Catena 81 (2010) 126–136

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Coarse bed material patch evolution in low-order, ephemeral channels

Brendan Yuill [a,*], Mary Nichols [b], Elowyn Yager [c]

[a] Pontchartrain Institute for Environmental Science, University of New Orleans, New Orleans, LA, 70148, United States
[b] USDA-ARS SWRC, Tucson, AZ, 85719, United states
[c] Department of Civil Engineering, Center for Ecohydraulics Research, University of Idaho, Boise, ID, 83702, United States

ARTICLE INFO

Article history:
Received 26 May 2009
Received in revised form 17 February 2010
Accepted 18 February 2010

Keywords:
Channel bed stability
Sediment transport
Ephemeral flow
Semiarid
Fluvial geomorphology

ABSTRACT

In river channel beds composed of a wide range of grain sizes, the bed material is often arranged in discrete patches discernable by relative texture. These bed material patches are the primary source of entrainable coarse sediment within the channel system and their composition and size have been found to influence the composition and rate of sediment transport. Twelve coarse (gravel–cobble) sediment patches distributed throughout the channel network within a 4.53 ha watershed in southeastern Arizona were monitored for 2 years. Changes in patch area and grain size were measured and painted patch grains were monitored to confirm that patch grains were mobilized during flow. Individual coarse bed material patches exhibited variable persistence during flows with return frequencies ranging from approximately 1 year to 4.6 years. While no patch fully dispersed during the study period, two new patches formed. Most coarse patches remained relatively stable in area and grain-size distribution despite the entrainment of patch grains as lost grains were sufficiently replaced with sediment from upstream. Because of the grain replacement process and the effect of other sediment supply dynamics, the changes in patch area and grain-size distribution display a complex relationship with the magnitude of predicted grain mobilization within each patch. Results indicate that relative stability varies from patch to patch, influenced by the balance of patch grains transported out of the patch and the deposition of new grains into the patch. Predictive models of coarse sediment transport and yield that assume the channel bed is a fixed source of sediment supply may not adequately capture the sediment dynamics within patchy channel beds and should be used with caution when applied to these environments due to the possibility of patch instability as documented in this study.

1. Introduction

In semiarid watersheds characterized by intense yet infrequent and short duration flows, the channel bed material is the primary source of the coarse fraction of the transported sediment (defined as material larger than sand) for any individual flow event (Lisle, 1995; Garcia et al., 1999). Because of this, the amount and grain-size distribution (GSD) of the bed sediment will directly influence the magnitude of the watershed's coarse sediment yield at the flow event timescale (Lisle and Hilton, 1999; Laronne et al., 2000; Habersack and Laronne, 2001; Oldmeadow and Church, 2006). The amount of coarse grains, relative to the amount of finer grains, permanently immobile grains (i.e., large cobbles, boulders), or exposed bedrock within the channel bed dictates how much coarse material is available for entrainment during individual flow events. Over longer time periods, coarse grains are supplied to the channel bed as the channel network incises or from the periodic mass movement of sediment stored in the channel banks or adjacent hillslopes through ravel, landslides, or debris flows. An increase in the amount of coarse sediment available for entrainment will typically increase the local coarse sediment transport rates during competent discharges as well as increase the watershed's coarse sediment yield over time. Further, the GSD of the bed material influences the size of the fraction of bed material that is capable of being entrained and transported during any given flow event (Lisle and Hilton, 1999; Laronne et al., 2000; Church and Hassan, 2002). Under typical flow regimes, smaller grains are more readily entrained by flow than larger grains due to relative differences in weight (Andrews, 1983; Parker and Sutherland, 1990; Church and Hassan, 1992). Past studies of sediment transport (e.g., Parker et al, 1982; Powell et al., 2001) have shown that size-selective entrainment and transport may break down at very high bed stresses (such as twice that required to entrain the median grain size within the channel bed), creating a condition of ‘equal mobility’. During equal mobility, all grain sizes are transported in proportion to their relative abundance within the channel bed irrespective of their relative weight. However, because smaller grains are more readily entrained than larger grains for the most frequent discharges, channel beds composed of smaller grains produce higher transport rates than those composed of relatively larger grains when other affecting parameters are held constant (Paola and Seal, 1995). Therefore, any changes in the

* Corresponding author.
E-mail address: byuill@uno.edu (B. Yuill).

0341-8162/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.catena.2010.02.002

amount or GSD of the bed material will impact the amount and GSD of the bed load transport. Any attempt to fully understand and accurately predict coarse sediment transport and yield during individual flow events requires an understanding of the abundance, texture, and arrangement of the channel bed material upstream within the watershed.

Past studies have found that the amount and grain-size distribution of the bed material within a watershed are controlled by many lithologic, tectonic, and climatic factors (Benda and Dunne, 1997; Sutherland et al., 2002; Bravo-Espinosa et al., 2003). However, over short time periods, the transport and storage of sediment within the channel bed may become a simple function of the upstream sediment supply and the hydraulic ability of the flow regime to entrain and sort sediment within the channel (Kirchner et al., 1990; Dietrich et al., 2005; Hassan et al., 2006). The ability of the flow regime to transport sediment is primarily controlled by the boundary shear stress produced by the flowing water and the local channel morphology. Our understanding of the relationships between sediment supply, flow hydraulics, and the channel bed has been advanced by numerous research studies conducted in both natural channels (e.g., Laronne and Carson, 1976; Lisle and Madej, 1992; Buffington and Montgomery, 1999a; Garcia et al., 1999; Lisle and Hilton, 1999; Wilcock and DeTemple, 2005; Clayton and Pitlick, 2007) and in laboratories (e.g., Dietrich et al., 1989; Paola et al., 1992; Lisle et al., 1993; Nelson et al., 2009). However, the majority of field-based sediment transport studies that specifically examine complex bed dynamics, such as sediment sorting, have taken place in perennial gravel-bed channels where bed material is stable for common, high frequency discharges (Powell, 1998; Parker, 2007). Similarly, laboratory studies of channel bed dynamics predominately use steady or uniformly changing sediment feeds of a singular grain-size distribution, which reproduces the effect of a stable channel bed up-stream (e.g., Paola et al., 1992; Hassan et al., 2006; Nelson et al., 2009). Less attention has been paid to low-ordered, ephemeral watersheds in which the flow discharge and the channel bed material are highly dynamic in time and space and more difficult to simplify.

This paper documents the evolution of coarse bed material in Lucky Hills, a low-ordered, ephemeral watershed in southeast Arizona. The bed material is arranged in discrete patches that are differentiated from one another by their grain-size distributions. Past informal observations of the coarse bed material patches show that the patches appear to change in size, location, and grain size through time. Because these patches are the primary source of coarse material transported during any flow event, a complete understanding of coarse sediment transport will likely require knowledge of their behavior in time (Garcia et al., 1999; Dietrich et al., 2005). Measurements of patch size (patch surface area) and composition (GSD) are recorded for a sample of coarse material patches throughout the study period, 2005–2006. The variability of patch size and GSD through time is used as a gauge of patch stability. These measures of patch stability are then correlated to values of predicted grain mobility. Grain mobility is predicted by calculating the local cross section-averaged fluid stress borne by the patch grains during each flow event. If a patch remains stable in size and GSD while experiencing significant grain motion, the sediment supply, in terms of the amount and grain-size, to the patch balances the sediment transported out of the patch. If a patch is unstable while experiencing grain motion the sediment supply to the patch is not well balanced with the amount or caliber of that transported out of the patch. If a patch is unstable while its grains lie immobile to flow, the observed patch change must be due to exogenous processes such as the transport dynamics of the finer bed material surrounding the patch.

Knowing the approximate cause of patch instability, if it exists, enhances our understanding of the dynamics of the channel bed and its likely influence on the coarse sediment yield. Stable patches serve as a consistent source of coarse material that may contribute to future sediment yields (Mueller et al., 2008). A pattern of patch instability and evolution within a channel reach indicates a dynamic sediment source that will likely produce considerable variations in sediment yield downstream. Further, it is important to test the assumption that sources of coarse material within the channel bed are predominately stable, explicit in many predictive models of coarse material transport (e.g., Bagnold, 1980; Parker, 1990; Wilcock and Crowe, 2003). Violations of this assumption may lead to inaccurate estimations of sedimentation and inefficient sediment management (Wyzga, 2001).

The objectives of this research are to (1) determine if the areas and grain-size distributions of a sample of coarse patches remain stable following successive flow events and (2) examine the relationship between changes in patch area and GSD, if present, and values of estimated patch grain mobility.

2. Methods

2.1. Field area

Lucky Hills 104 is a 4.53 ha (45,300 m^2) nested, sub-watershed within the Walnut Gulch Experimental Watershed (http://tucson.ars.ag.gov; Renard et al., 2008) located in southeast Arizona. It is situated in the semiarid, basin and range province and is characterized as shrubland, consisting primarily of drought resistant vegetation, including creosote bush (*Larrea tridentata* [DC.] Cov.), whitethorn acacia (*Acacia constricta* Benth.), and tarbush (*Flourensia cernua* DC.). The average temperature ranges seasonally from 22 °C in January to 33 °C in July. The mean annual precipitation is approximately 294 mm, with the majority occurring during the summer monsoon season (July–September) (Goodrich et al., 2008).

Lucky Hills is a headwater watershed so its hillslopes and channel bed are the source of the vast majority of the fluvial sediment transport. The local drainage network is incising into a Holocene alluvial veneer covering the Whetstone Pediment, a gentle transport slope composed of Gleeson Road Conglomerate underlying much of north-central Walnut Gulch (Gilluly, 1956; Osterkamp, 2008). The Gleeson Road Conglomerate is a poorly to well cemented basin fill of Plio–Pleistocene plutonic or volcanic clasts approaching 900 m in thickness near the Lucky Hills region. Surficial sediments were likely weathered from the granitic Dragoon Mountains located approximately 15 km to the east. Lucky Hill's soil is uniformly mapped as Luckyhills–McNeal Sandy Loam. The hillslopes are covered in a well-developed erosional pavement of rock fragments that average 16 to 32 mm in diameter, covering a finer substrate with a mean diameter of approximately 3 mm (Canfield et al., 2001). The size of the surface rock fragments increase with hillslope gradient, which averages 11% but increases up to 30% near the channel banks.

The channel network within Lucky Hills 104 lies primarily downstream of two internal flumes, Flume 102 (F102) and Flume 106 (F106), and upstream of Flume 104 (F104) at the watershed outlet (Fig. 1). Upstream of F106 and F102, channelized runoff occurs in rills with unstable channel dimensions and orientation. The channel width downstream of the internal flumes ranges from 0.5 to 2.0 m. The gradient of the channel banks measured normal to the direction of stream flow ranges from approximately 20% to near vertical for short reaches. The mean longitudinal slope of the channel network is 0.027 m m^{-1}. The bed material is not uniform but arranged in visually-discernable, textural patches throughout the channel network. The area and grain-size distribution of these patches vary considerably. Patch area varies from fractions of a square meter to tens of square meters while the median grain sizes ranges from sand to coarse gravel. There are no consistent, channel-wide textural differences between the surficial bed material and subsurface material (Yuill, 2009) which is consistent with observations in other ephemeral channels that lack the armoring processes common to perennial flow regimes (Laronne et al., 1994).

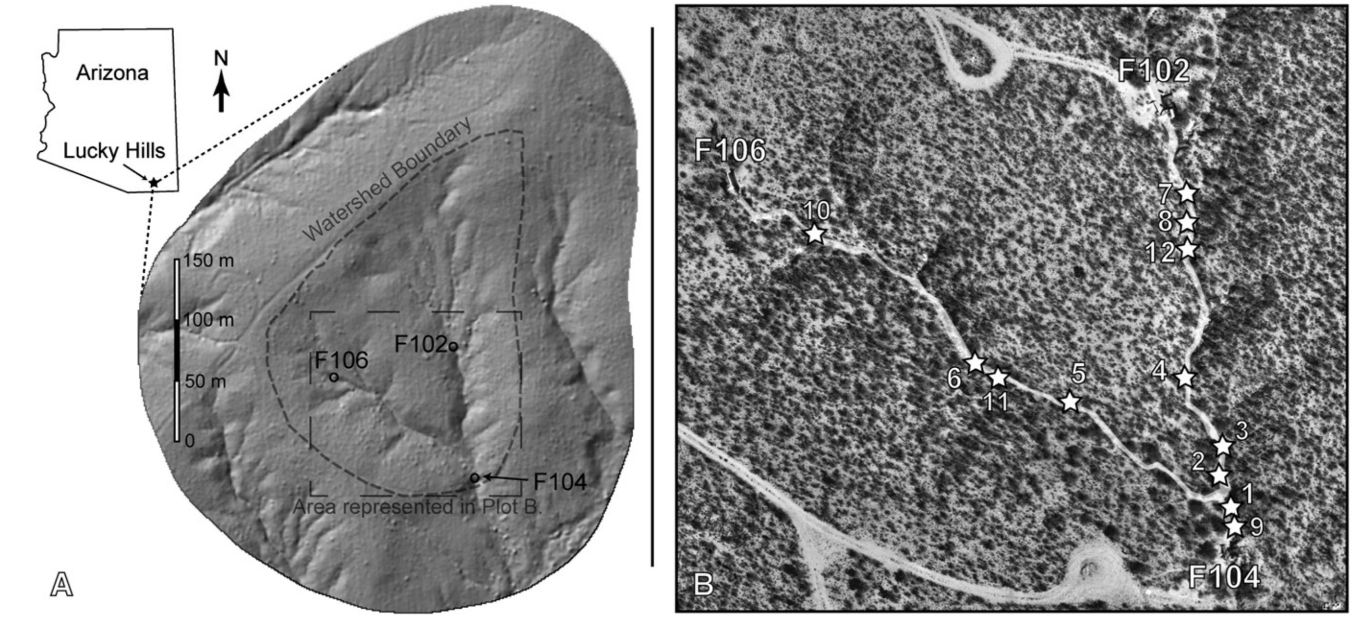

Fig. 1. (A) One meter resolution hillshade map of Lucky Hills 104 and (B) an orthophoto of the channel network showing the locations of the 12 sampled coarse material patches and flumes.

Approximately 5–10% of the channel bed surface is predominately composed of coarse sediments (i.e., greater than 8.0 mm in diameter) arranged in relatively coarse textural patches. These coarse material patches contain the majority of grains that compose the coarse fraction of the mean channel bed GSD. Fig. 2 illustrates the difference between the mean GSD for the coarse material patches and that for the channel as a whole. Despite their large sizes (diameters may exceed 64 mm), observations of sediment transport at the watershed outlet indicate most coarse grains are susceptible to mobilization during regularly occurring flow events (i.e., 1.3 year return interval flow magnitudes) (Yuill, 2009).

Cattle grazing has been a historical land use within areas of Walnut Gulch for over a century; however, the Lucky Hills watershed has been fenced since 1963 and access is restricted to research personnel, protecting it from the effects of cattle and unintended anthropogenic manipulation (Osborn and Simanton, 1983).

2.2. Flow measurement

Channelized runoff was measured at the watershed outlet using a pre-calibrated, Santa-Rita type supercritical flume (referred to as Flume 104 or F104) (Renard et al., 1986; Nichols et al., 2008). The USDA maintains an online database (http://www.tucson.ars.ag.gov/dap/) that includes flow and sediment measurements recorded at Flume 104. Over 30 years of data were used to calculate return intervals and flood frequency distributions. Local flow discharge was estimated at each patch location by scaling the discharge values computed at F104 by the ratio of the drainage area at the patch to that at F104. Drainage areas at each of the patch locations were computed using the Spatial Analyst toolkit in ArcGIS (http://www.esri.com) and a 1.0 m resolution digital elevation model (DEM) of the field site. Hydraulic parameters (mean flow velocity, flow depth, wetted width, and boundary shear stress) were calculated using the estimated discharge and the resistance equation of Hey (1979). This resistance equation was selected because the required input parameters of bed texture (D_{84}, i.e., the grain size for which 84% of the GSD is finer) and channel geometry were known at each patch location and because of its applicability to steep, low-order channels.

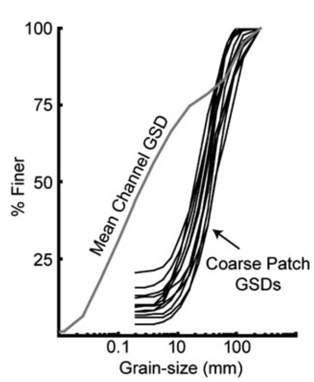

Fig. 2. The temporally averaged grain-size distributions (GSD) for the 12 coarse material patches and the spatially averaged GSD for the full channel bed.

2.3. Channel and bed material measurement

Bed texture was measured using a combination of bulk sampling and photo-sieving methods (further described in Section 2.4). A topographic survey of channel dimensions was conducted using a real time kinetic (RTK) global positioning system (GPS) before the first flow season in June 2005 and after the study's conclusion in spring 2007.

To calculate a mean channel GSD (as shown in Fig. 2), 12 bulk samples were taken from the channel bed at monumented cross sections distributed along the channel network and were combined to form a single aggregate sample. The size of each individual bulk sample was minimized to reduce the disturbance to the natural arrangement of bed material. Samples were collected to depths up to 0.2 m. The bulk sample was sieved and weighed to compute a representative GSD. The composite bulk sample size (~36 kg) was below that recommended by Church et al. (1987) to ensure an unbiased estimated GSD value but it was approximate to the 'practical' sample size recommended by Wentworth (1926) [32 kg]. Church et al. (1987) show that sample sizes below their recommend values may underestimate the presence of the coarsest grains (i.e., large gravels, cobbles).

The channel bed between F102, F106, and the watershed outlet at F104 was measured after 8 flow events as well as before the initial flow of 2005 (referred to as 'Time Zero') using digital photography. A high resolution digital camera was secured to a modified survey rod at a fixed height (2.5 m) and aimed directly downward by referencing an attached bubble-level. Each photograph had approximately the same spatial scale (calibrated to 1 pixel $= \sim 1.0\ mm^2$), with scale distortion increasing around the photograph edges and in areas recording sharp gradients in topographic relief. Photographs were taken at 1.0 m intervals, proceeding along the longitudinal axis of each channel. The area covered in each photograph (2.0 m by 2.5 m) was generally large enough to include the full width of the channel in addition to 0.5 m of bank width on each side and 0.4 m of overlap with the preceding and succeeding photographs. Analysis of the overlapping area was used to detect and quantify edge distortions present in the images. When possible, measurements were taken in the center of a photograph rather than near the edge where distortions were greatest. The individual photographs were digitally spliced together to create comprehensive bed material maps of the channel system (Fig. 3).

2.4. Patch measurement

The composite bed material maps were generated for nine different time periods to document changes in the arrangement and composition of bed material over time. Bed material patches were visually delineated in each bed material map. Patch boundaries ranged from easily discernable, discrete edges to gradual transitions. The coarse patches had visually apparent boundaries and were initially differentiated from finer textured patches using the topology defined in Buffington and Montgomery (1999b). Their topology classifies patches by the relative ratio of sand, gravel, and cobbles and then further differentiates them by the relative texture of the primary component (i.e., predominately sand patches may be further differentiated as coarse or very-coarse sand). It should be noted that this patch delineation process is subjective. During this study, multiple trials of patch delineation at a completely stable location produced variations in patch area of up to 10% of the mean.

Twelve coarse material patches (with a median grain size in the coarse gravel range, 16–63 mm) were selected for measurement of area and GSD. The patch locations within the watershed are illustrated in Fig. 1. Eight of the 12 patches were selected at random from 51 coarse patches identified from the bed material map taken at Time Zero. The remaining 4 patches were selected based on their inclusion into a related experiment (described in Section 2.7).

Patch area and GSD were calculated for each of the 12 patches at Time Zero and after each flow event. Patch area was measured using the Matlab Image Processing Toolbox (http://www.mathworks.com/) by calculating the area of the approximate polygon representing the patch within each bed material map.

Patch GSD was estimated using a "photo-sieving" methodology similar to that used in other studies of bed material (e.g., Garcia et al., 1999; Graham et al., 2005; Oldmeadow and Church, 2006). Grains were selected for sampling by overlaying a virtual grid over the digital image of the patch. Grains located at the intersection of each grid line were selected for measurement. The total grid area was scaled to sample at least 100 patch grains evenly distributed throughout the patch area. It was necessary to create samples of less than 100 grains in the case of very small ($<0.25\ m^2$), coarse patches. The exposed intermediate axis of each sampled grain was measured using commercial digital image processing software (Adobe Photoshop, http://www.adobe.com/). From these measurements, grain-size distributions were computed by binning measurements at half-phi intervals. Measurements of grains less than 2.0 mm (the largest resolvable grain size using this instrumentation) were truncated into a single bin. Photo-sieving is well established in published literature and its associated errors are understood. These errors result from the measurement of a three dimensional object in two dimensions (Kondolf et al., 2003). The errors associated with the method are that: 1) the measured axis may not be the intermediate axis as intended and 2) the full surface area of the grain may not be exposed in the image because the edges of the grain may be buried or hidden by other grains (Bunte and Abt, 2001; Kondolf et al., 2003; Graham et al., 2005). These errors should occur systematically in each computed GSD and will not significantly impact the results of this study because measured values are only contrasted against other values calculated using the same method. Calibration tests of this measurement method found that scale distortion could cause measurement error of up to 10% of the observed value for typical grain sizes. Photographs with identified distortions from instrument and user error were not used in the calculations.

This method of photogrammetry used to calculate the change in patch area does not distinguish between change by grain erosion or aggradation and by grain burial or excavation (unburial) at the patch margins. These processes would appear the same to overhead photographic representation.

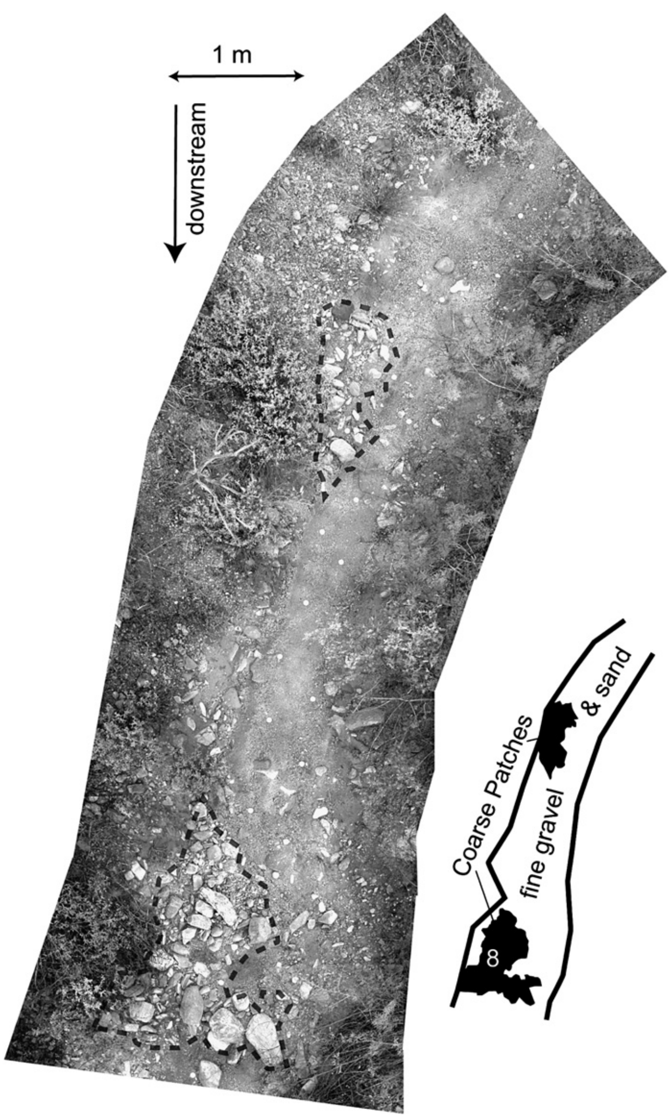

Fig. 3. A sample bed material map containing coarse patches (shown is Patch 8).

2.5. Estimation of patch material mobility

To estimate the relative mobility of patch grains during each flow event, the ratio of dimensionless boundary shear stress (τ^*) and the critical Shields stress (τ^*_c) was calculated for the median grain size of the patch (D_{50}). Dimensionless boundary shear stress is the ratio of the boundary shear stress (τ) to the submerged weight per unit length of the grain:

$$\tau^* = \frac{\tau}{(\rho_s - \rho)gD}$$

where ρ_s is the density of a sediment grain (~2560 kg m^{-3}), ρ is the density of water (~1000 kg m^{-3}), g is gravitational acceleration (~9.81 m s^{-2}), and D is the intermediate diameter of the grain. Boundary shear stress is approximated as $\tau = \rho gRS$, where R is the hydraulic radius and S is the longitudinal slope at each patch location. This derivation of boundary shear stress is an approximation of the fluid stress borne by the bed grains averaged over the wetted channel cross section containing each patch and while commonly employed in geomorphic study (e.g., Batalla and Martin-Vide, 2001; Habersack and Laronne, 2001; Tucker et al., 2006; Powell et al., 2007), it uses assumptions (steady, uniform flow) that are often violated in natural flows. The critical Shields stress value is the dimensionless boundary shear stress required to initiate motion of the median patch grain size (unless another grain-size is explicitly stated) and is assumed to be 0.03 for this study. This value is on the low end of the range of published values (Buffington and Montgomery, 1997) and reflects study results from Lucky Hills that show large grain sizes are often transported at relatively small flow discharges (Yuill, 2009).

The τ^*/τ_c^* value is a dimensionless metric of the transport competence of the flow for a specific grain-size class. Using the assumptions of previous bed material mobility research (e.g., Wilcock and McArdell, 1997; Lisle et al., 2000), grain sizes in flow with τ^*/τ_c^* values less than 1 are assumed predominately immobile, grain sizes with τ^*/τ_c^* values between 1 and 2 are partially mobile, and grain sizes with τ^*/τ_c^* values greater than 2 are fully mobile. Past studies (e.g., Hassan and Reid, 1990; Church et al., 1998; Oldmeadow and Church, 2006) have found that coarse bed material can resist mobilization beyond τ^*/τ_c^* values exceeding 1 if bed grains evolve into bed forms with tightly inter-locked geometric arrangements (i.e., pebble-clusters, stone cells). These bed forms have only been observed in coarser, gravel channels and further analysis is required to determine if they influence bed mobility sand–gravel channels.

Research on natural gravel channel beds (rivers with bed material primarily composed of gravel sediment mixtures, similar to the GSD of the coarse material patches) has shown that general bed material movement begins at boundary shear stresses values similar to those that move the D_{50}, despite the fact that larger grains within the sediment mixture weigh more than smaller grains (Parker and Klingeman, 1982; Parker et al., 1982). Coarser grains gain relative mobility compared to finer grains because they protrude away from the bed into swifter flow whereas the finer grains lose relative mobility because they are 'hidden' in the wake of larger grains immediately upstream (Parker and Klingeman, 1982; Parker, 2007). These 'hiding' effects combine to off-set the increased relative mobility of the finer grains due to their low weight, making the critical shear stress required for incipient motion more uniform (near that for the D_{50}) for each grain-size fraction. The actual extent to which the hiding effects reduce grain-size dependent transport has been shown to vary by fluvial system (Parker, 2007). This study assumes when τ^*/τ_c^* (as computed for the patch D_{50}) is less than 1.0, the majority of patch grains (irrespective of the specific patch GSD) are predicted to be immobile and when τ^*/τ_c^* is greater than 1.0, the majority of patch grains are predicted to be mobile. For the purposes of this text when a τ^*/τ_c^* value is reported, it refers to the peak τ^*/τ_c^* value for the patch D_{50} during the flow event unless otherwise noted.

2.6. Metrics for evaluating change in patch location

The changes in the longitudinal position of the coarse bed material patches were approximated before and after each flow event by calculating the longitudinal displacement of each patch's centroid. The location of the patch centroid was estimated using a Matlab algorithm that calculates the center of mass for the area of each patch as a *x,y* position on an arbitrary Euclidian grid assigned to each bed map with pixel units. In order to measure the displacement of the present location of a centroid as compared to its previous or future location, each location required geo-referencing. This was done by recording the relative distance of each centroid to not less than four immobile objects that are observable in each time series of bed maps (e.g., markings on immobile boulders, embedded rebar). The change in longitudinal position of a centroid was calculated by measuring the distance between a centroid position before and after a flow using image processing software (Adobe Photoshop). The total distance was partitioned into longitudinal and lateral (normal to the longitudinal direction) distances and the longitudinal distance was recorded. Multiple calibration tests of this method (over distances spanning 0.25 to 1.25 m) produced a mean error of 4% of the longitudinal distance and a maximum error near 8%.

2.7. Measuring grain replacement in patches

To quantify the fraction of the patch area composed of newly deposited coarse material, patch grains were painted for 4 coarse patches located near the watershed outlet before the onset of the 2006 flow season. During the patch area calculation procedure described in Section 2.4, the patch area composed of painted grains was visually delineated from the bed maps and was measured in the same manner as the total patch area. The area of the coarse patch composed of unpainted grains was assumed to be material deposited during flows after the date of painting. The patch grains were painted in-situ, leaving their unexposed surfaces unpainted. If the painted patch grains were rearranged within the patch area during a flow event leaving the painted surface obscured to surface observation (i.e., flipped up-side-down or buried) or if the paint was removed, the grains would have been susceptible to be erroneously classified as newly deposited material. This procedure is based on similar research described in Dietrich et al. (2005).

3. Results

3.1. General observations

Lucky Hills 104 experienced 10 flow events during the two years (2005 and 2006) of observation. Bed material was measured after 8 flow events. The bed material was not recorded after two flow events because there was not enough time to travel to the field site and take measurements between the end of the flow and the start of the following flow. For this study, the hydrologic values of the events for which no bed measurements were taken were summed with the following event's values (i.e., the flow volumes and duration of the unmeasured event and the following measured event were combined into an aggregate value). Topographical surveys completed before and after the study period show that the channel morphology remained relatively unchanged. Some sandy areas within the channel bed experienced local net aggradation or net erosion but coarser areas such as the coarse bed material patches and the channel banks experienced little net change. Table 1 summarizes event values while Table 2 summarizes the geomorphic parameters measured at each patch. The patch area, patch D_{50}, and patch sorting (σ_s) values appearing in Table 2 are the average of the computed values over the study period. The σ_s value is commonly referred to as the geometric standard deviation of the patch GSD and communicates the range of grain sizes at each patch location.

Fig. 4 illustrates the relationship between the mean patch D_{50} (as averaged over the study period) for each of the 12 patches and the local slope, width to depth ratio (W/D), and drainage area for the

Table 1
Values for flow events during study period (2005 – 2006).

Event	Date(s)	Volume (m^3)	Duration (min)	Q_P[a] ($m^3 s^{-1}$)	Tr_{VOL}[b] (years)
1	7/27/2005	43.8	26	0.07	1.08
2	8/7/2005	46.1	23	0.09	1.09
3	8/12/05 and 8/14/05	65.0[c]	41[c]	0.07	1.08, 1.02
4	9/8/2005	505.5	54	0.55	4.6
5	7/29/2006	5.1	36	0.02	< 1
6	8/9/2006	144.4	26	0.44	1.5
7	8/15/06 and 8/16/06	94.6[c]	73[c]	0.13	1.07, 1.12
8	9/12/2006	101.4	25	0.30	1.3

[a] Peak discharge.
[b] Return interval based on flow volume.
[c] Combined value.

Table 2
Geomorphic parameters at the 12 sampled coarse bed material patches for the study period (2005–2006).

Patch	Drainage area (m^2)	Reach W/D[a]	Reach slope	Patch area (m^2)	Patch D_{50} (mm)	Patch σ_g[b]
1	43,470	36.0	0.034	0.40	24	2.76
2	25,600	26.3	0.010	0.62	20	2.53
3	25,350	11.7	0.026	0.35	22	4.17
4	23,810	19.0	0.021	0.61	23	3.52
5	15,870	19.0	0.030	0.32	28	2.87
6	13,710	21.6	0.036	0.11	28	2.47
7	22,340	6.8	0.023	0.36	45	2.53
8	22,400	12.2	0.033	0.74	43	2.17
9	43,910	16.2	0.031	0.24	32	2.03
10	5180	5.0	0.029	0.16	34	2.78
11	13,760	8.4	0.031	0.28	38	2.07
12	22,540	5.5	0.051	0.61	34	2.47

[a] Inundated channel dimensions at ~1.5 year flood.
[b] $\sigma_g = (D_{84}/D_{50} + D_{50}/D_{16})^{0.5}$.

channel at each patch location. The observed relationships between the patch D_{50} and the three geomorphic parameters are weak (only Fig. 4[B] is significant at 95% confidence as determined by linear regression) but aligned with common assumptions in geomorphic theory. Higher channel slopes and decreased W/D ratios produce higher shear stresses for a given flow discharge. Past research has suggested a relationship between local gradients of bed texture and shear stress (Dietrich and Whiting, 1989) but field confirmation in natural channels has often been elusive (e.g., Lisle et al., 2000; Dietrich et al., 2005; Clayton and Pitlick, 2007). The relationship between drainage area and mean local bed texture within an alluvial drainage network is typically thought to be controlled by downstream fining processes (grain abrasion and grain-size dependent transport) (Paola et al., 1992; Parker, 2007); however, it is uncertain how important these processes are in determining the texture of bed material patches.

Flow volume during the study period varied over two orders of magnitude. The largest flow event had a calculated return interval of approximately 4.6 years. The wide range of flow discharges produced a similarly wide range of bed material responses. All of the 12 sampled coarse material patches were predicted to have experienced at least partial transport of the patch D_{50} during the study period (i.e., they experienced τ^*/τ_c^* values greater than 1). The sum of the 12 patch areas (total patch area) ranged from 3.2 m^2 to 5.3 m^2, equating to a 64% maximum change in total patch area during the study period (Fig. 5). On average, the total patch area changed by 17% during each measured flow event. The magnitude (i.e., the absolute value) of the change in the total area generally increased with increased flow volume and peak discharge during the study period.

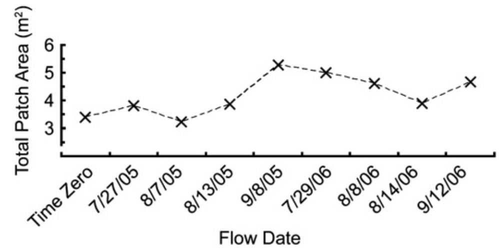

Fig. 5. The total area of the 12 coarse bed material patches before and after each flow event within the study period.

The degree to which patch texture changed during flow events varied between patches; however, all patches experienced both fining and coarsening during the study period. There were no flow events in which all the observed patches experienced net coarsening or net fining. On average, the patch D_{50} changed by 16% from its initial value during a flow event. For the study period, the mean increase in patch D_{50} ($n = 38$) was 21% and the mean decrease ($n = 48$) was -14%. Coarser patches typically experienced greater fluctuations in texture than finer patches (Fig. 6).

3.2. Trends in the changes of individual patches

The coarse bed material patches experienced observable change but appeared to be persistent coarse bed forms over time. Two patches formed during the largest observed flow event (9/08/05); but no patch completely dispersed. Analysis of the bed material maps revealed that each patch maintained its relative coarseness as compared to the surrounding bed material. The location of each individual patch (as determined by the patch centroid) remained relatively stable, never shifting more than 0.5 m either upstream or downstream during any one flow event nor shifting beyond 1.0 m total during the study period. Fig. 7 shows the shifting location of a representative sample of the coarse patches during the study period. Downstream movement of the patch centroid may indicate that the patch is dispersing (if the patch is increasing in area and fining in texture), translating (if its texture and area remain relatively unchanged), or a combination of the two processes. Upstream movement of the patch centroid implies that the downstream area of the patch is eroding, new coarse grains are

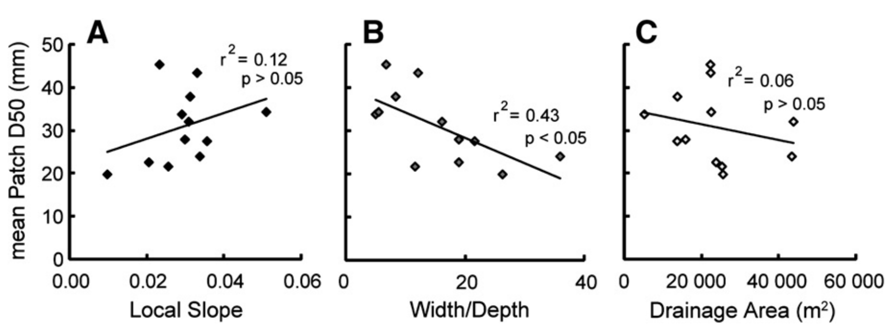

Fig. 4. The mean D_{50} for each coarse patch and its relationship with the (A) slope, (B) width/depth ratio, and (C) drainage area of the local channel reach.

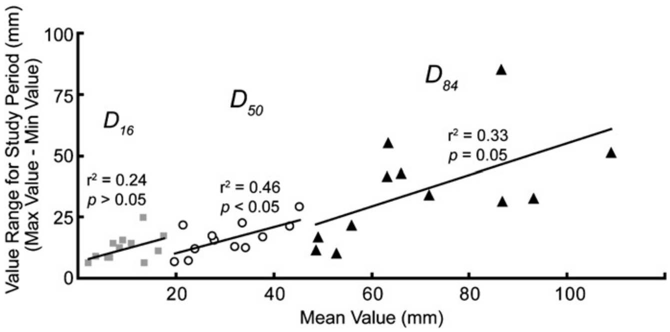

Fig. 6. The mean D_{16}, D_{50}, and D_{84} for each patch in relation to the difference in its maximum and minimum value observed during the study period.

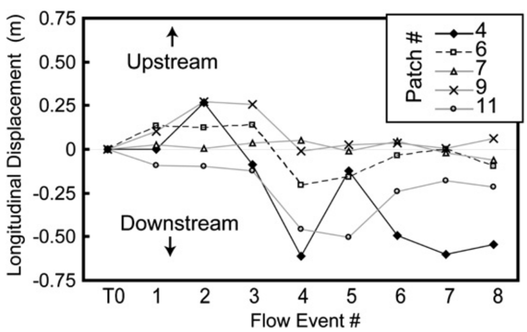

Fig. 7. The longitudinal displacement of the patch centroid for a sample of 5 patches after the 8 flow events within the study period.

becoming deposited along the upstream patch margins, or a combination of the two processes.

Fig. 8(A) displays the change in the individual patch areas (ΔArea), expressed as % change from the previous value, for each of the 12 coarse patches after each flow event occurring within the study period. The x-axis displays the corresponding peak τ^*/τ_c^* value for each occurrence of patch change. The peak τ^*/τ_c^* value estimates the maximum degree of mobility attained by the patch D_{50} during each flow event. This metric is useful in determining if the majority of patch grains were likely entrained by flow but does not provide information about the distance the entrained grains may have traveled. Table 3 summarizes the standard deviation of the distribution of ΔArea values subdivided into three intervals of increasing grain mobility: (1) $\tau^*/\tau_c^*<1$, (2) $\tau^*/\tau_c^*=1$–2, and (3) $\tau^*/\tau_c^*>2$. Under the assumptions of this study, these interval values correspond to (1) low or no grain mobility, (2) partial mobility, and (3) full mobility. The standard deviation of the distribution of ΔArea values in each interval increases as grain mobility increases. The Pearson product-moment correlation coefficient between the full distribution of τ^*/τ_c^* values and the magnitude (i.e., the absolute value) of the ΔArea values is 0.185 which defines a significant correlation at 0.90% confidence ($df=84$). A

Table 3
Summary statistics for the change in patch area and patch D_{50} as displayed in Fig. 7.

τ^*/τ_c^*	Standard deviation		Mean value		Count (n)
	ΔArea (% change)	ΔD_{50} (% change)	ΔArea (% change)	ΔD_{50} (% change)	
<1.0	25.7	25.4	5.7	8.0	34
1.0–2.0	42.2	17.2	2.3	−1.6	30
>2.0	51.6	22.2	7.2	−5.5	22

correlation coefficient is computed from two distributions of values and can range from 1.0 to −1.0 depending on the linear dependence between the distribution values. These observations indicate a weak correlation between the predicted mobility of patch grains during a flow event and the magnitude of the change in patch area.

Fig. 8(B) displays the change in patch D_{50} (ΔD_{50}), expressed as % change from the previous value, for each of the coarse patches during the study period. The magnitude of the change in D_{50} is not correlated (at 90% confidence) to predicted grain mobility. However, within the three intervals of grain mobility as defined above, the mean ΔD_{50} value decreased from 8.0% (in interval 1) to −1.6% (in interval 2) to −5.5% (in interval 3) with increased grain mobility. The Pearson product-moment correlation coefficient between the distribution of τ^*/τ_c^* values and the ΔD_{50} values as illustrated in Fig. 8(B) is −0.31, which defines a significant negative correlation at 0.95% confidence. These observations indicate that during flow events which produced low values of grain mobility ($\tau^*/\tau_c^*<\sim 1$), patches tended to coarsen in texture and during flow events which produced higher values of grain mobility, patches tended to fine in texture. No patch changed from being predominately gravel to being predominately cobble or sand.

3.3. Observations of the grain replacement process

The area and GSD of four painted patches were carefully monitored during the second year of this study. Fig. 9 shows the area of these patches in time. The total areas remained approximately stable after multiple events despite the entrainment and evacuation of a large fraction of its original grains (the painted area). This is because an influx of new grains into the patch (the non-painted area) occurred in near equal proportion to the grains evacuated out of the patch over the period of analysis. The ability for these patches to persist despite the observed loss of a large fraction of their original grains was likely a result of the grain replacement process. Patch area and D_{50} were able to remain stable in concurrence with likely grain erosion as long as a similar amount and caliber of grains were transported into the patch and deposited from sources upstream. The area composed of non-painted grains may have also included immobile grains which were either unburied or stripped of paint during the flow event; however, visual examination of the location and appearance of these grains indicated these effects were minimal.

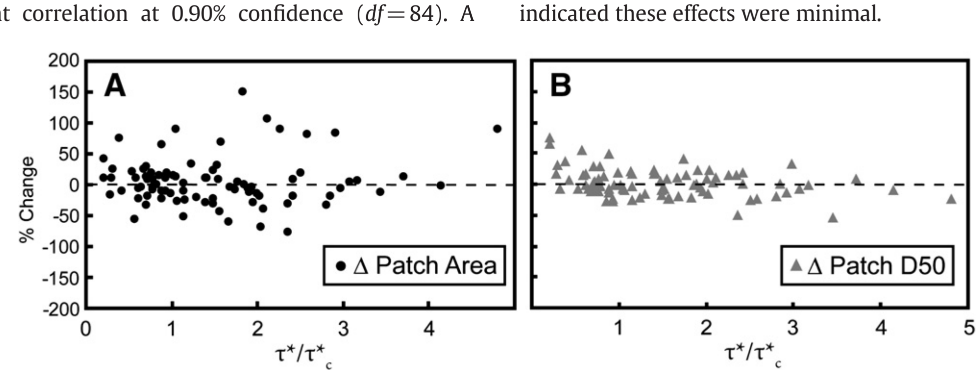

Fig. 8. The percent change in (A) patch area and (B) patch D_{50} for each of the 12 coarse material patches after the 8 flow events within the study period.

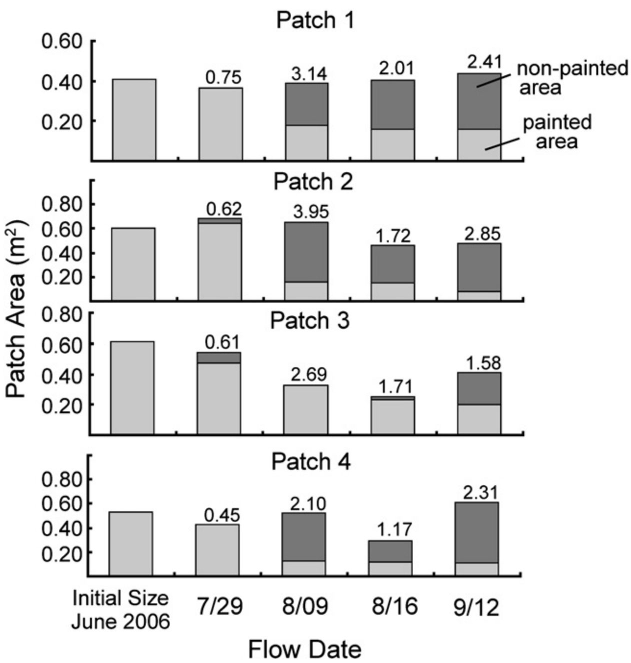

Fig. 9. The area of painted and unpainted grains within 4 coarse patches through the 2006 flow season. The surface of the patch grains were painted in June 2006, before the flow season. The value above each column is the estimated peak τ^*/τ_c^* value at each patch during the associated flow event.

Throughout the duration of the painted patch experiment (summer 2006), the paint slightly faded in color. However, grains with faded paint were still readily distinguished from non-painted grains. Additionally, there was no evidence that the paint became totally removed from the patch grains through mechanical or chemical weathering between measurements.

4. Discussion

Because of the grain replacement process, relative values of patch stability are not fully dependent on values of patch grain mobility. Patch stability is also dependent on the upstream sediment supply to the patch. These phenomena are exemplified by the lack of a clear relationship in the observations of patch changes and estimated grain mobility represented in Fig. 8. If the supply of sediment adequately replaces the sediment evacuated, the area and GSD of the patch may remain unchanged as observed in the painted patch experiment. If the sediment supply is much greater or less than the sediment flux out of the patch or if it has a different GSD, the patch may experience significant changes in area and GSD (Dietrich et al., 2005). The imbalance of incoming and outgoing sediment within a coarse patch may lead to changes in patch area or D_{50} despite little grain entrainment. This phenomenon is likely responsible for the observed patch changes that occurred when τ^*/τ_c^* values failed to exceed 1. For example, the mean channel bed GSD is much finer than that of the coarse patches and becomes entrained at much smaller discharges. The transport of relatively finer grains into an apparently stable patch (i.e., the majority of patch grains are immobile to flow) can decrease the patch area by burying coarse grains at the patch margins or fine the GSD by becoming intermittently deposited within the patch. Also, if fine grains from the channel bed adjacent to the patch's margins are eroded revealing coarser grains, similarly sized to the patch grains, the patch will increase in area. If fine grains from within the patch's GSD are eroded while the coarse grains remain immobile, the patch will coarsen.

Figs. 10 and 11 illustrate how measures of patch change may remain uncorrelated with grain mobility due to the balance or imbalance of the sediment supply rate and the patch grain erosion rate. In Fig. 10, Patch 1 experienced a decrease in area and D_{50} (Fig. 10 [A] vs. [B]) during a small flow that was not predicted to have entrained the patch D_{50} (Fig. 10[C]). During the represented flow, the majority of the bed material located outside of the coarse patch which is often much more fine than the patch material was likely entrained. Because it was unlikely that enough of the patch grains were eroded to affect the patch area, the decrease in area may have been a result of the deposition of fine grains at the patch margins, shielding the underlying coarse grains from observation. Additionally, some of the observed patch change was likely due to the transport of fine grains around and within the patch. Net deposition of grains smaller than the initial patch D_{50} could have produced the observed minor fining of the patch GSD during the flow event. In contrast to the patch instability illustrated in Fig. 10, Fig. 11 shows Patch 1 experiencing little change (Fig. 11[A] vs. [B]) during a much larger flow that was predicted to have the flow strength to transport the patch D_{50} grain size (Fig. 11 [C]). Despite the predicted entrainment of the majority of grain-size fractions present within the patch, the amount of sediment brought into the patch from upstream must have sufficiently replaced the amount of sediment evacuated out of the patch, preventing appreciable patch change.

Much of this analysis is based on predicted grain mobility and cannot discriminate if patch grains were actually entrained by flow or not. However, analysis of the painted patches as well as careful visual observation of the patch photographs indicate that patch grains were commonly entrained by the flows occurring in the study period.

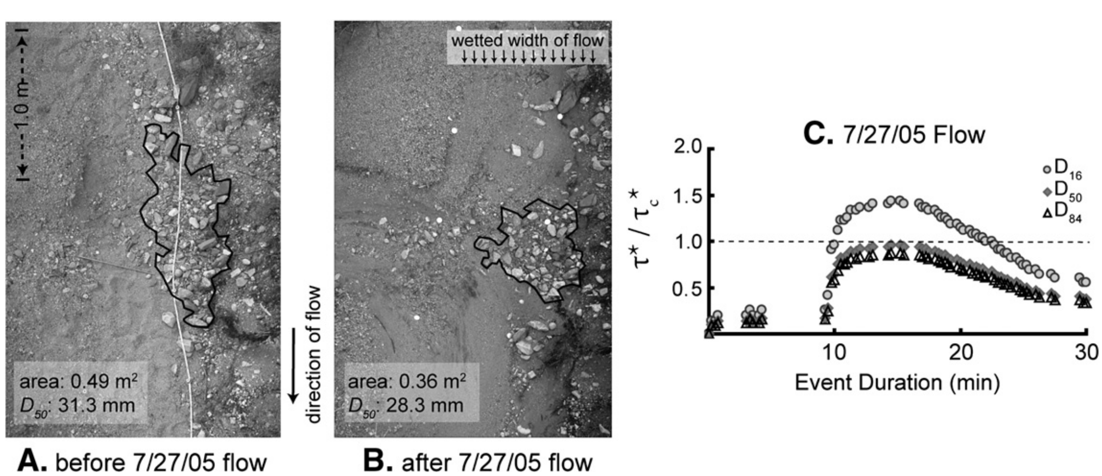

Fig. 10. Plots A and B display photographs of Patch 1, before and after the 7/27/05 flow event. Values for the patch area and D_{50} pertaining to each photograph are labeled. Plot C shows instantaneous values of τ^*/τ_c^* value estimated over the course of the flow event.

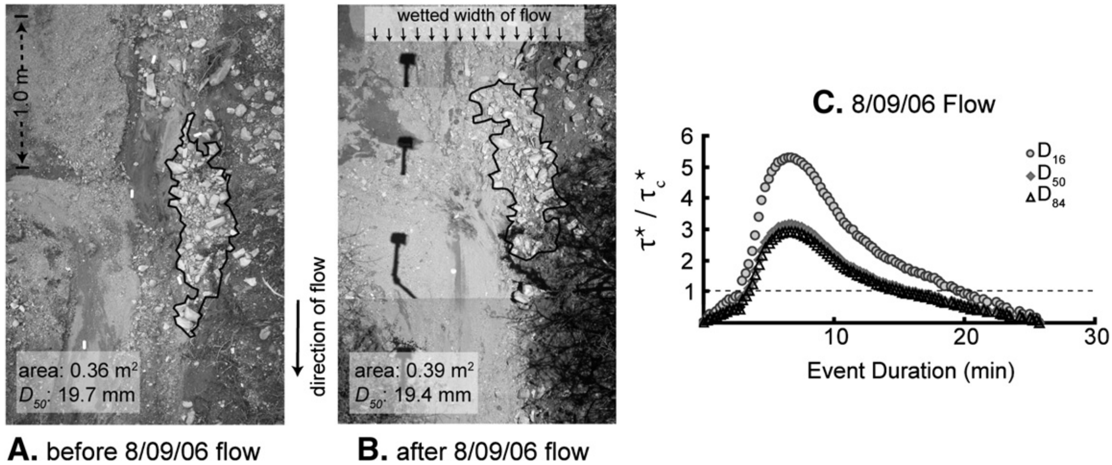

Fig. 11. Plots A and B display photographs of Patch 1, before and after the 8/09/06 flow event. Plot C shows instantaneous values of τ^*/τ_c^* value estimated over the course of the flow event.

The weak relationship observed between grain mobility and the change in patch area and D_{50} may also be due to the fact this study estimated grain mobility by using cross section-averaged values of shear stress. Averaged values may not accurately represent the local hydraulic forces (i.e., local skin friction and near-bed shear velocities) acting on the patch grains that represent the physical mechanisms of grain entrainment and transport (Parker, 2007).

While there were no apparent changes to the coarse patches between flow events, it was possible non-fluvial processes, such as bioturbation, impacted the arrangement of patch grains. The fence around the study area likely minimized manipulation from large animals and human activity. Small animal (e.g., rodents, snakes) activity or ravel may have moved patch grains; however, over the relatively short study period, their impact was likely insignificant to the study results.

5. Conclusions

1. Coarse bed material patches can be relatively persistent bed forms in an ephemeral channel during mild to moderate flow events. In this study, their area and grain-size distribution fluctuated but the patches did not significantly disperse or translate downstream. On average, the total area of the measured patches fluctuated by 17% during each flow event. If that fluctuation was typical of the behavior of every coarse patch within the watershed channel, the amount of coarse sediment available for entrainment during the next flow event would have likewise fluctuated by an average of 17%. This change in sediment availability would have likely influenced the coarse sediment transport rate within the next flow capable of transporting coarse grain sizes. Further, the bed material maps developed during this study illustrated that the majority of grains larger than 32 mm lying on the bed surface were located in coarse patches. As grain sizes 32 mm and larger commonly composed 5% of the total event sediment yield (Yuill, 2009), the coarse bed material patches present a non-negligible influence on the total watershed sediment yield.
2. Patch area and grain-size distribution often remained stable during flow despite the predicted entrainment of the majority of patch grains. Flow likely transported large fractions of the patch grains downstream, out of the patch. At least 50% of marked (i.e., painted) patch grains were no longer visibly present after four flow events. The lost grains were consistently replaced by new grains transported into the patch from upstream sources by flow. This grain replacement process was confirmed by monitoring the persistence of individually painted patch grains in time.
3. Changes in patch area and grain-size distribution displayed a complex relationship with the degree of patch grain mobilization predicted during each flow event. The magnitude of a change in patch area was weakly correlated to grain mobility. On average, the patch D_{50} coarsened during events with low values of grain mobility ($\tau^*/\tau_c^* < 1$) and fined during events with larger values. There was no clear linear trend between how patch area changed (i.e., if it increased or decreased) and grain mobility.
The lack of a consistent relationship between the measurements of patch change and grain mobility indicates that patch stability is not only dependent on the entrainment of patch grains but also on the balance between the sediment eroded from the patch and the sediment supplied to the patch from upstream sources. This balance creates and maintains the grain replacement process. A flume study by Nelson et al. (2009) demonstrated the importance of upstream sediment supply to patch formation within the channel bed. They found that in a simplified fluvial environment (in a “straight, low width to depth ratio channel with no bed topography and constant discharge”) a reduction in sediment supply over a mixed grain-size channel bed caused the formation and growth of coarse bed material patches.
4. In order to understand the sediment transport dynamics of watersheds similar to Lucky Hills with patchy bed material, it is important not to overlook the effects of the coarsest bed material patches. The research that have been conducted on bed material patches (e.g., Paola and Seal, 1995; Garcia et al., 1999; Lisle and Hilton, 1999; Vericat et al., 2008) suggest that, in many cases, the primary source of sediment transport is the finest bed material patches. While this is likely true for Lucky Hills, the results of this study show that the material located within the coarsest patches was routinely mobilized by flow and would have been an influential component of the coarse sediment evacuated from the watershed at the event timescale. In semiarid watersheds, the coarse sediment yield is often a significant fraction of the total yield (Powell et al., 1996). The persistence of the coarse patches through flow events was often due to the grain replacement process and not immobility. Further, there have been recent attempts to improve the accuracy of bed load formulae by explicitly accounting for the presence of bed material patches with the channel bed (e.g., Yager et al., 2007; Mueller et al., 2008). Such attempts would only prove beneficial if the bed material patches did not significantly change at timescales shorter than the timescale the model is parameterized. The results of this study show that values of stability can vary from patch to patch even within a small watershed. While some of this change can be correlated to metrics of grain mobility and flow size, the local balance of grain erosion and deposition also plays an influential role.

Acknowledgements

Bill Flack and Catlow Shipek ably assisted with data collection related to this research. Nicole Gasparini, Ann Commagere, and two anonymous reviewers aided the substance and clarity of this manuscript.

References

Andrews, E.D., 1983. Entrainment of gravel from naturally sorted riverbed material. Geological Society of America Bulletin 94 (10), 1225–1231.
Bagnold, R.A., 1980. An empirical correlation of bedload transport rates in flumes and natural rivers. Proceedings of the Royal Society of London, Series A 372, 453–473.
Batalla, R.J., Martin-Vide, J.P., 2001. Thresholds of particle entrainment in a poorly sorted sandy gravel-bed river. Catena 44, 223–243.
Benda, L., Dunne, T., 1997. Stochastic forcing of sediment routing and storage in channel networks. Water Resources Research 33 (12), 2865–2880.
Bravo-Espinosa, M., Osterkamp, W.R., Lopes, V.L., 2003. Bedload transport in alluvial channels. Journal of Hydraulic Engineering-ASCE 129 (10), 783–795.
Buffington, J.M., Montgomery, D.R., 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. Water Resources Research 33 (8), 1993–2029.
Buffington, J.M., Montgomery, D.R., 1999a. Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resources Research 35 (11), 3507–3521.
Buffington, J.M., Montgomery, D.R., 1999b. A procedure for classifying textural facies in gravel-bed rivers. Water Resources Research 35 (6), 1903–1914.
Bunte, K., Abt, S.R., 2001. Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics and streambed monitoring. Gen. Tech. Rep. RMRS-GTR-74. Fort Collins, CO, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, p. 428.
Canfield, H.E., Lopes, V.L., Goodrich, D.C., 2001. Hillslope characteristics and particle size composition of surficial armoring on a semiarid watershed in the southwestern United States. Catena 44, 1–11.
Church, M., Hassan, M.A., 1992. Size and distance of travel of unconstrained clasts on a streambed. Water Resources Research 28 (1), 299–303.
Church, M., Hassan, M.A., 2002. Mobility of bed material in Harris Creek. Water Resources Research 38 (11).
Church, M., McLean, D.G., Wolcott, J.F., 1987. River bed gravels: sampling and analysis. In: Thorne, C.R., Bathurst, J.C., Hey, R.D. (Eds.), Sediment Transport in Gravel Bed Rivers. Wiley and Sons, New York.
Church, M., Hassan, M.A., Wolcott, J.F., 1998. Stabilizing self-organized structures in gravel-bed stream channels: field and experimental observations. Water Resources Research 34 (11), 3169–3179.
Clayton, J.A., Pitlick, J., 2007. Persistence of the surface texture of a gravel-bed river during a large flood. Earth Surface Processes and Landforms 33 (5), 661–673.
Dietrich, W.E., Whiting, P., 1989. Boundary shear stress and sediment transport in river meanders of sand and gravel. In: Ikeda, S., Parker, G. (Eds.), River Meandering. American Geophysical Union, Washington, DC, pp. 1–50.
Dietrich, W.E., Kirchner, J.W., Ikeda, H., Iseya, F., 1989. Sediment supply and the development of the coarse surface layer in gravel bed rivers. Nature 340, 215–217.
Dietrich, W.E., Nelson, P.A., Yager, E., Venditti, J.G., Lamb, M.L., Collins, L., 2005. Sediment patches, sediment supply, and channel morphology. In: Parker, G., Garcia, C. (Eds.), River, Coastal and Estuarine Morphodynamics, RCEM 2005. Taylor and Francis Group, London, pp. 79–90.
Garcia, C., Laronne, J.B., Sala, M., 1999. Variable source areas of bedload in a gravel-bed stream. Journal of Sedimentary Research 69 (1), 27–31.
Gilluly, J., 1956. General Geology of Central Cochise County, Arizona. U.S. Geological Survey Professional Paper 281.
Goodrich, D.C., Unkrich, C.L., Keefer, T.O., Nichols, M.H., Stone, J.J., Levick, L.R., Scott, R.L., 2008. Event to multidecadal persistence in rainfall and runoff in southeast Arizona. Water Resources Research 44 (5). doi:10.1029/2007WR006222.
Graham, D.J., Rice, S.P., Reid, I., 2005. A transferable method for the automated grain sizing of river gravels. Water Resources Research 41 (7). doi:10.1029/2004WR003868.
Habersack, H.M., Laronne, J.B., 2001. Bed load texture in an alpine gravel bed river. Water Resources Research 37 (12), 3359–3370.
Hassan, M.A., Reid, I., 1990. The influence of microform bed roughness elements on flow and sediment transport in gravel bed rivers. Earth Surface Processes and Landforms 15 (8), 739–750.
Hassan, M.A., Egozi, R., Parker, G., 2006. Experiments on the effect of hydrograph characteristics on vertical grain sorting in gravel bed rivers. Water Resources Research 42 (9). doi:10.1029/2005WR004707.
Hey, R.D., 1979. Flow resistance in gravel-bed rivers. Journal of Hydraulic Engineering 105 (HY4), 365–379.
Kirchner, J.W., Dietrich, W.E., Iseya, F., Ikeda, H., 1990. The variability of critical shear-stress, friction angle, and grain protrusion in water-worked sediments. Sedimentology 37 (4), 647–672.
Kondolf, G.M., Lisle, T.E., Wolman, M.G., 2003. Bed sediment measurement. In: Kondolf, G.M., Piegay, H. (Eds.), Tools in Fluvial Geomorphology. John Wiley and Sons, Ltd, pp. 347–395.
Laronne, J.B., Carson, M.A., 1976. Interrelationships between bed morphology and bed-material transport for a small, gravel-bed channel. Sedimentology 23, 67–85.
Laronne, J.B., Reid, I., Yitshak, Y., Frostick, L.E., 1994. The non-layering of gravel streambeds under ephemeral flood regimes. Journal of Hydrology 159 (1–4), 353–363.
Laronne, J.B., Garcia, C., Reid, I., 2000. Mobility of patch sediment in gravel bed streams: patch character and its implications for bedload. In: Mosley, M.P. (Ed.), Gravel-bed Rivers V. New Zealand Hydrological Society, Inc, Wellington, NZ, pp. 249–289.
Lisle, T.E., 1995. Particle-size variations between bed-load and bed material in natural gravel-bed channels. Water Resources Research 31 (4), 1107–1118.
Lisle, T.E., Hilton, S., 1999. Fine bed material in pools of natural gravel bed channels. Water Resources Research 35 (4), 1291–1304.
Lisle, T.E., Madej, M.A., 1992. Spatial variation in armoring in a channel with high sediment supply. In: Billi, P., Hey, C.R., Thorne, C., Tacconi, P. (Eds.), Dynamics of Gravel-bed Rivers. John Wiley and Sons, pp. 277–291.
Lisle, T.E., Iseya, F., Ikeda, H., 1993. Response of a channel with alternate bars to a decrease in supply of mixed-size bed-load — a flume experiment. Water Resources Research 29 (11), 3623–3629.
Lisle, T.E., Nelson, J.M., Pitlick, J., Madej, M.A., Barkett, B.L., 2000. Variability of bed mobility in natural, gravel-bed channels and adjustments to sediment load at local and reach scales. Water Resources Research 36 (12), 3743–3755.
Mueller, E.N., Batalla, R.J., Garcia, C., and Bronstert, A., 2008. Modeling bed-load rates from fine grain size patches during small floods in a gravel-bed river. Journal of Hydraulic Engineering, doi:10.1061/(ASCE)0733-9429(2008)134:10(1430), 1431– 1439.
Nelson, P.A., Vendetti, J.G., Dietrich, W.E., Kirchner, J.W., Ikeda, H., Iseya, F., Sklar, L.S., 2009. Response of bed surface patchiness to reductions in sediment supply. Journal of Geophysical Research 114, F02005. doi:10.1029/2008JF001144.
Nichols, M.H., Stone, J.J., Nearing, M.A., 2008. Sediment database, Walnut Gulch Experimental Watershed, Arizona, United States. Water Resources Research 44 (5). doi:10.1029/2006WR005682.
Oldmeadow, D.F., Church, M., 2006. A field experiment on streambed stabilization by gravel structures. Geomorphology 78 (3–4), 335–350.
Osborn, H.B., Simanton, J.R., 1983. Runoff estimates for thunderstorm rainfall on small rangeland watersheds. Hydrology and Water Resources in Arizona and the Southwest 13, 9–15.
Osterkamp, W.R., 2008. Geology, soils, and geomorphology of the Walnut Gulch Experimental Watershed, Tombstone, Arizona. Journal of the Arizona–Nevada Academy of Science 40 (2), 136–154.
Paola, C., Seal, R., 1995. Grain size patchiness as a cause of selective deposition and downstream fining. Water Resources Research 31 (5), 1395–1407.
Paola, C., Parker, G., Seal, R., Sinha, S.K., Southard, J.B., Wilcock, P.R., 1992. Downstream fining by selective deposition in a laboratory flume. Science 258 (5089), 1757–1760.
Parker, G., 1990. Surface-based bedload transport relation for gravel rivers. Journal of Hydraulic Research 28 (4), 417–436.
Parker, G., 2007. Transport of gravel and sediment mixtures. In: Garcia, M.H. (Ed.), ASCE Manuals and Reports on Engineering Practice; no. 110. American Society of Civil Engineers, Reston, VA, pp. 165–253.
Parker, G., Klingeman, P.C., 1982. On why gravel bed streams are paved. Water Resources Research 18 (5), 1409–1433.
Parker, G., Sutherland, A.J., 1990. Fluvial armor. Journal of Hydraulic Research 28 (5), 529–544.
Parker, G., Klingeman, P.C., McLean, D.G., 1982. Bed load and size distribution in paved gravel-bed streams. Journal of Hydraulic Engineering 108 (4), 544–571.
Powell, D.M., 1998. Patterns and processes of sediment sorting in gravel-bed rivers. Progress in Physical Geography 22 (1), 1–32.
Powell, D.M., Reid, I., Laronne, J.B., Frostick, L., 1996. Bed load as a component of sediment yield from a semiarid watershed of northern Negev. Erosion and Sediment Yield: Global and Regional Perspectives. IAHS publication No. 236, pp. 389–397.
Powell, D.M., Reid, I., Laronne, J.B., 2001. Evolution of bed load grain size distribution with increasing flow strength and the effect of flow duration on the caliber of bed load sediment yield in ephemeral gravel bed rivers. Water Resources Research 37 (5), 1463–1474.
Powell, D.M., Brazier, R., Parsons, A., Wainwright, J., Nichols, M., 2007. Sediment transfer and storage in dryland headwater streams. Geomorphology 88, 152–166.
Renard, K.G., Simanton, J.R., Fancher, C.E., 1986. Small watershed automatic water quality sampler. 4th Federal Interagency Sedimentation Conference, Las Vegas, NV, pp. 51–58.
Renard, K.G., Nichols, M.H., Woolhiser, D.A., Osborn, H.B., 2008. A brief background on the U.S. Department of Agriculture — Agricultural Research Service Walnut Gulch Experimental Watershed. Water Resources Research 44 (5). doi:10.1029/2006WR005691.
Sutherland, D.G., Ball, M.H., Hilton, S.J., Lisle, T.E., 2002. Evolution of a landslide-induced sediment wave in the Navarro River, California. Geological Society of America Bulletin 114 (8), 1036–1048.
Tucker, G.E., Arnold, L., Bras, R.L., Flores, H., Istanbulluoglu, E., Solyom, P., 2006. Headwater channel dynamics in semiarid rangelands, Colorado high plains, USA. GSA Bulletin 118, 959–974.
Vericat, D., Batalla, R.J., Gibbins, C.N., 2008. Sediment entrainment and depletion from patches of fine material in a gravel-bed river. Water Resources Research 44, W11415. doi:10.1029/2008WR007028.
Wentworth, C.K., 1926. Methods of mechanic analysis for sediments. University of Iowa Studies in Natural History II, pp. 3–52.
Wilcock, P.R., Crowe, J.C., 2003. Surface-based transport model for mixed-size sediment. Journal of Hydraulic Engineering-ASCE 129 (2), 120–128.
Wilcock, P.R., DeTemple, B.T., 2005. Persistence of armor layers in gravel-bed streams. Geophysical Research Letters 32 (8). doi:10.1029/2004GL021772.

Wilcock, P.R., McArdell, B.W., 1997. Partial transport of a sand/gravel sediment. Water Resources Research 33 (1), 235–245.
Wyzga, B., 2001. A geomorphologist's criticism of the engineering approach to channelization of gravel-bed rivers: case study of the Raba River, Polish Carpathians. Environmental Management 28 (3), 341–358.
Yager, E.M., Kirchner, J.W., Dietrich, W.E., 2007. Calculating bed load transport in steep boulder bed channels. Water Resources Research 43. doi:10.1029/2006WR005432.
Yuill, B.T., 2009. Sediment transport and bed mobility in a low-ordered, ephemeral watershed. PhD Dissertation, University of Arizona, Tucson, AZ.