EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **38**, 383–390 (2013)

Published online 16 July 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.3287

Comparison of two stream gauging systems for measuring runoff and sediment yield for a semi-arid watershed

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Received 22 September 2011; Revised 28 May 2012; Accepted 11 June 2012

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ABSTRACT: Our ability to understand erosion processes in semi-arid ecosystems depends on establishing relationships between rainfall and runoff. This requires collection of extensive and accurate hydrologic and sediment data sets. A supercritical flume with a total load traversing slot sediment sampler used on several sites at the Walnut Gulch Experimental Watershed (WGEW) near Tombstone, AZ has proven to be a reliable way to measure flow and sediment discharge from small watersheds. However, it requires installation of a costly structure that is only suitable for relatively small flows. A more commonly used method based on ease of installation and expense is the pump sampler. One example of this is a set of instrumentation developed by the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), in which the pump sediment sampler is part of an in-channel, fully automated system for measuring water velocity, depth, turbidity and collecting runoff samples. A 3.7 ha arid watershed at WGEW was instrumented with both systems and hydrologic and sediment data were collected and compared during a 2 year period. Total sediment yield for the entire period measured by the CSIRO pump sampler (11.6 t ha^{-1}) was similar to that by traversing slot sampler (11.5 t ha^{-1}). The pump sampler accurately estimated the amount of fine (< 0.5 mm) sediment fractions exported, but consistently underestimated the coarse (>0.5 mm) sediment fractions. Median sediment diameter of samples collected by traversing slot and pump sampler were 0.32 and 0.22 mm, respectively. This study outlines the benefits and limitations of the pump sampler based system for monitoring sediment concentration and yield in high-energy headwater catchments, and makes recommendations for improvement of its performance. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: sediment sampler; erosion; sediment yield; runoff; watershed; semiarid

Introduction

Accurately measuring the sediment load in streams is a technically complex and expensive task. Sediment flux data are critical for understanding watershed functions, calibrating erosion models, and landuse planning. Errors in sediment sampling translate into uncertainty of model estimates and may lead to poor management decisions.

A vast majority of research related to sediment sampling has been conducted in perennial streams in humid environment (Reid and Frostick, 1987). Despite the evidence that in many river systems the majority of the sediments are carried during flood events (Wren *et al.*, 2000) sampling techniques in such systems are usually focused on base flow and suspended sediment (van Rijn and Schaafsma, 1986).

The arid environments are characterized by infrequent rainstorms and flash flood hydrologic regime. Sparse vegetation, non-cohesive soils, large transmission losses (Sharma and Murthy, 1994; Renard *et al.*, 2008), rapid mobilization and deposition of sediment in channels (Cohen and Laronne, 2005), all contribute to the sediment regime which is very different from that in humid environments. Desert ephemeral streams produce high total (Cohen and Laronne, 2005; Nichols, 2006) and suspended sediment concentrations (Reid and Frostick, 1987) compared with perennial ones (Turowski *et al.*, 2010). In addition, a larger fraction of the total load in ephemeral systems is transported as bedload (Laronne and Reid, 1993; Nichols, 2003) due to large amounts of coarser sediments.

Total sediment load in the flow is comprised of suspended and bed load. Although this division is arbitrary and varies with discharge magnitude it has significant implication for selection of an appropriate sampling technique. Suspended load is material held by turbulent upward eddies and is carried in the flow without touching the bed or while only intermittently touching it. In arid environment these are typically particles smaller than 0.25 mm while bedload are particles larger than 0.5 mm, the fraction in between being transitional (Malmon *et al.*, 2004). Suspended sediments usually show moderate variation through the vertical profile especially in turbulent flows (Malmon *et al.*, 2004; Fu *et al.*, 2005). The presence of significant amounts of bedload complicates sediment measurement because few techniques capable of sampling it are available (Wren *et al.*, 2000).

Sediment measuring methods available today include direct physical sampling (bottle, pump, slot), acoustic, optical (reflection, refraction, backscatter), nuclear, and remote sensing techniques (van Rijn and Schaafsma, 1986; Wren *et al*., 2000). There is no universal approach that fits every application. The choice of instrumentation is based on hydrological conditions and the type of data sought.

The concentration of sediment in samples obtained by a pump sampler relative to that in ambient flow depends on the orientation of the intake relative to the flow direction and intake velocity (Bosman *et al*., 1987). Orientation of the inlet facing the flow is usually recommended (Wren *et al*., 2000), however perpendicular orientation might be preferable to prevent clogging or under turbulent conditions (Black and Rosenberg, 1994). Samples obtained from a single intake suffer from poor representativeness due to insufficient mixing of water column (Clark *et al*., 2009). At low turbulence 40% difference between sediment concentration in the samples and in the original flow has been reported (Graczyk *et al*., 2000). However, several researchers (Krug and Goddard, 1986; Horowitz *et al*., 1990; Bossong *et al*., 2006) observed smaller, less than 20% differences when comparing depth-integrated and point intake samplers in turbulent flows.

Proportional samplers such as Coshocton wheel (Brakensiek *et al*., 1979), fixed slot (Barnes and Frevert, 1954), and traversing slot sampler (Renard *et al*., 1986), flow splitters (Brown *et al*., 1970; Pathak, 1991) have also been found to produce bias in particle size distribution and total load (Brown *et al*., 1970; Wang *et al*., 1971; Nichols, 2003).

Sediment sampling errors are a combination of spatial, temporal, and analysis errors. Phillips and Walling (1995) found that settling of suspended river sediment for 1 h followed by re-suspension caused increases in mean particle size up to 24%. This warrants the use of nonintrusive and automated systems, which have quick response times and are capable of obtaining large numbers of consecutive measurements.

Studies that directly compare different sampling approaches are limited (Black and Rosenberg, 1994; Harmel and King, 2005; Lecce, 2009; Harmel *et al*., 2010), often conducted for calibration purposes (Gao *et al*., 2008), and deal only with suspended load. Very few studies attempted to evaluate total load samplers performance theoretically (Replogle, 2009) or in the field (Nichols, 2003).

This paper provides a comparison of two gauging systems deployed simultaneously in a small arid watershed with ephemeral flow. One is a flume based traversing slot total sampler, and another is an in-channel system that employs two sediment measuring techniques (pump sampler and optical sensor). The objectives were to: (a) test and compare a simpler alternative to an existing flume-based watershed gauging system; (b) identify limitations and determine ways to improve the performance of the in-stream gauging system.

Methods

Experimental site

The study was conducted on Watershed 103 (31^0 44′ 42″ N; 110^0 3′ 17″ W) located within the 150 km^2 USDA-ARS Walnut Gulch Experimental Watershed (WGEW), which is an ephemeral tributary to San Pedro River in southeastern Arizona, USA. The area supports an array of land uses, among which are cattle grazing, mining, limited urbanization and recreation. The parent material throughout WGEW is deep alluvial fan deposits consisting of clay and silts to boulder conglomerates with inclusion of igneous-intrusive and volcanic rocks in the south and southeast.

The climate of the area is semiarid dominated by the North American Monsoon with highly spatially and temporally varying precipitation pattern. Monsoon storms are typically short-duration, high intensity, localized rainfall events. The mean annual precipitation from 1963 through 2004 at Watershed 103 was 289 mm, with 65% of the total occurring in July, August, and September. Mean annual temperature is 17.7 °C.

Watershed 103 is located at 1362 m above sea level, has an area of 3.7 ha and average slope of 5%. It is covered with shrub, dominated by Creosote (*Larrea tridentata* (DC.) Coville) and Whitethorn (*Acacia constricta* Benth.). Canopy cover reaches 25% during the rainy season, and approximately two-thirds of the ground area is covered with rock and the remaining area is bare soil (Nearing *et al*., 2007). Two soil series on the site are Luckyhill (coarse-loamy, mixed, superactive, thermic Ustic Haplocalcids) and McNeal (fine-loamy, mixed, superactive, thermic Ustic Calciargids) very gravely sandy loam (USDA, 2003). The soil consists of approximately 39% gravel, 32% sand, 16% silt, and 13% clay. The organic carbon content at the surface (0–2.5 cm) ranges from 0 to 1.0%.

The drainage network is well developed and actively incising with local base level control provided by the runoff measuring flume. The main channel near the flume is approximately 1 m deep, 6 m wide with trapezoidal shape and 4% gradient. It is fed by a tributary approximately 4 m upstream of the flume. Channel bed contains large amount of coarse alluvium with particles 1–3 mm and rock fragments up to 20 cm.

Instrumentation and sampling

Precipitation was measured using a weighing-type rain gauge with 0.25 mm, 1 min resolution located on the watershed. The watershed is equipped with a Smith-type supercritical flow flume rated up to 1.4 m^3 s^{-1}. Its design and calibration are described in detail by Smith *et al*. (1981). Flow depth in the flume is measured using a float and pulley mechanism with linear potentiometer, which is calibrated annually. A total load traversing slot sediment sampler (Renard *et al*., 1986) collects depth integrated samples. The size of the sampled sediment is limited by the 13 mm wide opening on the sampler arm. The traversing arm travels across the outlet of the flume and diverts a vertically integrated portion of the flow into 2 L bottles located in a conveyer. Sample collection is triggered when flow depth reaches 0.06 m. The sampling intervals are 3 min during the first 15 min of runoff, 5 min between 15 and 30 min of runoff, and 10 min if runoff continues after 30 min.

A fully automated system for stream monitoring was developed by CSIRO Land and Water (Hawdon *et al*., 2009). The system configuration used in this study enables measurement of water depth, velocity, temperature, turbidity, and collection of runoff samples. Flow depth is measured by pressure transducer (Greenspan Analytical PS7000) with 0 to 2.5 m range and 2.5 mm accuracy. The transducer is also used to detect flow and trigger the autosampler. Velocity is measured by ultrasonic doppler (Unidata Starflow) with 0.02 to 4.5 m s^{-1} range and accuracy equal to 2% of measured velocity. Turbidity is measured using an optical retro-scattering sensor (Analite NEP180) with 0–30 000 NTU range. Runoff samples are collected by a peristaltic pump auto sampler (ISCO 3700) with 24 1-L bottle capacity. The unit draws water through a 10 mm hose and intake strainer with 4 mm aperture. The sensors were mounted on a non-standard metal bracket located in the stream channel 1 m upstream from the flume entrance. The pressure transducer was placed at the channel bed level and other sensors at 5 cm above it. All instruments were controlled using CR10X

(Campbell Scientific) data logger and the system was powered by a 12 V 120 Ah battery and a 20 W solar panel.

Historical flow data were used to determine the initial threshold values, of water depth, that the system used to initiate event sampling and for sample collection. When the water depth in the channel exceeded 80 mm, data from all sensors was logged every 60 s and sampling commenced. Samples were collected when the water level changed by 50 mm or if the stage height did not change by 50 mm within 5 min. If required, the system optimized the sampling routine according to the number of empty bottles remaining in the sampler. This allowed sampling to continue up to the end of the flow event. The sampling hose was purged prior to taking each sample to prevent sample contamination.

Data and analysis

Watershed data gathered for the study included hyetographs and hydrographs (1963–2010) of storm events, sediment concentration in watershed runoff from slot sampler (1995–2010) and pump sampler (2009–10), turbidity, velocity and depth measurements. Channel cross-section at the instrument site and channel profile were surveyed using level and RTK GPS, respectively. Channel survey data were used to determine parameters of Manning's Equation (slope, wetted perimeter, and cross-sectional area). Channel roughness (n) was determined following a procedure (Arcement and Schneider, 1989; Chaudhry, 2007), which involves identifying channel type, factors that cause roughness, and evaluating bed material size. Watershed sediment yield was calculated by integrating the product of sediment concentration and flow rate. Total sediment yield was calculated for the events where three or more sediment samples were obtained (for slot sampler only). Runoff events with fewer than three sediment samples were considered to be inadequately sampled (Nearing *et al.*, 2007). Aggregate size distribution of runoff samples was determined by passing them through a series of sieves with 2, 1, 0.5, 0.25, 0.125, and 0.06 mm openings, oven drying and weighing. Care was taken to avoid breakup of aggregates during the process.

Statistical analysis was performed using SAS 9.1 program (SAS, 2008). In all statistical tests $P = 0.05$ was used, unless otherwise indicated.

Results

Precipitation and runoff

Long-term average rainfall on site is 289 mm y^{-1}. Monthly rainfall varies significantly, with 65% (188 mm) of the total occurring during the monsoon dominated months of July through September. The top 10% of events account for nearly half of the total annual precipitation. Long-term average annual runoff is 7.1% of total precipitation.

The precipitation during monsoon season of 2009 (73 mm) was below and 2010 (231 mm) above the average. During the observation period starting in July 2009 more than 90 rainfall events occurred at the site totaling 420 mm. Among these events, only ten (160 mm) produced measurable runoff (50 mm or 31% of precipitation). The largest of the storms (7/26/09, 37.8 mm) represented a return frequency of approximately 4 years.

Runoff events ranged between 0.2 and 20.7 mm with peak flows of up to 67.2 mm h^{-1} (Table I). A typical hydrograph measured with the flume had a sharp rising limb and well defined single peak that occurred between 1/4 and 1/3 of the event duration (Figure 1). Flow depth measurements obtained by pressure transducer and stage recorder followed similar pattern (Figure 1).

The doppler sensor proved to be an unreliable way to measure flow velocity in the given environment and current setup due to the unstable channel floor and frequent obstructions. Hence, discharge was determined using Manning's equation with $n = 0.07$ (Arcement and Schneider, 1989; Chaudhry, 2007). The in-channel system failed to record three runoff events due to shallow flow (10/28/09 and 9/22/10) and equipment malfunction (7/25/10). Overall the total discharge calculated using Manning's equation compares well with the flume data (Table II). However runoff during small events is underestimated by the in-stream system due to its relatively high flow detection threshold and poor representation of hydrograph tails. On the other hand, the in-stream system overestimated the volume of events with peak flow greater than 0.2 m. This was due to the placement of pressure transducer in close proximity of the flume. Flume entrance being narrower than the channel causes flow to backup resulting in overestimation of flow depth and discharge.

Sediment

The average annual sediment yield from watershed 103 has been 5.1 t ha^{-1} y^{-1} based on 16 years of records and 63 successfully measured sediment events (60% success rate). For a majority of the events that were not measured, the reasons for the lack of measurement were due to small runoff rates or an insufficient number of samples. Annual yields varied from zero (2004) to 18.1 t ha^{-1} y^{-1} (2000) with the largest single event on record generating 6.2 t ha^{-1}. Mean sediment concentration (2.9 ±1.6%) showed statistically significant correlation with discharge and time during the events.

Runoff samples obtained by both the pump and slot samplers were well distributed through the hydrograph. The pump sampled more frequently during abrupt changes in flow depth (Figure 1). The current sampling parameters resulted in an average of 10 samples per event collected by the pump compared with 6 by the slot sampler. From 10 runoff events that occurred during the period of observation 8 were successfully sampled by the

Table I. Comparison and main features of two watershed gauging systems

	Flume	In-channel
Construction	Permanent (fixed base level)	Semi-mobile (minimal flow obstruction)
Max. flow rate m^3s^{-1}	1.4	Not limited
Sample intake	Depth integrated	Point
Intake opening size, mm	13	6
CapacitySamples	20	24
Sampling interval	Fixed, programmable	Dynamic
Other measurements	Stage (flow rate)	velocity, turbidity, temperature, depth (channel cross section is needed to estimate flow rate)

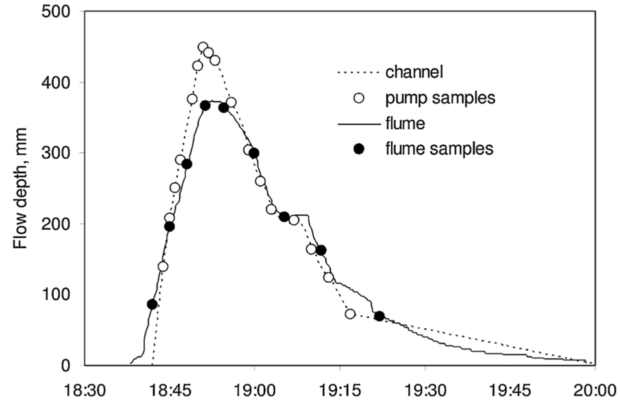

Figure 1. Hydrograph of runoff event on 07/26/10.

traversing slot sampler and 7 by the pump sampler (Table 3). Event sediment yields varied between 0.4 t ha^{-1} and 6.0 t ha^{-1} for the slot and between 0.2 t ha^{-1} and 4.4 t ha^{-1} for the pump sampler (Table III). Total sediment yields for 7 runoff events measured by the slot sampler (11.5 t ha^{-1}) was nearly identical to that measured by the pump sampler (11.6 t ha^{-1}). However, sediment yield of particles smaller than 0.5 mm measured by both system differed with 9.0 and 7.0 t ha^{-1} for slot and pump sampler respectively (Figure 2(a)–(b)). Bed load size particles (>0.5 mm), which according to the slot sampler comprised 40% of the total yield, were underrepresented by pump (22% of total yield).

To test the hypothesis whether sediment yields measured by the two systems were the same a linear regression was used

$$SY_p = \beta_0 + \beta_1 SY_s \quad (1)$$

where SY_p and SY_s are sediment yields (t ha^{-1}) measured by the pump and slot sampler, respectively. The model for total yield (Table IV) was significant (R^2 =0.79, $F_{(1,7)} = 23.2$, $P = 0.005$) while the regression slope was not significantly different from 1, indicating agreement between the two sampling methods. However, the same model applied to various sediment fractions individually (Table II) showed a lack of significant relationships for particles >0.25 mm. There was a general underestimation of coarse sediments measured by the pump sampler as compared to the slot sampler.

Table II. Rainfall and runoff evens and their characteristics as recorded by two measuring systems during the study period

	Precipitation			Runoff					
				Flume			Cross-section 2 m above flume intake		
	total	peak	duration	total	peak	duration	total	peak	duration
Rainfall event	mm	mm h^{-1}	min	mm	mm h^{-1}	min	Mm	mm h^{-1}	min
8/13/09	11.4	61.0	29	2.5	14.1	37	1.5	15.6	12
10/28/09	2.0	5.7	30	1.5	3.2	243			
7/25/10	22.6	68.6	63	3.5	12.2	67			
7/26/10	37.8	160.0	101	20.7	67.2	93	26.7	134.0	33
7/27/10	21.7	137.2	103	10.6	61.4	60	11.8	114.6	16
7/29/10	19.6	68.6	169	3.4	21.5	55	2.9	24.2	18
7/30/10	15.7	53.3	144	1.8	10.4	38	1.4	10.4	13
8/7/10	10.7	144.8	12	3.3	30.3	36	3.9	48.5	12
8/28/10	13.8	99.7	42	3.0	12.2	48	2.6	13.5	21
9/22/10	5.3	30.5	44	0.2	0.9	49			
Total for 7 events*				45.8			50.9		
Total	160			51					
Total for the period	420			51					

*Runoff events successfully measured by both flume and in-channel gauging systems.

Table III. Sediment yield and sediment characteristics during the study period

	Slot sampler			Pump sampler		
	Sediment yield	Mean particle diameter	N samples	Sediment yield	Mean particle diameter	N samples
Runoff event	t ha^{-1}	mm		t ha^{-1}	mm	
8/13/09	0.41	1.31	5	0.19	0.32	7
7/25/10	0.87	1.09	7			
7/26/10	5.99	1.03	9	4.43	0.28	17
7/27/10	2.09	0.79	6	3.07	0.45	14
7/29/10	0.86	1.56	6	0.72	0.60	8
7/30/10	0.47	1.43	5	0.75	0.59	6
8/7/10	0.95	1.64	4	0.70	0.34	9
8/28/10	0.75	1.52	6	1.75	0.53	8
Total for 7 events*	11.52			11.62	0.42	69
Total	12.39	1.13	48			

*Runoff events measured by both flume and in-channel gauging systems.

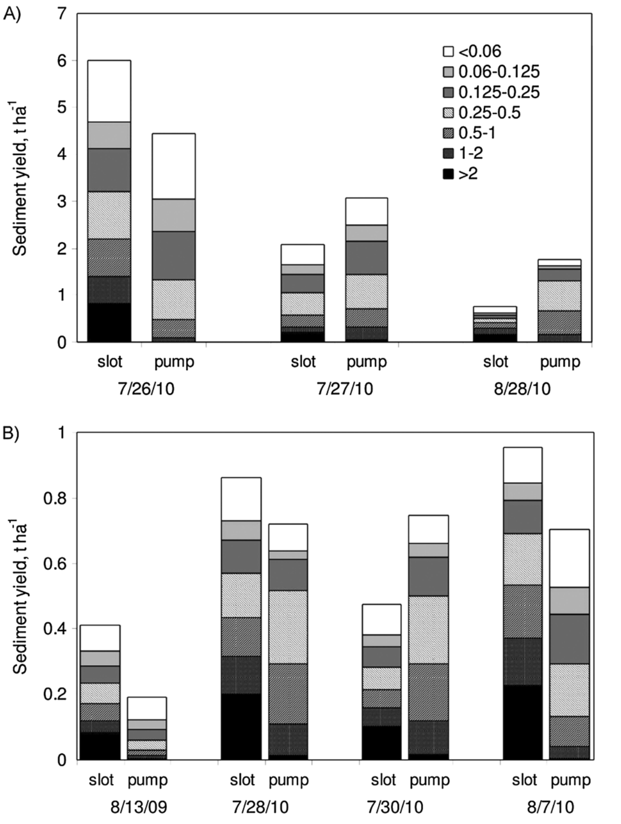

Figure 2. Total sediment yield and particle size distribution as determined from traversing (a) slot (flume) and (b) pump samplers.

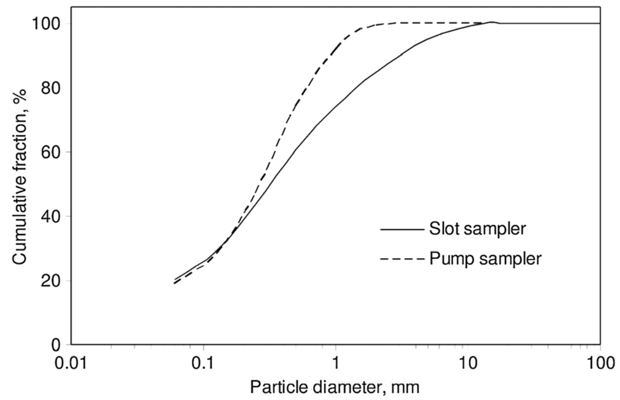

Figure 3. Particle size distribution of sediment collected by slot and pump samplers.

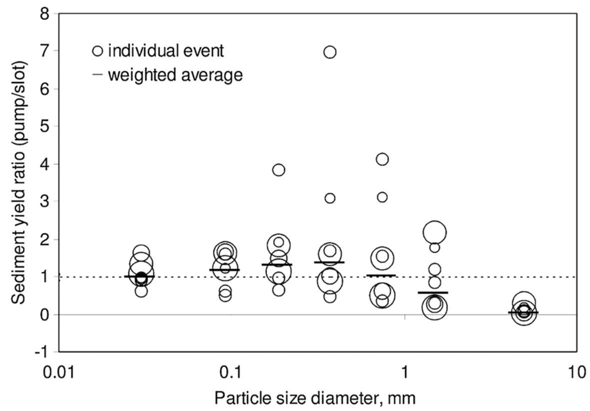

Figure 4. Ratio of sediment yields obtained by pump and traversing slot sampler (by sediment size fraction). The size of the circle represents average runoff rate of the event, which varied between 2.8 and 13.8 mm h^{-1}.

Table IV. Regression equation ($SY_p = \beta_0 + \beta_1 SY_s$) coefficients for comparison between sediment yield obtained by slot and pump sediment samplers during 7 runoff events

Sediment fraction, mm	β_0	β_1	$F_{(1,\ 7)}$	R^2
>2	0.060	−0.014	0.35	−0.12
1–2	0.374	0.013	0.01	−0.20
0.5–1	0.657	0.298	1.34	0.05
0.25–0.5	0.783	0.563#	4.73	0.38
0.125–0.25	0.340	0.713*#	27.25	0.81
0.06–0.125	0.079	0.747*#	126.5	0.95
<0.06	0.166	0.663 *	207.3	0.97
Total	0.497	0.706*#	23.2	0.79

Slope coefficient: *- significantly different from 0, #- not significantly different from 1. $\alpha = 0.05$.

The particle size distribution of all sediment combined is shown in Figure 3 with each sampler represented by a separate curve. The texture of sediments obtained by the two instruments is similar in the fine region (<0.25 mm). Above 0.25 mm the curves deviate from each other, indicating that the slot sampler collected a greater percentage of coarse particles. This deviation is especially pronounced for particles larger than 1 mm, which constitute 25% of total sediment collected by the slot sampler, compared with 8% collected by the pump. Median particle diameter (D50) of sediments collected by traversing slot and pump sampler was 0.32 and 0.22 mm, respectively.

The ability of the pump to obtain representative sediment samples was affected by runoff rate. Figure 4 shows the ratio of sediment yields by particle fraction obtained by the samplers for every event. Average runoff rate of these events varied between 2.8 and 13.4 mm h^{-1} and is represented by the size of the circle. The figure shows that for fine sediments (<0.125 mm) both samplers produced similar results (yield ratio ~1) regardless of the event size. Further, the pump greatly overestimated the amount of 0.125–1 mm particles during low intensity events, however the weighted average for all events in this particle range remained close to 1. Finally, the pump severely underestimated particles > 1 mm regardless of the runoff rate.

The D50 of individual samples was inversely related to runoff rate at which the sample was taken, and this relationship was statistically significant. The slot samples showed greater variation of D50 than pump samples over the range of runoff rates. At 5 mm h^{-1} runoff the D50 of the slot samples was more than double that of pump samples (0.55 and 0.25 mm, respectively), while at 50 mm h^{-1} D50 of samples from both instruments were equal (0.18 mm).

The turbidity meter failed often due to inundation by sediment deposits or other obstructions of the sensor window. As a result we were unable to collect a set of measurements that adequately represented a complete event. Turbidity measurements showed a good relationship with total sediment concentration ($R^2 = 0.60$), however there was considerable scatter in the low concentration range (Figure 5). A power model of the form

$$NTU = 2975{*}TC^{0.246} - 733 \quad (2)$$

was used, where NTU is Nephelometric turbidity units, and TC is total concentration of solids (g L^{-1}). This type of non-linear relationship has been attributed to variations of sediment properties

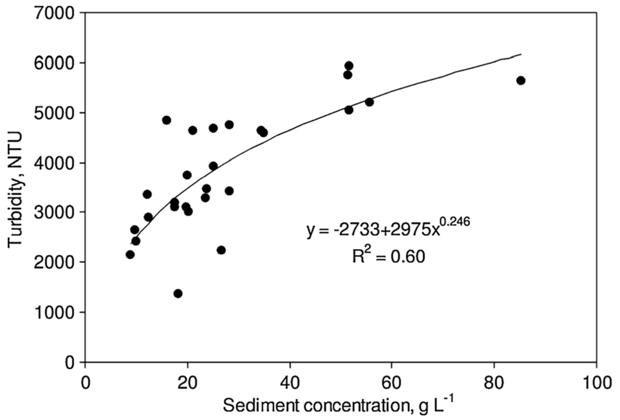

Figure 5. Non-linear relationship between total sediment concentration and turbidity during the study period (all samples combined).

(Gippel, 1995), particularly changes in particle sizes due to variation in discharge (Lewis, 1996). The scatter of data points in the lower section of the graph might be related to sediment size hysteresis when D50 of the sediment on the rising limb of the hydrograph is smaller than that on the receding limb.

Discussion

Slot type sediment samplers are considered to be most accurate among other devices in representing particle sizes in the sample relative to that in the flow (Barnes and Frevert, 1954). This notion is based primarily on theoretical considerations and laboratory tests (Replogle, 2009). Field data that verify the accuracy of these instruments is limited. Nichols (2003), using a traversing slot sampler on a small (0.4–1.5 ha) arid watershed, showed that particles larger than 8 mm were under-represented. The sampler had a 13 mm slot opening, identical to one used in the current study. Based on Nichols' data (2003) it is reasonable to assume that in our study the sediment fraction > 2 might have been underestimated by as much as 25% by the slot sampler. However, considering that particles >2 mm constitute 20% of the total sediment load, their underestimation by a quarter might not be critical. Hence, the traversing slot sampler provides a good reference for comparison of different sediment measuring techniques.

In the samples collected by the pump the concentration of fine particles (<0.125) was similar to that collected by the slot sampler. However, the pump over-represented mid-size particles (0.125–0.5 mm) and under-represented coarse particles (>0.5 mm). The former occurred primarily during low runoff events and the latter during all events regardless of the runoff rate. It suggests that the rate of entrapment of mid size fraction by the pump is most sensitive to flow rate. During turbulent flow events the pump also captured a range of particles that was more similar to that of the slot sampler. It appears that the pump intake was positioned too high to collect coarse particles, but too low to representatively collect intermediate fraction. Varying the intake height might not necessarily rectify particle distribution in the sample, but rather cause other, different fractions to be under- or over-represented.

An improvement over a single intake system could be a depth integrated intake, often employed on small watersheds dominated by overland flow carrying fine sediments (Nichols *et al.*, 2008). However, with the current setup and given channel hydrology this might not provide a satisfactory solution. In the current study the intake was located 5 cm above the channel bottom and could not be positioned lower due to recurring inundation of the channel by sediment deposits. This is typical of dryland streams with substantial bedload and dynamically adjusting channel beds. Hence, any additional intakes in the depth integrated setup would have to be located higher than 5 cm. This would likely increase intake of fine sediment into the sampler and cause further underestimation of coarse (> 0.5 mm) material. A further alternative to quantify bedload yield from small catchments is a bedload trap downstream of the monitoring point, which can be emptied manually between events.

It has been hypothesized (Clark *et al.*, 2009) that automatic pump samplers are not effective at sampling across a wide range of particle sizes especially >0.25 mm even if the flow is well-mixed. Our results suggest that this range of useful application could be extended up to 0.5 mm particles for channels of comparable size. In small arid streams with flash flood hydrology the water column is usually well-mixed and particles smaller than 0.5 mm represent over 60% of total sediment. If the relationship between concentration of fine and coarse particles could be established for a wide range of sediment loads, it would considerably increase the usefulness of pump samplers to predict total sediment loads in a wide range of ephemeral streams.

Turbidity can be used to determine sediment concentration if the proportion of various size particles in the flow remains constant (Gippel, 1995), in which case these two variables are linearly related. This is rarely the case in ephemeral arid channels (Cohen and Laronne, 2005). In our study concentration of fines was relatively stable regardless of the discharge, while the concentration of coarse particles fluctuated significantly: generally increasing with increased discharge and towards the end of the event. Also, the values of sediment concentrations observed in this study (up to 50 g L^{-1}) extend beyond the range where the light scattering technique is commonly applied. Most turbidity–concentration relationships reported in the literature deal with concentrations of a few grams per liter or less (Lane and Sheridan, 2002; Pfannkuche and Schmidt, 2003; Zabaleta *et al.*, 2007; Estrany *et al.*, 2009; Kandler and Seidler, 2009).

For a visible light source specific turbidity (backscatter) is highest for 1 μm particles. It decreases for larger particles with the same concentration (Gippel, 1995). As a result coarse fractions display a poor relationship with turbidity. In addition to this, large particles are more likely to be suspended and come into proximity of the instrument window only during larger discharges, while during low discharge these particles tend to move as bed load passing below the instrument. In a channel with flash flood hydrology this problem is further exacerbated due to changing distance between sensor window and channel floor caused by inundation or abrasion.

Although using turbidity as a surrogate of sediment load could lead to bias due to sensitivity to environmental factors (Gao *et al.*, 2008) or shortcoming in experimental setup, the method, unlike physical sampling, allows one to obtain a large number of consecutive measurements, which may help reduce statistical uncertainty. Turbidity may not be suitable for representing total sediment loads in arid watersheds, however if fine sediment is the primarily interest then the method could be a viable option. It could also be used to fill the gaps in the data obtained by direct sampling.

Contrary to expectation, flow velocity measured by the Doppler was inversely related to total flow depth. This might indicate that during the course of an event, inundation progressed and the distance between the sensor and channel bottom decreased. Fluctuating channel bottom elevation made velocity measurements unreliable because the distance between channel bottom and the instrument at the time of measurement was unknown. The current setup was developed for use in a more stable channel and where the distance between the instrument and the channel is much larger than channel bottom height fluctuations.

Conclusions

This study compares the performance and determines a range of application of a new automated stream gauging system in arid ephemeral streams. A flume based gauge with a total load traversing slot sampler was used as a reference, which despite its limitations (Nichols, 2003; Replogle, 2009) is considered to be the most accurate among available automated systems.

The new system is compact and uses standard components, which simplifies installation and relocation. The sensors mounted on the channel bed cause minimal flow obstruction and interference with erosion and transport processes. The ability to respond to changes in the hydrograph enables the sampler to accurately capture temporal sediment variability. However, this study has shown that the system may have limited application for monitoring small channels dominated by shallow flows with high sediment fluxes.

The total sediment yield measured by pump sampler was 9.7 t ha^{-1}, which underestimated that of the slot sampler (11.5 t ha^{-1}) by 16%. The pump sampler adequately measured particles <0.5 mm in diameter, while the coarse fraction (>0.5 mm) was greatly under-sampled. However, this was only true for high rate (>20 mm h^{-1}) flows. At smaller flows (<20 mm h^{-1}) only particles in the 0 to 0.25 mm were adequately measured, indicating that pump sampler performance is dependent upon discharge. Further improvements could be made by incorporating a depth integrated intake or by establishing a relationship between suspended sediment concentration and bed load to account for sampling bias.

Turbidity and sediment concentration were strongly related. The optical technique performed unreliably under the current circumstances, but it could be improved if inundation of the sensor is eliminated. Despite lower accuracy and narrower range of use in comparison with physical sampling, the optical method has the advantage of obtaining large numbers of measurements to overcome errors associated with variability.

The instruments examined in this study were designed to measure different populations of particles. The pump sampler and turbidity probe have inherent limitations with respect to particle size and are generally better suited to streams with dominant suspended load. The traversing slot sampler was designed for streams that carry substantial bed load and addresses these shortcomings, but is much more intrusive, expensive, and complex. However, there is a significant overlap in application ranges of all these instruments. The choice of a sampler suitable for a particular application will depend on technique constraints, hydrological conditions, and measurement objectives.

Acknowledgements—the authors wish to express their appreciation to the Southwest Watershed Research Center Staff, whose dedicated efforts in collecting data made this research possible.

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