Bedload flux and characteristic from flash floods in the Arroyo de los Piños, NM – initial results

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Abstract

Sampling bedload by conventional means is not possible in unwadeable flash floods, typical of large tracts of land in the American Southwest and in deserts worldwide. Instead, automated methods are required to monitor bedload. Reid-type (formerly termed Birkbeck) slot samplers have been demonstrated to be hydraulically efficient at monitoring and sampling bedload, have been deployed in various regions and climates, and have been used to calibrate surrogate techniques. Yet they are expensive and require considerable person-power to deploy. In addition to the Oak Creek vortex tube, automatic slot samplers have been deployed in the US (Wyoming and California) and presently by the ARS in Coon Creek. We report on preliminary results of monitoring bedload in the Arroyo de los Piños.

Three slot samplers, each with \( \approx 0.5 \text{ m}^3 \) capacity, are deployed across a 10 m wide constricted reach of the Piños, near the confluence with the Rio Grande. The local slope is 1.3\%, drainage area is 31 km², and sand and gravel yields are presumed to be high. These sediments are transported directly to the Rio Grande during the infrequent summer-season monsoon flash floods. The channel bed is unarmored, with coarser pebble-cobble rich bars and finer-grained thalwegs containing sand-rich gravels. The approach reach has two thalwegs with inter-event switching as to which is the deepest, thereby transporting higher bedload fluxes at shallow depths. The thalwegs are separated by a subdued (ca 10 cm) bar. The channel bed as a whole contains about equal proportions of sand, granules (2-8 mm) and coarser particles. The monitoring station contains a large number of surrogate bedload devices, and as it is located near New Mexico Tech, manual bedload sampling at wadeable depths is undertaken in most flash floods.

Five bedload-transporting events were monitored during 2018. Initial analyses establish that bedload fluxes are very high by global standards, as expected in unarmored, ephemeral channels (6.5 – 16.5 kg s\(^{-1}\) m\(^{-1}\)). Bedload transport is initiated even by shallow flow events (ca 8 cm depth at the site, similar to the depth in the feeder thalweg. At very shallow depths of flow (5-10 cm) such as in the September 1, 2018 event, bedload flux increased with depth in the range 0.1 – 1 kg s\(^{-1}\) m\(^{-1}\), though with considerable scatter.
Introduction

Bedload transport processes in ephemeral channels

Ephemeral streams constitute a large portion of most channel networks. This proportion varies with climate, with drier conditions typically increasing the proportion, but even wet regions have many low-order channels that only flow during precipitation events. Quantifying flow and sediment transport in ephemeral streams is inhibited by several challenges not present in perennial systems. First, the observer must wait for flow. This is analogous to waiting for floods in perennial systems, but whereas a great deal of work can happen during base flow in a perennial stream, limited useful data can be gleaned during no-flow. Second, the cross-sectional geometry of ephemeral streams changes more than most perennial streams during flood. There is widespread bed scour, bank erosion, and bar deposition, causing relationships between stage and discharge to change significantly over the course of a flow event. Finally, because they are not major sources of water, few ephemeral streams are gauged by federal or state agencies. There is a dearth of flow data from ephemeral streams, even in semi-arid regions such as the Southwest United States. In part this is due to challenges related to the typically rapid rising limb of the flood and the often-unpredictable timing (Cohen and Laronne, 2005). Additional challenges related to bedload measurement are the high magnitude and variability of these fluxes (Laronne and Reid, 1993; Reid et al., 1995).

Yet because of their ubiquity and high sediment transport capacity, ephemeral streams can dominate the fluvial system and its response to climate and land use change. Sediment delivered from ephemeral streams controls the geomorphology of many major perennial rivers and dictates the filling rate of reservoirs. Most destructive floods in semi-arid regions, even on perennial rivers, derive most of their water from ephemeral portions of the channel network. And because of their relatively large bed surface area and sequential wetting and drying, biogeochemical reactions on beds of ephemeral streams can be significant or even dominant at the landscape scale. Understanding the runoff generation, sediment transport, and biogeochemical cycling of ephemeral rivers is key to managing the scarce surface water resources of dryland societies.

The relationship between temporal intermittency and total sediment delivery is poorly understood. Ephemeral streams typically have higher sediment loads than perennial streams when they are flowing (Reid et al., 1995), but total sediment transport integrated through time may be smaller given the shorter duration of flow. Bed sediment is typically finer in ephemeral streams, all else being equal, because the time available for winnowing of fines is reduced. Additionally, flow rates typically change rapidly from high to low energy, allowing fines to drop out of transport throughout the channel network at the end of a flood event.

Most early efforts to quantify bedload transport focused on average conditions within perennial channels (e.g., Shields, 1936; White, 1940). But even these early researchers recognized that localized variations within the water column and in the bed structure could change the force balance acting on a grain. For example, grain protrusion reduces the shear stress required for grain entrainment because grains that are exposed above the rest of the bed will experience enhanced drag forces (Fenton & Abbott, 1977; Brayshaw et al., 1983). The protruding grains can also shield smaller grains downstream, altering sorting and grain size distribution within the reach (Brayshaw et al., 1983; Kirchner et al., 1990). Relative grain size plays a large role in grain protrusion and shielding: large grains tend to protrude and small grains tend to be shielded, helping to reduce the difference in transport thresholds across the bed material mixture, even in
armored perennial streams. Grains also tend to protrude into the water column if the bed on which they lie is very uniform. The result is that critical shear stress for a given bed is a probability distribution, not a single value (Kirchner et al., 1990). Grains on one part of the bed may readily erode because they are exposed to greater tractive forces, while grains of the same size in another part of the bed may be entrapped by still larger, more immobile grains. In spite of this, in laboratory flume experiments, grain sorting has been shown to have little effect on critical shear stresses for each grain size fraction (Wilcock, 1988). As shear stress increases, the percentage of coarser particles mobilized increases until some critical shear stress value when all fractions become mobilized.

Practical sediment transport equations are typically based on shear stress or stream power and are calibrated to perennial streams. Sediment supply is typically a limiting factor in perennial streams and plays an important role in the empirical calibration of most transport equations, but it is much less important in ephemeral streams (Reid et al., 1995) resulting in poor performance of equations calibrated in perennial streams and applied to ephemeral streams. Current methods to calculate sediment load typically involve applying sediment transport equations for the particular field conditions of the channel, often with very large incompatibility of equations for given conditions (Cao et al., 2010). In part, this is because nearly all transport equations have been developed based on perennial systems (Gomez & Church, 1989; Shih & Diplas, 2018). Water resource and reservoir managers are faced with multiple orders of magnitude of uncertainty in estimates of sediment delivery to regulated semi-arid rivers. Yet the need for data is essential to best manage the vital rivers in a large area in the American Southwest, where the input of bedload from such tributaries to main stems is a key constraint on predictive understanding. Agencies such as the United States Bureau of Reclamation (USBR) and the United States Army Corps of Engineers (USACE) have had to estimate lateral inputs with no data available to substantiate bedload formulae.

The most relevant formulae to be tested are those originally suggested for streams transporting both gravel and sand (e.g., Wilcock and Kenworthy, 2002). Because of the bed armoring and shielding in perennial streams, more complex bedload discharge models have been developed (Miwa & Parker, 2017; Wilcock & Crowe, 2003; Wilcock & Kenworthy, 2002). Though they are developed for perennial streams, they are one of the limited options for estimating bedload transport in ephemeral streams. This extrapolation may be partly justified due to these models’ conceptualization of the bedload into a two-component system: sand and gravel. In both flume experiments and field observations, grain entrainment depends on the sand content. With an increasing sand fraction, the gravel fraction becomes more mobile (Miwa & Parker, 2017) because effects of grain protrusion become more prominent. This effect continues until the sand fraction is 40% of the bed material. At this stage, model results indicate that the critical shear stress required for gravel entrainment increases. This transition has been interpreted to be the transition from a grain-supported bed to a matrix-supported bed (Wilcock & Crowe, 2003). Increasing the sand fraction beyond the 40% threshold continues to decrease the critical shear stress required to mobilize the sand fraction, but the shear necessary to transport the gravel fraction increases (Wilcock & Kenworthy, 2002). In effect, the importance of the protrusion and hiding effects of the gravel fraction fades away. Hence, ephemeral streams, with their broad bed grain size distribution, are excellent candidates to investigate this sand fraction effect.

**Previous bedload transport quantification in ephemeral channels**

Direct measurement of ephemeral, semi-arid channel bedload has taken place at a limited number of sites worldwide. The three most productive sites have been the Nahal Eshtemoa, the Nahal Yatir, and the experimental watershed at Walnut Gulch (Laronne et al., 1992, 1994;
Nichols et al., 2008). These previous studies demonstrate that rates of bedload transport are very high, primarily due to lack of armoring and readily erodible sediment (Cohen & Laronne, 2005; Laronne & Reid, 1993; Powell et al., 1996).

Transport events at all three sites are driven by high intensity precipitation that generates overland flow. The bedload flux in the Yatir and Eshtemoa channels varies linearly with boundary shear stress (Cohen et al., 2010), in contrast to their perennial counterparts, which are governed by a power function relationship. This linear relationship is dependent on sediment source and flood type. Changes in sediment storage during flooding is minimal in these regions due to the availability of sediment for entrainment (Powell et al., 2007). Total bedload flux is high when compared to global averages, with values reported up to 10 kg s⁻¹ m⁻¹ (Powell et al., 1996).

**Study Site**

Our bedload monitoring efforts have focused on the Arroyo de los Piños. Streams like the Piños are common in the Southwest: tributaries to a large, societally important river that has been dammed for water allocation and flood control. These main stem dams impede the transport of sediment downstream, leaving the tributaries as the primary contributors of sediment to the main river, which subsequently suffers from geomorphic instability (Kondolf, 1997; Graf, 2006). Yet there is no cost-effective way to quantify this important tributary flux. The USBR alone spends millions of dollars annually on river maintenance merely in the Middle Rio Grande, and uncertainty regarding sediment flux leads to over-engineering of river infrastructure nationwide. Therefore the USBR, with assistance from the USACE, decided to fund the construction of a state-of-the-art long-term sediment transport observatory at the Arroyo de los Piños.

The Arroyo de los Piños watershed (31.5 km²) has an average slope of 3.5%, with the channel slope decreasing downstream to 1.3% at the constricted monitoring site near the Rio Grande confluence. The upper two-thirds of the basin consists of extensively faulted Paleozoic limestone, sandstone, and shale, while the lower third of the basin is carved into Quaternary basin fills of the axial Rio Grande Rift. The channels in the upper two thirds of the basin are single thread and constrained by bedrock slopes, whereas in the lower portion an anastomosing pattern prevails, in part due to the abundance of bushes scattered throughout the unconfined valley floor, as is typical of the washes in the region. Creosote is the dominant vegetation, with interspersed grasses and other small shrubs such as saltbush. There is moderate grazing pressure throughout the basin, administered by the Bureau of Land Management. Occasional juniper trees are scattered about the basin, primarily concentrated on localized sand sheets or on limestone hillslopes.

Flow in this basin is almost exclusively generated by intense localized thunderstorms associated with the North American Monsoon. Precipitation averages 250 mm annually, with over 150 mm falling during the monsoon season of July–October. Monsoon season storms tend to be short duration and high intensity, with limited spatial extent, while winter precipitation tends to be widespread and low intensity, rarely generating runoff.

Approximately 200 m upstream of the Piños’ confluence with the Rio Grande an agricultural drain ditch crosses under the arroyo. Constructed in the 1950s, it is presently unused and unmaintained, with negligible farming activity on this side of the Rio Grande. However, levees at the crossing prevent the wash from flowing into the drain and constrict the channel to a width of 10 m. The monitoring site is located here, to take advantage of the fixed cross-section. The bed
material of the channel at the monitoring station is unarmored, as is typical of ephemeral desert washes (Laronne et al., 1994), and contains approximately equal amounts of sand, granules (2–8 mm) and coarser gravel. The pebbles and cobbles are somewhat angular. Further upstream in the Paleozoic bedrock the fraction of sand decreases and the median and maximum grain sizes increase to cobbles and occasional boulders. With three depth transducers and two rain gauges already deployed at the monitoring site and in the upper basin, during the 2017 monsoon season we monitored ten flow events with rainfall depths as high as 40 mm/event, flow depth at the site up to 0.5 m, depth averaged water velocity up to 2.6 m/s, and SSC in the range of 1-5% (10,000-50,000 mg/L).

Methods

Direct bedload sampling over extended periods and in deep (greater than 40 cm) flows presents both technical and safety challenges. Handheld samplers (e.g., Helley-Smith) alter near-bed hydraulics, and wading becomes dangerous in many flood stages when bedload transport is often high. Collection reservoirs permit cumulative estimates at event-scale resolution, but cannot describe intra-flood variation. One solution is to install Reid-type slot samplers (aka pit traps) with weighing pressure pillows in the channel bed, but this solution is costly for adequately large traps and requires diligent maintenance. Three such slot samplers were installed on the Arroyo de los Piños, and were active during five flow events in the 2018 monsoon season.

Bedload flux was determined by the rate of increase of mass within the Reid-type slot samplers (Reid, et al. 1980). Bedload falls through a slot in the channel bed into a buried vault containing a steel box. The width of the slot can be adjusted using sliding plates, set at 11 cm in this case. The chamber below was kept flooded, therefore suspended sediment could not settle into the sampler, but bedload could. The box rests on a pillow that records the pressure change associated with the mass of sediment displacing water within the box. Pressure in the pillow is corrected against a co-located vented water column pressure transducer. These pressure gains are then converted into a time series of bedload flux per unit width of channel. The samplers also allowed determination of the temporal variation in the grain size of bedload based on the known time when given layers of sediment mass accumulated in the samplers (Powell et al., 2001), even when a considerable fraction of the bedload was sandy, as during low depths and low imposed shear stresses (Lucía et al., 2013).

The benefits of slot samplers are well established (e.g., Laronne et al., 2003). They do not alter flow hydraulics, due to their placement within the riverbed. They do not sample suspended sediment, because the box is kept filled with water, meaning that even at the beginning of a flood the exchange of water across the pit opening is minimized, and likewise the delivery of suspended sediment. Instead, flow passes over the slot opening. Only those particles that are dragging or saltating along the bed can descend through the opening. The opening is long in the downstream dimension, so that few particles can hop entirely over the slot. Also, slot samplers record continuously in time, as bedload mass accumulates in the weighing box. Finally, by retaining the sediment, they enable subsequent excavation, sampling, and grain size analysis of the bedload that was actually in transport.

Yet slot samplers have key limitations, and their effective use must properly take these into account. They are expensive to install and require a stabilized channel cross section. Most importantly, the volume of the weighing box acts as a limit on their useful life for each event. In areas with high bedload flux, they fill quickly relative to event duration. Narrowing the slot width can extend this sampling duration, but at the cost of excluding particles that are larger
than the slot width. By nature, slot samplers collect data at a single location in the cross section, however in most installations multiple traps crossing the channel are used to provide data on lateral variability of transport, which is typically significant. Finally, the mass resolution of the pressure pillow necessitates an integration time period. The pressure response can be noisy and variable, due to turbulence and the bouncing or shifting of particles in the box. Therefore, captured sediment pressure trends over longer time periods (minutes) are more representative of the mean than typically fast changes over seconds. In short, while slot samplers are one of the only ways to obtain a bedload sample without altering the observation environment in the process of collecting it, there are limitations in terms of temporal duration and resolution.

**Results**

In all the Reid-type slot sampler data sets, there is a time limit on the usefulness of the sampler data. Measured flux declines as the box approaches its capacity and capture efficiency decreases. Typically a cone of sediment fills nearly to the opening, at which stage settling and rearrangement of material can permit additional mass to enter, but not at a rate representative of bedload flux. This occurs when the box is roughly 85-95% full. Not all figures in this paper cut off the pressure pillow derived flux data at this stage, but it is clear from the rapid drop off in the captured bedload flux independent of declines in stage or discharge. The bedload flux data are presented as a 3-minute moving average to alleviate noise in the signal due to turbulence.

Bedload flux for the five measured events was generally well correlated with stage (Figure 1). The left slot sampler appears to have collected the most stage-sensitive data, possibly due to the presence of the thalweg on river left. However, the figures presented here show the mean bedload flux for all three samplers.

In the July 16, 2018 event, the flood arrived as a bore, and flux immediately reached peak value. It then declined with stage until the sampler was full. The August 9, 2018 event rose more slowly, and to a lower peak stage (20 cm vs. 45 cm), with a commensurately lower peak cross-section average bedload flux (4 kg s⁻¹ m⁻¹ vs. 6 kg s⁻¹ m⁻¹). The slower stage rise is mirrored in a slower flux rise. The left sampler, where the stage is used for this comparison, had a somewhat higher peak bedload flux of 8 kg s⁻¹ m⁻¹ (Figure 2). In both events, there appears to be a small initial flush effect, with greater transport when the flow first approaches the peak. This may be due to the turbulence of the arriving bore, or alternatively, due to bed material reorganization during the flood.

Peak measured fluxes at the left sampler have a non-linear relationship with the stage at the time of peak flux (Table 1). The August 24 event had a higher peak bedload flux than the July 16 event, in spite of its lower peak stage. It may be that this event, as well as the August 9 event, benefited from the major flood on July 26 disrupting the bed structure and leaving readily mobilized sediment as its stage fell. Based on personal communication with residents in the area of the Piños as well as aerial photographic evidence, we estimate the July 26 event had a 10-25 year recurrence interval.
Figure 1: Average bedload flux for the three slot samplers and water depth for the July 16, 2018 event and the August 9, 2018 event.

Figure 2: Bedload sediment flux separately monitored at the left and right slot samplers for the July 16, 2018 event.
In this major flood, the left slot sampler filled within 10 minutes of bedload transport initiation, or 15 minutes following initial flood rise (Figure 3). The peak bedload flux for this sampler, 16 kg s\(^{-1}\) m\(^{-1}\), was the highest recorded in our study. At this time, water depth was only 50 cm, well below the eventual peak at 160 cm, suggesting it may have continued to rise. In contrast, the right sampler filled more slowly, and had a peak flux of 5 kg s\(^{-1}\) m\(^{-1}\), which was sustained across a wide range of flow depths, from 50 to 120 cm. Yet bedload transport was initiated earlier on the right side of the channel. This lateral variability and apparent migration of the thalweg is characteristic of our observations from the Piños, likely due to the topography of the approach reach.

![Figure 3: Time series of right, center, and left sampler bedload flux during July 26th event (peak stage: 160 cm). Flux lines are dotted where it is inferred that the sampler was full or nearly so. Left sampler filled within ~ 15 minutes of beginning of flood; right sampler within ~ 30 minutes.](image)

For individual events, there are typically strong relationships between flux and stage, at least within the limits of the trap accuracy and data collection duration. However, the slope of this relationship is not necessarily the same for all three slot samplers. For example, in the August 24 event, the left sampler experienced greater bedload transport for a given stage (Figure 4). This may be due to slight differences in the height of the sill in which the samplers are set. Due to settling during pouring of the concrete, the left sampler is approximately 3 cm lower than the right, yet we use a single stage height, from the left sampler, for this analysis. In this case, the resulting difference in water depth would not be enough to explain the entire difference in the stage-flux relationship, suggesting an additional role for thalweg location. However during the September 1 flow event, a low stage event with multiple flood waves (Figure 5), using the stage...
The stage-flux relationship in Figure 4 superficially appears to show a clockwise hysteresis. Unfortunately, this observation may simply be an artifact driven by trap capacity and capture efficiency. Because the box fills and collects no data during most of the falling limb, such a hysteretic effect would be greatly exaggerated or even falsely created. The flux-stage data for the September 1 event (Figure 6) are noisy, and while a clockwise hysteresis again might be interpreted, the pattern is not clear.
Figure 5: Time series of bedload flux for the three pit samplers (L: left, C: center, R: right) for the September 1 event (two flood waves, peak depth of 15 cm, as measured over left sampler). The lateral variability demonstrated here is present to varying degrees in most events. In this case, the thalweg in the approach reach was located near the left bank.

Figure 6: Influence of local water depth on bedload flux during the September 1 event. Gray bar indicates approximate depth at initiation of bedload transport. Shallower water on right bank can explain lower transport rates seen in Figure 5.
The initiation of bedload transport occurs at flow depths of approximately 10 cm within our study reach of the Arroyo de los Piños (Table 2). The July 16 event arrived with such a sudden flood bore, that stage went from 0 to 30 cm in the first minute (data recording interval was one minute), meaning that useful initiation data was not collected for that event. For comparison, the July 26 event rose much more slowly; transport commenced at 14 cm depth of water. The three events following the major flood on July 26 initiated motion at less than 10 cm water depth. As with the peak bedload flux data (Table 1), it is possible that the large July 26 event left the bed material in a more easily transported configuration than prior to the event.

Table 2: Stage at initiation of bedload transport

<table>
<thead>
<tr>
<th>Event Date</th>
<th>Stage at Initiation of Motion (cm)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 16</td>
<td>30</td>
<td>First minute depth measurement</td>
</tr>
<tr>
<td>July 26</td>
<td>14</td>
<td>eventual peak stage: 160 cm</td>
</tr>
<tr>
<td>Aug 9</td>
<td>8</td>
<td>eventual peak stage: 19 cm</td>
</tr>
<tr>
<td>Aug 24</td>
<td>9</td>
<td>eventual peak stage: 33 cm</td>
</tr>
<tr>
<td>Sept 1</td>
<td>8</td>
<td>eventual peak stage: 15 cm</td>
</tr>
</tbody>
</table>

We documented considerable lateral variability of bedload transport through time (Figures 2, 3, and 5). The thalweg migrated across the channel during some flow events; this was more frequent in the 2017 monsoon season (Stark, 2018). The fixed bed elevation may have contributed to somewhat increased stability in 2018. Nonetheless, a mid-channel bar developed and varied in relative height during the season, though it never exceeded 10 cm above the side thalwges, at least when exposed between floods. It was particularly well developed following the July 26 flood. Additionally, the temporal variability of bedload flux, with short duration spikes frequently observed (e.g., Figure 5) suggests the passage of sediment waves. Some are more extensive than others and affect multiple slot samplers (for example, at 13:10 in Figure 5).

Sieving of the captured bed material reveals greater variability in grain size distribution between events than within events (Figure 7). Samples were taken in 10 cm lifts from the ~ 80 cm deep boxes, yielding 8 samples for most event-sampler combinations. The first two events (July 16 and 26) had similar size distributions, near the middle of the overall distribution (yellow and green hues in Figure 7). The two smallest events (August 9 and September 1), each with ~15 cm maximum flow depth, collected the finest grain size distributions. Unexpectedly, the moderate sized (33 cm peak stage) late season (August 24) event had the coarsest transported material. Within an event, the coarsest samples were typically the earliest collected. We intend to compare these grain size distributions to bed material samples, but these have not yet been sieved.
Figure 7: Percent finer grain size distribution for all analyzed transported sediment samples. L0 is the top of the sampler (last collected) and L8 is the bottom (first collected). NA indicates samples that are not yet processed.

Discussion

These bedload data represent the initial results from a new semi-arid site with detailed bedload transport data. The peak measured flux of 16 kg s\(^{-1}\) m\(^{-1}\) is one of the highest reported from other existing monitored sites. Comparison of measured flux can be made with the other semi-arid and arid areas, worldwide: Walnut Gulch (Arizona, USA), Northern Negev Desert (Israel), and the Southern Judean Desert (Israel).

The Walnut Gulch data is not directly comparable, since it records annual changes in stock pond sedimentation. Watershed yields on this annualized basis reach as high as 3 m\(^3\)/ha, or 0.3 mm/year of denudation, for a watershed of 44 ha (Nichols, 2006; Nichols et al., 2008). Estimating peak bedload flux from this value that includes all suspended and bedload sediment
from a full year is unreliable. Nevertheless, it helps emphasize the large amounts of sediment moved even though the channel is ephemeral.

Bedload flux rates up to 10 kg s\(^{-1}\) m\(^{-1}\) are reported from the Nahal Eshtemoa in the Northern Negev Desert of Israel, measured using slot samplers, with flux interacting linearly with shear stress in most cases (Cohen et al., 2010). The nearby Nahal Yatir has a similar maximum value, \(\sim 7\) kg s\(^{-1}\) m\(^{-1}\) (Reid et al., 1995). The range of bedload flux rates we observed at the Piños generally overlaps with the range from the Eshtemoa and Yatir. Only during the July 26 flood did our observations exceed those at the Eshtemoa. The highest reported bedload flux in the published literature is from the Nahal Rahaf, in the Southern Judean Desert of Israel, where the maximum 1-minute flux was 37 kg s\(^{-1}\) m\(^{-1}\) (Cohen et al., 2005). The maximum reported value from the nearby Nahal Qanna’im was 15 kg s\(^{-1}\) m\(^{-1}\). The Rahaf is slightly steeper than the Piños at 1.7% slope and drains a larger catchment (78 km\(^2\)). The Qanna’im is steeper still, at 2.7% slope.

The threshold for motion in the Piños is very low, with a mere 10 cm initiating flow (Table 1). Before the flow depth even reaches 35 cm, the full bed is mobile, as demonstrated by the coarse grain size and abundant clasts exceeding 50 mm diameter transported throughout the August 24 event (Figure 7). This ready mobility may be attributable to the mix of sand and gravel in the bed material, not far from the 40% sand optimum observed by Wilcock & Kenworthy (2002).

Within an event, the coarsest samples were typically the earliest collected (Figure 7). This could be explained by flood bore turbulence enhancing the transport capacity of the flow. Within a flow event, the grain size distribution curve does not otherwise vary systematically. A possible explanation for this variability is the passage of discrete waves of coarser bedload sediment within a more consistent supply of finer bedload. Variation in grain size distribution between events is broader than within an event. The events with lowest peak stage produced the finest sediment distributions.

Though channel geometry is rectangular and simple at the monitoring site, cross sectional variations occur, due to the morpho-texture of the feeder reach. As of next year the inter-event morphology and texture of the feeder reach will be determined using SfM-based DEMS. We identified many gravel deposits and respective high water marks after the July 26, 2018 flood. These demonstrate that bedload fluxes were also very high in anabranches throughout the 250 m wide braided reach located immediately upstream of the monitoring site, so typical of many washes in the SW.

We do not observe any backwater effects from the Río Grande at the monitoring station. During the large July 26 flood, in fact, the Río Grande stage (which serves as local base level) was so low that knickpoint incision occurred, lowering the channel bed elevation by \(\sim 60\) cm just downstream of the site. The sill containing the slot samplers acted as a grade control structure during this event, preventing the incision from advancing farther upstream. Despite this major downstream morphology change, the upstream morphology remained qualitatively the same to pre-flood, with no notable change in the grain size distribution of the bars or thalweg. We anticipate slow re-aggradation of the reach between the samplers and the Río Grande in future events, both due to the lowered slope and the likelihood of higher river stage in future floods.

In conclusion, we observe high bedload fluxes at the Arroyo de los Piños, up to 16 kg s\(^{-1}\) m\(^{-1}\). Initiation of transport occurs at very low water depths, less than 10 cm, so bedload transport occurs essentially whenever flow concentrates in the channel, even in very small, shallow flow events. Both observations are consistent with previously reported results from other unarmored ephemeral channels.
References


