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Quantitative Measurement of Arid Fluvial Processes: Results from an Upland Catchment in Thar Desert

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Abstract: A quantitative study on fluvial processes was carried out in an upland stream catchment (9.3 ha) near Agolai in the NE of Jodhpur district in the Thar Desert in Rajasthan. The catchment of the studied second order ephemeral channel (1.0 - 1.4 km long and 1.0 - 1.5 m deep) has developed on a hill – rocky/gravelly pediment - colluvial plain sequence on rhyolite. Initial results of measurements of channel parameters during two significant runoff generating events of 42 mm and 52 mm in 2007 showed peak discharges of 20 m^3s^{-1} (upstream) and 13 m^3s^{-1} (downstream) that moved sediments (bedload) to distances of 43 m – 141 m in the upstream reach, 6-28 m in the middle reach and 63-95 m in the lower reach. The long profile and cross profile measurements showed a balance between load and discharge through a sequence of alternate deposition and erosion throughout the channel. Hypsometry curves revealed maximum erosion (7.7 cm) in the upper reach and aggradation (2.90 cm) in the lower reach. Cross profile measurements showed bank cuts (6 cm) and vertical incisions (1-2 cm) on the rocky-gravelly V shaped valley in the upper reach, incision (4-30 cm) and localized higher deposition (10-12 cm) in the narrow (<1m) and deep (>1m) U shaped valleys in middle reach and mainly deposition (13 cm) on the wide (1-4 m) and shallow channels (0.1 to 0.2 m) in the lower reach.

Keywords: Arid catchment, Channel morphology, Erosion, Hypsometry, Particle movement, Ephemeral flow, Monitoring, Thar Desert, Rajasthan.

INTRODUCTION

In arid regions, fluvial processes function much less frequently and more episodically than the aeolian processes, but their impacts on landforms and society are large, as noticed on several occasions in the Thar Desert, especially after the high-intensity rainfall events for short period of time during the summer monsoon.

On an average Thar Desert experiences flood-causing rainfall in 2-3 years in a decade, but a maximum of 5 flood-causing rainfall years in a decade was recorded during the 1950s, 1970s and the 1990s (Rao et al. 2006). In most cases the floods are caused when rainfall of ~300 mm or more is recorded in 2-3 consecutive days (Kar et al. 2007). Major flood-causing rainfall during the last three decades took place during 1975, 1979, 1983, 1990 and 2006. In July 1979 intense rainfall of 514-773 mm in the upper catchments of the Luni River basin in 5 days (15-19 July) due to a well-marked monsoon trough resulted in flood in the Luni and its major tributaries, the Jojri, the Guhiya and the Bandi. The flood volume at the confluence of the Luni with the Bandi was estimated to be 2651 mcm. About 6850 km^2 area in Jodhpur-Pali-Pachpadra tract was affected. The peak flood level in the Luni was recorded on 16th July, which traveled to Gandap at the head of the Luni delta by the evening of 18th July (Dhir et al. 1982; Sharma and Vangani, 1982; Vangani, 1997). Heavy rains during the first week of July 1990 and then in the first week of August 1990 also caused flood damages in the Luni basin (Kar, 1994). However, unlike during the 1979 flood, this time the high rainfall was concentrated more in the catchment areas of the Jawai and its tributaries in Pali and Sirohi districts, and hence more impact was felt in those districts. In 2006 several stations in the northern part of Barmer district and adjoining part of Jaisalmer district received rainfall of 300-400 mm during 17-24 August, causing flood (Kar et al. 2007).

Despite such records, there are very few quantitative studies (Sharma and Murthy, 1996; Moharana and Kar, 2002) on the arid stream catchment processes in the Thar Desert, including western Rajasthan, to understand the behaviour of the different catchment parameters during a rainfall event for meaningful control measures. Problems of logistics in installation and maintenance of field instruments, long gaps between the flow-generating rainfall events, uncertain prediction of rainfall and large spatio-temporal variability in the rain events make it difficult for researchers to carry out systematic studies. Yet, the need for quantitative information on the catchment processes has been felt for a long time to model the impacts and to harness the benefits of water and sediment flows. In this paper, we provide some of the initial results from an upland stream catchment to the north-east of Jodhpur in the central part of Thar Desert.

STUDY SITE

The studied catchment (9.3 ha) has developed on a hill – rocky/gravelly pediment - colluvial plain sequence on rhyolite near Agolai, a small town in Jodhpur district of western Rajasthan (Fig. 1). Based on visual interpretation of standard FCC of IRS-L4 satellite images, the catchment's area can be divided into: hills (20%), rocky pediments (13%), gravelly pediments (15.7%) and sandy plains (50%) with an average aeolian sand thickness of 0.8 - 1.0 m, underlain by carbonate nodules in the middle and lower reaches. The sandy plain is used for cultivation of rainfed crops like pearl millet and clusterbean, while much of the gravelly pediment is used for open grazing. The rocky pediment remains largely unused except that it is the principal donor area for runoff. Two ephemeral channels (av. depth 1.0 - 1.5 m), originating from low rhyolite hills (relative relief ~18 m), join together on the pediment to form a second order shallow gully that carries the water and sediments from the catchment to a sink (a pond) about 1 km downstream of the source. The channels are narrow (1-4 m) and deep (0.5 – 1 m) with beds of gravels and fine aeolian sand. In the lower reaches and near the sink, the channel shows a braiding tendency on a small alluvial fan of its own, where aeolian sand interspersed with colluvium brought down from the catchment is the dominant formation.

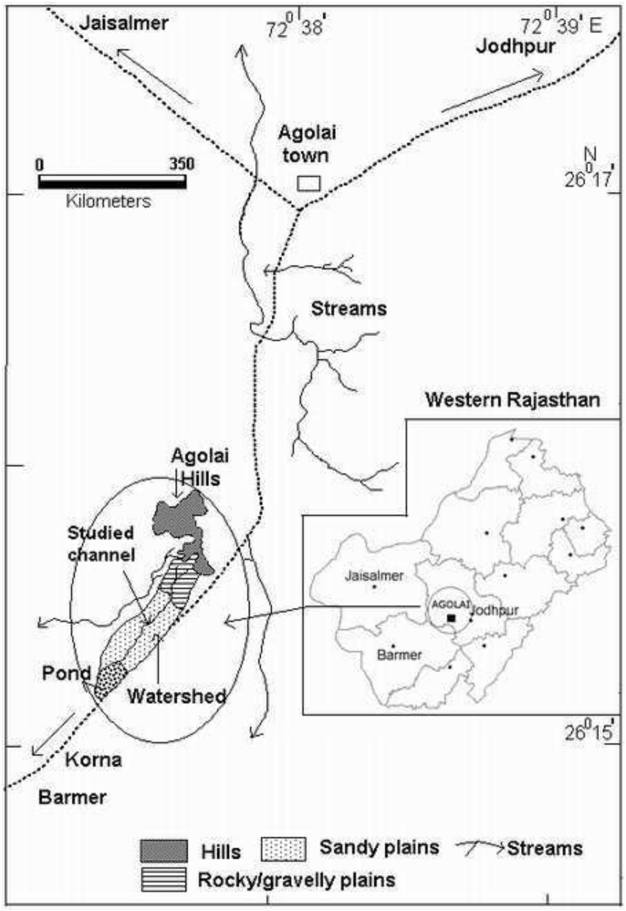

Fig.1. Location of Agolai watershed in Jodhpur district in western Rajasthan.

DATA USED AND METHODOLOGY

A range of field methods (Miller and Leopold, 1970; Graf, 1980) were used to measure erosion from the hill-slopes, gullied channels and stream banks, as well as to monitor the particle movement after a measured rainfall event during the year 2007.

A standard Theodolite was used for measuring height along and across the main channel before and after every runoff-generating rainfall event, which helped to construct hypsometric curves at different time intervals. Long profile of the main channel was measured at 104 fixed locations with reference to a benchmark, both before and after a runoff generating event. Simultaneously, channel cross profiles were measured at 19 locations, for which colored wooden stacks were placed at fixed end points on either side of the channel and height was measured at 40 cm interval.

Discharge was calculated at 6 cross section locations using the Manning equation

$$Q = 1/n\ AR^{2/3}\ S^{1/2}$$

where Q = discharge ($m^3 s^{-1}$); A = cross-sectional area (m^2); R (A/P) = hydraulic radius (m); P= wetted perimeter (m); S = average gradient (m/m) and n = Manning's roughness coefficient.

A rough estimate of velocity was made by measuring the time taken by a float to travel a fixed distance along the channel at selected cross-sections. This was done to see the difference in runoff velocity calculated in the field and using Manning's equation.

To monitor bedload movement along the main channel, we coloured groups of key particles >2 mm size and placed them at different locations along the long profile of the channel: saffron (U1, 185 m from source) and parrot (U2, 335 m) in the upper reach, green (M1, 497m) and blue (M2, at 624 m) in the middle reach, and yellow (L1, 733 m) and red (L2, at 833 m) in the lower reach. Long axis, intermediate axis, short axis and weight of the particles were measured before and after a rainfall event. All the particles were grouped under 3 weight groups of >100 g, 51 - 100 g, and <50 g. Visual detection of painted particles has been found to be a useful method to trace sediment movement (Kondolf, 2003).

The degree of flattening (flatness index) of each particle was calculated using the following equation:

$$FI = E/L \times 100$$

where FI = Flatness index; L = Long axis (length) of pebble; E = short axis of pebble.

The particles were grouped into three categories of FI : <25, 26-50 and >50.

OBSERVATIONS AND RESULTS

Rainfall and Runoff

We measured the channel processes during the summer monsoon of 2007. There were six rainfall events and four runoff events in July-August. Two high rainfall events on the 4th (42 mm) and the 28th August (52 mm), with a total rainfall of 123 mm, resulted in measurable flows along the channels (Fig. 2). Storm rainfall ranged between 9 mm and 52 mm. Runoff varied from 3 to 18%, which yielded 670.4 m^3 of water on 4th August and 895.2 m^3 on 28th August.

The longitudinal profile Fig. 3 shows changes in main channel profile in response to the above two major rainfall events. Two major changes noticed are: (a) the profile was cut by 4.5 - 7.7 cm in the upper section between U1 and U2 and by 0.01 to 0.04 cm between U2 and M1; (b) the middle and the lower sections received deposits of 0.02 - 2.90 cm thickness (at M1,M2, between M2 and L1 and at L1). At the distal end, beyond L2 and up to the pond, 0.42 cm thick deposition took place. The channel was 4 m wide at this location, almost 4 times that at L1 (0.8 m).

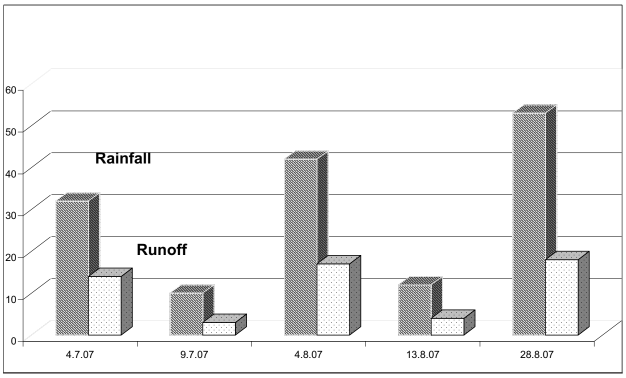

Fig.2. Rainfall and runoff characteristics at Agolai.

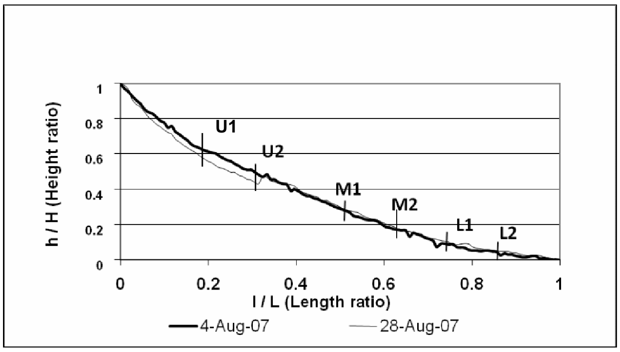

Fig.3. Longitudinal profile of channel for two rainfall events.

Cross Profile

The cross profiles at measured sections (Fig.4) reveal incision as well as deposition of varying dimensions. The upper catchment with an average elevation of 118 m is rocky, barren and devoid of any vegetation with more than 8% slope. The channel here has rock exposure along both bed and banks. Incision at U1 eroded the right bank of the channel by 6 cm. At U2, 150 m distance down the channel, the incision was 1-2 cm less than at U1, occurring along the left bank where 1-3 cm deposition also took place. In the middle reach of the catchment with a barren and undulating gravelly surface (average elevation 103-106 m and slope, 3-4%), the channel, between M2 and L1 is considerably narrow (<1m) and deep (>1m) with a U shaped valley. It experienced high incision and localized higher deposition

Table 1. Depth and width of channel after two rainfall events, 2007

Cross profile	Distance from hills	Channel width (m) August 2007			Channel depth (m) August 2007		
locations	(m)	4th	28th	Change	4th	28th	Change
CP-1(U1)	**185**	**1.1**	**1.12**	**0.02**	**0.53**	**0.55**	**0.02**
CP-2	274	0.9	0.85	-0.05	0.81	0.85	0.04
CP-3(U2)	**335**	**1.43**	**1.45**	**0.02**	**0.36**	**0.4**	**0.04**
CP-4	385	1.15	1.2	0.05	0.5	0.54	0.04
CP-5	440	1.5	1.6	0.1	0.27	0.34	0.07
CP-6(M1)	**497**	**1.4**	**1.45**	**0.05**	**0.33**	**0.35**	**0.02**
CP-7	513	1.4	1.35	-0.05	0.5	0.43	-0.07
CP-8	571	1.28	1.45	0.17	0.39	0.27	-0.12
CP-9(M2)	**624**	**0.85**	**0.9**	**0.05**	**0.58**	**0.66**	**0.08**
CP-10	647	0.6	0.55	-0.05	0.8	0.81	0.01
CP-11	692	0.4	0.42	0.02	0.98	1.28	0.3
CP-12(L1)	**733**	**0.62**	**0.45**	**-0.17**	**1.3**	**1.4**	**0.1**
CP-13	786	0.38	0.39	0.01	1	1.6	0.6
CP-14	807	0.9	1.22	0.32	1.26	1.5	0.24
CP-15(L2)	**833**	**1.42**	**1.45**	**0.03**	**0.66**	**0.6**	**-0.06**
CP-16	861	0.65	0.77	0.12	0.58	0.6	0.02
CP-17	881	1.1	0.95	-0.15	0.89	1.06	0.17
CP-18	901	1.9	1.87	-0.03	0.33	0.3	-0.03
CP-19	926	2.13	2.1	-0.03	0.27	0.25	-0.02

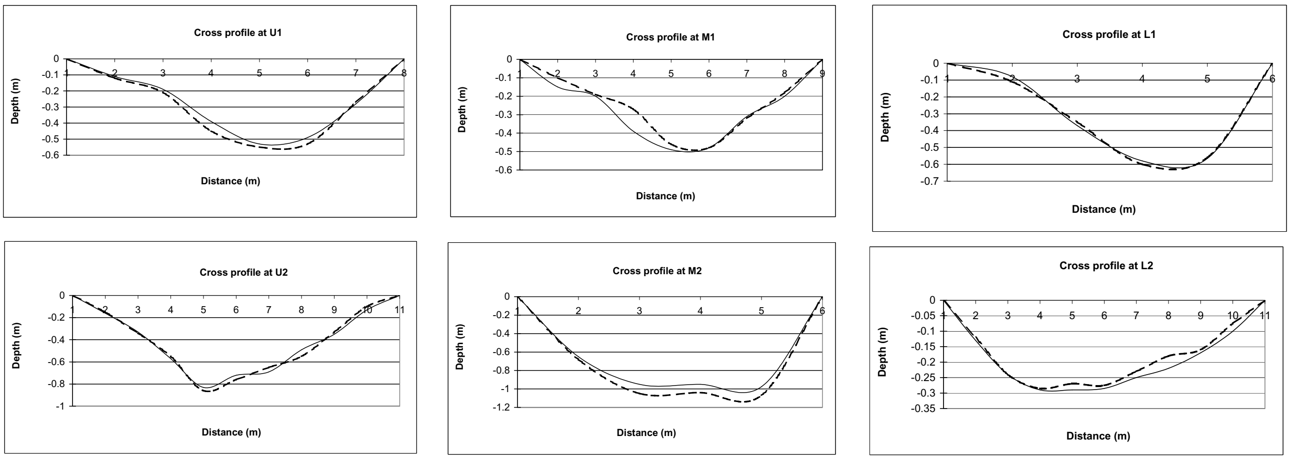

Fig.4. Measured changes in cross profiles at upper (U1 and U2), middle (M1 and M2) and lower sections (L1 and L2) of channel due to high rainfall on 4th August (———) and on 28th August 2007 (– – – –).

(10-12 cm at M2). The lower section of the channel (av. elevation 100 m and slope 0-1%) can be divided into two parts, (1) the section between L1 and L2, where the channel is wider (> 1 m), and (2) the section beyond L2, including the fan area near the pond, where the channel is very wide (>4m) and shallow (0.1 to 0.2 m). These sections mainly recorded deposition. The fan area near the pond recoded maximum deposition of 13 cm, comprising of fine to coarse gravels and rock particles. Notable changes in channel width (Table 1) were recorded between U2 and M2 (0.1 m to 0.17 m) and between L1 and L2 (0.22 m). Localized aggradation caused narrowing of the channel at L1 (0.17m). The difference of width to depth ratio (w/d) was higher (3.8 to 4.3) between U2 and M2, minimum at L1-L2 (0.39 to 1.72). This value however increased to maximum beyond L2 (6 to 9), indicating increase in channel width and more aggradation (Fig 5).

Runoff Discharge

The discharge calculated using Manning's equation for the rainfall events of 4th August and 28th August 2009, shows two peaks at U2 (20 m^3s^{-1}) and at L1 (13 m^3s^{-1}). Moderate discharges were recorded at U1, M1 and M2 (10-12 m^3s^{-1}) and low discharge at L2 (4 m^3s^{-1}). Higher rainfall on 28th August yielded more discharge. The two peak discharges at U2 and L1 were followed by low discharges. At U1, the channel has a rocky bed with >8% slope, and therefore experienced more vertical erosion. At U2, a similar velocity caused lateral erosion along with vertical incision due to a change from rocky to gravelly configuration. The middle reach with inflow of aeolian sand from surrounding croplands and gravels from upstreams makes the channel shallow and wide enough to spill out excess runoff during heavy rains and encourage aggradation between M1 and M2. A lower discharge (av 12 m^3s^{-1}) was noticed in the middle reach. As the runoff entered the lower reach, there was a sharp drop in bed level between M2 (105 m) and L1 (102 m). As mentioned earlier, about 100 m of channel section between M2 and L1 was considerably narrow (<1m) and deep (>1m), making the section constricted. It increased the runoff velocity, causing higher discharge (18.8 $m^3 s^{-1}$) at L1. The channel near L2 is wide downstream, where the discharge dropped (4.9 $m^3 s^{-1}$), leading to deposition mainly on the right bank side, and erosion further down. Such activities (deposition or erosion on either of the banks) lead to burial and resurfacing of particles in desert streams (Schick, 1987) and configures the channel shape which ultimately controls the flow. Beyond L2, within 100 m long run of channel, the bed elevation drops down from 101.21 m to 100.62 m and channel width increases from 1.1 m to 3.3 m. Further down slope, and till the pond, the channel width was maximum (15 m) with a change in bed relief from 0.88 m to 0.33 m. The bedload here consisted of sand, gravel, and rock

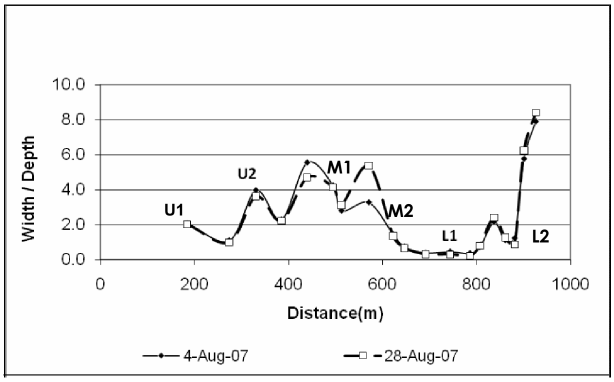

Fig.5. Change in channel width/depth during two major rainfall events.

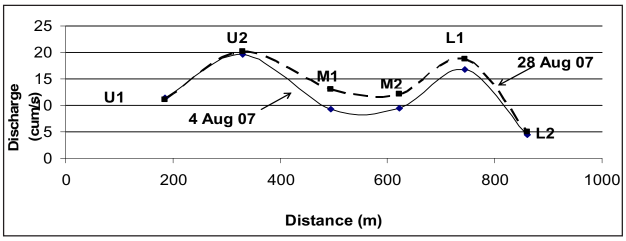

Fig 6. Runoff discharge ($m^3 s^{-1}$) at different locations during two rainfall events

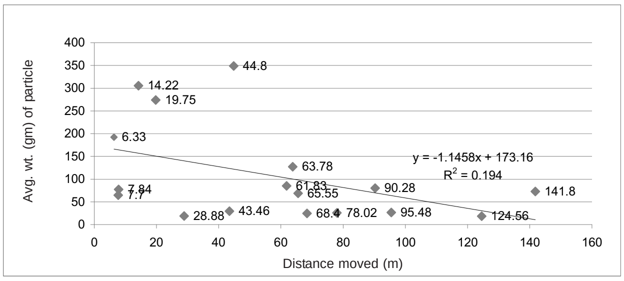

Fig.7. Movement of particles with distance.

fragments. Nearer the pond, the sediments are dominated by fine sand.

Particle Movement

Measurement of the movement of bedload after the two major events is presented in Table 2. Among the lighter weight group (<50 g), the highest (124.56 m) and the lowest (28.80 m) displacements were recorded for U2 and M1 particles, respectively. In the 50-100 g group, the highest displacement (141.8 m) was for U2 and the lowest (~7 m) was for particles in the middle reach (M1 and M2). In case of heavier particles (>100 g), the highest displacement (72.5 and 63.8 m) was confined to lower reaches (L1 and L2 particles) but the lowest displacement (6.33 m) was recorded for M1 particles. In general, 62.5% particles in the upper reach (av wt = 214 g), 87% in the middle reach (av wt = 129.7 g) and 26.4% in the lower reach (av wt = 83.1 g) moved less than 50 m distance. In the lower reach, higher number of particles (36.8% each, with an average weight of 47.5 g and 59.7 g) moved more than 50 m and 100 m distances, respectively.

Flatness Index and Particle Movement

Among the less flat particles (FI ~ 0-25), the highest movement (106 m) was for particles kept at L1 and the lowest was at M1 and M2. In the moderately flat category, particles moved shorter distances (<10m) in the middle section (between M1 and M2). However, particles having high FI (in the >50 categories), moved higher distances as seen at U2 (>100 m). On the whole, particles in the lower reaches (L1 and beyond) moved higher distances (av. of 60-95 m) irrespective of their FI. It was found that particles in the less weight group (< 50 gm) and less flat (FI < 25) experienced the highest displacement (95-106 m). Some of the particles even with more FI experienced higher displacement in the lower reach as they were comparatively lighter. In the middle reach, particles, irrespective of their FI, experienced very less displacement.

DISCUSSION

The present study is an attempt to monitor the upland processes during the infrequent monsoon rainfall in Central Thar and their impact on sediment movement, especially the bedload. Only two significant runoff generating events took place during 2007 that moved bedloads to measurable distances. Our measurements show that the two events produced higher runoff, increased the channel incision, and sediment discharge in the upper section. Although it is commonly believed that the sediment load will flow down the channel to fill the pond (sink), we found that a higher quantum of the sediments displaced from upper section got arrested in the middle reach where the channel maintained a balance between load and discharge through a sequence of alternate deposition and erosion, as evident from the discharge curve (Fig 6). Since runoff contribution from the middle reach was much lower than in the upper reach, the bedload travel depended on the runoff generated in the upper reach. In the sandy lower reach, there were several incidence of down cutting along with

Table 2. Movement of particles under different weight groups

Weight group(g)	Upper reach		Middle reach		Lower reach	
	U1	U2	M1	M2	L1	L2
	Av. Distance traveled (m)		Av. Distance traveled (m)		Av. Distance traveled (m)	
<50	43.5 (29.6)	124.6 (18.5)	28.9 (18.9)	68.4 (24.53)	95.5 (26.6)	78.1 (25.7)
50-100	61.8 (85.1)	141.8 (72.7)	7.84 (77.33)	7.7 (64.6)	65.6 (68.9)	90.3 (80)
>100	19.8 (274.2)	44.8 (348.8)	6.3 (192.2)	14.2 (305.6)	72.5 (185)	63.8 (127.3)

Figures in parenthesis show average weight of the particles in the group

Table 3. Effect of flatness of particles on their movement

Flatness index	U1	U2	M1	M2	L1	L2
<25	48.8	65	5.4	6	106	24.9
26-50	43.16	88.8	7.65	8	104.7	77.9
>50	25.68	107.2	18.13	35.8	58.2	90

aggradation. Under normal topographical situation, this lower section of channel would have received sediments rather eroding it. Erosion occurring at few places, here, was therefore, linked to channel bed topography upstream. Incidentally, the channel width, at this place, was almost half the width at middle reach, while the depth was doubled. The peak discharge has been utilized here to accentuate the erosion through pebbles and gravels that form the majority of sediment. Leopold et al. (1964) also showed that scour tends to occur in reaches that are narrower and deeper, while wider and shallower reaches tend to aggrade. In the lower most reach the dominance of coarse sediments in the beginning and finer deposits near the pond represent the diminishing flow velocity. The wider channel, bifurcation of flow and spreading of sediments over a larger area suggest weak runoff which is a general phenomenon along such ephemeral channels (Schick, 1977).

CONCLUSION

The results of our experiment are based on field observations during two effective rainfall events in the desert. It was found that the apparently low rainfall of desert sometimes causes significant runoffs that can influence channel morphology and sediment movement. At the same time, channel dimensions have also been found to influence the erosion pattern at several locations along the channel. Unlike, the sequential pattern of erosion and depositions in channels in humid channels, here, there has been alternate erosion and depositional activities. This is due to characteristics influence of short duration rainstorms in arid zone, duration and velocity of runoffs and their ability to erode/deposit the sediments. While scouring has remained the dominant erosion process in the upper and in a section of lower part of the channel, the middle and the extreme end of the channel have favoured depositions. Due to such erosion/depositional activities as well as change in channel slope, runoff velocities have been either high or low causing more/less movement of particle. Relationship between particle shape (flatness) and their movement showed that flatness influenced particles in all the sections of channel. In the lower part even more flat particles moved greater distances because those were lighter in weight. Though these observations are based on field measurements, definite conclusions would depend upon the number of traceable particles and the number of observations. The spatial relationship between discharge and erosion/deposition has been good; however, the conventional relationship between velocity-runoff-discharge is yet to be established at each section of the channel which needs a much larger data set. Despite this our preliminary results provide some field level information on process-form interactions along gravel – bed upland ephemeral channels in the monsoon – driven Thar desert that will help to further understand the process and monitor the situation.

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