Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Geomorphology 88 (2007) 152–166
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

Sediment transfer and storage in dryland headwater streams

D. Mark Powell [a,*], Richard Brazier [b], Anthony Parsons [c], John Wainwright [c], Mary Nichols [d]

[a] Department of Geography, University of Leicester, Leicester, LE1 7RH, UK
[b] Department of Geography, University of Exeter, Exeter, EX4 4RJ, UK
[c] Sheffield Centre for International Drylands Research, Department of Geography, University of Sheffield, Sheffield, S10 2TN, UK
[d] USDA-ARS Southwest Watershed Research Centre, 2000 E Allen Rd, Tucson, AZ, 85719, USA

Received 17 January 2006; received in revised form 1 November 2006; accepted 1 November 2006
Available online 8 December 2006

Abstract

This study describes the dynamics of sediment transfer and storage in three headwater channels of the Walnut Gulch Watershed in the Chihuahuan Desert, southeastern Arizona, USA. Spatially distributed information on volumes of stream-bed scour and fill and the resultant net changes in sediment storage was collected from three channel reaches using dense arrays of scour chains. Reach-averaged estimates of volumetric scour for individual events ranged between 0.001 and 0.11 m^3 m^{-2}. Scour volumes combine with relatively little scatter when rated against peak unit stream power demonstrating that flood magnitude accounts for much of the variance. As a result of locally compensating scour and fill, net changes in sediment storage during individual events were small. Because aggradation and degradation fluctuated with no persistent temporal trend over the study period, sediment transfers through the reaches were not significantly affected by movement of sediment into or out of storage. Measurements of the volume of sediment trapped in a stock-pond downstream of the study sites suggest that scoured bed material travelled several hundred m $year^{-1}$ with a virtual velocity of about 350 m h^{-1}.

Keywords: Dryland rivers; Scour and fill; Sediment storage

1. Introduction

Headwater channels in semi-arid environments receive large amounts of sediment from the surrounding hillslopes due to the predominance of surface runoff and its effectiveness in eroding sparsely vegetated soils (Abrahams, 1972; Gregory and Gardiner, 1975). Relatively little, however, is known about the sedimentary dynamics of low-order dryland streams and their role in storing material during transit. Some workers, for example, have suggested that the narrow valley floors and steep gradients of headwater streams ensure that sediment eroded from hillslopes is conveyed downstream with little storage (Butcher and Thornes, 1978) and that where hillslope and channel systems are strongly coupled, channel behaviour may be controlled by hillslope rather than in-stream hydraulic and sedimentary processes (Lekach and Schick, 1983). Both aspects are in marked contrast to the morphodynamics of higher order channels where sediment transfers are likely to be mediated by the movement of

* Corresponding author. Tel.: +44 116 2523850; fax: +44 116 2523854.
E-mail address: dmp6@le.ac.uk (D.M. Powell).

0169-555X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2006.11.001

sediment into and out of storage (Ham and Church, 2000) and, at a larger scale, the structure of the channel network (Richards, 1993).

In order to develop a better understanding of dryland headwater channel behaviour, information is required on the spatial pattern of stream-bed scour and fill as it occurs at the scale of the channel reach. Scour and fill refer to the vertical fluctuations of alluvial stream-beds that occur in response to the entrainment (scour) and deposition (fill) of bed-material during flood events. Whether a particular channel location experiences scour or fill is contingent on the rate of bed material transport at that location relative to locations immediately upstream (Andrews, 1979). Scour will occur if the rate of bed material transport from a point exceeds that to the point. Fill will occur if the converse is true. Channel adjustment results from local imbalances between scour and fill and reach-scale changes in sediment storage occur if material lost through scour is not balanced by sediment gained elsewhere through fill. As such, scour and fill reflect the morphological response to the transfer of sediment within dryland river channels (Thornes, 1994) and can be used to investigate the processes that regulate the transfer of sediment through them.

Some observations from dryland channels with sandy bed materials have been reported in the literature (e.g. Colby, 1964). Most, however, are restricted to isolated cross sections (e.g. Leopold and Maddock, 1953) or to chance locations where magnetically tagged particles have become buried (e.g. Hassan, 1990). As a result, there is considerable uncertainty about channel behaviour (Andrews, 1979). Some researchers have studied scour and fill more extensively. Leopold et al. (1966), for example, measured stream-bed scour and fill at 51 locations within a 10 km reach of the Arroyo de los Frijoles near Santa Fe in New Mexico (see also Gellis et al., 2005). Their data suggest that the stream-bed is scoured extensively during rising flood stages and that the channel is maintained in approximate balance by compensating fill during falling flood stages. However, the low density of data acquisition (the downstream spacing between measurements was generally 300 m) prevents an analysis of the spatial variability and pattern of scour and fill occurring within a reach. To address this problem, we have deployed dense arrays of scour chains in three sand-bed channels in SE Arizona to obtain spatially intensive measurements of scour and fill. Detailed statistical analyses of the variability and spatial pattern of scour and fill for individual events have shown that 1) mean depths of scour and fill increased with event magnitude; 2) populations of scour depths were exponentially distributed and 3) stream-bed activity was highly non-uniform with scour and fill concentrated at certain locations within the reaches, perhaps in response to local differences in shear stress generated by secondary circulations (Powell et al., 2005, 2006). In this paper, we present an analysis of the volumes of material eroded and deposited within the study reaches in order to examine the relationships between the transfer of sediment downstream and the storage of sediment within the channels.

2. Field site

The study was undertaken at the Walnut Gulch experimental watershed of the United States Department of Agriculture Agricultural Research Service (USDA-ARS) in southeastern Arizona (Fig. 1a). The watershed is representative of the shrub- and grass-covered rangelands of the semi-arid SW USA in general and the Sonoran and Chihuahuan Deserts in particular. The mean annual rainfall and temperature is 350 mm and 17.6 °C respectively. Although rainfall can occur at any time during the year, virtually all runoff originates from intense summer thunderstorms generated by the North American Monsoon. As a result, flood hydrographs are flashy (flood peaks are attained within minutes of the onset of rainfall) and the duration of runoff is short (typically varying between a few minutes to a few hours depending on the size of the event and the scale of the watershed).

Measurement efforts were concentrated in subcatchment 223 of the main watershed (also called Lucky Hills; Fig. 1b). The catchment area was approximately 0.5 km^2 with a well-defined channel system that drained into a stock pond. The stock ponds on the Walnut Gulch Watershed serve the common purpose of supplying water needed to support cattle ranching. Since they trap sediment, a significant number have been routinely monitored by the USDA-ARS to provide information on sediment yields from the upstream catchments (Lane et al., 1997; Nichols, 2006). One study reach was located on the lower portion of the main-channel (MCR; drainage area = 0.21 km^2) approximately 300 m above the stock pond. Two additional reaches were located on upper and lower tributaries (UTR and LTR respectively) with drainage areas of about 0.04 km^2. The tributary channels were incised by up to 0.5 m into the catchment hillslopes and received water and sediment from numerous rills as well as from upstream. Hillslope channel coupling was less strong in the main-channel and in its lower reaches, a small, discontinuous flood plain acted as a buffer between the two systems. All three channels, however, were single thread, relatively

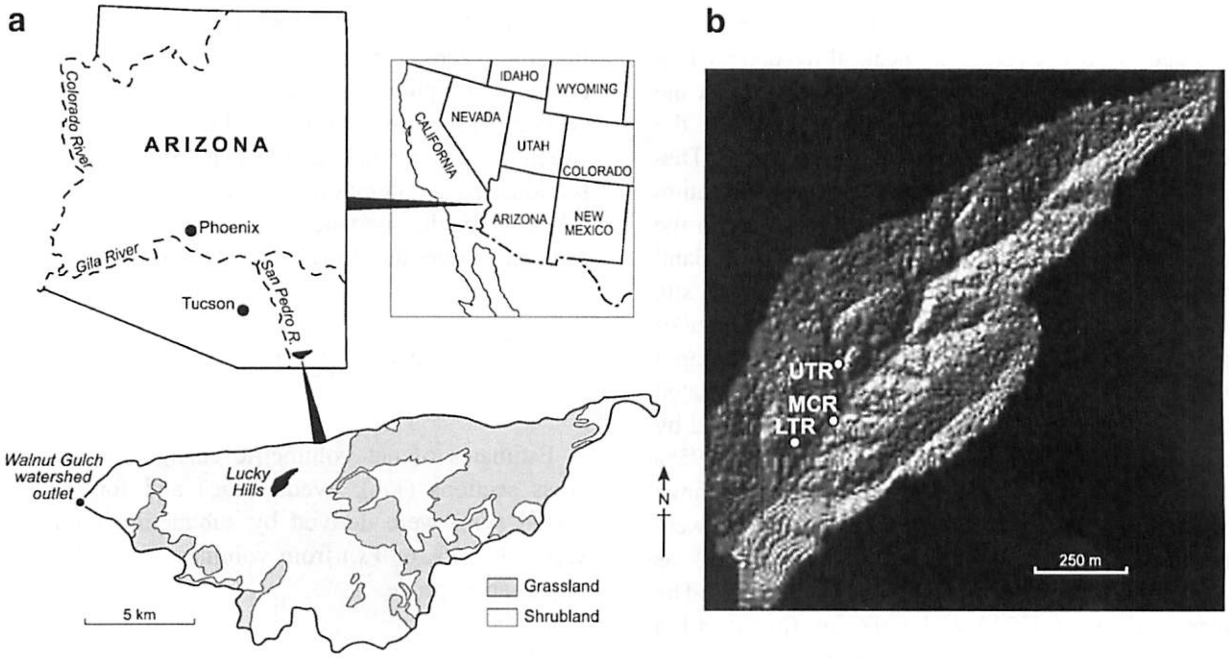

Fig. 1. Location of study area (a) and shaded relief model of subcatchment 223 (Lucky Hills) showing locations of the study reaches (b).

steep and narrow and with flat, planar beds of medium-coarse sand and fine gravel (Table 1).

3. Methods

3.1. Scour and fill

Depths of scour (zs) and fill (zf) were obtained using scour chains (Laronne et al., 1994). In each reach, scour chains were inserted across 30 cross sections with a downstream spacing of one channel width (w). In general, between three and five scour 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.

Data were collected from ten consecutive events in the MCR and nine consecutive events in the LTR and UTR over a three-year period. The chains were resurveyed after each event by measuring the length of the chain above the elbow where the chain had kinked following maximum scour (a) and the length of chain exposed at the surface once it had been rest in anticipation of the next flood (b). Most chains were buried by fill and their locations after each event required careful excavation at precisely measured distances along the cross sections. The chains were measured to the nearest 0.005 m (c. half a link length). Depths of scour and fill were calculated as $zs = a - b_1$ and $zf = a - b_2$ where b_1 and b_2 are the lengths of chain exposed on the pre- and post-flood beds respectively.

3.2. Flow

Flow stage in the main-channel was measured to ±0.003 m with an ultrasonic water-level recorder that was logged at 30-second intervals. Flows in the tributaries were monitored with maximum-stage

Table 1
Characteristics of the study reaches

Site	Reach length, m	No. of chains	Width,⁺ m	Depth,* m	No. of events	Discharge, $m^3 s^{-1}$	Slope, %	D_{50},˜ mm
MCR	87.0	99	3.1	0.45	10	0.2–11.4**	1.9	1.3
UTR	29.8	45	1.2	0.75	9	0.03–1.1	1.9	3.2
LTR	58.7	95	2.0	0.42	9	0.04–1.2	1.7	1.8

⁺ mean bed width; * bank-full depth; ** includes two bank full flows ($Q_p \approx 4$ $m^3 s^{-1}$ and one overbank flow ($Q_p = 11.4$ $m^3 s^{-1}$); ˜ undifferentiated sample of surface and subsurface material.

recorders with an accuracy of ±0.01 m. Estimates of peak stage were converted to peak flow depths (Y_p) using the geometry of the local cross section under the assumption that the depths of scour recorded at the measurement section coincided with peak stage. Discharge (Q) was estimated using Manning's equation since direct measurement was impracticable due to the unpredictable and short-lived nature of the dryland runoff regime, the difficulty of accessing the field site safely during violent thunderstorms and the danger of working in fast-flowing stream channels subject to rapid increases in stage. The friction slope was approximated by the reach-average bed gradient (S) as determined by levelling down the centres of the reaches. The 95% confidence intervals for the bedslope estimates range between 0.06 and 0.1S. Roughness coefficients (n) were estimated using the method of Cowan (1956) as described in Arcement and Schneider (1989). The resultant values of 0.035 and 0.08 for flows within and outwith the channel banks respectively seem reasonable when compared with data and photographs of other streams in Arizona (Phillips and Ingersoll, 1998; O'Day and Phillips, 2000) though none of the published examples is directly comparable to the study streams. Poorly constrained uncertainties in the values of n and in the cross section geometry of the channel greatly exceed those associated with the measurement of stage and channel bedslope and generate considerable uncertainty in the estimates of discharge. Tillery et al. (2001) report errors in slope-conveyance estimates of discharge in dryland streams of up to 25% which suggest that the discharge estimates obtained in this study should be interpreted with some care.

3.3. Construction of sediment budgets

The scour and fill data were used to construct a sediment budget for each reach. Volumes of scour and fill for the ith cross section were calculated by summing the volumes of a number of prisms defined along the cross section, i.e.

$$V_i = \sum_{j=1}^{k+1} x_j y_i \overline{z}_j \tag{1}$$

where V_i, x_j and $\overline{z}_j$ are the volume of scour (or fill), the cross-stream distance and the mean depth of scour (or fill) of the jth prism respectively, y_i is the downstream length of the prism and k is the number of chains along the cross section. In applying the prism formula, it was assumed that depths of scour and fill varied linearly between adjacent chains along the section and declined linearly to zero at the channel margins. y_i was calculated on the assumption that the area of scour at that cross section was representative of the channel length between it and the half distance to the adjacent cross sections. Total volumes of scour and fill for the rth event (V_r) and for the sequence of n events that occurred in each reach over the study period (V_t) were calculated as

$$V_r = \sum_{i=1}^{30} V_i \text{ and } V_t = \sum_{r=1}^{n} V_r \tag{2a, b}$$

Estimates of net volumetric change for individual cross sections (Vn_i), events (Vn_r) and for the study period (Vn_t) were derived by subtracting volumes of scour (Vs_i, Vs_r or Vs_t) from volumes of fill (Vf_i, Vf_r or Vf_t) as appropriate.

3.4. Uncertainty analysis

All sediment budgets are subject to uncertainty (Martin and Church, 1995; Ham and Church, 2000). Potentially significant sources of uncertainty in this study arise from measurement errors and the downstream and cross-stream sampling strategies. These uncertainties were quantified using standard rules for combining errors (Beers, 1957). All sources of uncertainty were analysed separately so their magnitudes can be compared.

3.4.1. Measurement error

The uncertainty in V_i due to measurement error is given by

$$\partial V_i' = \sqrt{\sum_{j=1}^{k+1}\left[\sqrt{\left(\frac{\partial x_j}{x_j}\right)^2 + \left(\frac{\partial y_i}{y_i}\right)^2 + \left(\frac{\partial \overline{z}_j}{\overline{z}_j}\right)^2}\, Vs_j\right]^2} \tag{3}$$

where ∂x, ∂y, $\partial \overline{z}$ are the errors in x_j, y_i and $\overline{z}_j$ respectively. ∂x and ∂y=0.01 m, the precision of the topographic survey. $\partial \overline{z} = \sqrt{2.(\partial z/2)^2} = 0.005$ m where $\partial z = \sqrt{\partial a^2 + \partial b^2}$ is the error in the depths of scour and fill (=0.007 m). The uncertainties in the total volumes of scour (or fill) for individual events ($\partial V_r'$) and for the study period ($\partial V_t'$) are calculated from

$$\partial V_r' = \sqrt{\sum_{i=1}^{30} \partial V_i'^2} \text{ and } \partial V_t' = \sqrt{\sum_{r=1}^{n} \partial V_r'^2} \tag{4a, b}$$

Equivalent uncertainties in Vn_i ($=\partial Vn_i'$), Vn_r ($=\partial Vn_r'$) and Vn_t ($=\partial Vn_t'$) were estimated as

$$\partial Vn_i' = \sqrt{\partial Vf_i^2 + \partial Vs_i^2}\,; \quad \partial Vn_r' = \sqrt{\sum_{i=1}^{30} \partial Vn_i^2}\,;$$
$$\partial Vn_t' = \sqrt{\sum_{r=1}^{n} \partial Vn_r^2} \qquad (5a, b, c)$$

where $\partial Vf_i'$ and $\partial V's_i$ are the uncertainties in Vf_i and Vs_i respectively.

3.4.2. Downstream sampling strategy

Uncertainties in volume estimates due to the downstream sampling strategy arise from the spacing and location of the cross sections within the study reaches. Although the uncertainties due to cross-section spacing cannot be quantified, they are unlikely to be significant given that the cross sections were spaced relatively closely at intervals of one channel width (c. 1–3 m). Interestingly, an analysis of the effect of relaxing the downstream sampling density on the estimates of volumetric scour and fill suggests that tolerable estimates of ±10% can be obtained using a cross section spacing of $2w$, but that errors can increase to more than 20% at higher cross section spacings. These results replicate those of Ashmore and Church (1998). The effect of cross section location on the volume estimates was assessed by deriving 10 estimates of volumetric scour and fill for each event using random subsamples of cross sections. If $\tilde{V}_x$ is the volume associated with the xth random estimate of scour (or fill) and $\bar{\bar{V}}$ is the mean random volume estimate, then the root mean square error (ε)

$$\varepsilon = \sqrt{\frac{\sum_{x=1}^{10} \left(\tilde{V}_x - \bar{\bar{V}}\right)^2}{10}} \qquad (6)$$

represents an estimate of the error in $\tilde{V}_x$ due to cross section location. Defining $\hat{\varepsilon} = \varepsilon/\bar{\bar{V}}$ gives the uncertainty in V_r as $\partial V_r'' = \hat{\varepsilon}\, V_r$. Uncertainties in V_t ($=\partial V_t''$), Vn_r ($=\partial Vn_r''$) and Vn_t ($=\partial Vn_t''$) due to cross section location were calculated by making the appropriate substitutions for the error terms in Eqs. (4a, b) and (5a, b, c) respectively.

In the MCR and LTR, $\tilde{V}_x$ was defined by randomly sampling 20 of the 30 of the available cross sections in each reach. This strategy was not possible in the UTR because the downstream alternating sequence of one centre chain and two chains at left and right cross section locations would have confounded the analysis. In this reach, therefore, the cross sections containing two chains were analysed separately from those containing one chain. In each case, $\tilde{V}_x$ was defined by 10 randomly sampled cross sections. The results of the separate analyses were combined to get an estimate of $\partial V_r''$ for the reach.

3.4.3. The cross-stream sampling strategy

In general, scour and fill depths in the MCR and LTR were measured at three cross section locations (left, centre and right). However, chains were also installed at left-centre and right-centre locations at five cross sections in the MCR and at four cross sections in the LTR. These additional chains allow the uncertainty associated with sampling at left, centre and right locations to be estimated as

$$\partial V_i''' = \sqrt{\frac{\sum_{i=1}^{n} (V_{5i} - V_{3i})^2}{n}} \qquad (7)$$

in which V_{5i} is the cross sectional scour volume for the ith cross section calculated using all five chains, V_{3i} is the cross sectional scour volume for the same cross section calculated using only the left, centre and right chains and n = the number of cross sections. Uncertainties in V_r ($=\partial V_r'''$), V_t ($=\partial V_t'''$), Vn_i ($=\partial Vn_i'''$), Vn_r ($=\partial Vn_r'''$) and Vn_t ($=\partial Vn_t'''$) were calculated by making the appropriate substitutions for the error terms in Eqs. (4a, b) and (5a, b, c) respectively.

The uncertainty associated with the cross-stream sampling strategy in the UTR was assessed by sampling from the LTR data set in a similar manner. The uncertainty in volumetric estimates of scour (and fill) derived from sampling odd numbered cross sections at left and right cross section locations (V_{2i}) and from sampling even numbered cross sections at the channel centreline (V_{1i}) are c. 0.1 and 0.2 V_{3i} respectively. The resultant uncertainties in $V_r = \sum_{i=1}^{15} V_{2i} + \sum_{i=1}^{15} V_{1i}$ are typically 0.1–0.2 V_r. As a result, $\partial V_i'''$ for the events in the UTR was estimated as 0.15 V_r.

3.4.4. Total uncertainty

The total uncertainty in the volumetric estimates of scour (or fill) and net change for individual events (ΔV_r

Table 2
Volumes of scour, fill and net change with associated uncertainty estimates

Event	Discharge Q_P, m^3 s^{-1}	Scour, m^3					Fill, m^3					Net change, m^3				
		V_r	$\partial V_r'$	$\partial V_r''$	$\partial V_r'''$	ΔV_r	V_r	$\partial V_r'$	$\partial V_r''$	$\partial V_r'''$	ΔV_r	V_r	$\partial V_r'$	$\partial V_r''$	$\partial V_r'''$	ΔV_r
Main-channel reach																
30/7/2000 MCR	4.6	11.7	0.12	0.76	0.57	0.96	15.0	0.12	0.79	0.57	0.99	3.2	0.17	1.10	0.81	1.37
10/8/2000	3.9	12.4	0.12	1.10	0.46	1.20	14.2	0.12	0.93	0.07	0.94	1.8	0.17	1.44	0.47	1.53
20/8/2000	0.2	3.4	0.11	0.25	0.16	0.32	3.1	0.11	0.21	0.16	0.28	−0.3	0.15	0.33	0.23	0.43
5/8/2001	0.7	7.7	0.12	0.65	0.40	0.77	6.4	0.11	0.41	0.15	0.46	−1.2	0.16	0.77	0.43	0.89
11/8/2001	0.5	8.1	0.12	0.45	0.16	0.49	4.0	0.11	0.24	0.07	0.27	−4.1	0.16	0.51	0.17	0.56
12/9/2001	0.3	2.9	0.11	0.18	0.18	0.28	3.2	0.11	0.21	0.12	0.27	0.3	0.16	0.28	0.22	0.39
19/7/2002	0.5	4.1	0.10	0.28	0.15	0.34	4.3	0.11	0.13	0.36	0.40	0.2	0.15	0.31	0.39	0.52
26/7/2002	1.5	9.8	0.12	0.41	0.33	0.54	8.5	0.12	0.60	0.41	0.74	−1.4	0.16	0.73	0.53	0.91
4/8/2002	11.4	28.0	0.14	1.11	0.34	1.17	25.0	0.13	1.46	0.37	1.51	−3.0	0.19	1.83	0.50	1.91
30/8/2002	0.4	8.6	0.11	0.48	0.63	0.80	10.6	0.11	0.54	0.58	0.80	2.0	0.16	0.72	0.86	1.13
Total		96.8	0.37	2.05	1.20	2.40	94.4	0.36	2.15	1.08	2.44	−2.4	0.52	2.97	1.62	3.42
Lower-tributary reach																
30/7/2000 MCR	0.2	2.0	0.046	0.10	0.18	0.21	2.2	0.050	0.131	0.10	0.17	0.2	0.068	0.16	0.20	0.27
10/8/2000	0.3	2.3	0.049	0.11	0.16	0.20	2.4	0.050	0.127	0.071	0.15	0.1	0.070	0.17	0.18	0.26
20/8/2000	0.2	1.5	0.050	0.07	0.22	0.23	1.7	0.046	0.065	0.11	0.13	0.2	0.068	0.10	0.24	0.27
5/8/2001	0.04	0.36	0.039	0.04	0.036	0.067	0.73	0.045	0.037	0.11	0.13	0.4	0.060	0.056	0.12	0.15
11/8/2001	0.1	1.5	0.051	0.16	0.24	0.29	0.74	0.044	0.048	0.036	0.075	−0.8	0.067	0.16	0.24	0.30
12/9/2001	0.04	0.60	0.038	0.11	0.03	0.12	0.71	0.045	0.046	0.16	0.17	0.1	0.059	0.12	0.16	0.21
19/7/2002	0.3	2.4	0.050	0.10	0.11	0.16	1.7	0.048	0.087	0.33	0.35	−0.7	0.069	0.13	0.35	0.38
26/7/2002	0.6	3.5	0.053	0.14	0.10	0.18	2.6	0.047	0.135	0.16	0.22	−0.9	0.071	0.20	0.19	0.28
4/8/2002	1.2	7.0	0.059	0.28	0.20	0.35	4.5	0.051	0.270	0.26	0.38	−2.6	0.078	0.39	0.33	0.52
Total		21.2	0.15	0.42	0.48	0.65	17.1	0.14	0.38	0.52	0.66	−4.0	0.20	0.56	0.71	0.93
Upper-tributary reach																
30/7/2000 MCR	0.1	0.7	0.021	0.017	0.10	0.11	0.9	0.022	0.018	0.13	0.13	0.2	0.030	0.02	0.16	0.17
10/8/2000	0.1	0.7	0.020	0.013	0.10	0.10	0.3	0.020	0.011	0.05	0.05	−0.4	0.028	0.02	0.11	0.12
20/8/2000	0.06	0.2	0.018	0.006	0.027	0.03	0.2	0.020	0.0031	0.02	0.03	0.0	0.027	0.01	0.036	0.046
5/8/2001	0.03	0.0	0.013	0.005	0.007	0.016	0.1	0.016	0.0059	0.01	0.02	0.0	0.020	0.008	0.015	0.026
11/8/2001	0.08	0.4	0.020	0.030	0.056	0.07	0.1	0.015	0.0073	0.01	0.022	−0.3	0.025	0.03	0.058	0.070
12/9/2001	0.05	0.1	0.017	0.008	0.019	0.03	0.2	0.019	0.0064	0.02	0.03	0.0	0.025	0.01	0.030	0.040
19/7/2002	0.1	0.1	0.018	0.003	0.016	0.02	0.4	0.020	0.0091	0.06	0.06	0.3	0.027	0.01	0.059	0.065
26/7/2002	0.3	0.7	0.022	0.024	0.11	0.12	0.9	0.022	0.012	0.13	0.13	0.1	0.031	0.03	0.17	0.18
4/8/2002	1.1	1.0	0.023	0.043	0.15	0.16	2.2	0.024	0.040	0.33	0.33	1.2	0.033	0.06	0.36	0.37
Total		3.9	0.06	0.06	0.24	0.26	5.1	0.06	0.05	0.39	0.39	1.2	0.08	0.08	0.46	0.47

and ΔVn_r respectively) and for the duration of the study period in each reach (ΔV_t and ΔVn_t respectively) were calculated as

$$\Delta V_r = \sqrt{\partial V_r^2 + \partial V_r''^2 + \partial V_r^{\prime\prime\prime 2}} \text{ and} \tag{8a, b}$$

$$\Delta Vn_r = \sqrt{\partial Vn_r^2 + \partial Vn_r''^2 + \partial Vn_r^{\prime\prime\prime 2}}$$

$$\Delta V_t = \sqrt{\sum_{r=1}^{n} \Delta V_r^2} \text{ and } \Delta Vn_t = \sqrt{\sum_{r=1}^{n} \Delta Vn_r^2} \tag{9a, b}$$

4. Results

4.1. Reach-scale volumes of scour, fill and channel change

Reach-scale estimates of the volumes of scour and fill and net change for individual events are shown in Table 2 together with estimates of their uncertainties. It shows that the magnitude of the uncertainties in estimates of scour and fill are generally comparable. In the MCR and LTR, uncertainties due to measurement error are low in comparison with the magnitude of the volume estimates ($0.005 \le \partial V_r'/V_r \le 0.11$; mean $\overline{(\partial V_r'/V)} = 0.03$. Measurement error assumes more significance in the UTR where the lower discharges generated smaller volumes of scour and fill ($0.01 \le \partial V_r'/V_r \le 0.26, \overline{\partial V_r'/V} = 0.09$). The largest source of error in the MCR is due to the location of the cross sections within the reach ($0.03 \le \partial V_r''/V_r \le 0.09, \overline{\partial V_r''/V} = 0.06$). In the LTR, errors due to the location of the cross sections ($0.04 \le \partial V_r''/V_r \le 0.018, \overline{\partial V_r''/V_r} = 0.06$) and sampling along the cross sections ($0.03 \le \partial V_r'''/V_r \le 0.22$; $\overline{\partial V_r'''/V_r} = 0.09$) contribute equally to the uncertainty in volumes of scour and fill. Significant uncertainty is associated with the cross-stream sampling strategy in the UTR ($\partial V_r'''/V_r = 0.15$). Overall, the total errors in the volumetric estimates of scour and fill in the MCR, LTR and UTR average 8, 12 and 19% respectively for individual events and equal c. 2, 3 and 7% respectively for the study period.

In some studies of channel fills, stratification at the depth of maximum scour can be traced to the channel banks to give some idea of the depths of scour and fill at the channel margins. No such stratification was observed in the sediments of the present channels and the volumes reported in Table 2 are based on the assumption that scour and fill declined to zero at the channel margins. To assess the sensitivity of the results to this assumption, a comparison was undertaken with estimates calculated on the assumption depths of scour and fill at the channel margins of each cross section were equal to the mean depths of scour and fill recorded over the cross section. On average, volumes of scour and fill estimated under the 'cross section average' assumption are 30% higher in the MCR and LTR and 70% higher in the UTR than estimates based on the 'zero' assumption. The results suggest that the assumption of zero scour at the channel margins is a source of potentially significant error that requires further investigation through the deployment of scour chains close to the channel banks.

Volumes of scour and fill increase with event magnitude (peak discharge; Q_p) in each reach (Table 2). This can be attributed to increases in both the mean depth and areal extent of bed activity as has been shown in gravel-bed rivers (e.g. Carling, 1987; Haschenburger and Church, 1998; Haschenburger, 1999). In the main-channel, for example, the increase in scour volume from 3.4 m^3 at $Q_p = 0.2$ m^3 s^{-1} (the lowest flow) to 27.99 m^3 at $Q_p = 11.4$ m^3 s^{-1} (the highest flow) is associated with an increase in the mean depth of scour from 1.5 cm to 15.6 cm and an increase in the proportion of chains registering more than 1 cm of scour from 0.57 to 0.98. The ordinary least-squares relationships between volumes of scour for individual events (Vs_r) and peak discharge (Q_p) are shown in Fig. 2a. For each channel, data from individual floods combine with relatively little scatter and the resultant trends are represented well by simple power-law functions of peak discharge. A general indication of the consistency of the results at each site is provided by the relatively high correlation coefficients ($0.78 \le r \le 0.96$). It should be noted, however, that the data for the UTR indicate little increase in bed activity at discharges above 0.1 m^3 s^{-1}. This threshold is unlikely to reflect a limitation in the depth of alluvium available for scour since this greatly exceeds the maximum depths of scour recorded in the reach. Further information is required to clarify the relationship between Vs_r and Q_p in this reach.

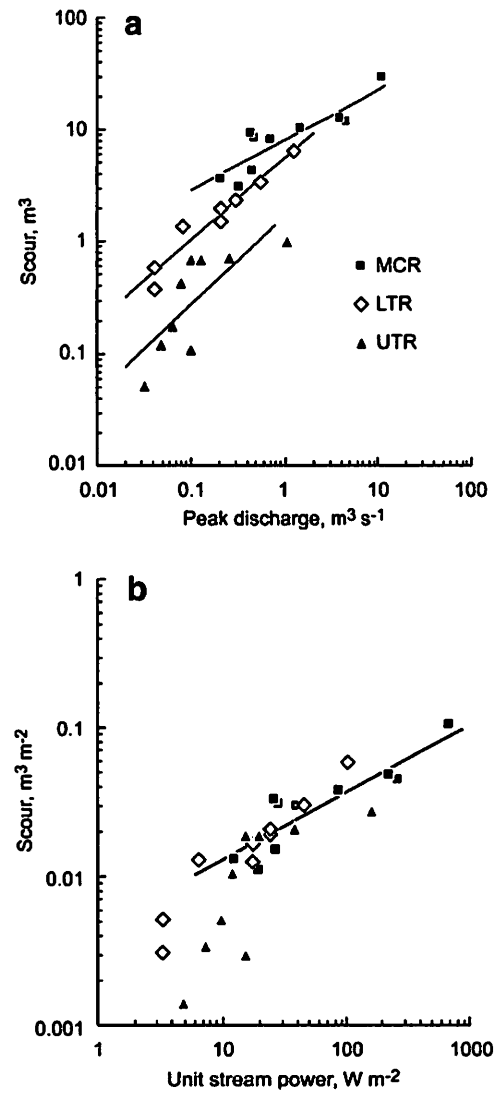

Fig. 2. Volumes of scour as a function of peak discharge (a); volumetric scour per unit bed area as a function of peak unit stream power (b). In (a), the curves for the MCR, LTR and UTR are $Vs_r = 7.72Q_p^{0.46}$, $r = 0.89$; $Vs_r = 5.81Q_p^{0.74}$, $r = 0.96$; $Vs_r = 1.67Q_p^{0.80}$, $r = 0.78$ respectively. In (b), the curve represents data from events with $\hat{Vs}_r \ge 0.01$ m and is $\hat{Vs}_r = 4.57 \times 10^{-3}\omega_p^{0.45}$, $r = 0.88$.

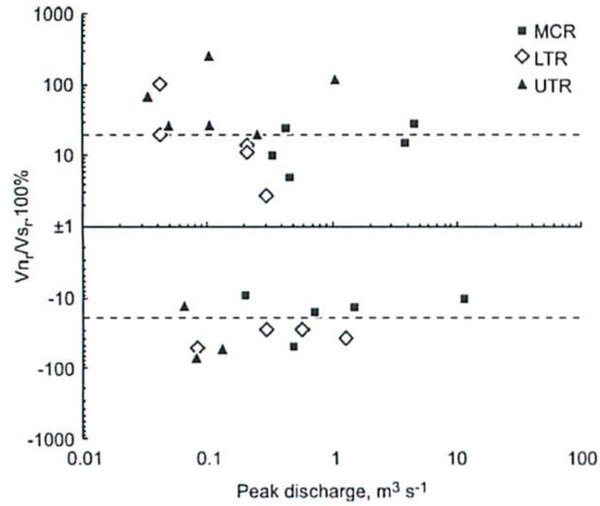

Fig. 3. Plot of Vn_r/Vs_r.100% against peak discharge.

It is interesting to compare the activity of the three stream-beds, especially since the channels share similar geomorphic characteristics and were subject to similar flow events (Table 1). In Fig. 2b, we plot volumetric scour per unit bed area ($\hat{Vs}_r$) against peak unit stream power (ω_p) for individual flow events. The latter was calculated as $\rho g Q_p S/w$ where ρ=is the density of the flow (kg m^{-3}), and g is the acceleration due to gravity (m s^{-2}). The plot reveals that the three data sets dovetail exceedingly well once $\hat{V}s_r$ exceeds a threshold of about 0.01 m^3 m^{-2}. The six events below this threshold were associated with patchy bed activity (on average, only 20% of scour chains registered scour in excess of 1 cm) suggesting that the scatter at $\hat{V}s_r$<0.01 m reflects an arbitrary channel response at low stream powers (ω_p<c. 12 W m^{-2}). Excluding these events yields a least-squares regression with a correlation coefficient of 0.88 indicating that the three channels behaved consistently once flows had become sufficiently strong to cause widespread bed mobilisation.

The net balance between volumes of scour and fill determine the sediment storage characteristics of the channels. Volumes of scour and fill recorded in the three reaches are compared in Fig. 3 as $\langle Vn_r \rangle = Vn_r / Vs_r * 100\%$. The temporal sequences in scour, fill and net changes in sediment storage are shown in Fig. 4. In the main-channel, differences between volumes of scour and fill are small for the majority of events ($\langle Vn_r \rangle$< 20%). These relatively small imbalances between scour and fill generate net changes in sediment storage volumes (Vn_r) of 2–3 m^3 during individual events (Fig. 4a) which are equivalent to changes in mean bed-elevations (z_b) of about 1 cm. The exceptions are 30/8/02, 30/7/00 and 11/8/01 in which $\langle Vn_r \rangle$=23, 28 and −50% respectively. These events generated channel changes of 3–4 m^3 ($z_b \approx 1.6$ cm). Reasons for the uncharacteristically large differences between scour and fill in the latter event are unclear. The event was the middle of three low to medium flows that occurred in 2001 and was fairly typical in comparison with the others in terms of rainfall characteristics (amount, duration and distribution) and hydrograph shape. Overall, the cumulative total net sediment loss of 2.4±3.42 m^3 is equivalent to a 0.9±1.3 cm reduction in mean-bed elevation and represents only 2.5% of the total volume of sediment scoured from the channel. It should be noted, however, that some sediment would have been stored on the flood-plain as a result of overbank sedimentation during the event of 4/8/02. The rainfall that generated this event (34 mm of rainfall in 30 min) has a recurrence interval of between 5 and 10 years (Osborn and Renard, 1988).

Absolute differences between the volumes of scour and fill recorded in the LTR and UTR are less than those observed in the MCR (Table 2). However, scour activity was also generally lower so values of $\langle Vn_r \rangle$ are higher (Fig. 3). In the LTR, $-52\% \leq \langle Vn_r \rangle \leq 102\%$ and $\langle Vn_r \rangle$< 20% in only four of the nine events and in the UTR, $-74\% \leq \langle Vn_r \rangle \leq 251\%$ and $\langle Vn_r \rangle$<20% for only two

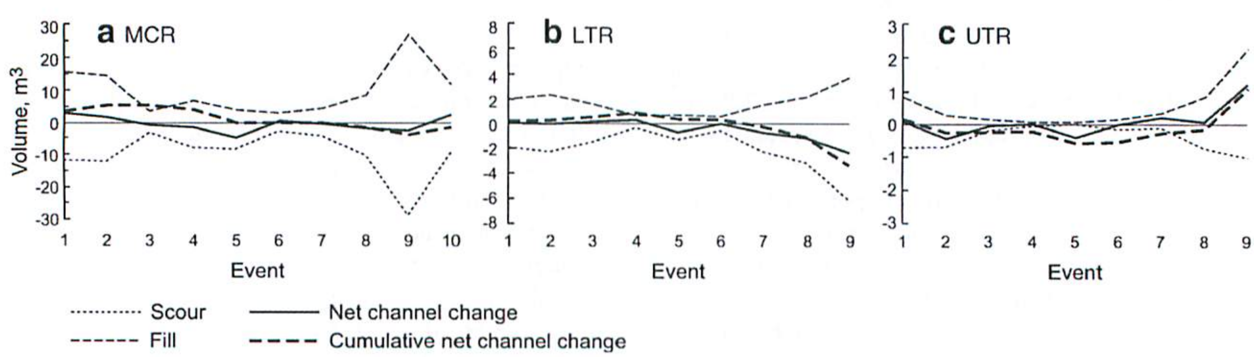

Fig. 4. Temporal variation in the volumes of scour, fill and net change over the study period.

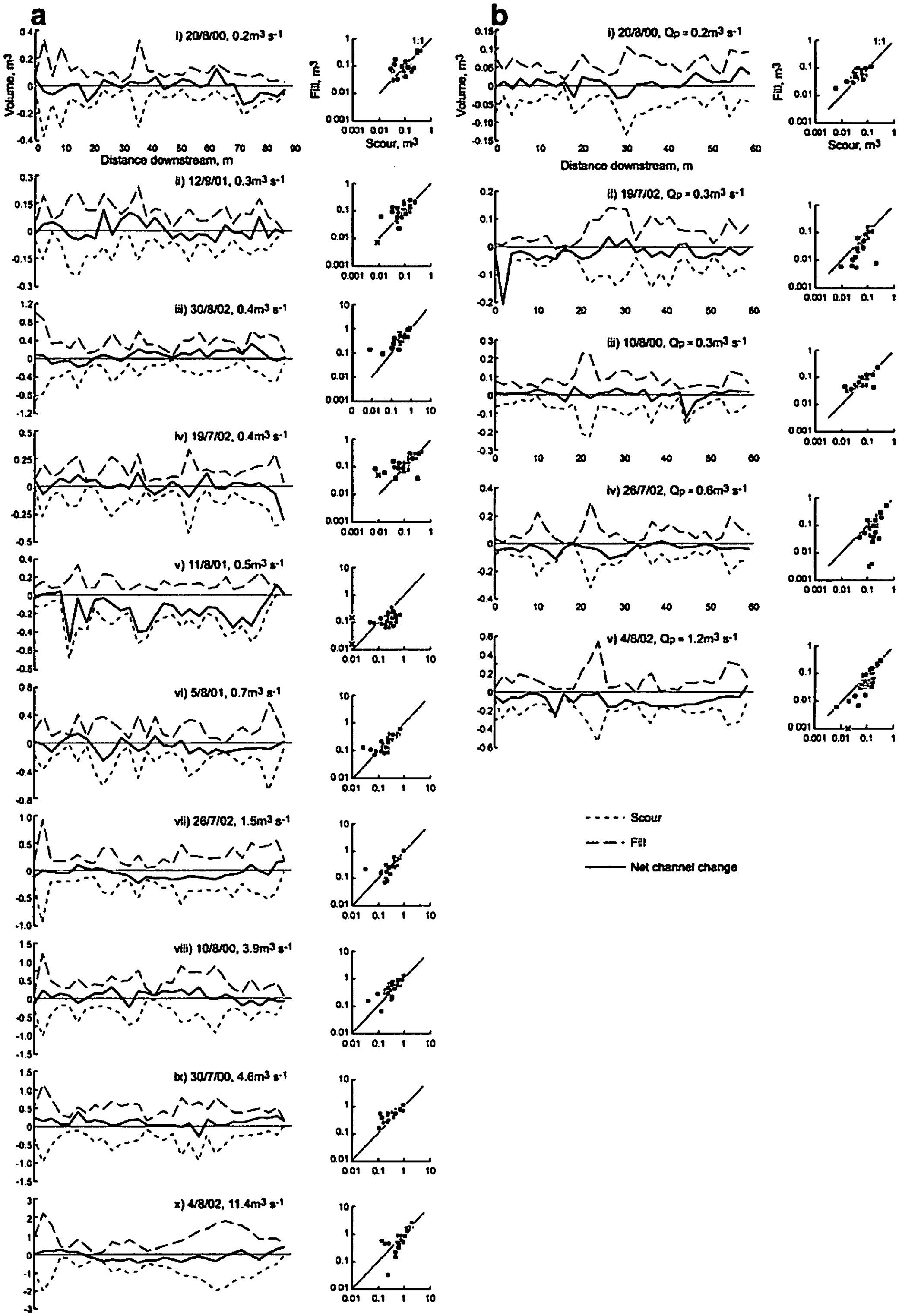

Fig. 5. Spatial patterns of stream-bed scour, fill and net change for the 10 events recorded in the main-channel reach (a) and for the five largest events recorded in the lower-tributary reach (b). In both channels, events are ordered by peak discharge. The scatter plots allow direct comparison of the volumes of scour and fill recorded at individual cross sections for each event. Zero scour or fill is recorded as 0.01 m^3 and is indicated by a cross symbol.

events. Moreover, the cumulative volume changes of -4 ± 0.93 m^3 in the LTR and $+1.2\pm0.47$ m^3 in the UTR are equivalent to 23 and 31% of the total scour volumes respectively. However, much of the change in the volume of sediment stored within the tributary reaches occurred during the high magnitude event of 4/8/02. Prior to this event, the lower-tributary is characterised by net changes in sediment storage of -0.95 to $+0.37$ m^3 (Fig. 4b) and the total net sediment loss of 1.49 ± 0.77 m^3 is equivalent to 10% of the total volume of scour (Table 2). For the same flow events in the upper-tributary reach, $-0.36\leq Vn_r\leq0.27$ m^3 (Fig. 4c) and $Vn_t=0\pm0.29$ m^3 (Table 2). It is not known whether subsequent flows promoted restorative aggradation of the LTR and

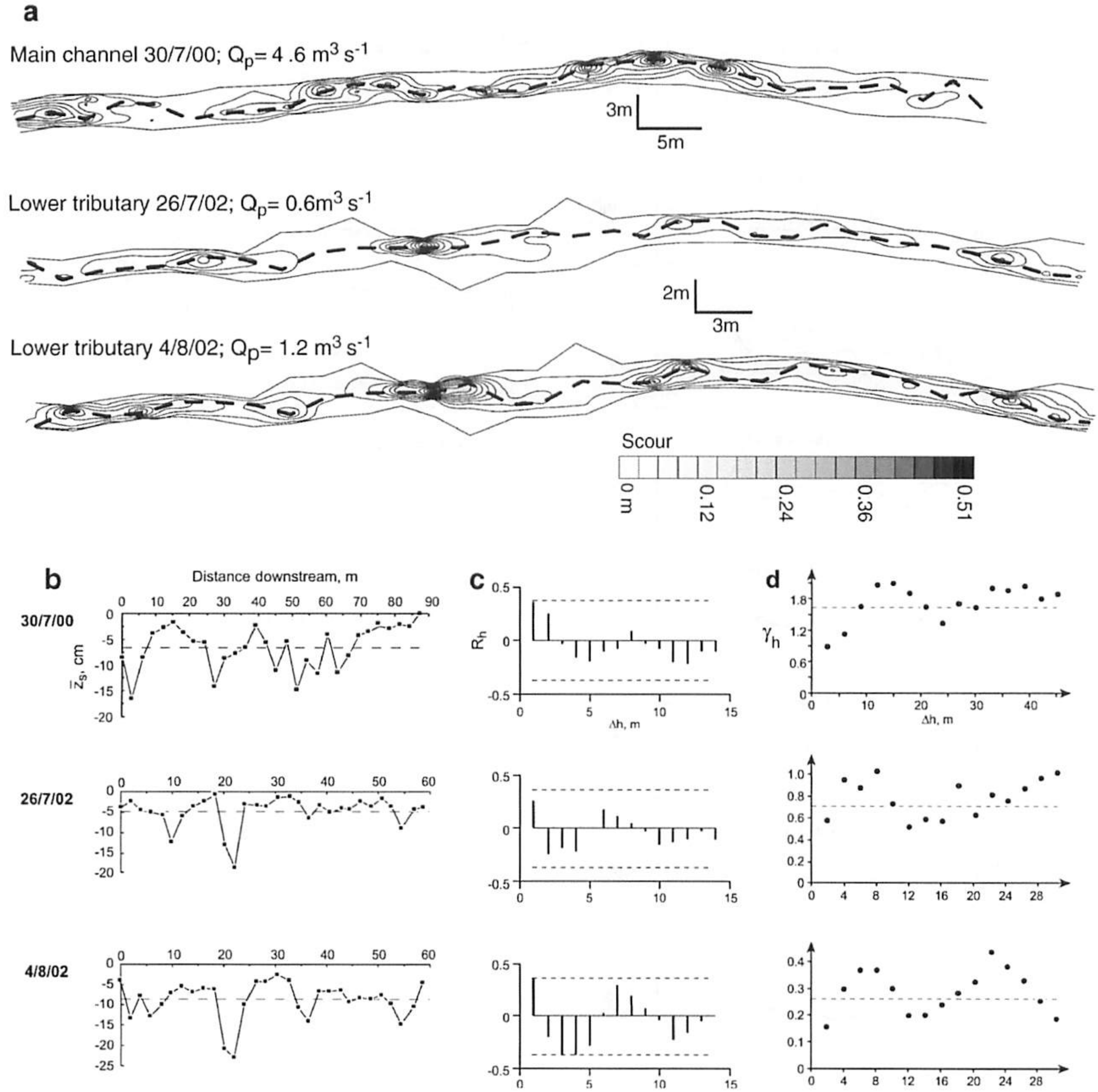

Fig. 6. Spatial patterns of stream-bed scour for selected events in the main-channel and tributary reaches. Spatial pattern of scour depths (a); downstream variation in mean cross-stream scour depths (b); autocorrelograms for mean cross section scour depths (c); semi-variograms for mean cross section scour depths (d). In (a), the dashed line shows the locus of the maximum depth of scour. In (b), (c) and (d) the dashed horizontal lines represent the mean depth of scour for the reach, 95% confidence intervals of the autocorrelogram and the sill of the semi-variogram respectively. The range and wavelength of the semi-variograms (d) imply that the downstream variation in scour depths shown in (a) and (b) has a wavelength of about 7 times the width of the respective channels.

degradation of the UTR since the event of 4/8/02 was the last event to be monitored in these reaches. However, it appears that for much of the study period, aggradation and degradation fluctuated with no persistent temporal trend so that sediment transfer through all three channels did not lead to significant and progressive changes to the volume of sediment stored within them.

4.2. Spatial patterns of scour, fill and channel change

The previous section demonstrates that stream-bed activity varied in a relatively simple manner with increasing discharge and that the volume of sediment stored within the channels did not change appreciably over much of the study period. However, distributed information on patterns of erosion and deposition within the reaches indicates a more complex sedimentary response. Downstream variations in the volumes of scour, fill and net channel change recorded in the main and lower-tributary channels are shown in Fig. 5. It is apparent that although scour was longitudinally continuous, some areas of the beds experienced significantly greater scour than others. The variation is such that volumes of scour at individual cross sections differ from the reach mean by a factor of 2–3 in the main-channel and 3–4 in the lower-tributary channel. Powell et al. (2006) undertook a detailed geostatistical analysis of the spatial patterns using autocorrelation and semi-variogram techniques. Although the analysis was constrained somewhat by the limited length and inherent noisiness of the data, it suggested that stream-bed activity was not random, at least at moderate to high flows, but varied in a periodic manner along alternate sides of the channels with a wavelength of approximately seven channel widths. Some results from this analysis are shown in Fig. 6. The quasi-regular downstream variation in stream-bed activity is evident in the contour plots of scour depth recorded at individual chain locations

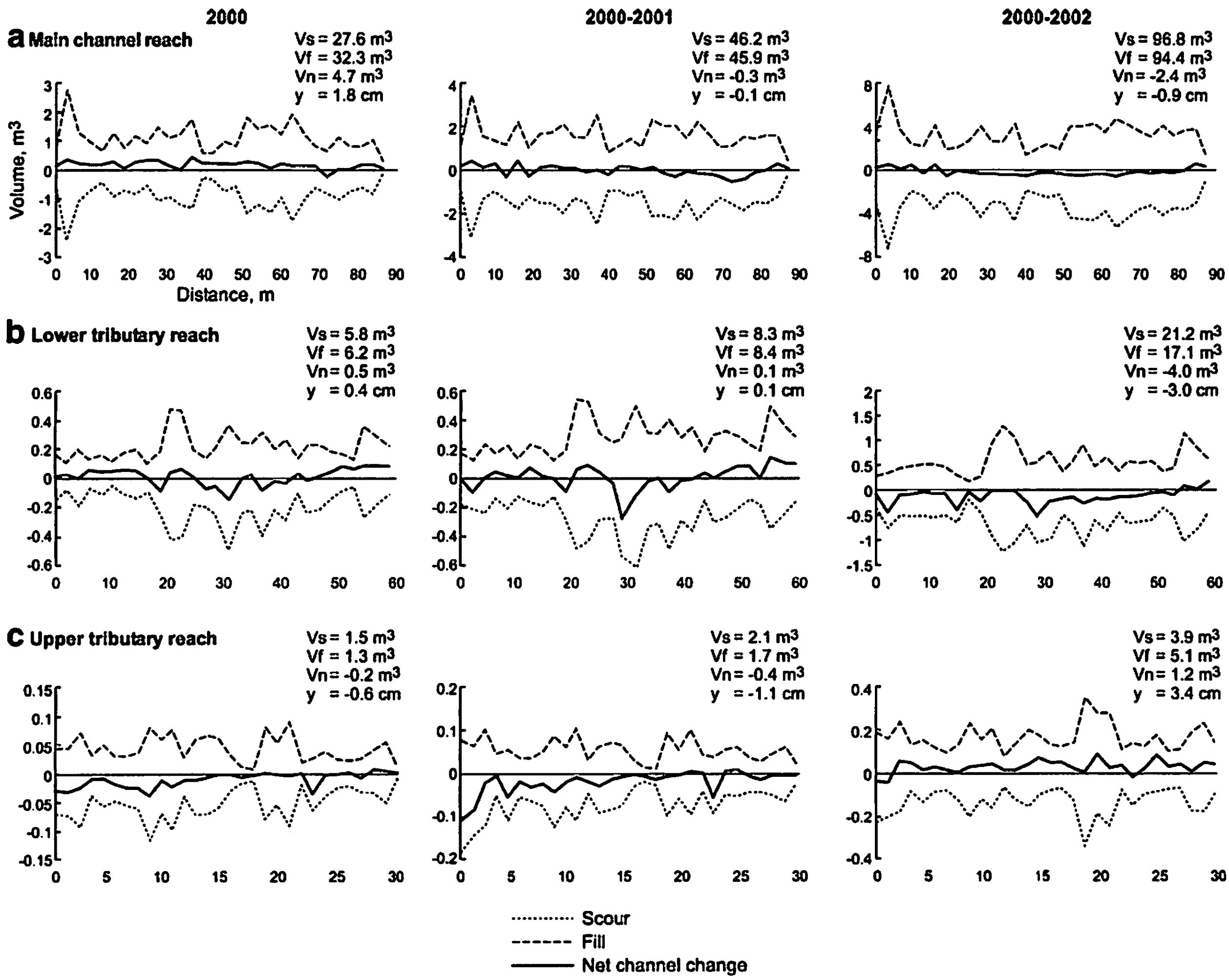

Fig. 7. Cumulative patterns of volumetric scour (Vs_r), fill (Vf_r), net change (Vn_r) and average change in stream-bed elevation (z_b) at the end of 2000, 2001 and 2002 in the main-channel reach (a), lower-tributary reach (b) and upper-tributary reach (c).

(Fig. 6a) and in the downstream pattern of cross section average scour depths (Fig. 6b). It is reflected in the autocorrelograms (Fig. 6c) and semi-variograms (Fig. 6d) by the alternating sequence of positive and negative correlations and by the cyclic variation in semi-variance at increasing lag distances. In terms of deposition, a comparison of the magnitude of scour and fill at individual channel locations revealed a close correspondence. This indicates that the neutral sediment budgets developed as a consequence of locally compensating scour and fill that maintained stream-bed elevations and the planar bed topography. Fig. 5 confirms the approximate balance between scour and fill at the scale of the channel cross section. In the main-channel, for example, mean values of the ratio Vs_i/Vf_i for individual events are generally 1 ± 0.25.

The cause of these patterns of scour and the compensating nature of the subsequent fill is difficult to isolate without detailed hydraulic information and direct observations of the scour process. However, one mechanism may be the generation of non-uniform distributions of bed shear stress by periodically reversing helical secondary flow (Rhoads and Welford, 1991 p. 132–140). If correct, it suggests that the observed spatial patterns of stream-bed scour reflect active bed-reworking at particular locations of the stream bed where shear stresses are augmented by the development of secondary flows. The increase in the volume of material scoured from the reaches at progressively higher flows results from the general increase in flow strength and further localised increases in shear stress and bed activity caused by strengthening secondary flows. The neutral sediment budgets can be attributed to the subsequent infilling of the scour holes, perhaps as the secondary flows weaken and shear stresses decline during the flow recession, resulting in the approximate balance between scour and fill at individual cross sections. This is shown in Fig. 7 which illustrates the cumulative patterns of scour, fill and net change in sediment storage over the three flood seasons.

4.3. Transport distances and virtual velocities

An important question that has not hitherto been considered in studies of scour and fill is how far the eroded material moves. Information on particle travel distances is usually obtained by monitoring the movement of tagged particles over a series of events. Tagging and tracing sand-sized particles is technically difficult and was not attempted. However, crude estimates of sediment transfer distances (L) for the main-channel can be derived by comparing the volume of material eroded from MCR with the volume of material trapped in the downstream stock pond (V_p) (Table 3). The calculation uses the identity

$$V_p.(1-p_{po}) = L.w.\overline{zs}(1-p_{ch}) \tag{10}$$

where $p_{po}=0.49$ and $p_{ch}=0.34$ are the mean porosities of the pond and channel sediments respectively. Furthermore, estimates of the virtual rate of travel (U; Einstein, 1937) can be obtained by dividing the distance of sediment transfer by the duration of competent flow (T).

Estimates of V_p for 2001 and 2002 were obtained from detailed topographic surveys of the pond. Estimates of $\overline{zs}$ and T for the corresponding periods were made using data from MCR. The former was estimated as $\hat{V}s$ (Fig. 2b) and the latter was estimated as the duration of flow above an approximate threshold for scour (c. 5 cm; Powell et al., 2005). Values of p_{po} and p_{ch} were calculated from measurements of sediment density and bulk density obtained for a number of random locations within the pond and the lower reach of the main-channel. The analysis assumes that there is no net scour or fill in the channel between the MCR and the stock pond. Although we are unable to verify this directly, it seems a reasonable assumption given that sediment transfers through the three study reaches were not mediated by movement of sediment into and out of storage. A more significant limitation of the analysis is its failure to account for sediment delivered via hillslope and tributary inputs. Significant sediment inputs to the channel reach between the MCR and the stock pond will cause L and U to be overestimated. With these provisos in mind, the results of the analysis are presented in Table 3. The volumes of sediment trapped in the stock pond during 2001 and 2002 imply mean annual particle travel distances of 401 and 734 m respectively. The corresponding virtual velocities are 370 m h^{-1} for 2001 and 282 m h^{-1} for 2002. These

Table 3
Estimates of annual particle travel distances ($L=V_p(1-p_{po})/(\overline{zs}.w(1-p_{ch}))$ and virtual velocities ($U=L/T$) for the lower portion of the main-channel

	2001	2002
Volume of sediment trapped in stock pond, V_p, m^3	113.8	436.6
Mean depth of scour, $\overline{zs}$, m	0.071	0.192
Particle travel distance, L, m	401	734
Duration of competent flow, T, min	65	156
Virtual velocity, U, m h^{-1}	370	282

The calculation of L assumes that there is no movement of the channel sediments into or out of storage and that the average depths of scour recorded in the main-channel study reach are representative of the lower portion of the main-channel. Actual travel distances and virtual velocities are likely to be somewhat lower than those calculated because some of the material deposited in the stock pond will have been derived from tributary and hillslope inputs (Fig. 1).

travel distances and virtual velocities are for sand moving over sand. Leopold et al. (1966) report similar travel distances for gravel moving over sand in the ephemeral arroyos of New Mexico. Although their data do not allow the calculation of virtual velocities, it is likely that they are comparable to those calculated in this study. Rates of particle travel for sand and gravel moving over sand appear to be two-three orders of magnitude higher than those recorded for gravel moving over gravel at comparable flow strengths (Hassan et al., 1992).

5. Conclusions

The dynamics of bed material transfers in three headwater channels of a dryland river catchment subject to flash flooding have been examined. In each channel, dense arrays of scour chains were used to derive spatially distributed information on volumes of stream-bed scour, fill and net changes in sediment storage for a range of competent flows. The results demonstrate that sediment transfers through the reaches were accompanied by complex patterns of compensating scour and fill which maintained the channels in approximate steady state. As suggested by Butcher and Thornes (1978), sediment storage did not appear to be a significant control on sediment transfers. The efficiency by which fluvial processes delivered sediment through these dryland headwater channels is in marked contrast to the dynamics of sediment transfers in humid-temperate upland environments which are dominated by sediment storage processes (e.g. Benda et al., 2005). Much of the variability in the magnitude of stream-bed scour generated by individual flow events can be explained by the magnitude of the floods (cf. Lekach and Schick, 1983). Estimates of total volumetric scour per unit bed area for the three channels correlate strongly with values of peak unit stream power and the resultant trend is described well by a simple power law function. Accounting for the complex patterns of compensating scour and fill within the reaches is more difficult without more detailed hydraulic information. They may, however, reflect spatial and temporal variations in bed shear stress arising from the growth and decay of secondary flows during the passage of flood flows. This study also highlights the ability of scour chains to document sediment transfers that do not result in morphological change over the time of survey. As such, scour chains may provide a methodological basis for the application of morphological approaches to investigating sediment transport (e.g. Ashmore and Church, 1998; Haschenburger and Church, 1998) in dryland channels characterised by compensating scour and fill during individual events. These approaches have yet to be applied in dryland settings despite their ability to document spatial and temporal variations in erosion and deposition and to overcome many of the problems associated with deploying conventional techniques for measuring sediment transport in these environments (Laronne et al., 1992).

Notation

a (b)	Length of scour chain above elbow (exposed on bed surface), m
g	Acceleration due to gravity, m s^{-2}
L	Sediment transfer distance, m
n	Manning's n
p_{po} (p_{ch})	Mean porosity of stock pond (channel) sediments
Q Q_{p}	Discharge (peak discharge), m^3 s^{-1}
R_{h}	Autocorrelation coefficient at lag h
S	Reach-average bed slope, m m^{-1}
T	Duration of competent flow, min
U	Virtual rate of travel, m h^{-1}
V_{p}	Volume of sediment trapped in stock pond, m^3
V_i, V_r, V_t	Volume of scour or fill for the ith cross section, rth event and all events in a reach, m^3
V_{ki}	Volume of scour (or fill) at the ith cross section calculated using k chains along the section, m^3
Vn_i, Vn_r, Vn_t	Net volume change for the ith cross section, rth event and all events in a reach, m^3
Vf_i (Vs_i)	Volume of fill (scour) for the ith cross section, m^3
Vf_r (Vs_r)	Volume of fill (scour) for the rth event, m^3
Vf_t (Vs_t)	Total volume of fill (scour) for all events in a reach, m^3
$\hat{Vs}_r$	Volumetric scour per unit bed area, m^3 m^{-2}
$\tilde{V}_x$	xth random volume estimate of scour (or fill), m^3
$\bar{\bar{V}}$	Mean random volume estimate of scour or fill, m^3
$\langle Vn_r \rangle$	Vn_r as a percentage of Vs_r, %
w	Channel width, m
x_j	Cross-stream distance of the jth prism, m
y_i	Downstream length of the prisms at the ith cross section, m
Y_{p}	Peak flow depth, m
z_{b}	Mean bed elevation change, m
zf (zs)	Depth of fill (scour), m
$\overline{\mathrm{zs}}$	Mean depth of scour, m
$\bar{z}_j$	Mean depth of scour or fill of the jth prism
∂a (∂b)	Error in a (b), m
$\partial V_i'$, $\partial V_r'$, $\partial V_t'$	Uncertainties in V_i, V_r and V_t due to measurement error, m^3
$\partial Vf_i'$, $\partial Vs_i'$	Uncertainties in Vf_i and Vs_i due to measurement error, m^3
$\partial Vn_i'$, $\partial Vn_r'$, $\partial Vn_t'$	Uncertainties in Vn_i, Vn_r and Vn_t due to measurement error, m^3
$\partial V_r''$, $\partial V_t''$	Uncertainties in V_r and V_t due to cross section location, m^3

$\partial Vn_r''$, $\partial Vn_t''$ Uncertainties in Vn_r and Vn_t due to cross section location, m^3
$\partial V_i'''$, $\partial V_r'''$, $\partial V_t'''$ Uncertainties in V_i, V_r and V_t due to cross-stream sampling strategy, m^3
$\partial Vn_i'''$, $\partial Vn_r'''$, $\partial Vn_t'''$ Uncertainties in Vn_i, Vn_r and Vn_t due to cross-stream sampling strategy, m^3
∂x, ∂y, $\partial \bar{z}$ Error in x_j, y_i and $\bar{z}_f$, m
ΔV_r, ΔVn_r Total error associated with V_r and Vn_r, m^3
ΔV_t, ΔVn_t Total error associated with V_t and Vn_t, m^3
ε ($\hat{\varepsilon}$) Root mean square error (relative root mean square error)
γ_h Semi-variance at lag h, cm^2
ρ Density of flow, kg m^{-3}
ω_p Peak unit stream power, W m^{-2}

Acknowledgements

This research has been funded by the Natural Environment Research Council (Grant GR3/12754). We thank the ARS for access to their field site and facilities, Burt Devere for permission to conduct our experiments on his ranch, Art Dolphin, Howard Larsen, John Smith and Jim Smith for their invaluable support and assistance throughout and the many field assistants who aided with the data collection.We are grateful to Rob Ferguson, Kirk Vincent and three anonymous reviewers for their helpful comments on this manuscript.

References

Abrahams, A.D., 1972. Drainage densities and sediment yields in eastern Australia. Australian Geographical Studies 10, 19–41.
Andrews, E.D., 1979. Scour and fill in a stream channel, East Fork River, western Wyoming. United States Geological Survey Professional Paper, vol. 1117.
Arcement, G.J., Schneider, V.R., 1989. Guide for selecting Manning's roughness coefficients for natural channels and flood plains. United States Geological Survey Water-supply Paper, vol. 2339.
Ashmore, P.E., Church, M.A., 1998. Sediment transport and river morphology: a paradigm for study. In: Klingeman, P.C., Beschta, R.L., Komar, P.D., Bradley, J.B. (Eds.), Gravel-Bed Rivers in the Environment. Water Resources Publications, Colorado, USA, pp. 115–148.
Beers, Y., 1957. Introduction to the theory of error. Addison Wesley, Reading.
Benda, L., Hassan, M.W., Church, M., May, C.L., 2005. Geomorphology of steepland headwaters: the transition from hillslopes to channels. Journal of the North American Water Resources Association 41, 835–851.
Butcher, G.C., Thornes, J.B., 1978. Spatial variability in runoff processes in an ephemeral channel. Zeitschrift für Geomorphologie, Supplementband 29, 83–92.
Carling, P., 1987. Bed stability in gravel streams, with reference to stream regulation and ecology. In: Richards, K.S. (Ed.), River Channels: Environment and Process, vol. 17. Institute of British Geographers, Special Publication Series, Oxford.
Colby, B.R., 1964. Scour and fill in sand-bed streams. United States Geological Survey Professional Paper, vol. 462-D.
Cowan, W.L., 1956. Estimating hydraulic roughness coefficients. Agricultural Engineering 37, 473–475.
Einstein, H.A., 1937. Bedload transport as a probability problem. PhD thesis, translated by W.W. Sayre in Shen, W.W. (Ed), 1972, Sedimentation. Colorado State University, Appendix |C.
Gellis, A.C., Emmett, W.W., Leopold, L.B., 2005. Channel and hillslope processes revisited in the Arroyo de los Frijoles watershed near Santa Fe, New Mexico. United States Geological Survey Professional Paper, vol. 1704.
Gregory, K.J., Gardiner, V.G., 1975. Drainage density and climate. Zeitschrift für Geomorphologie 19, 287–298.
Ham, D.G, Church, M., 2000. Bed material transport estimated from channel morphodynamics: Chilliwack River, British Columbia. Earth Surface Processes and Landforms 25, 1123–1142.
Haschenburger, J., 1999. A probability model of scour and fill depths in gravel-bed channels. Water Resources Research 35, 2587–2869.
Haschenburger, J., Church, M., 1998. Bed material transport estimated from the virtual velocity of sediment. Earth Surface Processes and Landforms 23, 791–808.
Hassan, M.A., 1990. Scour, fill and burial depth of coarse bed material in gravel-bed streams. Earth Surface Processes and Landforms 15, 341–356.
Hassan, M.A., Church, M., Ashworth, P.J., 1992. Virtual rate and mean distance of travel of individual clasts in gravel-bed channels. Earth Surface Processes and Landforms 17, 617–627.
Lane, E.W., Hernandez, M., Nichols, M., 1997. Processes controlling sediment yield from watersheds as functions of spatial scale. Environmental Modelling & Software 12, 355–369.
Laronne, J.B., Reid, I., Yitshak, Y., Frostick, L., 1992. Recording bedload discharge in a semiarid channel, Nahal Yatir, Israel. In: Bogen, J., Walling, D.E., Day, T.J. (Eds.), Erosion and Sediment Transport Monitoring Programmes in River Basins, vol. 210. International Association of Hydrological Sciences, Publication, Oslo, Norway, pp. 79–96.
Laronne, J.B., Outhet, D.N., Carling, P.A., McCabe, T.J., 1994. Scour chain deployment in gravel-bed rivers. Catena 22, 299–306.
Lekach, J., Schick, A.P., 1983. Evidence for transport of bedload in waves: analysis of fluvial sediment samples in a small upland stream channel. Catena 10, 267–279.
Leopold, L.B., Maddock, T., 1953. The hydraulic geometry of stream channels and some physiographic implications. United States Geological Survey Professional Paper, vol. 252.
Leopold, L.B., Emmett, W.W., Myrick, R.M., 1966. Channel and hillslope processes in a semi-arid area, New Mexico. United States Geological Survey Professional Paper, vol. 352.
Martin, Y., Church, M., 1995. Bed material transport estimated from channel surveys: Vedder River, British Columbia. Earth Surface Processes and Landforms 20, 347–361.
Nichols, M.H., 2006. Measured sediment yield rates from semiarid rangeland watersheds. Rangeland Ecology and Management 59, 55–62.
O'Day, C.M., Phillips, V.J., 2000. Computed roughness coefficients for Skunk Creek above Interstate 17, Maricopa County, Arizona. United States Geological Survey, Water-Resources Investigations Report 99-4248.
Osborn, H.B., Renard, K.G., 1988. Rainfall intensities for southeastern Arizona. Journal of Irrigation and Drainage Engineering 114, 195–199.

Phillips, J.V., Ingersoll, T.L., 1998. Verification of roughness coefficients for selected natural and constructed stream channels in Arizona. United States Geological Society of America, Professional Paper, vol. 1584.

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

Powell, D.M., Brazier, R., Wainwright, J., Parsons, A., Nichols, M., 2006. Spatial patterns of scour and fill in dryland sand bed streams. Water Resources Research 42, W08412, doi:10.1029/2005WR004516.

Rhoads, B.L., Welford, M.R., 1991. Initiation of river meandering. Progress in Physical Geography 15, 127–156.

Richards, K.S., 1993. Sediment delivery and the drainage network. In: Beven, K., Kirkby, M.J. (Eds.), Channel Network Hydrology. Wiley, Chichester, pp. 221–254.

Thornes, J.B., 1994. Channel processes, evolution and history. In: Abrahams, A.D., Parsons, A.J. (Eds.), Geomorphology of Desert Environments. Chapman and Hall, London, pp. 288–317.

Tillery, A.C., Phillips, J.V., Capesius, J.P., 2001. Potential errors associated with stage-discharge relations for selected streamflow-gaging stations, Maricopa County, Arizona. United States Geological Society, Water Resources Investigations Report 00-4224.