narrowness of the channel and the proximity of the three cross-stream sampling locations). The pattern is particularly clear between cross sections 9 and 23 where the zone of maximum scour crosses the channel at least twice so that it

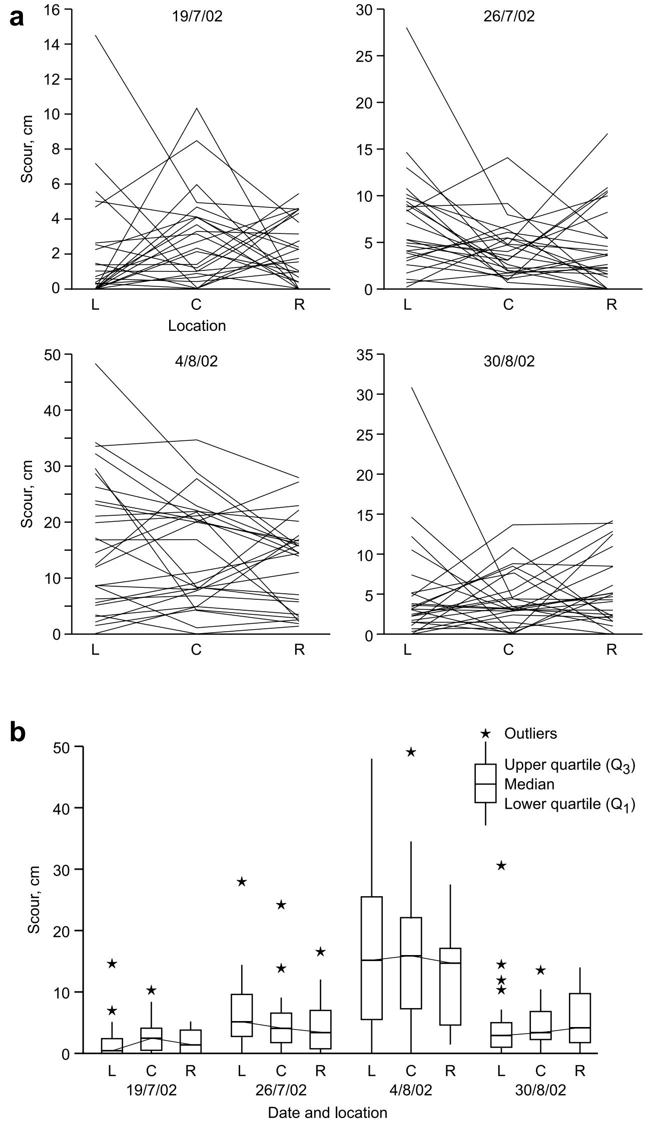

Figure 7. Cross-stream variation in scour depths recorded in the main channel during the four events of 2002. (a) Data recorded at left (L), center (C), and right (R) sampling locations for individual cross sections are linked by tie lines. (b) Data are grouped by sampling location. Outliers are defined as values that lie outside the upper limit $Q_3 + 1.5 (Q_3 - Q_1)$.

Figure 8. Spatial pattern of fill for the 10 events recorded in the main channel. The events are ordered by peak discharge (Q_p), and the locations of the scour chain are shown in Figure 8a. Flow is from left to right. Note the general similarity with the spatial patterns of streambed scour (Figure 2).

alternates between the left- and right-hand sides of the channel (Figures 2f–2i). A similar pattern is also observed during the event of 4 August 2002 in the tributary channel (Figure 6a).

4. Spatial Pattern of Streambed Fill

[23] Spatial patterns of fill recorded for the 10 events in the main channel are shown in Figure 8. Median depths of fill range from 1–12 cm with a maximum of 53 cm occurring during the largest event (Figure 8j). As for scour, there is considerable variability in the depths of fill recorded within the reach. Comparison of Figures 2 and 8 indicate a close correspondence between depths of scour and fill recorded at particular channel locations. It appears that the reach is in approximate steady state; depositional processes compensate for the considerable and highly variable depths of scour to restore the bed to its preflow elevation and planar condition.

5. Discussion

[24] It is well known that dryland streams are effective agents of erosion and transport. As illustrated in this study, however, the extent to which the beds of sandy dryland streams are reworked by sediment-transporting flows is often masked by compensating scour and fill that maintain a remarkably subdued bed topography in approximate steady state [see also *Leopold et al.*, 1966]. Although scour and fill processes have been studied previously, the phenomenon is usually described as it operates at isolated channel cross sections. The extent to which these results are representative of, or are affected by, wider streambed behavior is poorly understood.

[25] This study has shown that that scour in straight, narrow sand bed channels is longitudinally continuous, but highly variable. Consequently, results obtained at particular locations may not be representative of more extensive lengths of channel. As expected, the depth and areal extent of bed activity increased with discharge. However, this activation did not result in a uniform lowering of the streambed. Instead, active bed reworking at particular locations within the reach resulted in a downstream pattern of alternate shallower and deeper areas of scour. The variation was such that mean scour depths for individual cross sections varied about the mean for the reach by a factor of 2–4 while the locus of maximum scour traced a sinuous path about the channel centerline. Although the limited length and inherent noisiness of the data preclude the development of a statistically robust model of this variability, there is some evidence that the downstream variation in scour depths in the main and tributary channel had a wavelength of 24 and 14 m, respectively. Since intraevent comparisons suggest a degree of consistency in the patterns of scour, especially at moderate to high flows, the question arises as to their cause.

[26] One obvious mechanism for the periodic deformation of the streambed along alternate sides of the channel is periodically reversing helical flow. In straight channels, such flows result from the development of vorticity by either anisotropic turbulence [*Einstein and Li*, 1958a] or eddy generation and shedding [*Einstein and Li*, 1958b]. *Einstein and Shen* [1964], for example, describe a model of twin periodically reversing asymmetric surface convergent helical flow cells. The secondary flows initiate a meandering channel thalweg that locally increases shear stresses alongside alternate sides of the channel. Secondary flows in the main channel study reach may also be encouraged by the slight channel curvature (Figure 2). An alternative mechanism is provided by *Yalin*'s [1971] model of macroscale eddying whereby turbulence-induced large-scale roller eddies generate zones of flow acceleration and deceleration. The greatest scour occurs where velocities are highest thereby creating an undulating channel bed. Although Yalin's model has yet to be fully tested, it is regarded as a plausible model for the development of the pool-riffle sequence commonly observed in coarser grained stream channels [*Clifford*, 1993]. The spacing between pools and riffles is generally recognized to be five to seven times the channel width which is close to the wavelength of the longitudinal velocity variations in Yalin's model ($2\pi w$). As noted above, there is some evidence that mean cross-section scour depths recorded in the main and tributary channel vary downstream in a quasi-regular downstream with wavelengths of about 24 and 14 m, respectively. Although we can only speculate as to processes responsible for the observed patterns of streambed scour, it is interesting to note that these distances approximate seven times the width of the respective channels. The fact that these patterns are only observed at relatively high discharges may reflect the weakness of secondary flow structures at lower flows.

[27] It should be recognized that the validity of these and other models of helicoidal flow in straight channels have been questioned by many workers and it remains far from clear how well the theoretical flow patterns would be recognized in either natural or laboratory channels or reproduced in numerical models [*Rhoads and Welford*, 1991; *Ma et al.*, 2002]. Moreover, although some of the morphological consequences of the models of *Einstein and Shen* [1964] and *Yalin* [1971] are reflected in the field situation, many are not. The former model, for example, is often associated with the development of alternate channel bars and a meandering channel form [e.g., *Thompson*, 1986], whereas the latter should generate sequences of pools of riffles as noted above. It may be that some of these morphological consequences are, in fact, realized at high flows but not preserved at low flows. This would require that the associated flow structures decay faster than the overall competence of the flow during the falling limb of the hydrograph so that topographic highs and lows are planed off or infilled as the flow recedes. Clearly, further development of our understanding of the behavior of dryland streambeds requires a fuller characterization of the scales of variability in patterns of streambed scour and knowledge of the prevailing hydraulics.

Notation

D_{50} median particle size of bed material, mm.
h lag.
N sample size.
Q discharge, $m^3\ s^{-1}$.

Q_p peak discharge, $m^3\ s^{-1}$.
R_h autocorrelation coefficient.
s^2 variance, cm^2.
Y flow depth, m.
Y_p peak flow depth, m.
w channel width, m.
x_s depth of scour at a channel location, cm.
$\overline{x_s}$ mean depth of scour for the cross section, cm.
$\overline{X_s}$ mean depth of scour for the reach, cm.
z percent point function of the standard normal distribution.
α significance level.
β range of the semivariogram, m.
Δ separation vector.
γ_h semivariance at lag h, cm^2.
γ_{hs} value of γ_h at the sill of the semivariogram (= s^2), cm^2.
λ_h wavelength of the semivariogram, m.

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References

Box, G. E. P., and D. R. Cox (1964), An analysis of transformations, *J. R. Stat. Soc., Ser. B*, *26*, 211–246.

Box, G. E. P., and G. Jenkins (1976), *Time Series Analysis: Forecasting and Control*, Holden-Day, Boca Raton, Fla.

Burgess, T. M., and R. Webster (1980), Optimal interpolation and isarithmic mapping of soil properties. I. The semi-variogram and punctual kriging, *J. Soil Sci.*, *31*, 315–331.

Chatfield, C. (1984), *The Analysis of Time Series: An Introduction*, CRC Press, Boca Raton, Fla.

Clifford, N. J. (1993), Formation of riffle-pool sequences: Field evidence of an autogenic process, *Sediment. Geol.*, *85*, 39–51.

Colby, B. R. (1964), Scour and fill in sand-bed streams, *U.S. Geol. Surv. Prof. Pap. 462-D*.

Culbertson, J. K., and D. R. Dawdy (1964), A study of fluvial characteristics and hydraulic variables, middle Rio Grande, New Mexico, *U.S. Geol. Surv. Water Supply Pap. 1498-F*.

Davis, J. C. (2002), *Statistics and Data Analysis in Geology*, John Wiley, Hoboken, N. J.

Dutton, S. P., C. D. White, B. J. Willis, and D. Novakovic (2002), Calcite cement distribution and its effect on fluid flow in a deltaic sandstone, Frontier Formation, Wyoming, *Am. Assoc. Pet. Geol. Bull.*, *86*, 2007–2021.

Einstein, H. A., and H. Li (1958a), Secondary currents in straight channels, *Eos Trans. AGU*, *39*, 1085–1088.

Einstein, H. A., and H. Li (1958b), The viscous sublayer along a smooth boundary, *Trans. Am. Soc. Civ. Eng.*, *123*, 293–317.

Einstein, H. A., and H. W. Shen (1964), A study of meandering in straight alluvial channels, *J. Geophys. Res.*, *69*, 5239–5247.

Emmett, W. W., and L. B. Leopold (1965), Downstream pattern of river-bed scour and fill, in *National Inter-Agency Conference, 1963*, *Misc. Publ. 90*, pp. 399–409, U.S. Dep. of Agric., Washington, D. C.

Foley, M. G. (1978), Scour and fill in steep, sand-bed ephemeral streams, *Geol. Soc. Am. Bull.*, *89*, 559–570.

Hassan, M. A., and P. Shaw (1999), The transport of gravel in an ephemeral sandbed river, *Earth Surf. Processes Landforms*, *24*, 623–640.

Journal, A. G., and C. J. Huijbregts (1978), *Mining Geostatistics*, Elsevier, New York.

Lane, E. W., and W. M. Borland (1954), River-bed scour during floods, *Trans. Am. Soc. Civ. Eng.*, *119*, 1069–1080.

Lane, E. W., M. Hernandez, and M. Nichols (1997), Processes controlling sediment yield from watersheds as functions of spatial scale, *Environ. Modell. Software*, *12*, 355–369.

Laronne, J. B., D. N. Outhet, P. A. Carling, and T. J. McCabe (1994), Scour chain deployment in gravel-bed rivers, *Catena*, *22*, 299–306.

Leopold, L. B., and T. Maddock (1953), The hydraulic geometry of stream channels and some physiographic implications, *U.S. Geol. Surv. Prof. Pap. 252*.

Leopold, L. B., W. W. Emmett, and R. M. Myrick (1966), Channel and hillslope processes in a semi-arid area, New Mexico, *U.S. Geol. Surv. Prof. Pap. 352G*.

Ma, L., P. J. Ashworth, J. L. Best, L. Elliott, D. B. Ingham, and L. J. Whitcombe (2002), Computational fluid dynamics and the physical modelling of an upland urban river, *Geomorphology*, *44*, 375–391.

Osborn, H. B., and K. G. Renard (1988), Rainfall intensities for southeastern Arizona, *J. Irrig. Drain. Eng.*, *114*, 195–199.

Pannatier, Y. (1996), *VARIOWIN: Software for Spatial Data Analysis in 2D*, Springer, New York.

Pitlick, J. (1988), Variability of bedload measurement, *Water Resour. Res.*, *24*, 173–177.

Powell, D. Mark, I. Reid, and J. Laronne (1999), Hydraulic interpretation of cross-stream variations in bedload transport rates recorded in two straight alluvial channels, *J. Hydrol. Eng.*, *125*, 1243–1252.

Powell, D. M., R. Brazier, J. Wainwright, A. Parsons, and J. Kaduk (2005), Streambed scour and fill in low-order dryland channels, *Water Resour. Res.*, *41*, W05019, doi:10.1029/2004WR003662.

Rennie, C. D., and R. G. Millar (2000), Spatial variability of stream bed scour and fill: A comparison of scour depth in chum salmon (*Oncorhynchus keta*) redds and adjacent bed, *Can. J. Fish. Aquat. Sci.*, *57*, 928–938.

Rhoads, B. L., and M. R. Welford (1991), Initiation of river meandering, *Prog. Phys. Geogr.*, *15*, 127–156.

Robert, A. (1991), Fractal properties of simulated bed profiles in coarse-grained channels, *Math. Geol.*, *23*, 367–382.

Robert, A. (2003), *River Processes: An Introduction to Fluvial Dynamics*, Arnold, London.

Schick, A. P., J. Lekach, and M. A. Hassan (1987), Bed load transport in desert floods: Observations form the Negev, in *Sediment Transport in Gravel-Bed Rivers*, edited by C. R. Thorne, J. C. Bathurst, and R. D. Hey, pp. 617–636, John Wiley, Hoboken, N. J.

Thompson, A. (1986), Secondary flows and the pool-riffle unit: A case study of the processes of meander development, *Earth Surf. Processes Landforms*, *11*, 631–641.

Yalin, M. S. (1971), On the formation of dunes and meanders, paper presented at 14th International Congress of the Hydraulic Research Association, Paris.

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