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International Journal of Sediment Research 26 (2011) 193-209

INTERNATIONAL
JOURNAL OF
SEDIMENT
RESEARCH
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Flash flood sediment transport in a steep sand-bed ephemeral stream

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Abstract

This paper reports about flow and sediment transport measurements undertaken during the rainy season (July-August) 2008 on Gereb Oda, a steep, sand-bed ephemeral stream, draining the western margin of the Kobo structural basin in northern Ethiopia. Gereb Oda streambed is dry for most of the year since it is subjected only to sporadic flash floods in response to individual, high intensity and spatially confined rainstorms. Information about hydraulic and sediment transport processes in steep sand-bed, ephemeral stream is very poor and, though only two flash floods occurred during the field campaign, the data gathered may contribute to improve our knowledge on these kind of rivers. Froude numbers were calculated in order to verify the occurrence of supercritical flow conditions as postulated by a few authors from the analysis of sedimentary structures characteristics. Flow data are also compared to simple models to predict flow velocity and discharge since flow recording systems are seldom installed on ephemeral streams in remote areas and developing countries. Dryland rivers are known for their very high suspended sediment transport, but very little bedload data exist for sand-bed, ephemeral streams. The variation of suspended sediment concentration with discharge is analysed and simple rating curves for both suspended and bed load transport are derived. A few equations to predict bedload are tested against Gereb Oda data and the relationship between en masse bedload transport processes as thin sand sheets and the development of horizontal lamination through the migration of leaf-shaped, sheet-like bedforms is investigated. Individual, large boulders were observed to move at flow depths of the same order of magnitude of their size. A few functions to predict the threshold conditions for large particles entrainment are used to verify if and to what extent they match Gereb Oda field conditions. The increased density of the water-sediment mixture, for the very high suspended sediment concentrations ranging from 100,000 to 200,000 ppm, is considered as well.

Key Words: Ephemeral stream, Bedload, Suspended load, Flash flood, Ethiopia

1 Introduction

Arid and semi-arid landscapes are sculptured by drainage systems that bear a water flow for no more than 20% of the time. Dryland rivers are not supplied by groundwater and flow is intermittent and impulsive, as it is generated in response to individual, short and high intensity rainstorms. Ephemeral streams floods are very short (from minutes to hours), have a high ratio of large to small flows (Tooth, 2000) and hence deploy a large quantity of energy that is dissipated through the entrainment of large amounts of sediment, channel scouring, avulsions and downstream water loss for infiltration. Both suspended and bed sediment transport of ephemeral streams are reported to be very high (Laronne and Reid, 1993; Sharma and Murthy, 1994; Nanson et al., 2002) and, according to a few authors (Powell et al., 1996; Alhamid and Reid, 2002), suspended sediment dominates the total sediment yield of dryland catchments whereas others found bedload to make up the most of sediment flux (68% in southern Negev, hyper-arid study basin of Schick and Lekach, 1993). These conclusions are based on few field studies but support the general convincement that infrequent floods may concentrate the sediment supply, expected to

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Note: The original manuscript of this paper was received in Sept. 2010. The revised version was received in Mar. 2011. Discussion open until June 2012.

be high due to the sparse vegetation on slopes. Though sediment dynamics processes such as erosion and deposition can increase the frequency of overbank flooding and infrastructures damage, field measurements of sediment transport of ephemeral streams are very small in number (Chang, 1994; Dunkerley and Brown, 1999). In fact, permanent field installations are very expensive as all the measuring equipments are to be automatized and require a relatively high technology to be ready to work properly after long intervals of inactivity. On the other hand, direct, hand-made measurements are difficult because of our limited capacity to predict the erratic rainstorms producing ephemeral streams floods and their flashyness. As a result of that, flow and sediment transport data are commonly collected during the receding flood flows (Nordin, 1963; Bourke, 2002). Very good data sets have been obtained by fixed installations on two gravel bed streams in the Negev desert (Laronne and Reid, 1993; Schick and Lekach, 1993), whereas bedload data of sand-bed ephemeral streams are very poor. Reid and Laronne (1995) and Mussetter (1994) have attempted to predict bedload for a gravel bed river in Israel and a couple of sand-bed ephemeral streams in Arizona, respectively, by using a few of the most renown equations developed for perennial rivers. Their attempts were unsuccessful for a number of reasons, including the lack of armouring in gravel bed streams, the lack of information on the threshold conditions for bed particles motion as the onset of the flood bore and the particle entrainment are almost instantaneous (Reid et al., 1998) and, especially in sand-bed and pebbly sand-bed rivers, the large amount of suspended sediment that may change the viscosity and density property of the carrier flow, significantly affecting the sediment transport capacity of the stream (Scott, 2006) and inducing the entrainment and transport of large particles at low flow depths (Billi, 2008). Reid et al. (1998) obtained a good power relationship linking their field data of bedload flux with shear stress for a gravel bed river in Israel, whereas Mussetter (1994) found his equation to overpredict the bed material load of two steep, sand-bed arroyos. Given the lack of studies and data on bedload transport in sand-bed ephemeral streams and the common occurrence of these kind of rivers in many drylands of the planet, the need for field measurements and testing of existing bedload equations is patent and straightforward.

Moreover, in many ephemeral streams high concentrations of suspended sediment are commonly observed (Leopold and Miller, 1956; Nordin, 1963; Dunkerley and Brown, 1999; Alexandrov et al., 2003). They can be as much as 200,000 ppm by weight (9% by volume) leading to hyperconcentrated flows conditions (generally from 1 to 25%) (Pierson and Costa, 1987; Coussot and Meunier, 1996; Svendsen et al., 2003). According to these authors, hyperconcentrated flows are two-phase stream flows with intense bedload in which solid particles are essentially dragged by water. Billi (2008) has described the sandy gravelly deposits of a few ephemeral streams in Ethiopia as typically massive, with crude horizontal stratification, no scour and fill structures and commonly punctuated by outsized cobbles and boulders. This author has interpreted these sediment characteristics and the ubiquitous occurrence of horizontal lamination as produced by hyperconcentrated turbulent flows at near critical or supercritical conditions. Billi (2008) has also postulated that the increased density of the sediment-water mixture may favour bouncing conditions and the entrainment and transport for long distances of outsized boulders even with flow depth of the same order of magnitude of their largest diameter. These larger particles were found to make up the core of the coarsest divisions and to be overlain by thinly horizontally laminated sand deposited during the flood recession limb by flows maintaining critical or near critical conditions (Billi, 2008).

The objective of this paper is therefore to verify the occurrence of hyperconcentrated flows during flash floods, their characteristic Froude numbers, their capacity to entrain outsized boulders and to understand the factors affecting sediment transport processes. A few equations to predict bedload transport are tested against field data in order to contribute to develop a model for predicting the sediment flux of sand-bed ephemeral streams at unmeasured locations. Furthermore, to understand the basic dynamics of sediment transport in ephemeral channels is crucial to predict and mitigate flash flood impacts on infrastructures and human activities. To shed some light on this complexity, field measurements of flow, bed and suspended load were undertaken during flash floods in the Gereb Oda, a sand-bed ephemeral stream of the Kobo basin in Tigray (northern Ethiopia). Though, unexpectedly, only two floods occurred during the big rains season field campaign of 2008, the data gathered may contribute to expand the very poor data sets reported in the literature (Leopold and Miller, 1956; Nordin, 1963; Dunkerley and Brown, 1999; Bourke, 2002) on hydraulics and sediment transport processes in sandbed ephemeral streams. More data on a larger range of discharges are however needed to make an exaustive comparison with rivers in different climatic setting, nevertheless, the Gereb Oda data, though limited in number, can provide an insight on the peculiar behaviour of sandbed ephemeral streams, the observation of which is limited by the flashyness of floods and the difficulty of using fixed installation, especially for bedload transport measurement.

2 Study area

The Gereb Oda R. drains the western margin of the Kobo structural basin (Fig. 1). Its catchment has an elongated shape in a west-east direction and an area of about 68 km^2. The relief ratio is very high since the most and the least elevated points are at 3,288 m and 1,400 m, respectively. Bedrock consists mainly of basalts of the Tertiary main trap series, limited outcrops of Oligocene-Miocene rhyolitic ignimbrites and tuffs and the Quaternary basin filling, in which the lower reaches of ephemeral streams are incised (Merla et al., 1979).

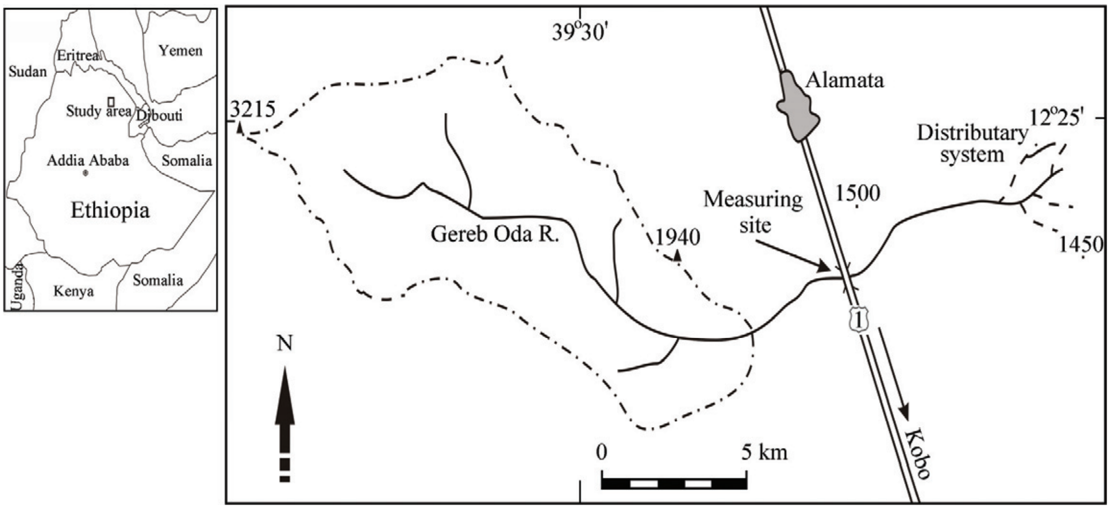

Fig. 1 Location map of Gereb Oda study river

The climate of the area is characterised by three seasons; the dry spell from October to February, the short rains from March to May and the big, monsoon type rains from July to September. At the nearest gauging station of Alamata, mean monthly minimum and maximum temperatures range from 12.4 and 26.9°C in January to 18.5 and 34.1 °C in June, respectively.

Annual precipitation amounts to 768 mm (63 rainy days), with about 171 mm (12.5 rainy days) in the dry spell, 209 mm (16.6 rainy days) in the small rains and 355 mm (30.1 rainy days) in the big rains. The rain gauge in Alamata provides only daily rainfall intensities. The maximum rainfall intensity in the 1969-2003 interval is 96 mm day^{-1}, recorded in August 1992, but peaks higher than 50 mm day^{-1} are recorded in every month with the exception of September (Fig. 2). Rainfall occurs as very intense, confined downpours typically lasting no more than one hour. Field observations indicate that the actual rainfall intensities, especially during the big rains, may be as much as 50 mm hr^{-1}, with virtual peaks of 200 mm hr^{-1}. The hydrological response of Gereb Oda to such high intensity rain is very fast, given the small size of its catchment and its elongated shape, and the flood bore may reach the measuring site, located at the bridge of the main Kobo-Alamata road (Fig. 1), in less than a couple of hours after the beginning of the rainstorm.

Unfortunately, neither the Gereb Oda nor all the other rivers of the Kobo basin are equipped with flow gauges, hence there is no information about their flow hydrology characteristics.

The Gereb Oda headwater catchment is covered by sparse bushy vegetation with large portions of bare soil and very small terraced cultivations. The Kobo basin floor is instead totally cultivated.

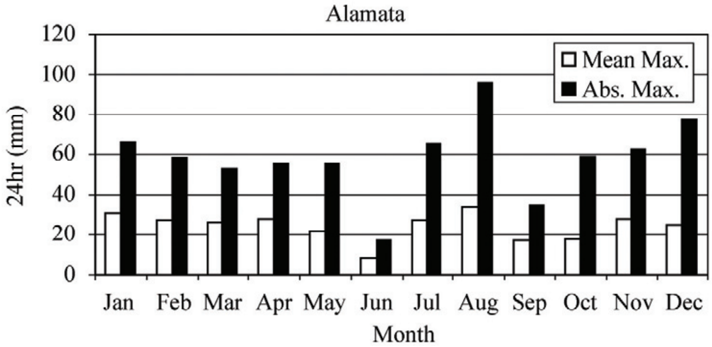

Fig. 2 Monthly mean maximum and absolute maximum of rainfall intensity in 24 hours at Alamata

3 Field measurements

The measuring section was set at the bridge of the main road from Kobo to Alamata (Fig. 1). The bridge consists of two rectangular spans, 12 m wide each (Fig. 3). The river reach upstream of the bridge is straight and about 120 m long. The streambed gradient is 0.0148 and 0.0133 upstream and downstream of the measuring section, respectively. The main bed material grain-size characteristics are the following: D_{16} = 0.15 mm, D_{50} = 0.57 mm, D_{84} = 9.4 mm, standard deviation 2.8 mm (Fig. 4). Bed material grain size distribution was obtained by transect line, frequency by number sampling method (Leopold, 1970). Since bed material is for two thirds sand and for one third fine gravel, the sandy particles were identified by means of a visual comparator with specimens of all the sand fractions arranged on 1/2 phi scale. The modal class grain of the sand in a 1×1 cm area near the meter dent is considered and visually compared to the reference sieve specimens (Billi, unpublished). The frequency distribution of transect line surface samples are equivalent to bulk bed material samples and, hence, can be compared to bedload samples without applying any conversion factor (Kellerhals and Bray, 1971). Scattered, large boulders, as much as 0.2-0.4 m in intermediate diameter, rest on the streambed surface (Fig. 3).

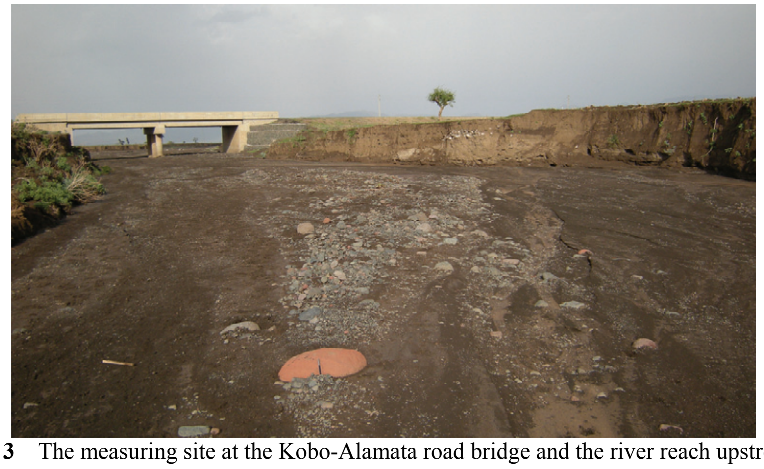

Fig. 3 The measuring site at the Kobo-Alamata road bridge and the river reach upstream. Notice the streambed flat morphology and the scattered large boulders resting on it

The bed of the reach approaching the measuring section is flat and devoid of any relevant bedform, with plane bed prevailing on very thin (20-50 mm thick), overlapping leaf-shaped sandy sheets and accumulations of coarser material in the form of poorly defined longitudinal bars, mainly resulting from receding flood flow dissection rather than depositional processes (Fig. 3).

The cross-section at the measuring site is very regular and almost rectangular with the deepest point next to the left shoulder of the bridge, where a flow depth staff gauge was installed. Flow velocity was initially planned to be measured with a current meter, but the very shallow flows occurred during the field measuring campaign (maximum flow depth observed 0.45 m) imposed the use of the floats method.

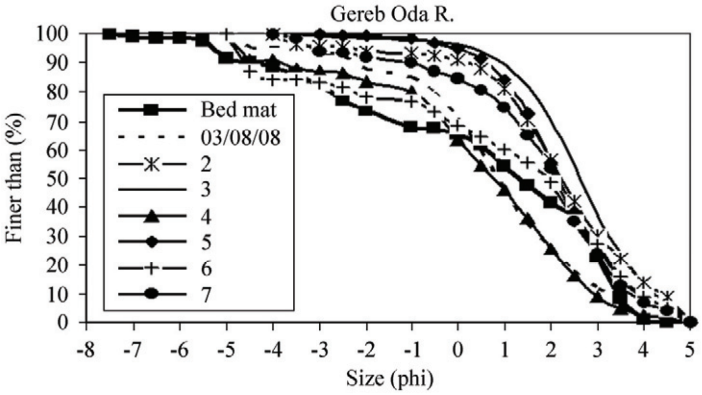

Fig. 4 Grain-size distribution curves for bed material of the reach upstream of the measuring site (thick line), the 3 August 2008 flood bedload sample (dashed line), 2-7 bedload samples taken approximately every 15 minutes during the 6 August 2008 flood (thin lines)

Suspended load was collected by the hand-held, depth integrating sampler US DH-59 and bedload was measured by a standard (1.4 expansion rate) cable suspended, Helley-Smith sampler (Helley and Smith, 1971).

Sediment transport samples were collected along three verticals: two in the left bridge span where most of the flow passes (at one third of bridge span to the left bank and to the central pier) and one in the middle of the right bridge span.

Bedload samples were dry sieved using sieves arranged on a 1/2 phi scale.

The field measurements were undertaken from the last week of July to the last week of August 2008 for statistical analysis indicates that as the time interval with the highest probability of occurrence of high intensity rainstorms capable to produce individual flash floods. Unfortunately, during the 2008 field campaign the monsoon rains were abnormally late and only two flash floods formed in Gereb Oda. The first occurred on August 3, lasted only 45 minutes and was very shallow with a maximum flow depth of 0.2 m. During this very small flood only one sediment transport measurement was undertaken. The second flood occurred on August 6, lasted longer (about two hours) and flow was deeper (maximum depth 0.45 m). Though the data set obtained by this measuring campaign is rather limited, its usefulness and relevance stand in the lack of field data on hydrology and sediment transport of steep, sand-bed ephemeral streams and the difficulty to be on the measuring section at the right time given the flashyness of floods and the current limited capability to predict the runoff response to individual, high intensity rainstorms in arid and semi-arid environments.

4 Data analysis and discussion

4.1 Hydrology

The flashy character of Gereb Oda is well illustrated by the August 6 flood. The flood wave approached the measuring site at hr 15.15 with a discharge of 2.1 m^3s^{-1}, but in 15 minutes it rose to 19.3 m^3s^{-1} and reached its peak at 15.45 with 29.7 m^3s^{-1}. One hour later discharge was again as low as at the beginning of the flood, i.e. 2.6 m^3s^{-1} (Table 1). In Gereb Oda there is no flow record and the flat morphology of the channel, slightly incised in the basil fill alluvium and devoid of large scale bedforms such as bars, does not allow to infer the bankfull channel geometry, so it is not straightforward to rank the discharge measured in terms of return time. McMahon (1979) and Farquharson et al. (1992) have proposed two empirical equations to calculate bankfull discharge for world wide arid zone rivers. They are:

$$Q_{2.33} = 1.22A^{0.58} \quad \text{(McMahon, 1979)} \tag{1}$$

$$Q_{2.33} = 1.87A^{0.58} \quad \text{(Farquharson et al., 1992)} \tag{2}$$

in which $Q_{2.33}$ is bankfull flow (in m^3s^{-1}), i.e. the discharge with 2.33 years return interval and A is catchement area (km^2). Equations (1) and (2) predict for Gereb Oda a bankfull discharge of 14.1 and 21.6 m^3s^{-1}, respectively, with an average value of about 17.8 m^3s^{-1}. According to these calculations, the peak discharge measured during the 6 of August flood is a little higher than bankfull discharge. Bankfull discharge is commonly associated with dominant discharge (Leopold et al., 1964; Andrews, 1980; Torizzo and Pitlick, 2004), but Graf (1988) has argued that for dryland rivers the return time of bankfull flow is higher and probably closer to five years. The dominant discharge of Gereb Oda can be considered to lay within the range of the higher discharges measured during August 6 flood.

Table 1 Main flow data for the flash floods measured on Gereb Oda R

	U (ms^{-1})	Q (m^{3}s^{-1})	h_m (m)	Fr
03/08/2008	1.23	1.549	0.09	1.32
06/08/2008				
hr 15.15	1.70	2.09	0.20	1.21
hr 15.30	2.37	19.34	0.35	1.28
hr 15.40	2.60	24.19	0.40	1.31
hr 15.45	2.83	29.71	0.45	1.35
hr 16.00	2.83	23.11	0.35	1.53
hr 16.15	2.15	7.50	0.30	1.25
hr 16.30	1.96	4.66	0.25	1.23
hr 16.45	1.70	2.64	0.20	1.21

The time from flood bore arrival to flood peak discharge is very fast, between 15 to 30 minutes, and similar to that observed by Reid and Frostick (1987) and Dunkerley and Brown (1999) in a flashy, ephemeral stream of northern Kenya and Australia, respectively.

For the many reasons exposed in the previous paragraphs, ephemeral streams are seldom equipped with flow gauges. So, whenever discharge or flow velocity data are required they have to be inferred from hydraulic models. In order to provide a simple tool to predict or retrodict flash flood discharge and flow velocity a few equations to calculate flow velocity and the Darcy-Weisbach uniform flow equation, combined with roughness criteria reported in the literature as suitable for sand-bed or sandy gravel bed streams have been tested against the field data. The criteria used were the following:

$$U = (gh_mS)^{0.5}4.8(h_m/D_{50})^{0.11} \quad \text{(Grant, 1997)} \tag{3}$$

$$U = 10.8h_m^{0.67}S^{0.33} \quad \text{(Lacey, 1946)} \tag{4}$$

$U = (8gh_mS/f)^{0.5}$ is the Darcy-Weisbach uniform flow equations in which were used the following criteria to asses the friction factor f:

$$1/f^{0.5} = 0.8log(4.35h_m/D_{84}) \quad \text{(Knighton, 1998)} \tag{5}$$

$$1/f^{0.5} = 0.696S^{-0.256} \quad \text{(Bray, 1982)} \tag{6}$$

$$f = [(1-[0.1k_s/h_m])2log(12h_m/k_s)]^{-2} \quad \text{(Thompson and Campbell, 1979)} \tag{7}$$

in which: U is flow velocity [ms^{-1}]; g is acceleration due to gravity [9.88 ms^{-2}]; h_m is mean flow depth [m]; S is streambed gradient; D_{50} and D_{84} are the grain size [m] for which 50 and 84 % respectively of bed material is finer; k_s is the Nikuradse roughness length and following Dunkerley (1992) it has been assumed as equivalent to $2D_{90}$, i.e. two times the grain size for which 90% of bed material is finer.

A comparison between the measured values of flow velocity and those obtained by using Eqs. (3-7) is reported in Fig. 5. The determination coefficient is the same for all the criteria and it is rather high (R^2 = 0.86), but predictions obtained by Grant (1997) and Thompson and Campbell (1979) equation are those closer to the equality line than the results provided by Eqs. (4-6). The good performance of Eq. (7) is particularly surprising since the original work of Thompson and Campbell was intended for a coarse grained, paved channel. The good results are probably due to the different calculation of the Nikuradse coefficient (k_s) adopted by Dunkerley (1992). In fact, in their original work, Thompson and Campbell suggest for k_s a value equivalent to four-five times D_{50}. Likewise Gereb Oda, the study rivers of Dunkerley (1992) are typical dryland rivers with a predominantly sandy bed punctuated by boulder as large as 0.5m. In spite of the prevalence of sand, the most of flow resistance is performed by the boulder particles standing on the streambed surface and Dunkerley's assumption of $k_s = 2D_{90}$ seems reasonable.

Grant's (1997) criterion is based on observations on sand-bed streams with critical and super critical flow conditions, a situation that is common in the Gereb Oda. In fact, during both the 3 and 6 August floods, supercritical flow conditions were commonly observed as confirmed by Froude numbers constantly higher than 1 (Table 2). During these floods, standing waves were a common feature all along the river reach upstream of the measuring site and, at times, standing waves developed into breaking waves. This change was typically induced by the transit (and likely the resting) of outsized boulders such as those in the foreground of Fig. 3.

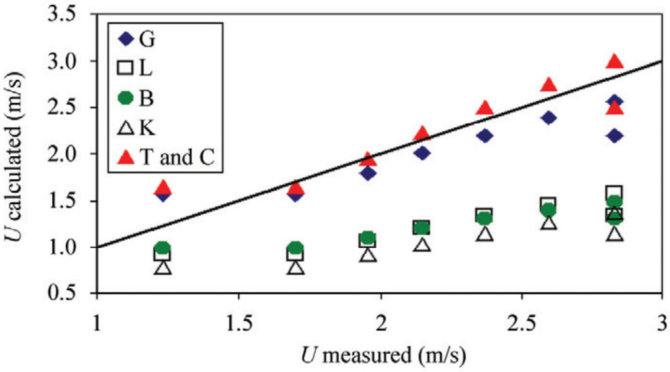

Fig. 5 Comparison between measured and calculated flow velocity by different criteria: G = Grant (1997); L = Lacey (1946); B = Bray (1982); K = Knighton (1998); T&C = Thompson and Campbell (1979)

Table 2 Ratio between measured (Q_{bm}) and predicted (Q_{bp}) bedload rate using different criteria

Criterion	Meyer-Peter and Muller (1948)	Bagnold (1980)	Reid et al. (1998)	Martin (2003)
Mean Q_{bm}/Q_{bp}	0.09	0.05	0.05	1.04
Range	0.04-0.014	0.01-0.09	0.01-0.12	0.35-1.72

The predominance of critical flow conditions, measured on Gereb Oda even at low discharges, were observed also by Nordin (1963) in the Rio Puerco in New Mexico, but contrasts with other authors findings on other dryland rivers, where subcritical flows are more commonly observed (Reid and Frostick, 1987; Dunkerley, 1992; Cohen and Laronne, 2005). Such a difference can be probably accounted for by the streambed gradient of Gereb Oda that is one order of magnitude steeper than the study streams of these authors. It is worth noticing that during the 6 August flood, the Froude number variation follows a counter-clockwise hysteresis curve (Fig. 6). During the receding limb, flow depth decreases at a high rate because of infiltration and, at the same time, deposition takes place smoothing the boundary roughness (Polyakov and Nearing, 2003). The unbalance among gravity, frictional terms and a decreasing flow depth sustains the flow inertia and tends to keep the Froude number high also during the waning flow.

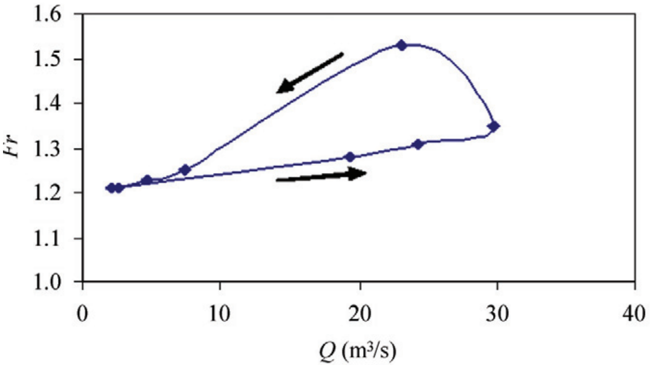

Fig. 6 Counter-clockwise hysteresis curve of Froude number on 6 August 2008 flood

4.2 Suspended sediment

Flash flood, ephemeral streams are known for their high suspended sediment concentration, typically in the range of 10-200 gl^{-1}, with peaks up to 600 gl^{-1} (Boundurant, 1951; Nordin, 1963; Nouh, 1988; Mussetter, 1994; Sharma, 1996; Abdulaziz and Reid, 2002; Alexandrov et al., 2003; Alexandrov et al., 2007) (Fig. 7). Gereb Oda is not exception to this general pattern since suspended sediment concentration was measured to vary between 44 and 136 gl^{-1} (Fig. 7). The highest values of concentrations are close to (Pierson and Costa, 1987) or beyond (Coussot and Meunier, 1996) the threshold for hyperconcentrated flows. The property of the stream fluid may be remarkably influenced by a high content in fine sediment thereby its transport capacity is greatly increased, especially as regards sand. For instance, the Rio Puerco, in which high concentrations of suspended load are commonly observed, is capable to transport, for the same unit discharge, ten times as much sand as the Rio Grande that notoriously has concentrations two order of magnitudes lower (Nordin, 1963). The augmented density of the water/sediment mixture is noteworthy since it provides non conventional conditions for the entrainment and transport of bedbload in general, including the larger bed particles such as cobbles and boulders that are commonly observed to rest scattered on the stream bed of sandy ephemeral streams like Gereb Oda. This issue will be analysed in more detail in the next paragraph.

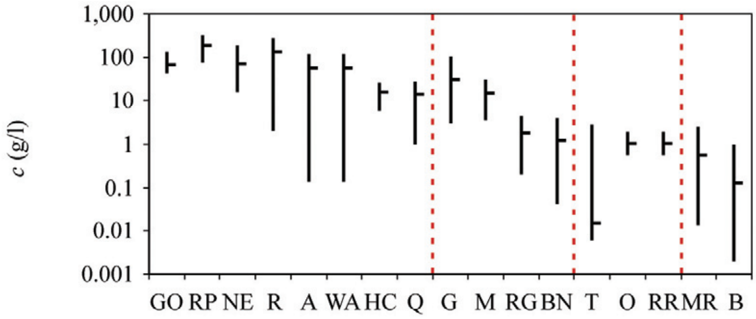

Fig. 7 Range of suspended sediment concentration for rivers in different environments: SAP = semi-arid permanent; Med = Mediterranean; Hum = humid. Rivers: GO = Gereb Oda (this study); RP = Rio Puerco (Nordin, 1963); NE = Nahal Eshtemoa (Alexandrov et al., 2003); R = Rahaf (Cohen and Laronne, 2005); A = Wadi Abd (Achite and Ouillon, 2007); WA = Saudi Arabia wadis (Nouh, 1988); HC = Homestead Creek (Dunkerley and Brown, 1999); Q = Qanna'im. (Cohen and Laronne, 2005); G = Geba (Vanmaercke et al., 2010); M = Meki (Billi, 2000); RG = Rio Grande (Nordin and Beverage, 1965); BN = Blue Nile (Billi and Badri, 2010); T = Tordera (Rovira and Batalla, 2006); Ombrone (Billi and Paris, 2002); RR = Reno (Billi et al., 2007); MR = Malaysia rivers (Ghani et al., 2003); B = Boise (King et al., 2004)

Suspended sediment concentration (C) is commonly associated to flow discharge according to a power relation of the type $C = aQ^b$. The coefficient a and the exponent b assume different values for different morpho-climatic settings, but in most cases the goodness of fit is relatively low. This is accounted for by the natural variability of suspended sediment concentration, affected by a number of factors including time and space variations in sediment supply, the occurrence of hysteresis curves with different patterns, seasonality, channel bed and banks instability leading to pulsed of sediment supply, land use/cover, etc. (Graf, 1988). Also the Gereb Oda does not escape from this rule, though the low correlation ($R^2 = 0.55$) between C and Q refers to just a single flood in which suspended sediment concentration follows a clockwise hysteresis curve and the interpolation function is a straight line. Notwithstanding the data measured on Gereb Oda refer only to an individual flash flood, it is interesting to compare these data with other C-Q rating curves available in the literature for rivers with similar high concentrations, namely the Nahal Eshtemoa in Israel (Alexandrov et al., 2007), Wadi Abd in Algeria (Achite and Ouillon, 2007) and the Wudinghe R., a seasonal tributary of the Yellow R. in China (Xu, 2002) (Fig. 8). In these rivers, but Gereb Oda, the variation of concentration with discharge follows a power function the correlation coefficient of which is low for Wadi Abd ($R^2 = 0.46$) and Wudinghe R. ($R^2 = 0.53$) and relatively high for Nahal Eshtemoa ($R^2 = 0.74$). Higher correlation coefficients were reported by Bourke (2002) for the Todd R. in Australia ($R^2 = 0.99$) and by Cohen and Laronne (2005) ($R^2 = 0.96$) for the Rahaf R. in Israel. Likewise Gereb Oda, these latter data refer to individual floods and not to long time series as is the case of Nahal Eshtemoa and Wadi Abd. Gereb Oda has the highest concentration and its variation pattern almost parallel that of the Wudinghe R. (Fig. 8). By contrast, Nahal Eshtemoa and Wadi Abd concentration patterns are similar with concentration that tends to increase at a reduced rate with respect to discharge (*b* exponent equals 0.5 and 0.75, respectively). These two latter rivers have similar annual precipitation and general physiographic characteristics and their similar response in terms of sediment concentration is not surprising. The *b* exponent of Wudinghe R. is very close to one ($b = 1.12$), as a result of its suspended sediment concentration increasing almost linearly with discharge in response to virtually unlimited sediment supply conditions provided by the extensive occurrence of loess deposits in the catchment. The linear relationship of Gereb Oda seems to indicate that for the flash flood of 6 August, with peak flow close to or a little higher than bankfull discharge, sediment availability on slope is in excess with respect to the transport capacity and volume of runoff. This leads to consider the time interval between consecutive floods and the travelling time of dislocated sediment on slopes as important variables that can explain the poor correlation coefficients of *C*-*Q* plots for ephemeral streams and presently limit our capacity to derive physically deterministic model of suspended sediment transport in desert streams. Further field investigation is however needed.

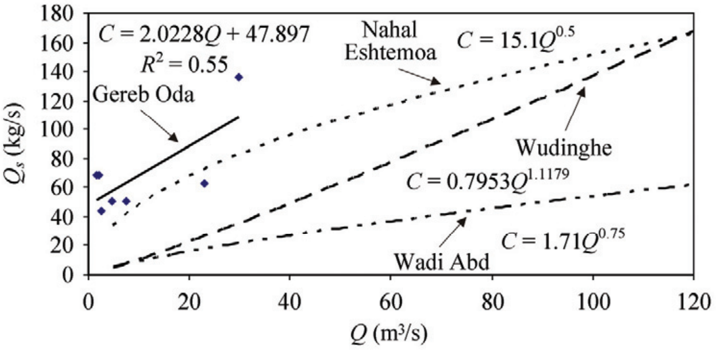

Fig. 8 Suspended sediment concentration rating curves for different rivers: Gereb Oda (this study); Nahal Eshtemoa (Alexandrov et al., 2003); Wudinghe (Xu, 2002); Wadi Abd (Achite and Ouillon, 2007)

According to Seeger et al. (2004), the sediment supply conditions postulated for Gereb Oda should result in a counter-clockwise hysteresis because the sediment sources are widespread throughout the catchment and do not exhaust rapidly. By contrast, in Gereb Oda 6 August flood, the variation of concentration with discharge is represented by a clockwise loop that, according to a few authors (Williams, 1989; Steegen et al., 2000; Seeger et al., 2004) should be generated by low suspended sediment concentration and high superficial runoff coefficients, i.e. a condition that is seldom matched in dryland, ephemeral streams. Other authors (Slattery et al., 2002; Lefrancois et al., 2007), however, suggest a different process of clockwise loops formation. They attribute this pattern to the flushing and subsequent exhaustion of sediment from channel or nearby sources prior to the discharge peak. None of these explanations seem to fully account for the clockwise hysteresis of Gereb Oda. Runoff is very sporadic in this catchment and sediment availability on slopes is relatively high, given the sparse vegetation and large proportions of bare soil on slopes. The 6 August flood was generated by a very short (15-30 minutes) and intense rainstorm and overland flow was able to entrain much of the readily available sediment on the steep slopes. The approach of the flood bore to the measuring site was very fast and peak flow was reached after 30 minutes from the flood beginning. Suspended sediment concentration was therefore very high in the fast rising limb and likely included also a significant proportion of bed material fine sediment. As the flood peak passed by, a moderate decrease in turbidity was observed. Though no data on the grain size of the suspended sediment is available, the high Froude numbers and flow velocity measured in the receding limb lead to presume that as the volume of sediment readily available on slope has been washed out during the rising limb, turbidity decreased but not at a fast rate because of a relative increase in the suspension of fine bed material. Though these observations confirm the role of bed material suspension during the receding flood flow, postulated by Bourke (2002), further field data are necessary to support this hypothesis.

Unlike concentration, the suspended sediment transport rate (Q_s) of Gereb Oda is very well correlated with discharge (R^2 = 0.97) (Fig. 9) through an exponential relationship ($Q_s = 108.11e^{0.1202Q}$ in which Q_s is in kgs^{-1}). This is again a marked difference with other ephemeral streams for typically Q_s-Q relationship varies according to a power low, the correlation coefficient of which, however, is not so high (Negev, 1969; Renard and Laursen, 1975; Lekach and Schick, 1982; Powell et al., 1996) (Fig. 6.2) (for instance, in Wadi Abd, $Q_s = 1.712Q^{1.769}$ and R^2 = 0.826 - Achite and Ouillon, 2007). In a sand-bed stream, bed scour and fill structures are very uncommon and a few authors (Svendsen et al., 2003; Billi, 2008) have associated that with hyperconcentrated flows. The sparse vegetation of Gereb Oda catchment, the very intense rainstorms and the sandy bed provide conditions for virtual unlimited sediment supply. Moreover, Frostick et al. (1983) and Reid and Frostick (1987) have shown that in sand-bed ephemeral streams, where bed material is an important source of suspensible material, suspended sediment discharge depends not only on sediment supply from slopes, but also on flow energy parameters such as shear stress (Renard and Laursen, 1975). In Gereb Oda, as discharge increases, significant large proportion of bed material are therefore expected to be put in suspension, significantly contributing to feed suspended sediment concentration and, hence, resulting in a marked increase of suspend load transport at any even small increment in flow discharge. This seems to support the opinion of Reid et al. (1998) that at the level of individual floods a statistical relation between sediment yield and flood discharge can be reasonably deterministic.

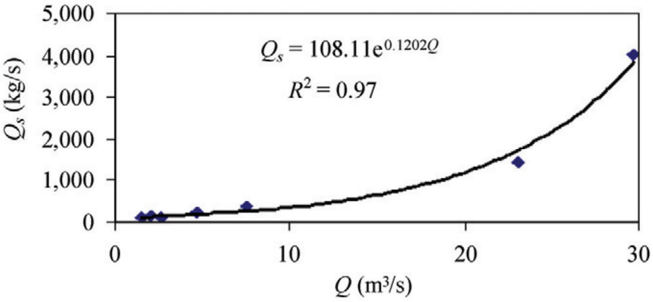

Fig. 9 Suspended sediment transport rating curve for Gereb Oda

4.3 Bedload

Information about bedload transport of sand-bed ephemeral streams is deemed insufficient by many authors (Chang, 1994; Alhamid and Reid, 2002; Scott, 2006) and the data measured on Gereb Oda, though relative to only two flash floods (one of which lasted only 30-45 minutes), may contribute to shed some light on the governing processes and to develop predictive relationships. Bedload transport of dryland, ephemeral streams is notoriously high, higher than their permanent, semi-arid or temperate/sub-humid counterparts (Fig. 10). In Gereb Oda bedload transport rate varied from 0.06 to 1.014 kgm^{-1}s^{-1}, that is equivalent to an instantaneous bedload yield range of 104-2041 tday^{-1}. Bedload D_{50} is commonly finer (0.22-0.38 mm) than bed material D_{50} (0.57 mm), but becomes coarser at peak flow and bedload transport rate (0.79 and 0.83 on 3 and 6 August floods, respectively) (Fig. 4). Since in general the transport capacity of Gereb Oda flood flows is in large excess as regards sand, the observation of the previous paragraph that as discharge increases a larger proportion of bed material fines is transported in suspension (resulting in a relative coarsening of bedload) seems to be confirmed.

The total sediment transport to bedload ratio is lower than what expected since it ranges from 0.004 to 0.018. Schick and Lekach (1993) report that bedload makes up 68% of total sediment transport in their hyper-arid basin of the southern Negev. Gereb Oda data are closer to, though still far from, the data of Powel et al. (1996) that for their study river in the Negev found a ratio of 0.08. Gereb Oda low ratio is not surprising since this river has a sandy bed compared to the gravelly sand, albeit not armoured, bed of the Negev streams ($6<D_{50}<20$ mm) and a steeper bed gradient (0.0148 and 0.0087 for Gereb Oda and Nahal Yatir, respectively) that may respond quickly and in a more deterministic way to the increase in shear stress (Frostick et al., 1983; Reid and Frostick, 1987) by transferring a large quantity of fine bed material into suspension.

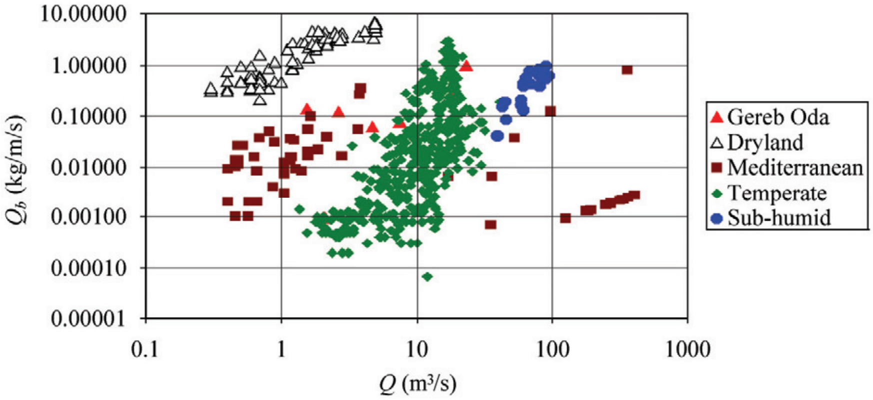

Fig. 10 Comparison of bedload transport rates for Gereb Oda and rivers in different environments

Reid et al. (1996) observed that in dryland rivers bed-load flux responds to changing hydraulic conditions in a comparatively simple fashion. This conclusion is supported by Gerb Oda data whereby bedload is well predicted by the following simple relations:

$$Q_b = 0.0648e^{0.0962Q} \qquad (R^2 = 0.71) \tag{8}$$

$$Y_b = 70.768e^{0.2033Q} \qquad (R^2 = 0.90) \tag{9}$$

$$Q_b = 0.0545e^{0.1684\omega} \qquad (R^2 = 0.75) \tag{10}$$

in which Q_b is bedload transport rate in kgm^{-1}s^{-1}, Y_b is the instantaneous bedload yield in tday^{-1}, Q is flow discharge in m^{3}s^{-1} and ω is unit stream power in kgm^{-1}s^{-1}. The good performance of Eqs. (8-10) contrast with the poor predictions of a few equations specifically developed for dryland (Reid et al., 1998), sand-bed (Bagnold, 1980) and fine grained, non armoured rivers (Meyer-Peter and Muller, 1948; Martin, 2003). Reid et al. equation was derived from the field data on the Nahal Eshtemoa river in the Negev desert and has the form:

$$Q_b = 0.027(\tau\text{-}7)^{1.52} \tag{11}$$

in which τ is shear stress in Nm^{-2}.

In this study, the modified version, sensu Wong and Parker (2006), of Meyer-Peter and Muller was used, whereas Martin's is an empirically derived unit stream power relation, based on the field data set of gravel and sandy gravel bed rivers reported by Gomez and Church (1989), and has the following form:

$$Q_b = 0.0505\,\omega^{0.89} \tag{12}$$

A comparison between measured and predicted bedload by these criteria is reported in Fig. 11. All the criteria used overpredict the bedload transport rate of Gereb Oda (Table II). Bagnold equation has the highest correlation coefficient (R^2 = 0.72), but its predictions are the most distant from field data as the average measured/predicted bedload ratio (Q_{bm}/Q_{bp}) of 0.05 indicates (Table II). Martin equation provides by far the best predictions with Q_{bm}/Q_{bp} = 1.04 (range 0.35-1.72) (Table II), but its correlation coefficient (R^2 = 0.67) is a little lower than Bagnold's. The corrected Meyer-Peter and Muller equation predictions are intermediate between the previous two and the correlation coefficient is lower (R^2 = 0.57). Reid et al. equation overpredicts bedload, its results are in between Bagnold's and the corrected Meyer-Peter and Muller's and has the lowest correlation (R^2 = 0.40).

The good performance of Martin equation is not surprising since in Gereb Oda bedload was found to respond in a simple way to changes in the hydraulic environment as shown by Eqs. (8-10) and as postulated by Reid et al. (1996). The poor predictions of Eq. (11) are probably due to the fact that Gereb Oda has a sandy, steeper bed, whereas the study river of Reid et al. (1998) has a gravel bed and a lower gradient.

During the 6 August flood, at discharges around peak flow, large boulders of 0.3-0.4 m in mean diameter (such as those in the foreground of Fig. 3) were entrained and were observed to travel downstream with flow depths of the same order of magnitude of their size. At peak flow, shear stress was 66.4 Nm^{-2} and maximum flow depth 0.45 m. A few of the most renown equations to predict the threshold for large particles entrainment were test against the field data. The criteria used were: Shields (1936), Milhous

(1973), Baker and Ritter (1975), Carling (1983), Costa (1983) and Williams (1983). The maximum size of particles entrained by peak flow as predicted by these criteria is reported in Table 3. Costa and Williams equations give the best predictions with D_{max} equal to 0.367 and 0.391 m, respectively. Shields criteria provides the lowest value (D_{max} = 0.091 m) and Carling the highest (D_{max} = 1.135 m). Baker and Ritter and Milhous predictions of D_{max} (0.176 and 0.242 m, respectively) are intermediate between Shields' and Costa's. Increasing the fluid density by 10% and 20 % for the high suspended sediment concentration, the results do not change significantly; Costa and Williams predictions are still the closest to the actual boulder size entrained at peak flow, Shields and Carling results are still far from field observations, Baker and Ritter is not improving significantly, whereas Milhous prediction improves remarkably, approximating the size of the large particles entrainment observed in the field. The poor predictions of Shields and Carling are due to their inappropriateness to Gereb Oda field conditions. In fact, Shields criterion was derived from laboratory experiments with uniform size granules whereas Carling's data were measured in a mountain, fine gravel bed river in UK with selective bedload transport, i.e. conditions that do not match those of an ephemeral stream like Gereb Oda. Baker and Ritter equation is based on heterogeneous data and fossil deposits with limited information about flow characteristics and Milhouse entrainment criteria was derived from field measurement on a fine grained, forested river with selective transport in Oregon and, hence, it is not surprising their poor performances. Costa and Williams equations are instead based on a large set of data, including post flood hydraulic measurements, in rivers from a variety of environments, including arid and semi-arid conditions (Costa, 1983). Costa's equation was derived from data of long return interval floods with en mass sediment transport processes prevailing on selective transport hence, given its good performance, is likely the criterion that best depict the entrainment of large boulders in ephemeral streams. The easy way in which boulder are entrained at low flow depths in Gereb Oda seems to confirm the hypothesis of Laronne et al. (1994) and Billi (2008) about the common occurrence during floods of ephemeral streams of almost equal mobility conditions for fine sediment and boulders, with the latter subjected also to buoyancy forces given the high concentration of both suspended and bedload sediment.

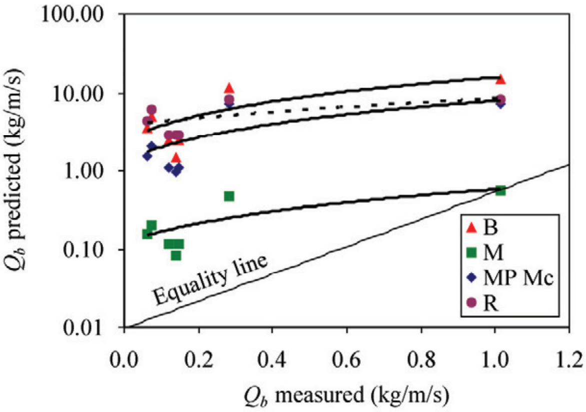

Fig. 11 Plot diagram of measured and predicted bedload transport rate by means of different criteria: B = Bagnold (1980); M = Martin (2003); MPMc = Meyer-Peter and Muller (1948) corrected according to Wong and Parker (2006); R = Reid et al. (1998)

Table 3 Prediction of maximum particle size (D_{max}) entrained at peak discharge of the 6 August 2008 flood according to different criteria

	Shields (1936)	Milhous (1973)	Baker and Ritter (1975)	Carling (1983)	Costa (1983)	Williams (1983)
D_{max} (m)	0.091	0.242	0.176	1.135	0.367	0.391

Billi (2008) has described the typical arrangement of sediment divisions within an individual layer of ephemeral streams of the Kobo basin as consisting of a coarse core division, supporting the large boulders, underlain by a massive or reversely graded, fine gravel and sandy division and overlain by planar, horizontal laminated sand and grains. The horizontal beds are by far the most common sedimentary structure. They are from a few centimetres to a few decimetres thick and consist of massive sand, pebbly sand, clast-supported gravel and grains, roughly horizontal laminated sand and pebbly sand, thin, horizontal laminated sand and grainy sand. Individual beds may be either normally or reversely grade and do not show a distinctive erosive base (Billi, 2008). Billi (2008) has postulated en masse bed material transport to be the prevalent bedload process giving rise to these thin beds. The bedload flux measured during 6 August flood corresponds to a moving bed material layer ranging in thickness from 5 to 250 mm, with an average value of 48 mm. Karim and Kennedy (1983) developed a simple relation to calculate the thickness (T_s) of sandy bedload sheets as

$$T_s = D_{50}(U_*/U_{*c}) \tag{13}$$

in which U_* is shear velocity and U_{*c} is critical shear velocity.

Applying Eq. (13) to the 6 August flood data, a mean bedload sheet thickness of 30 mm is obtained, with 8 and 65 mm extreme values. These results are very close to the field measurements and, albeit more field data are needed, seem to confirm that Karim and Kennedy (1983) criterion can be used for sand-bed ephemeral streams, at least as an attempt to quantify the order of magnitude of bed material bedload sheets thickness.

The sandy bed of all the ephemeral streams of the Kobo basin is commonly flat and devoid of any relevant large and small scale bedforms with the exception of a few centimetres thick leaf-shaped and overlapping sand sheets (Fig. 12). It is worth noticing that the average thickness of these leaf-shaped sheets is 40-50 mm, i.e. very similar to that of the bedload sheets calculated from the bedload sampling and predicted by Karim and Kennedy (1983) equation. Yet, this observations seem to confirm Billi (2008) hypothesis that in sand-bed ephemeral streams bedload transport takes place predominantly through carpet traction processes of thin sheets the thickness of which varies with flow discharge. The leaf-shaped sheets may results from such process and their occurrence may account for the predominance of horizontal lamination and the lack of small scale bedforms like ripples and dunes.

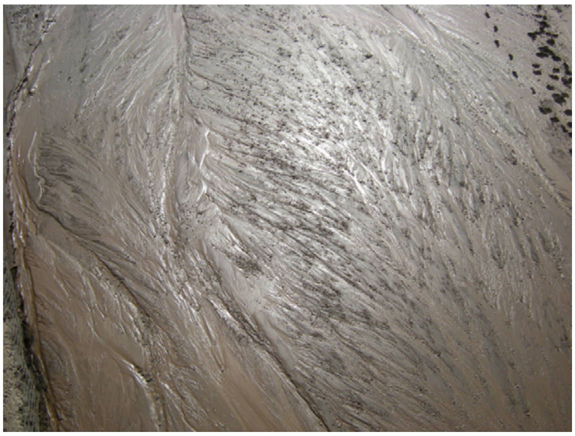

Fig. 12 The thin, leaf-shaped, sheet-like bedforms commonly observed on the streambed of Gereb Oda

5 Conclusions

Though only two floods were measured on Gereb Oda, the data gathered provided an insight into many issues of flow hydraulics and sediment transport in steep, sand-bed ephemeral streams subjected to flash floods. While the limitations of such a small data set are evident, they are balanced by the lack of (and the difficulty of carrying out) field measurements on such dryland rivers. Notwithstanding the individual flood approach, some general conclusions can be drawn:

1) The Thompson and Campbell (1979) friction factor equation and Grant (1997) criterion proved to be the best for predicting flow velocity in Gereb Oda. Though Thompson and Campbell equation was derived for a coarse grained, paved channel, its good performance was obtained by adopting Dunkerley's (1992) calculation of Nikuradse coefficient as equivalent to $2D_{90}$.

2) During the flash floods monitored, Froude number was constantly higher than one and supercritical

flow conditions occurred also at shallow flow depths. The variation of Froude number with discharge follows a counter-clockwise hysteresis curve.

3) Suspended sediment concentration was very high (as much as 136 gl^{-1}) leading close to hyperconcentrated flow conditions.

4) The lack of correlation between suspended sediment concentration and flow discharge is known, but in Gereb Oda the apparent contradiction between the occurrence of a clockwise hysteresis curve of suspended sediment concentration with the high sediment availability on slope, in excess with respect to the transport capacity and volume of runoff, suggest that the dry conditions duration between floods and the travelling time of dislocated sediment from slopes to channel are additional factor that should be taken into account in order to improve our capability to predict suspended sediment transport in dryland streams.

5) Unlike concentration, the suspended sediment transport rate (Q_s) of Gereb Oda is very well correlated ($R^2 = 0.97$) with discharge through an exponential relationship of the type $Q_s = 108.11e^{0.1202Q}$.

6) The grain size of bedload is commonly finer than bed material. However, as discharge increases bedload coarsens (its median size becomes larger than that of bed material) as a larger proportion of fine bed particles is conveyed into suspension, contributing to increase the density of the water-sediment mixture.

7) Gerb Oda bedload transport rate is well predicted by the variation of discharge and unit stream power through exponential functions (Eqs. 8-10). This confirms the observation of Reid et al. (1996) that in ephemeral streams rivers bedload transport responds to changing hydraulic conditions in a comparatively simple fashion.

8) The equations of Reid et al. (1998), Bagnold (1980), Meyer-Peter and Muller (1948), modified according to Wong and Parker (2006) and Martin (2003) to predict bedload transport were tested against the field data. All these criteria over predict the bedload transport rate of Gereb Oda. Martin equation provides the best predictions with an average measured/predicted bedload ratio of 1.04 and a correlation coefficient $R^2 = 0.67$.

9) The streambed of Gereb Oda is punctuated by large boulders of about 0.3-0.4 m. They were observed to be entrained and transported at discharge near to or slightly higher than banbkfull and shallow flows as deep as their size. Costa (1983) and Williams (1983) equations proved to give the best predictions for the entrainment of these large boulders.

Costa's equation was derived from data of long return interval floods with en mass sediment transport processes prevailing on selective transport, hence it is likely the best criterion to calculate the threshold conditions for large particles entrainment in sand-bed ephemeral streams.

10) The only bedforms observed on the stream bed of Gereb Oda are leaf-shaped, thin sand sheet. Their thickness is similar to that of bedload sheets as calculated from the bedload samples and by the Karim and Kennedy (1983) equation. This latter criterion was found to predict with sufficient accuracy the thickness of the sandy bedload sheets. The development of the leaf-shaped bedforms can be associated with the onset of bedload flux and confirms the hypothesis of Billi (2008) about the role of sheet-like bedload transport for the wide occurrence of horizontally laminated sediment and the lack of small scale bedforms on steep, sand-bed ephemeral streams.

Though these conclusions can be tentatively extended to other similar rivers and considered as a starting point for future research, further field studies and data are strongly required to improve our understanding of flash flood processes and streambed response in steep, sand-bed ephemeral streams.

Acknowledgements

The author is grateful to Aklilu Amsalo for his invaluable help in making possible the field work and to Fabrizio Vannacci and Azeb for assistance during the field measurements. The research was funded by National Geographic Society, Committee for Research and Exploration, grant n. 8400-08. This paper was prepared while the author was a visiting professor at the Department of Geography of the University of Gent, Belgium.

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