12 Fluvial Landscape of the Dabaan Basin, Northern Somalia

Paolo Billi

Abstract

The Dabaan is a Middle Eocene to Early Miocene sedimentary basin. It stretches from the plateau margin to the Gulf of Aden and is drained by two main ephemeral streams: the Byoguure and the Kalajab. The climate ranges from semiarid in the headwaters to hyper-arid in the middle and lower reaches. Both rivers have an ephemeral flow regime as they are dry for long periods, and water flows only in response to occasional, very intense rainfalls. Field investigations were carried out to investigate channel morphology and sediment organisation in order to improve our knowledge of dryland rivers hydrology and sediment transport processes. The main morpho-sedimentary units of the streambed were identified and measured. Sediment samples were collected, and detailed observations on bed material sediment organisation, the occurrence of bedforms and sedimentary structures were carried out. The results indicate that, despite the braided channel morphology, the bars do not originate by depositional processes and downstream migration, as in permanent rivers. The bars and the channels, in fact, have no sedimentary structures but horizontal lamination, which implies flows with Froude numbers around one and the formation of a plane bed. During extreme floods, the upper part of the streambed is supposed to move en masse, and the bars are formed by scouring processes during the receding flood flow. Other, much less common bedforms are described. Boulder crescent scours and a new bedform, the cuspate sand waves, are found to be formed in flashy streams and, therefore, are considered as diagnostic of arid environments.

Keywords

Ephemeral streams • Braided channels • Horizontal lamination • Boulder crescent scours • Cuspate sand waves • Dryland

12.1 Introduction

Recently, ephemeral streams have attracted attention of several scientists for their importance as the only surface water resource for irrigation in many drylands (FAO 2010), for their flashy and devastating floods with negative implications such as casualties, property damage and infrastructure destruction (Lin 1999; Billi et al. 2015; Korichi et al. 2016; Pacheco-Guerrero et al. 2017), for their channel dynamics (Demissie et al. 2019), high sediment transport (Billi 2011) and deposition rates (Hooke 2019) and bridge clogging (Demissie et al. 2016) affecting roads and settlements. The sedimentology of modern ephemeral streams is also studied as a valid analogue of ancient dryland depositional systems in the context of oil exploration (Kelly and Olsen 1993; North and Taylor 1996; Billi 2007).

Ephemeral streams have peculiar characteristics that make them very different from perennial rivers of humid and sub-humid areas (Billi et al. 2018). Ephemeral stream channels, in fact, are dry for the most of the time and water flows only in response to sporadic, very intense rainfalls. Such an impulsive nature and the great availability of sediment supply, given sparse or absent vegetation in the headwaters, provide these dryland rivers with high mobility and peculiar geomorphological and sedimentological features that, despite increasing interest from several scientists, are still poorly known.

This chapter reports about the fluvial landscape in the Dabaan basin, an arid zone in northern Somalia, and investigates morphological and sedimentological characteristics of

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two neighbouring ephemeral streams that flow from the margin of the escarpment of the Gulf of Aden trough to the Gulf of Aden coast, near the town of Berbera.

12.2 Study Area

The Dabaan basin is located to the southeast of the town of Berbera, in northern Somalia (Somaliland), and has an approximate area of 600 km^2 (Fig. 12.1). The basin is underlain by Proterozoic to Cambrian rocks of the basement and a 2400 m thick sedimentary sequence of Middle Eocene to Early Miocene age, formed during the early phases of opening of the Gulf of Aden through (Fig. 12.2) (Abbate et al. 1983; Sagri et al. 1989).

To the south, the Dabaan basin is bound by a major faulting system, associated with rifting of the Gulf of Aden that formed a 1500 m high escarpment. The basin structure mainly consists of a mild asymmetric syncline whose northern beds dip southward with an inclination of 15°–20° that tends to decrease in the central part of the basin. In the southern part of the basin, the beds dip northward with high dip angles and the sedimentary sequence is juxtaposed with the crystalline basement along an important fault (Abbate et al. 1983).

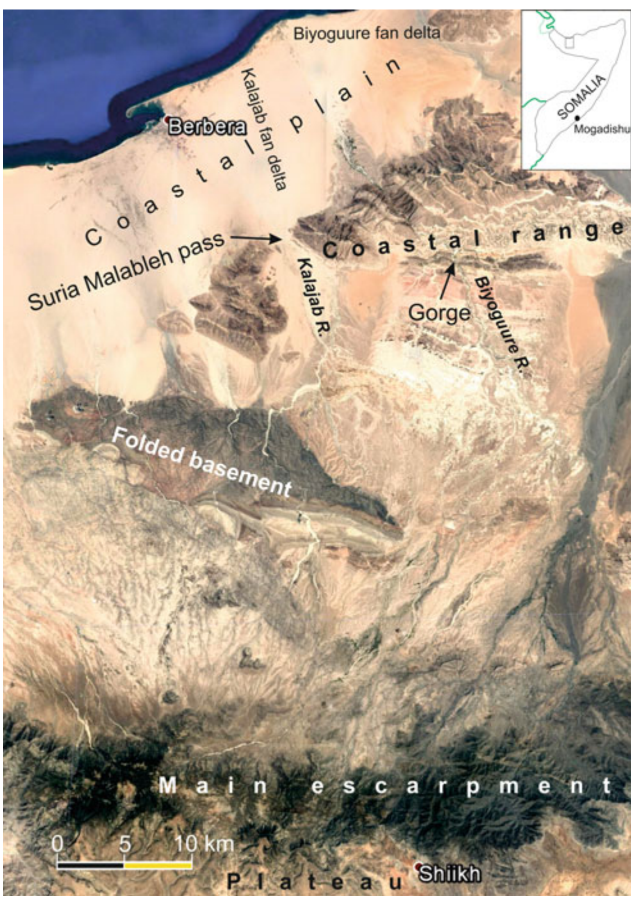

Fig. 12.1 Main physiographic elements of the study area

The studied rivers, the Biyoguure and Kalajab, originate within the rift escarpment margin near the town of Shiikh (Fig. 12.1) and occasionally reach the sea 10 and 4 km east of the town of Berbera, respectively. The catchment of the Biyoguure is about 696 km^2, and the main river stem is about 52 km long. The Kalajab River has a catchment of about 356 km^2 and the length of 33 km (Billi and Tacconi 1985) (Fig. 12.3).

The headwater portions of both catchments are underlain by crystalline rocks of the basement and correspond to the escarpment of the Somali highland plateau. This mountainous part extends from the continental divide to the elevation of 700 m asl and comprises 25% and 10% of the catchment of the Biyoguure and Kalajab, respectively. From the elevation of 700–450 m asl, both rivers flow incised into a gently inclined terrain underlain by the Yesomma Sandstones for about 10 km. Proceeding northward, the two rivers cross the Dabaan Tertiary sequence (Sagri et al. 1989) for a distance of about 20 km, as far as the elevation of 250 m asl. Beyond this reach, both rivers cross the coastal mountain range (the highest peak of which is at 950 m asl) consisting of Mesozoic and Eocene sandstones and evaporates. The Biyoguure River, which probably predates uplift of the coastal range, has incised a deep and narrow gorge (Fig. 12.4), beyond which it enters the coastal plain, where it forms a flat and poorly developed delta and finally debouches into the Gulf of Aden. The Kalajab River crosses the coastal range through a wide saddle (the Suria Malableh pass) (Fig. 12.1), beyond which it forms a large (12 km long and 9 km wide) fan delta between Berbera and the Biyoguure streambed and delta (Fig. 12.5). A large, right branch of Kalajab fan delta joins the Biyoguure about 4.5 km downstream of the coastal range, whereas smaller distributive channels on the left side of the fan delta proceed towards Berbera and its vicinity (Fig. 12.5), which are occasionally flooded.

In both catchments, rock-weathering processes are very active. Slopes are covered by fine rock fragments that are easily washed away by sporadic but intense rainfalls. The flat alluvial paleo-surfaces of the Tertiary deposits in the central part of the catchments are covered by rock fragments, similar to the desert pavement. The larger blocks are not moved because no runoff is generated and are weathered in place; the finer particles are blown away by the wind.

12.2.1 Climate

Unfortunately, very few climatic data are available for the Dabaan basin. Old data, collected by Hunt (1960) for the 1944–1950 interval, were combined with more recent data

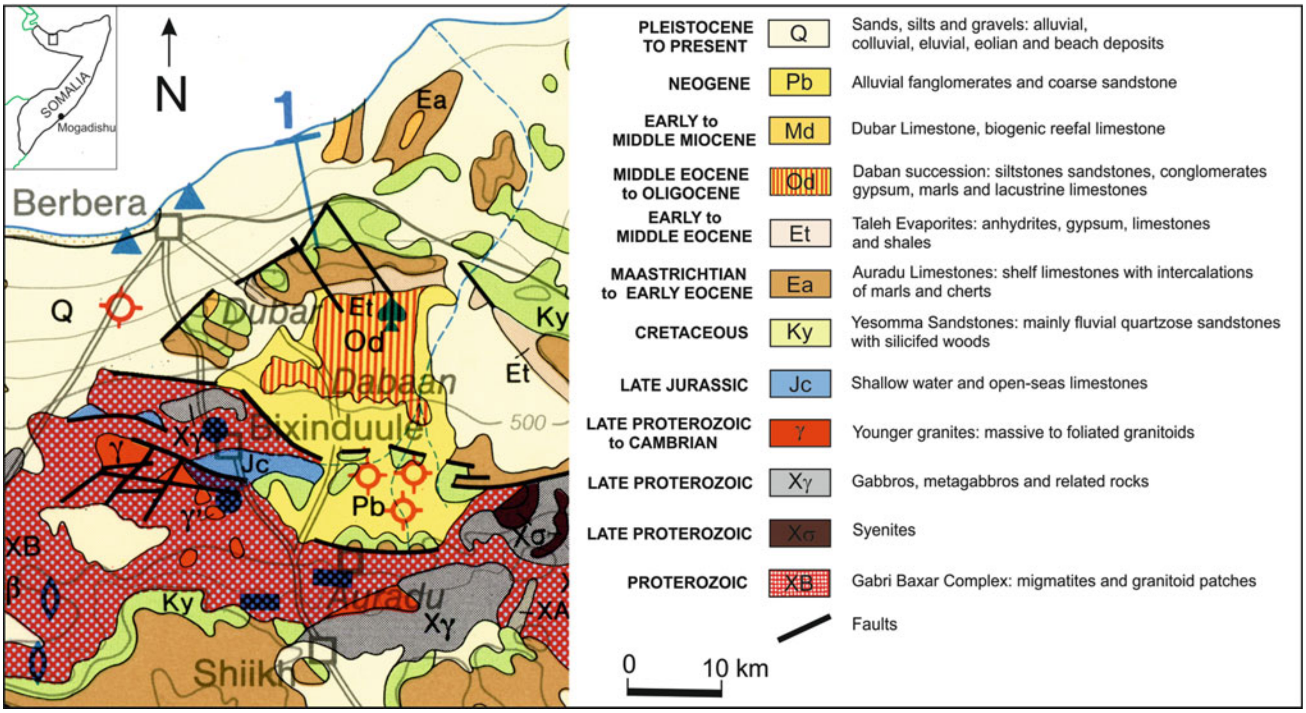

Fig. 12.2 Basic geology of the study are (modified from Abbate et al. 1983 and Sagri et al. 1989). Symbols: red circle = oil well; blue triangle = monazite, zircon, rutile placers; blue circle = Pb, Zn, Ba, F veins; blue rectangle = stratiform Mn mineralization (gondite); blue tears = Nb, Ta, Be quartz-pegmatites; blue spade = lignites and coals

spanning the last decade (https://en.climate-data.org/) for the stations of Berbera, Bixinduule and Shiikh (Fig. 12.3).

As expected, temperatures are higher in Berbera and lower in Shiikh due to their different location: Berbera is on the coastline, whereas Shiikh is on the plateau, at an elevation of 1441 m asl (Fig. 12.6c). Bixinduule is in between these stations, at an elevation of 750 m asl, and shows intermediate values. In Berbera, the average maximum monthly temperature is recorded in July, with 42.1 °C, whereas in Bixinduule and Shiikh the highest temperatures are in August and September, with 36.3 and 29.0 °C, respectively. The average monthly temperature range is wider in Shiikh, with 12.4 °C, and narrower in Berbera (7.9 °C). With such high temperatures, Berbera can be ranked among the hottest inhabited places in the world.

Like temperature, annual and monthly precipitation amounts are largely influenced by the elevation of the meteo-station. In Shiikh, annual rainfall is 461.5 mm, in Bixinduule the respective value is 257.9 mm, and in Berbera, annual rainfall is only 49.7 mm. The monthly distribution indicates that in Boxinduule two rainy seasons occur (Fig. 12.7b). The main one is in April and May, and minor rains occur in October. In Shiikh, the monthly rainfall distribution follows a similar bimodal pattern, but appreciable rains occur also in June and September (Fig. 12.7c). In Berbera, rainfall is so sparse that no evident monthly pattern can be pointed out (Fig. 12.7a). In Fig. 12.7, the highest monthly rainfalls ever recorded are also reported. These data indicate that in Bixinduule maximum precipitation is recorded in April and October (Fig. 12.7b), whereas in Shiikh high rains are recorded in April, May and June and a secondary peak is observed in October (Fig. 12.7c).

It is worth noticing considerable difference between mean and maximum monthly precipitation (Fig. 12.7). The largest one is recorded in Shiikh, with 125.9 mm in June, but the highest ratio is observed in Bixinduule where, in November, maximum rainfall is five times the mean rainfall (Fig. 12.7b and c). Unfortunately, no long time series of rainfall data are available for these meteo-stations, but information obtained from local people, who report occasional, very intense rainstorms, and the large difference between low mean and high maximum monthly rainfalls, with the latter corresponding to 40–70% of the mean annual precipitation, suggest a wide interannual and monthly variability of precipitation. Such high rainfall accounts for the ephemeral nature of the two rivers, in which floods occur only occasionally and seldom the water flow is able to reach the sea. Nevertheless, high floods are described by local people as very impressive, very fast and powerful. Given scarce precipitation, the streambed of the Kalajab is completely dry for most of the time. The Biyoguure would be the same except that, due to the uplifted impervious strata of the coastal

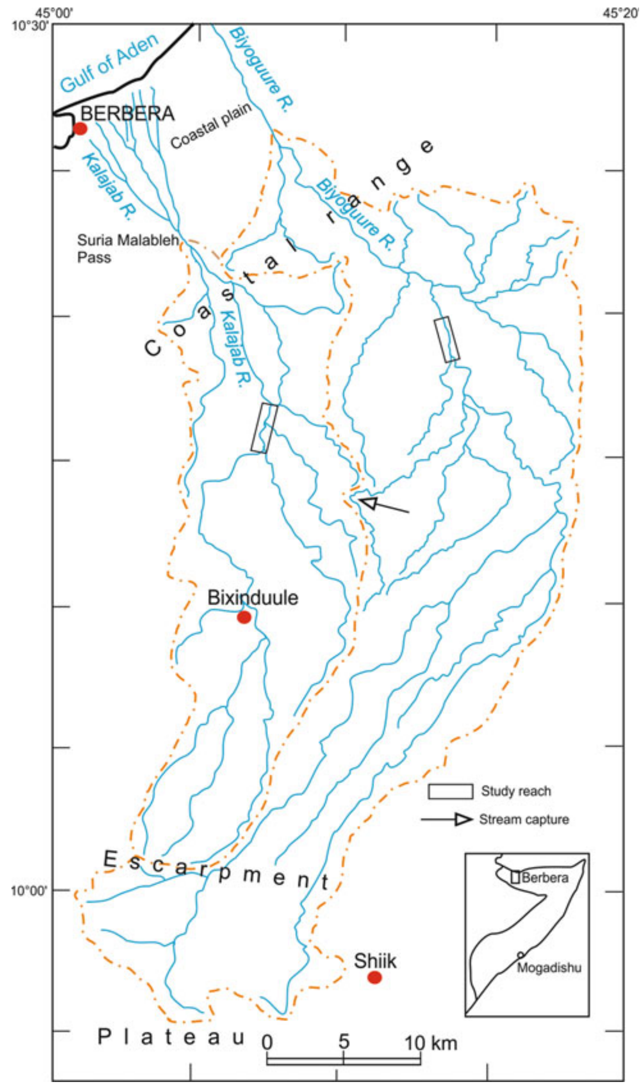

Fig. 12.3 Simplified drainage networks of the studied rivers

range, the subsurface water emerges in the streambed, resulting in a permanent flow of a few litres per second in the gorge and for a few kilometres upstream (Figs. 12.4 and 12.8).

For the high temperatures and low precipitation, the climate of the Dabaan basin can be classified as a hot desert climate (*BWh* according to Koeppen classification), and the environment is typical of a rocky desert devoid of vegetation (Fig. 12.9), except some shrubs in the dry river beds with very sparse vegetation (Fig. 12.10).

12.2.2 The Rivers

Both the studied rivers have narrow catchments, with a similar shape (Fig. 12.3). In the headwaters, parallel drainage network occurs, with a N-NE flow direction as far as 10° 15′ N. Beyond this latitude, the rivers turn to N-NW and the drainage network has a more angular shape. An instructive example of river capture, caused by a left tributary of the Biyoguure at the expense of a right tributary of the Kalajab, is visible in the field (Fig. 12.3).

The drainage network is substantially influenced by the geological structure as are all the main orographic elements of this area. In the headwaters, which correspond to the rift escarpment, the landscape is typically mountainous with deeply incised valleys and steep slopes. The streams have steep gradients; their beds are carved into bedrock and devoid of streambed sediment, with the exception of very big boulders.

In their middle reaches both the rivers flow on the bottom of narrow and shallow (a few tens of metres) canyons incised into the Tertiary depositional sequence, the flat top of which is a preserved alluvial surface (Fig. 12.11). In these middle reaches, the streambed gradient ranges between 0.01 and 0.02, the rivers have a braided channel morphology and there is no real, well-developed alluvial plain. The lateral, alluvial deposits, in fact, do not show marked sedimentological differences with the main channel deposits. The former are topographically higher than the latter and seem to have been deposited during very high floods rather than being a typical fine-grained overbank deposit. In ephemeral streams, large floods are commonly able to mobilise the entire streambed, which is then dissected during the receding flood flows (Billi 2016).

While crossing the coastal range, the Kalajab does not show marked changes in its channel morphology. By contrast, the Biyoguure has cut a deep and narrow gorge, in which the river changes the pattern from braiding into an entrenched meandering channel. Downstream of the coastal range, the Biyoguure resumes a straight braided channel morphology as far as the fan delta, where the main channel divides into a main distributary channel and a few smaller ones (Figs. 12.4 and 12.5).

12.3 Channel Morphology, Bedforms and Sedimentary Structures

For both rivers, field data were collected along four cross sections representative of typical morphology and sedimentology of the streambed, within a middle reach about 6.5 and 5.5 km long for the Biyoguure and the Kalajab, respectively (indicated by rectangles in Fig. 12.3). The broadest cross sections measured 709 m in the Biyoguure and 542 m in the Kalajab. The streambed gradient was measured across a stretch of about 500 m centred on each cross section. The data collection and observations carried out along each cross section included recording of channel geometry (width and depth), bed material grain-size

Fig. 12.4 Narrow and deep gorge of the Byoguure River cutting through the coastal range. The white arrows indicate flow direction

distribution sampled using the transect line method (Leopold 1970), the average size of the largest particles, the occurrence of bedforms and their geometry and sedimentary structures of specific morpho-sedimentary units.

12.3.1 Channel Morphology

The channel morphology of both rivers is typically braided (Fig. 12.12). The streambed, in fact, consists of several braided channels separated by median longitudinal bars. The channels are very large and shallow: the average width/depth ratio is 85 (range 12–253) in the Biyoguure and 100 (range 23–400) in the Kalajab; i.e., they show typical values of dryland ephemeral streams (Graf 1988). The braided channels are very shallow (mean depth 0.62 m; range 0.30–1.75 m) and have an average streambed gradient of 0.015.

At the cross-sectional scale, the longitudinal profile is characterised by the alternation of steeper and almost flat segments that could be associated with riffle and pool sequences. The general structure of the streambed consists of flat surfaces placed at different elevation and commonly steeper segments connect a higher surface with a lower one. This is not in agreement with the typical riffle geomorphology of braided rivers in more humid climates as these steeper segments seem to have been formed during the receding flood flows, when most of discharge occurs in the channels and the higher elevated surfaces are washed out by water flowing into the deeper and lower elevated channels. A similar setting was found also by Billi (2016) in boulder bed ephemeral streams.

Similar to braided rivers in humid environments, lateral and median longitudinal bars have typical rhomboid shape, and their maximum width is of the same order of magnitude as the channel width. What makes these bars very different from those of perennial rivers is their internal structure. The Biyoguure and Kalajab bars, in fact, are devoid of any sedimentary structures that would indicate lateral or downstream accretion. In other words, unlike perennial braided rivers, the study reaches do not show any evidence of bar downcurrent migration taking place through bar head erosion and bar tail sedimentation (Bluck 1979, 1982). Moreover, no substantial longitudinal variation of grain size was observed within the bars to point out bar components with

Fig. 12.5 Kalajab fan delta and the Byoguure delta. Notice the larger size of the Kalajab fan delta despite the catchment area of this river is about the size of the Byoguure. Occasionally, the rightmost distributary channel of the Kalajab fan delta joins the Byoguure

different gran size and morphology. The most common sedimentary structure of the bars is horizontal planar lamination of fine, sandy sediment, locally resting on a massive coarse gravel platform as observed by Bluck (1974) on sandur deposits in Iceland. The lack of both accretionary fronts and typical sedimentary structures of braided streams indicates that the bars in the study reaches are not formed by localised deposition processes but, rather, they are the product of channel incision during the receding flood flows or subsequent smaller floods. This hypothesis is supported by the presence of sedimentary structures and their arrangement that are the same for bars and channels (see also the next sections) and by the spatial continuity of facies architecture between channel and bar deposits. This implies that during large floods the whole streambed is entrained, and when discharge decreases, flow is mainly confined in shallow channels that dissect the streambed and transport finer sediment that is deposited in the pool-like flat stretches. Billi (2016) found a similar uniformity between bar and channel deposits in very coarse boulder bed ephemeral streams and postulated that bedload is transported as massive bedload sheets. Also, in the Biyoguure and the Kalajab, horizontal planar lamination and massive sand and/or fine gravel layers are the most common sedimentary structures.

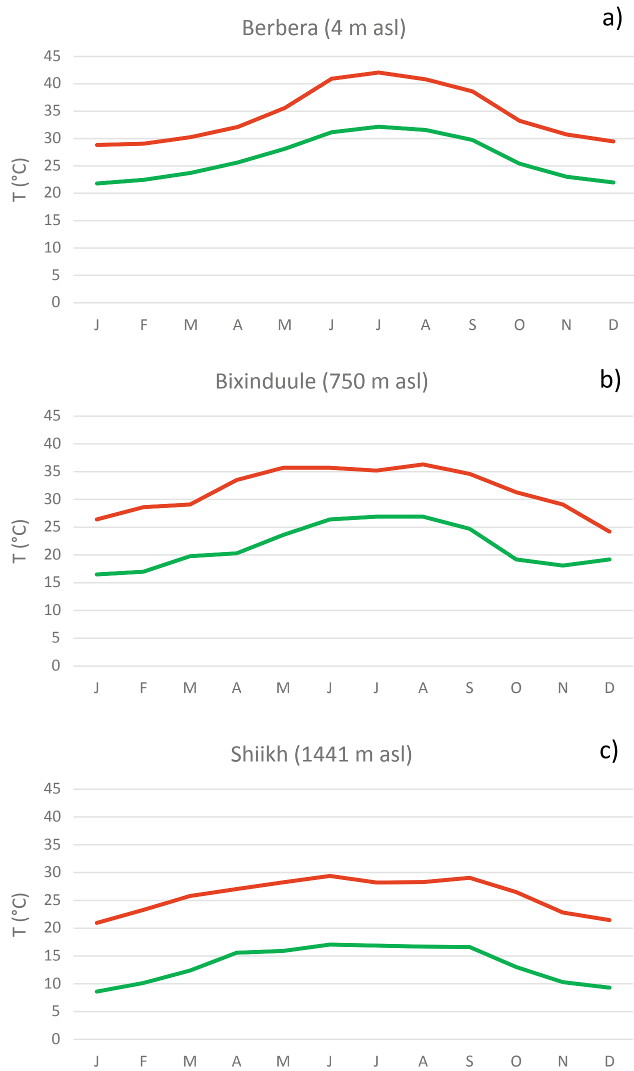

Fig. 12.6 Mean monthly temperature measured at three meteo-stations located at different elevations within the basin: Berbera (**a**) on the coast; Bixinfuule (**b**) in the middle reaches; Shiik (**c**) in the headwaters

12.3.2 Sediment

The bed material grain-size distribution of the Biyoguure River is very similar to that of the Kalajab. Composite samples from both rivers were aggregated to represent the grain size of main morpho-sedimentary units, i.e. channels, riffles and bars rivers (Fig. 12.13). Bars and channels have very similar grain-size characteristics: D_{50} is the same (−0.84 phi; 1.79 mm), sorting is almost the same (2.16 and 2.72 mm for channels and bars, respectively), and sand prevails over gravel. Riffles, instead, are substantially coarser (D_{50} = −5.58 phi or 47.8 mm), a little less sorted (standard deviation = 3.17), and 78% of bed material is gravel.

The three main streambed units appear more dissimilar if the size of the largest particles (D_{max} or D_{90}) is considered.

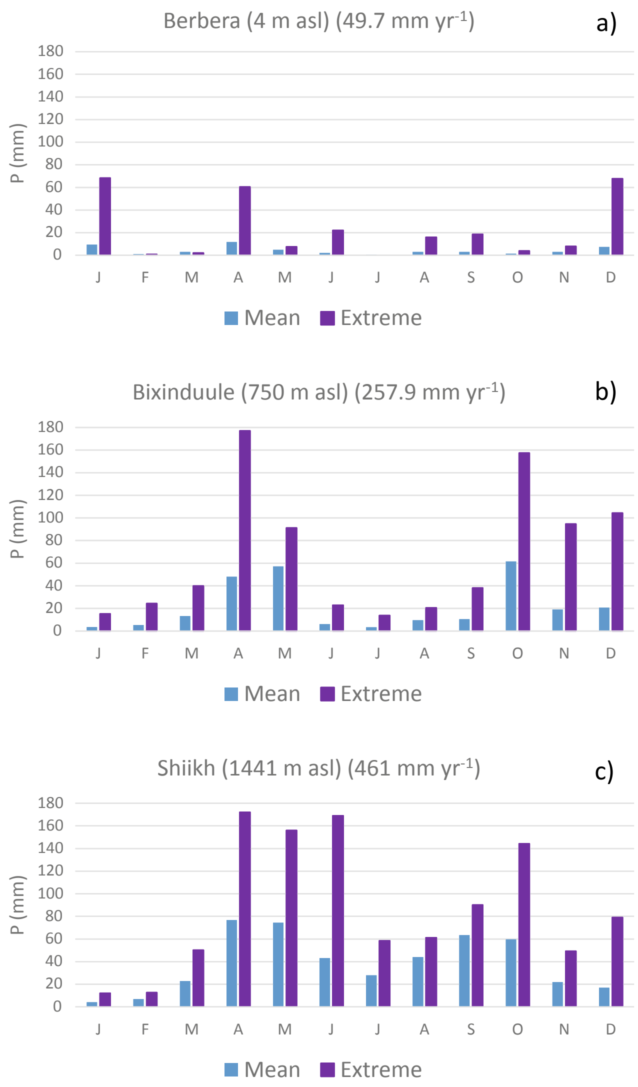

Fig. 12.7 Mean and maximum monthly precipitation measured at three meteo-stations located at different elevations within the basin: Berbera (**a**) on the coast; Bixinfuule (**b**) in the middle reaches; Shiik (**c**) in the headwaters

On bars, mean D_{max} is 500 mm; in channels, it is 225 mm, and on riffles, it is 425 mm. D_{90} follows a slightly different pattern, with the largest D_{90} on riffles (−6.89 phi or 119 mm), whereas D_{90} of bars (−6.49 phi or 89.7 mm) is substantially coarser than of the channel streambed (−5.29 phi or 39.1 mm). The occurrence of larger particles on the bar top suggests that the bar surface experienced higher stream power than the channels and that bars and channels were likely formed in different moments within a flood (or between floods), i.e. when depositional processes occurred with different flow discharges.

Using the equations proposed by Costa (1983) to calculate the flow velocity (v) capable to entrain large boulders,

$$v = 4.63D^{0.455} \tag{12.1}$$

$$v = 5.2D^{0.487} \tag{12.2}$$

and introducing the values of D_{max} measured on top of three main streambeds, the average values of the threshold flow velocity of 3.54, 2.43 and 3.28 ms^{-1} were obtained for the largest particles on bars, channels and riffles, respectively. Moreover, for the average channel depth and gradient a shear stress (τ) of about 92 Nm^{-2} was calculated. This result (in kg m^{-2}) was introduced in the equations of Baker and Ritter (1975), Costa (1983) and Williams (1983), which were reversed to calculate the largest particle entrainment by a given shear stress:

$$D_{max} = (\tau/88.5)^{0.67} \tag{12.3}$$

$$D_{max} = (\tau/24.4)^{0.824} \tag{12.4}$$

$$D_{max} = \tau/17 \tag{12.5}$$

The predicted D_{max} ranges between 220 and 550 mm, i.e. values comparable to those of the largest particle size measured in the field.

The bimodal particle size distribution of riffles may be explained by deposition of coarse particle, transported during higher flows, which are lately infiltrated by finer sediment during the receding flood flow phase.

12.3.3 Bedforms

Commonly, ephemeral streams do not show a wide variety of bedforms. This is probably due to short duration of floods and their high Froude numbers (Billi 2011). The bedforms observed on the streambed of the studied rivers are the following:

Plane bed Plane bed is by far the most common bedform in the Biyoguure and Kalajab rivers. Classical flume experiments (e.g. Simons and Richardson 1961) have shown that the plane bed is formed when the Froude number ($Fr = v/(gh)^{0.5}$ in which v is flow velocity, h is flow depth and g is gravity) is around 1. Taking the flow velocity calculated in the previous sections and the average flow depth of 0.625 m, Froude numbers in the 0.98–1.43 range are obtained. Imposing alternative, though reasonable, flow depths of 1.0 and 0.5 m, the Froude number is still around 1. The hydraulic calculations confirm that flow conditions during floods are suitable for the development of a plane bed. The short duration of floods must be considered as well. In fact, floods of dryland ephemeral streams are typically very intense, but also very short. Flash floods commonly last only

Fig. 12.8 Very small, though semi-permanent base flow of the Byoguure River a few kilometres upstream of the gorge in the coastal range

Fig. 12.9 Arid climate conditions are well reflected by hillslopes devoid of vegetation and covered by large quantities of rock fragments and loose material produced by weathering

a few hours, which is a too short time for the formation of more complex bedforms such as dunes and ripples.

Current ripples These bedforms are not common and are found mainly in restricted areas in the streambed, such as the deepest channels, where shallow flow may have lasted for a longer time after the flood wave has passed by (Fig. 12.14). Two-dimensional ripples have wavelength ranging from 100 to 200 mm, and their height is between 5 and 12 mm. Three-dimensional ripples are smaller, with wavelength between 90 and 140 mm and height between 8 and 15 mm. The size of these bedforms allows one to classify them as ripples as the diagram (Fig. 12.15) demonstrates. Dunes of any kind were not observed.

Wind ripples These bedforms are rather uncommon, probably because their preservation potential is limited. Their geometry is rather constant; wavelength and height range are between 50 and 100 mm and between 5 and 10 mm, respectively.

Fig. 12.10 In the study area, the only vegetation consists of sparse shrubs and very few shrubby trees in the dry riverbeds

Boulder crescent scours These are mainly erosive rather than depositional bedforms. They are formed by the horseshoe vortex flow that develops upstream and on the sides of a standing obstacle like a large boulder and is strong enough to erode the sediment around the standing particle (Picard and Heigh 1973) (Fig. 12.14). Downcurrent of the obstacle stone, a narrow wake of sediment may accumulate. These bedforms are formed during later stages of a flood, when large particles stop moving and very shallow, a few centimetres deep, separation flows are still capable to develop local eddies. Pebble crescent scours are typical of dryland ephemeral streams characterised by low flows and flash floods. In the studied rivers, they were found also in older deposits (Fig. 12.16), confirming that they can be used in paleo-environment reconstructions.

Pebble clusters This coarse-grained bedform is rather uncommon in the studied rivers. Pebble clusters consist of aggregations of smaller particle upstream of a larger stone and the downcurrent formation of a wake made of fine gravel and sand wake (Brayshaw 1984). They are found mainly on steep-gradient surfaces and where bed material is coarse, such as on riffles. Occasionally, they may form also on low-gradient channel bottom.

Transverse ribs Transverse ribs are lines of pebbles/boulders across a small channel. They are normally formed under shallow flow conditions during the receding flood limb and are not typical of dryland rivers as they are more common in perennial rivers (Koster 1978). In the study rivers, transverse ribs have an average spacing of 1.35 m, rest on streambeds with gradients ranging from 0.052 to 0.026, with D_{50} = 70 mm and $D_{\max}$ = 350 mm. Applying the relationship between flow depth (h) and transverse rib spacing (L_s) developed from flume data of McDonald and Day (1978),

$$h = (L_s - 0.02)/4.47 \qquad (12.6)$$

to the studied rivers data, a flow depth of about 0.30 m is obtained, which is comparable to the mean diameter of the largest stones forming the transverse ribs.

Mud drape This is a very fine-grained deposit, no more than a few centimetres thick, that is very common and covers large portions of the streambeds. It is deposited during the very last flood phases or by very shallow flood flows. On mud drapes, dissection cracks and flakes are rather common (Fig. 12.17).

Salt crust and raindrop prints Salt crust are very common on the streambeds of the two rivers for two main reasons: (1) high temperatures and evaporation rates; (2) high concentration of salt in the subsurface water which rests on the uplifted Lower to Middle Eocene Taleh evaporates. Raindrop prints are well preserved in the salt crust because often the sporadic rainfalls evaporate a few tens of metres above the ground, which is impacted by only a few drops (Fig. 12.18).

Cuspate sand waves In the streambeds, several examples of very thin (10 mm) cuspate bedforms were observed (Fig. 12.19). Their shape recalls that of linguoid bars (Collinson 1986), but the latter are much thicker and larger and were found mainly in perennial rivers of humid and sub-humid environments. According to Collinson (1970), in fact, “linguoid bars are large enough to have smaller forms superimposed on their stoss sides (though they do not always have them) and … are synonymous with the mid-channel bars”. In the Tanana river, linguoid bars are longer than 30 m, but they may also reach a maximum length of as much as 200 m (Ashley 1990), have a sharp slip face 0.5–2.0 m high and are arranged in a generally out-of-phase relationship with one another (Collinson 1970). The cuspate sand waves of the Dabaan rivers do not have smaller superimposed bedforms and are found in groups of a few bedforms

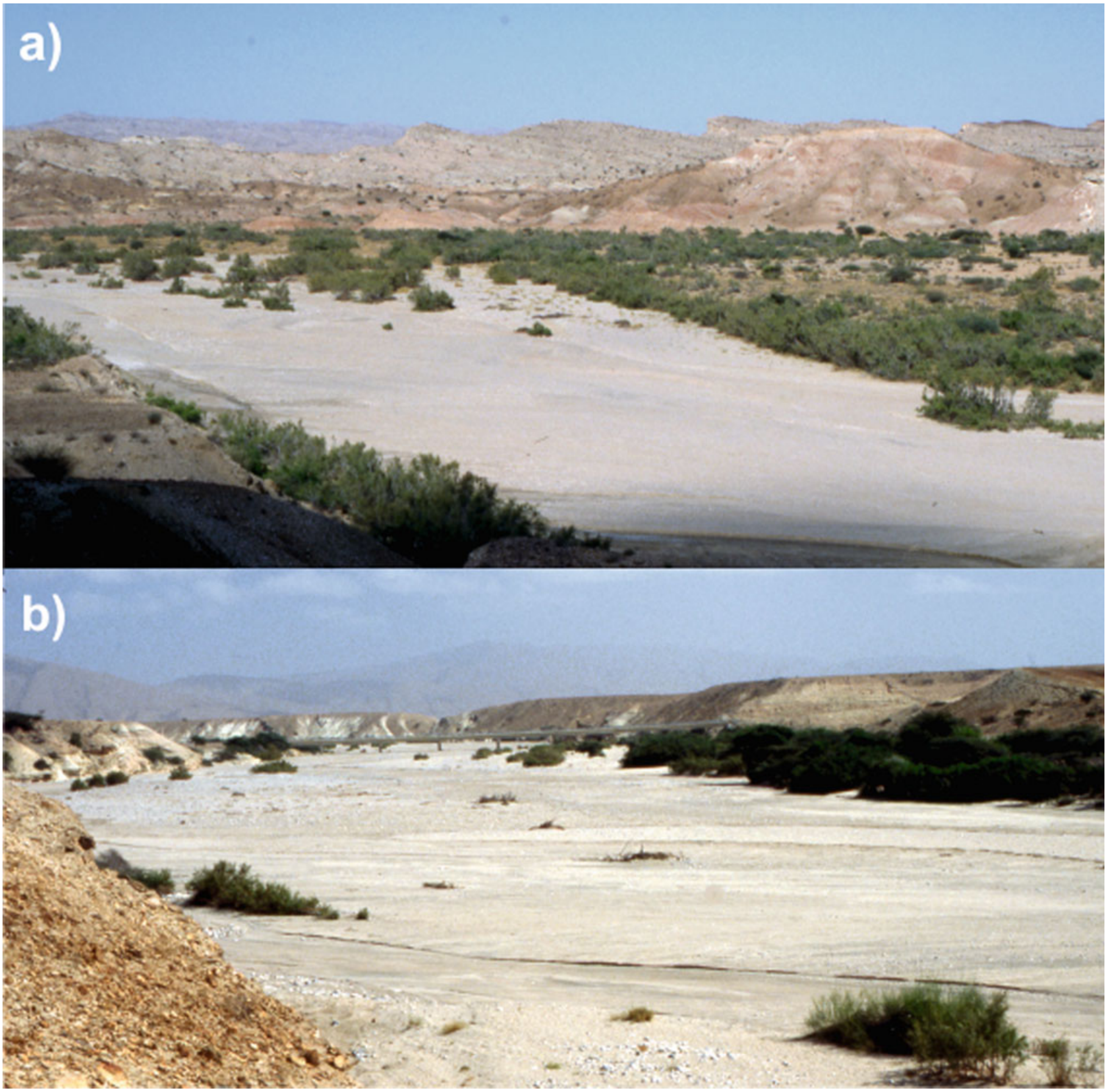

Fig. 12.11 In their middle reaches both the rivers occupy narrow and shallow (a few tens of metres) canyons incised into the Tertiary depositional sequence: **a** Byoguure; **b** Kalajab

(Fig. 12.20) or are isolated. Their length varies between 2 to 10 m, the length/maximum width ratio is around 4, and the length/thickness ratio is around 1000, whereas it is about 100 in the Tanana river. The cuspate sand waves reported in this study have a similar shape and are arranged in a way reminding that of lunate or linguoid ripples, but the latter are much smaller, made of finer sediment and have distinct lee and stoss sides.

The cuspate sand waves of this study consist of a narrow water and sediment supply channel, 0.10–0.30 m wide, from which divergent streaming lineations radially depart to form the main bedform body (Figs. 12.19 and 12.20), reflecting rapid washing away flow typical of dryland ephemeral streams.

Cuspate sand waves were reported in an early report by Billi and Tacconi (1985), but no other paper has investigated

Fig. 12.12 Example of braided channel morphology: the Byoguure River middle reach

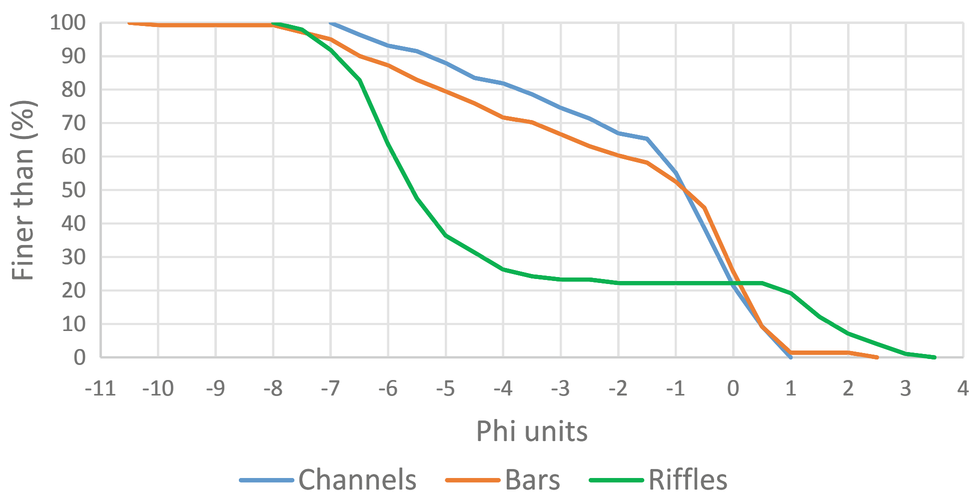

Fig. 12.13 Composite grain-size distributions representative of both rivers for the three main morpho-sedimentary units: channels, bars and riffles

this bedform, which seems to be typical of dryland ephemeral streams. Since it can be considered as a bedform diagnostic of ephemeral streams, further studies are necessary to define the hydraulic conditions of their formation and their relation with horizontal lamination.

12.3.4 Sedimentary Structures

Stratification and sedimentary structures were observed in natural sections and in shallow observation pits. The most common sedimentary structure is horizontal planar lamination, which is present in 90% of field inspection sites. The typical thickness of the laminae ranges between 5 and 15 mm (extreme values are 1–40 mm), and commonly, the thicker laminae are composed of coarser particles. The base of the laminae is often marked by dark heavy metal granules. Such widespread occurrence of horizontal plane lamination can be accounted for by three main factors: (1) short duration of floods, so that more complex bedforms do not have time to develop; (2) flows with Froude numbers commonly around 1, which corresponds to the plane bed; (3) rapid waning of flood flow for infiltration, which causes a rapid decrease in shear stress and high sedimentation rates, thus favouring the formation of the plane bed configuration.

Other authors (Karcz 1972; Picard and High 1973; Graf 1988) did not find such a predominance of horizontal planar lamination over the other bedforms, but this difference can be explained by a more pronounced flashy character of floods in the studied rivers.

Fig. 12.14 Boulder crescent scour with current ripples all around. The white arrow indicates the flow direction

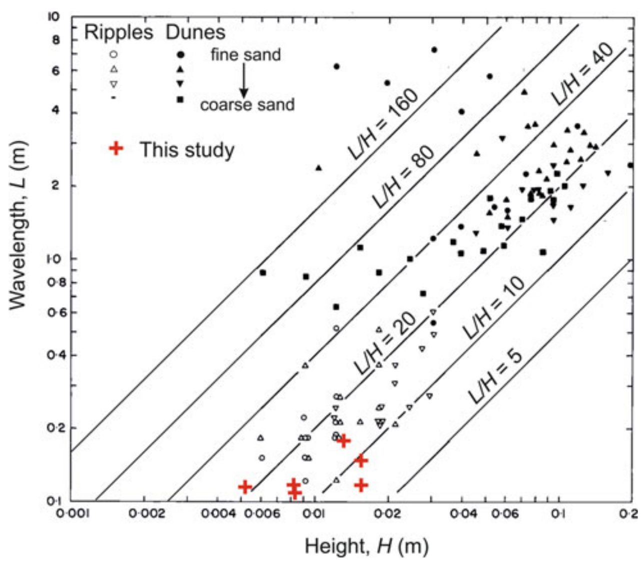

Fig. 12.15 Diagram of bedform hight versus bedform wavelength. Bedforms of the studied rivers plot in the field of fine sand ripples (modified from Allen 1982)

Other sedimentary structures observed are, in a decreasing order of frequency: horizontal massive beds, inclined planar lamination, and trough cross-lamination. Massive sandy or fine to coarse gravel layers are typically found in the channel deposits and their average thickness is 140 mm (extreme values 10–700 mm).

The inclined planar lamination was observed in a few accretionary fronts downstream of small transverse bars and consist of sand and fine gravel. The average inclination of the laminae is 7° (range 4–11°), and their typical thickness ranges from 5 to 20 mm (extreme values 1–70 mm).

The trough cross-lamination is very rare in the studied rivers and was observed only in three cases, downstream of large lateral bars. The scarcity of these sedimentary structures reflects the marked flashy character of floods and accounts for the occasional occurrence of three-dimensional current ripples, the migration of which generates the through cross-bedding.

Fig. 12.16 Example of a boulder crescent scour in the Kalajab River older alluvium

Fig. 12.17 Clay flakes in the Byoguure streambed

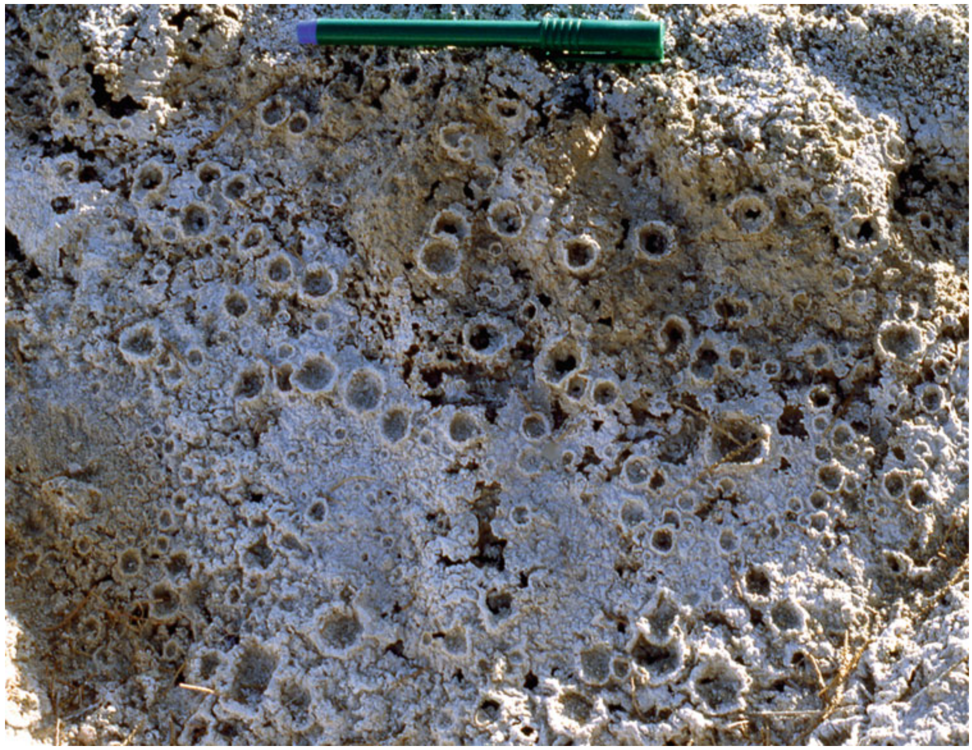

Fig. 12.18 Raindrop impact on a salt crust in the streambed of the Byoguure

12.4 Concluding Remarks

The Dabaan basin is subjected to a semiarid to hyper-arid climate. It is drained by two ephemeral rivers, the Byoguure and the Kalajab, which are dry for most of the time. Water flow is sporadic and shallow, but very occasional intense rainfalls may propel powerful floods. Like in other hot desert environments, the Dabaan basin is characterised by the lack of vegetation and active weathering processes producing large quantities of loose material on slopes. The combination of sporadic floods with the high sediment supply provides the rivers with very high width to depth ratios (85–100 on average with maximum values between 250 and 400) and a braided channel morphology. Though braided channels and bars are commonly observed, the bars are not formed by depositional processes as described by various authors (e.g. Bluck 1979) for braided rivers in humid and sub-humid areas. The sediments of both the channels and the bars have the same structure and internal organisation. The bars do not show any evidence of downstream migration or accretionary faces. The streambed does not show lateral differences in terms of the internal organisation of the sediment, which seems to be transported en masse. During extreme floods, the entire streambed is moved in a thickness of a few tens of centimetres and the bars are probably formed by local scouring processes and the concurrent development of braided channels during the receding flood flows. Flow velocities (2.5–3.5 ms^{-1}) calculated by Costa's (1983) Eqs. (12.1) and (12.2) and flow depths inferred from field observations return Froude number values around 1, which are compatible with the ubiquitous occurrence of planar horizontal lamination, very commonly observed in the bed material. Flow depths of 30 cm were obtained from Eq. (12.6), based on the wavelength of transverse ribs, and are consistent with field observations.

Plane bed by far prevails over other classic bedforms reported in the literature. Current ripples are occasionally present on the streambeds, but not dunes of any kind. Boulders and pebble crescent scours are instead very

Fig. 12.19 Example of a cuspate sand wave. Notice the radial flow away from the bedform body. Flow is towards the reader

common and can be considered as bedforms indicative of ephemeral flows in arid environments.

A new bedform, also indicative of flash floods, is the cuspate sand waves. They consist of a narrow water and sediment supply channel, 0.10–0.30 m wide, from which streaming divergent lineations radially depart to form the leaf-shaped bedform body, reflecting a rapidly vanishing flow, as typically observed in dryland ephemeral streams. Apparently, the cuspate sand waves are similar to the linguoid bars of Collinson (1986), but the former are much smaller (maximum length is between 2 and 10 m, whereas the linguoid bars can be longer than 30 m), thinner (a few centimetres compared to 0.5–2.0 m of linguoid bars), have no superimposed bedforms nor any downstream accretionary faces. Further field investigations on the cuspate sand waves are, however, necessary to better understand the hydraulic conditions for their origin and occurrence in other environments.

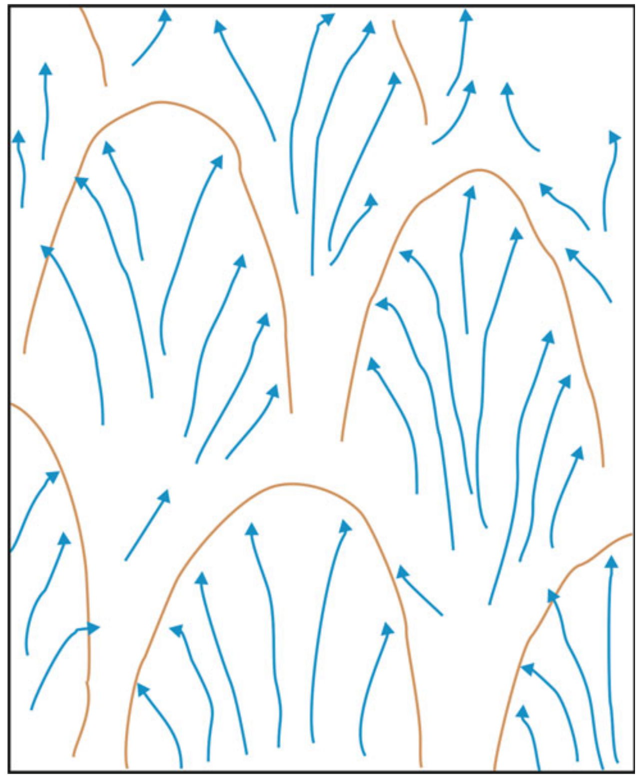

Fig. 12.20 Sketch of the arrangement of cuspate sand waves. The blue arrows indicate flow lines on the bedform body

References

Abbate E, Sagri M, Sassi FO (1994) Geological map of Somalia. Somali National University, S.E.L.C.A, Firenze

Abbate E, Bruni P, Fazzuoli M, Sagri M (1983) Le facies di transizione e continentali nel bacino Terziario del Daban, Somalia settentrionale. Dati preliminari. Quaderni Di Geologia Della Somalia 7:7–37

Allen JRL (1982) Sedimentary structures. Their character and physical basis, volume I. In: Developments in sedimentology 30A, Elsevier, Amsterdam

Ashley GM (1990) Classification of large-scale subaqueous bedforms: a new look at an old problem. J Sediment Petrol 60(1):160–172

Baker VR, Ritter DF (1975) Competence of rivers to transport coarse bedload material. Geol Soc Am Bull 86:975–978

Billi P (2007) Morphology and sediment dynamics of ephemeral streams terminal reaches in the Kobo basin (northern Welo, Ethiopia). Geomorphology 85:98–113

Billi P (2011) Flash flood sediment transport in a steep sand-bed ephemeral stream. Int J Sedim Res 26(2):193–209

Billi P (2016) Channel processes and sedimentology of a boulder-bed ephemeral stream in the Western Afar margin. Z Geomorphol 60 (1):35–52

Billi P, Tacconi P (1985) Morfologia, sediemntologia e dinamica fluviale di due corsi d'acqua effimeri della Somalia settentrionale. Quaderni Di Geologia Della Somalia 8:43–83

Billi P, Alemu Y, Ciampalini R (2015) Increased frequency of flash floods in Dire Dawa, Ethiopia: change in rainfall intensity or human impact? Nat Hazards 76(2):1373–1394

Billi P, Demissie B, Nyssen J, Moges G, Fazzini M (2018) Meander hydromorphology of ephemeral streams: similarities and differences with perennial rivers. Geomorphology 319:35–46

Bluck BJ (1974) Structure and directional properties of some valley sandur deposits in southern Iceland. Sedimentology 21:533–554

Bluck BJ (1979) Structure of coarse-grained braided stream alluvium. Trans R Soc Edinb 70:182–221

Bluck BJ (1982) Texture of gravel bars in braided streams. In: Hey RD, Bathurst JC, Thorne CR (eds) Gravel-bed river. Wiley, Chichester, pp 339–355

Brayshaw AC (1984) Characteristics and origin of cluster bedforms in coarse-grained alluvial channels. In: Koster EH, Steel RJ (eds) Sedimentology of gravels and conglomerates. Memoir 10, Canadian Society of Petroleum Geologists, Calgary, pp 77–65

Collinson JD (1970) Bedforms of the Tana river, Norway. Geogr Ann Ser A Phys Geogr 52(1):31–56

Collinson JD (1986) Alluvial sediments. In: Reading HG (ed) Sedimentary environments and facies, 2nd edn. Balckwell, Oxford, pp 20–62

Costa JE (1983) Paleohydraulics reconstruction of flash-flood peaks from boulder deposits in the Colorado front range. Geol Soc Am Bull 94:986–1004

Demissie B, Billi P, Frankl A, Haile M, Nyssen J (2016) Excess river sedimentation at bridges in the Raya graben (northern Ethiopia). Land Degrad Dev 28:946–958

Demissie B, Nyssen J, Billi P, Haile M, Frankl A (2019) Land changes in relation to stream dynamics in a marginal graben along the northern Ethiopian Rift Valley. Phys Geogr 40(1):71–90

FAO (2010) Guidelines on spate irrigation. FAO Irrigation and Drainage Paper 65, FAO, Rome

Graf WL (1988) Fluvial processes in dryland rivers. Springer, Berlin

Hooke JM (2019) Extreme sediment fluxes in a dryland flash flood. Sci Rep 9:1686

Hunt JA (1960) Report on teh Geology of the Berbera - Sheik area. Report No. 4, Geological Survey, Somaliland Protectorate, Eyre and Spottiswoode, Margate

Karcz I (1972) Sedimentary structures formed by flash floods in southern Israel. Sed Geol 7(161):182

Kelly SB, Olsen H (1993) Terminal fans—a review with reference to Devonian examples. Sed Geol 85:339–374

Korichi K, Hazzab A, Atallah M (2016) Flash floods risk analysis in ephemeral streams: a case study on Wadi Mekerra (northwestern Algeria). Arab J Geosci 9(11):589

Koster EH (1978) Transverse ribs: their characteristics, origin and paleohydraulic significance. In: Miall AD (ed) Fluvial sedimentology. Canadian Society of Petroleum Geologists, Memoir 5, Calgary, pp 161–186

Leopold LB (1970) An improved method for size distribution of stream bed gravel. Water Resour Res 6(5):1357–1366

Lin X (1999) Flash floods in arid and semiarid zones. UNESCO-IHP, Paris

McDonald BC, Day TJ (1978) An experimental flume study on the formation of transverse ribs. Canada Geological Survey Paper 78-1A:441–451

North CP, Taylor KS (1996) Ephemeral-fluvial deposits; integrated outcrop and simulation studies reveal complexity. AAPG Bull 80 (6):811–830

Pacheco-Guerrero A, Goodrich DC, González-Trinidad J, Júnez-Ferreira HE, Bautista-Capetillo CF (2017) Flooding in ephemeral streams: incorporating transmission losses. J Maps 13(2):350–357

Picard MD, High LR Jr (1973) Sedimentary structures of ephemeral streams. In: Developments in sedimentology, vol 17. Elsevier, Amsterdam

Sagri M, Abbate E, Bruni P (1989) Deposits of ephemeral and perennial lakes in the tertiary Daban basin (Northern Somalia). Palaeogeogr Palaeoclimatol Palaeoecol 70:225–233

Simons DB, Richardson EV (1961) Forms of bed roughness in alluvial channels. Proc ASCE J Hydraul Div 87, HY 3, paper 2816:87–105

Williams GP (1983) Paleohydrological methods and some examples from Swedish fluvial environment, I—cobble and boulder deposits. Geogr Ann 65:227–243