Stream-bed Scour and Fill in Low-order Ephemeral Stream Channels

D. Mark Powell, R. Brazier, M. Nichols, J. Wainwright, A. Parsons.

Abstract
Reach scale patterns of scour and fill have been studied in three, low-order dryland ephemeral stream channels with sandy bed materials. Depths of scour within the reaches are highly variable though scour is generally matched by equal amounts of fill. As a result, there is little net change in bed elevations over the flood season. A preliminary examination of the data using serial correlation and spectral analysis reveals no systematic pattern within the reaches although interpretation of the results is constrained by the limited length of the spatial series. For many of the events studied, the exponential model provides a satisfactory approximation for the distribution of scour and fill depths and may provide a basis for predicting sediment exchange depth distributions, at least to a first approximation, in low-order sand-bed streams.

Keywords: scour and fill, sand-bed channels, dryland rivers, flash floods

Introduction

Scour and fill refer to fluctuations in the vertical position of an alluvial stream-bed during a flood event. The fluctuations occur in response to the entrainment (or scour) and deposition (or fill) of bed material and reflect both the redistribution of sediment within the channel and the short-term hydraulic adjustments that help a river to maintain a quasi-equilibrium channel form (Andrews 1979). As a result, scour and fill processes have been of longstanding interest to geomorphologists, engineers and aquatic ecologists seeking to understand the morphodynamics of alluvial rivers (Haschenburger 1999) the stability of artificial structures such as bridge piers, pipelines and water abstraction points (Chang, 1988) and the role of flood disturbance in structuring lotic ecosystems (Lapointe *et al.* 2000; Rennie and Millar 2000).

Although scour and fill are characteristic of all alluvial rivers, they are of particular importance in dryland environments where there is commonly an almost unlimited supply of sandy-gravelly material that is readily entrained by infrequent, but intense, flooding. However, there is considerable uncertainty about the dynamics of scour and fill in dryland fluvial systems. Some studies have suggested that scour tends to occur in reaches that are narrower and deeper, while wider and shallower reaches tend to aggrade (Lane and Borland 1954). This is thought to reflect the control of channel width on unit discharge and as a result, predictive relationships between unit discharge and scour depths have been identified (Leopold *et al.* 1966). Other studies, however, have shown that patterns of scour are independent of channel morphology (Emmett and Leopold 1965) and to be consistent with the migration of bed forms (Foley 1978).

Uncertainty over channel behaviour arises because few studies have featured measurements of sufficient density to characterise the magnitude and distribution of scour and fill occurring within a reach. Gauging station measurements are limited because they are restricted to observations made at isolated cross-sections whilst other studies are constrained by the low density of data acquisition (e.g. Leopold *et al.* 1966). In this paper, we present an analysis of event-based measurements of scour and fill made with sufficient spatial resolution to capture reach-scale variability and

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pattern. The purpose of the study is to characterise the variability of scour and fill at the scale of the channel reach. The measurements were made in three steep, low-order, sand-bedded ephemeral stream channels as part of a wider study investigating erosion by water in dryland catchments.

Study Area and Methods

The study was undertaken at Walnut Gulch, the Experimental Watershed of the United States Department of Agriculture, Agricultural Research Service in south-eastern Arizona (USDA-ARS 2003). The catchment consists of grass and shrub covered piedmont sands and gravels. The climate is semi-arid and the channels flow ephemerally in response to intense, short-lived and highly localised convective storms during the summer months.

Measurement efforts were concentrated in three reaches within Lucky Hills, a 43.7 ha sub-catchment of the main watershed. One reach was located on the main channel and two reaches were located on tributary channels (upper and lower). All three reaches were straight, single thread and relatively narrow and steep with planar beds of medium-coarse sand with a small gravel fraction (Figure 1).

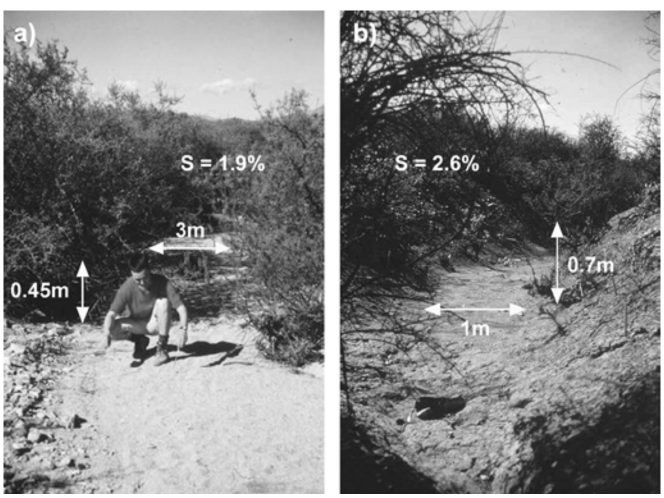

Figure 1. Downstream views of (a) the main channel and (b) the upper tributary study reaches. In (a), the author is holding two scour chains.

Scour and fill data were collected using lengths of metal-linked chain (Laronne *et al.* 1994). Each chain was inserted vertically in the streambed with a length of chain left exposed at the channel surface (Figure 2). After each flood, the elbow of the chain was located. The difference in the length of chain above the elbow before and after a flood yielded the depth of scour. When fill occurred, the distance between the elbow and the post flood bed gave the depth of fill. Once these measurements had been taken, the chain was reset in anticipation of the next flood.

Between three and five chains were installed at equally spaced distances across each cross-section in the relatively wide main channel and lower tributary reaches. In the narrower upper tributary reach, chains were installed in an alternating sequence of one in the channel centre and two at left and right locations to ensure that adjacent chains did not become entangled. Accordingly, the number of chains installed in each reach ranged from about 45 in the upper tributary reach to nearly 100 in the main channel and lower tributary reaches. Chain densities varied between 0.36-1.3 m^{-2}, values that exceed those in previous studies by two-three orders of magnitude (Rennie and Millar 2000).

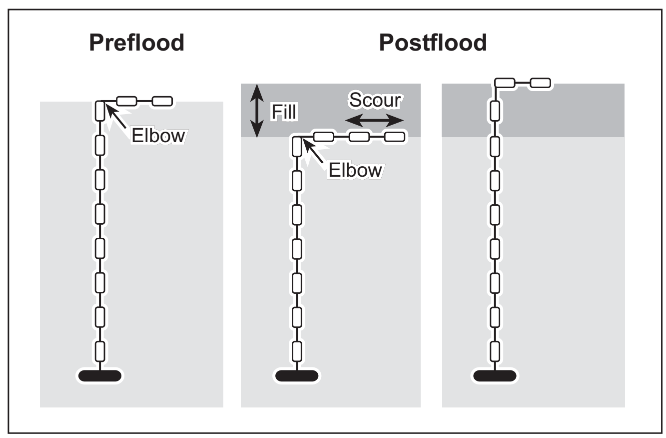

Figure 2. Schematic illustration of scour chain defining a net fill event.

Flow stage was measured using a combination of gantry mounted ultra sonic depth recorders and rudimentary crest stage recorders. Discharge was estimated from the stage records using Manning's flow resistance equation.

Spatial Patterns of Scour and Fill

Cross-sectional average depths of scour, fill and net elevation change recorded in the main channel during a bankfull event are shown in Figure 3a. Scour was observed over entire reach length, though the depths varied from over 15 cm to less than 5 cm. The reach average scour depth was 6.5 cm. Depths of fill range over similar values, though fill just exceeds scour. As a consequence, there was a reach-average net elevation gain during this flood of just under 2 cm. Other reaches show similar results. Figure 3b shows the pattern of scour and fill and net elevation change recorded in the lower tributary reach during the same event. Here, unit discharges were less than 1/10th that recorded in the main channel and as a result, bed activity was less intense. However, there was still significant variability in depths of scour and fill and as before, depths of scour and fill were approximately equal at each cross-section.

A preliminary analysis of the spatial pattern of stream-bed scour provides some evidence for oscillatory behaviour. Theoretical analyses of turbulence suggest that flow in a straight, uniform channel generates alternate zones of faster and slower flow with an average spacing of 5-7 times the channel width (Yalin 1992). The pseudo-cyclic distribution of scour depths may, therefore, reflect the interaction between alternate faster and slower areas of flow with the mobile bed sediment. We are currently investigating this hypothesis using serial correlation and spectral analysis

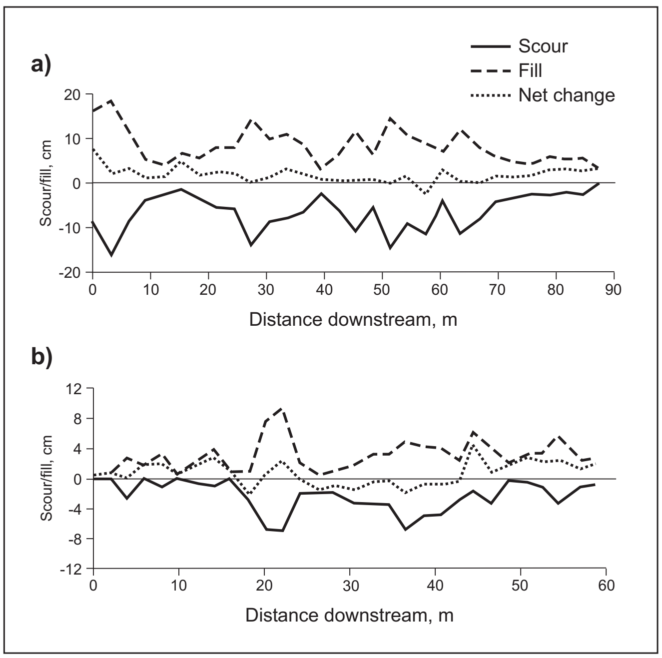

Figure 3. Spatial patterns of cross- sectional average scour, fill and net change in (a) the main channel (Q_p = 4.5 m^3 s^{-1}) and (b) the lower tributary reach (Q_p = 0.2 m^3 s^{-1}).

techniques to define the scale and regularity, or otherwise, of variations in scour depths. Early results, unfortunately, are equivocal, largely because of the limited length of the spatial series.

Reach Scale Variability in Scour and Fill

The reach scale variability in scour and fill can most readily be investigated using frequency distributions. Distributions of scour depths obtained from the main channel for five representative flow events (characterised by peak discharge Q_p) are shown in Figure 4. Scour depths are monotonically distributed. At low flow events (Q_p = 0.2 m^3 s^{-1}) bed activity extends to depths less than 8-10 cm. In contrast, maximum observations of scour equalled 30 cm during the flood with the largest peak discharge (Q_p = 4.5 m^3 s^{-1}). Overall, the channel bed experienced an increasing depth of activity over an increasing proportion of the bed as peak discharge increased. Consequently, mean depths of scour increased with peak magnitude.

The distributions shown in Figure 4 have been modelled by the exponential function. The exponential density function is defined as $F(x, \lambda) = \lambda e^{-\lambda x}$ in which F(x) is the proportion of the channel bed scouring or filling to a given depth increment x in centimetres and λ is the model parameter that is the inverse of the distribution mean. Application of the Chi Square goodness-of-fit test indicates that the exponential function fits four of the five scour depth distributions at a significance level of 0.05 with parameter values of between 0.65 and 0.15 (Figure 4a). The exception is the largest flood where there is an over-abundance of observations in the first class and insufficient observations in the second class. Figure 4b shows the corresponding distributions of fill. Four of the five fill distributions conform to the exponential distribution at the 95% confidence level. The exception here is one of the smaller events.

Other sites show similar distributions of scour and fill depths. Figure 5, for example, shows the distribution of scour and fill for three flow events recorded in the lower tributary reach. The flows are about the same magnitude as the lowest flows recorded in the main channel and bed activity extends to comparable depths - less than 8 cm, in general, with a limited number of channel locations experiencing up to 22 cm of activity at the slightly higher flow. More significantly, it is seen that the shape of the scour and fill distributions are similar to those recorded in the main channel with five of the six distributions conforming to the exponential model ($\alpha < 0.05$; $0.33 < \lambda < 0.55$).

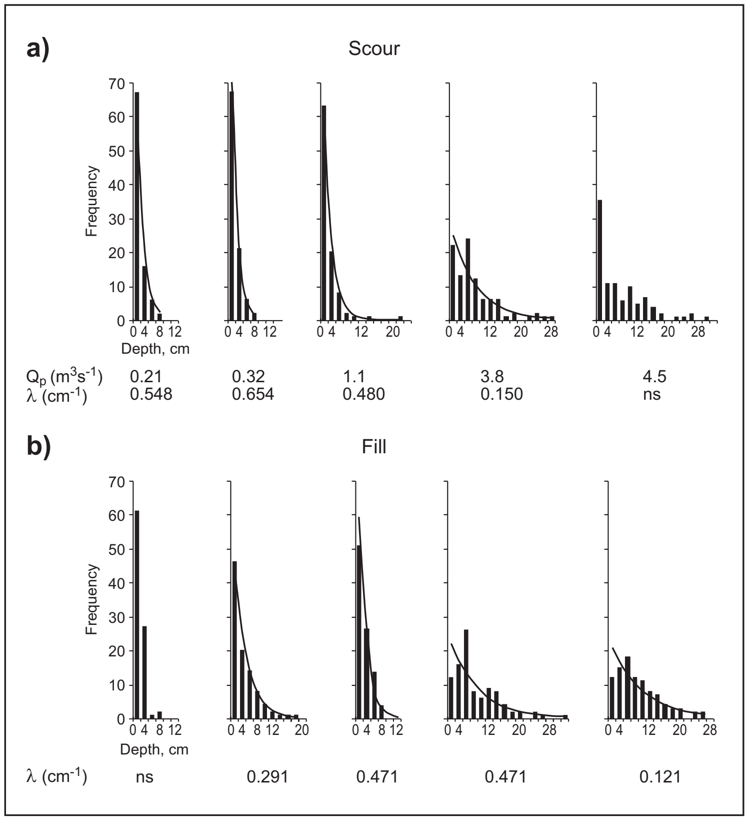

Figure 4. Frequency distributions of scour (a) and fill (b) for five runoff events in the main channel (n = 96). Statistically significant exponential distributions are shown by the fitted lines (ns = not significant).

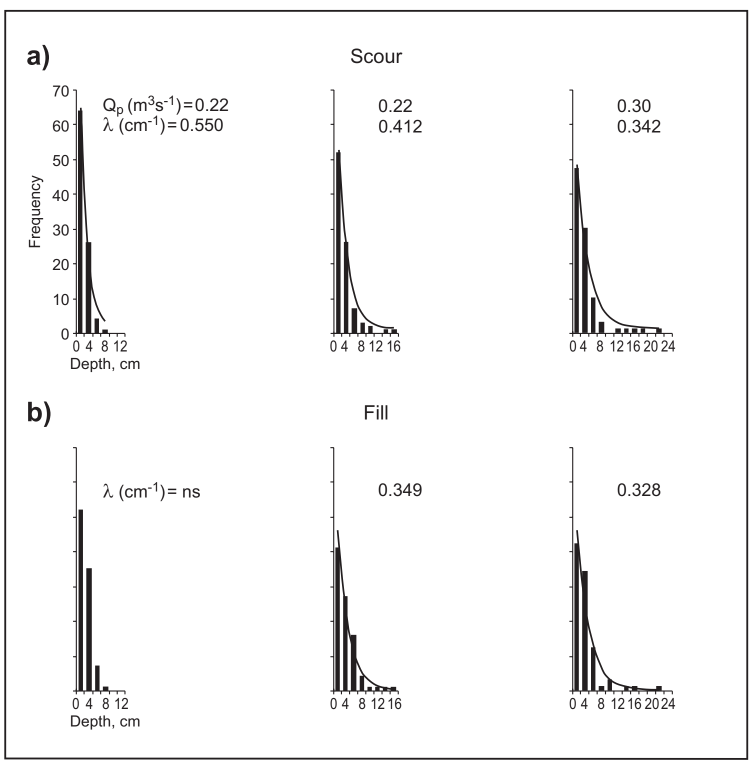

Figure 5. Frequency distributions of scour (a) and fill (b) for five runoff events in the lower tributary reach (n=95). Statistically significant exponential distributions are shown by the fitted lines.

In all, 56 frequency distributions of scour and fill were recorded over the three-year study period (28 for scour, 28 for fill. Of these, 15 were characterised by only two bins and thus could be modelled successfully by several probability distribution functions. Of the remaining 41 distributions, 26 (63%) can be fitted by the exponential function. This suggests that the exponential model may give a satisfactory approximation of sediment exchange depth distributions in sand-bed streams where scour is not restricted by sediment availability.

Conclusions

This study has investigated reach scale patterns of scour and fill in sandy, dryland streams. Although significant variability in the depth of scour and fill has been recorded at the scale of the channel reach, the depths of scour and fill are approximately equal at each measurement location. There is some evidence of spatial organisation in scour depths though the limited length of the spatial series hampers quantitative confirmation of this. The exponential density function describes the spatial variation in event-based scour and fill depths for the majority of the events examined. Given that stream powers were generally greatly in excess of entrainment thresholds, this finding is somewhat surprising since it implies that significant areas of the streambeds experienced little, if any, bed activity during an event. This may reflect the fact that much of the data was collected during floods of low-medium intensity. Confirmation of the appropriateness of the exponential model for characterising the distribution of scour and fill depths in sand-bed streams awaits further testing using data obtained at higher magnitude flows in higher order channels.

Acknowledgements

This research was sponsored by the Natural Environment Research Council of the UK. The authors are grateful to the technicians of the USDA-ARS for their help and assistance in the field.

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