
Geomorphic characteristics of dryland distributive systems

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ABSTRACT

Dryland distributive systems include different types of depositional bodies: distributary systems, alluvial fans, fan deltas, lacustrine deltas and sea deltas. Geomorphic data of 81 distributive systems from different arid lands in the world were selected and simple geomorphic parameters such as distributive system area, the average length of the radius, average slope and apex angle were measured. The data analysis indicates that these typologies have different characteristics, though the most distinctive groups include fans, deltas and distributary systems, the geomorphic characteristics of which are constantly intermediate between the two former groups. The results seem to confirm the hypothesis of De Chant et al. (1999) that the shape of distributive systems is mainly controlled by sediment diffusion, channel processes and accommodation space characteristics.

KEYWORDS distributive systems; ephemeral streams; fans; deltas; drylands

1. Introduction

All rivers have an upstream start, in the headwaters, and a downstream end when they reach their base level, be it a water body (sea, lake, or another river) or the lower elevated land they are not able to cross. While erosion is the main process in the headwaters, deposition dominates in the river terminus (Schumm, 1977). Here, commonly in association with a sharp change in bottom gradient and/or some frontal confinement (e.g., the water body or a flat land), stream power substantially decreases and river channels become transport limited as sediment transport capacity is exceeded by sediment supply,

thus resulting in sediment accumulation. High depositional rates result in bank crevasses, channel bifurcation and avulsions (Bristow et al., 1999; Jones and Schumm, 1999; Charlton, 2008; Donselaar et al., 2013). The occurrence of all these fluvial processes give way to alluvial fans and inland distributary systems and, when combined with wave action and longshore drift, lacustrine deltas and fan deltas result.

Several papers have been published on the geomorphology of alluvial fans (e.g., North and Warwick, 2007; Harvey, 2011 and Ventra and Clarke, 2018, for a comprehensive review) and sea deltas (e.g., Galloway, 1975; Bhattacharya, 2006; Olariu and

Bhattacharya, 2006; Syvitski and Saito, 2007; Woodroffe and Saito, 2011; Mikhailova, 2015). Depositional features, stratigraphy and facies of distributive systems have also attracted the attention of scientists also for their potential as oil reservoirs (Kelly and Olsen, 1993; Fisher et al., 2007; Nichols and Fisher, 2007).

Most of the studies on alluvial fans include examples from different climates, whereas those on deltas commonly deal with perennial rivers. Inland distributive systems are typically found in arid regions and make up the terminus of ephemeral streams (Mukerji, 1976; Billi, 2007). In arid regions, with the exception of very steep fans, distributive systems are important because they are among the very few land portions on which agriculture is possible due to the flat morphology, the occurrence of fertile soils and occasional surface and subsurface water supply from the rivers distributary channels that can guarantee some soil humidity. The understanding of dryland distributive systems geometry is also important in oil exploration since no, even conceptual, models have been proposed yet. Therefore, this paper is on distributive systems formed by ephemeral streams in arid lands. Ephemeral streams are dry most of the time and have water flowing only occasionally, following sporadic intense rainstorms. The intermittence of water flow, often characterized by transport capacity limited conditions, makes these depositional systems unique and though they are an important geomorphological aspect of arid environments, they are still very poorly known.

North and Warwick (2007) dispute terms like "terminal-fan" or "fluvial distributary system" because they find a discrepancy between the depositional models adopted by sedimentologists and the modern analogs. Yet, these authors consider distributary systems as relict lacustrine deltas, influenced by non-fluvial processes, though they provide only sedimentological evidence in support of their hypothesis.

The aim of this paper is to contribute to clarifying such uncertainties by means of geomorphic characterization of arid region ephemeral stream distributive systems, which are very poorly known as distinct climatic endmember, notwithstanding the

comprehensive and inspiring work by Hartley et al. (2010), which, however, is mainly aimed at investigating geotectonic control on modern fluvial distributive systems and at providing a descriptive database for comparison with the rock record, though no distinction is made between the distributive system of different climates.

2. Distributive systems terminology

North and Warwick (2007) proposed an interesting and stimulating, though not exhaustive, discussion about distributive systems terminology and Hartley et al. (2010) identified six broad plan form types, based mainly on channel number, sinuosity and bifurcation. For consistency with past and future studies, a simplified classification of ephemeral stream distributive systems is adopted in this study on the basis of previous work (e.g., Stainstreet and McCarthy, 1993; Billi, 2007). In this paper, the term "distributive" is used as a higher hierarchical definition including all the more or less flat cone-shaped depositional bodies formed by a single channel of any sinuosity lateral shifting, though keeping hinged on the distributive system apex, or multiple channels of any sinuosity splitting from the main river stem at the apex or within the main body of the distributive systems.

In arid regions, five main types of distributive systems were identified: distributary systems *sensu stricto*, alluvial fans, fan deltas, lacustrine deltas and sea deltas (Fig. 1). The distributary systems typically originate from flow splitting and the formation of few distributary channels of smaller size than the main river stem, which in their turn bifurcate as they proceed downstream (Fig. 1a). Bifurcation ends where flow reduces substantially for infiltration, channel width decreases from hundreds of meters to centimeters and water vanishes into shallow puddles (Billi, 2007). Distributary systems are not confined and are commonly found on the bottom of closed basins. Their sediment is predominantly sand with small percentages of gravel and scattered boulders, even of very large size.

Alluvial fans form at the exit of a narrow valley at the downstream end of the mountainous part of the catchment. Due to the vicinity to the sediment supply area and a sharp change in gradient, sedimentation

rates are very high and the depositional body may be very thick. Typically, several channels originate from the main river stem in the fan apex, but also one individual channel may shift across the fan, thus contributing to its construction. Alluvial fans may not be the river terminus as the stream channel may proceed beyond it also for many kilometers (Fig. 1b) to reach its main base level. Alluvial fans may be laterally confined, especially for the growth of adjacent fans, whereas they are seldom frontally confined, but when the fan is formed at the confluence with a larger river in a narrow valley. Fan deltas have the same characteristics as alluvial fans,

but the former are always frontally, partially confined by a water body (sea or lake) (Fig. 1c).

Lacustrine and sea deltas are very similar (Fig. 1d and e), but for a few differences: wave action on the former is almost negligible, whereas, in the latter, waves may play a crucial role in controlling the delta size. In arid regions, sea deltas are very rare because most ephemeral streams very seldom reach the coast during exceptionally large floods. The infrequent floods of ephemeral streams result in a low sediment supply to the coast and the small amount of sediment accumulated can be easily dispersed by the waves and the longshore drift.



Figure 1 The main typology of distributive systems considered in this study: a) distributary system, *sensu stricto*; b) alluvial fan; c) fan delta; d) lacustrine delta; e) sea delta; f) the main geomorphic parameters measured: area is the area of the distributive system body; R_d is the radius; α is the apex angle.

3. Data and methods

Through inspection of the planet's arid lands by means of Google Earth Pro®, 81 ephemeral streams distributive systems were selected (Fig. 2). Distributive systems of allogenic, perennial, or seasonal rivers crossing arid regions were not considered for the high annual precipitation in the far headwaters that distinguish these rivers from ephemeral streams, which are dry for most of the year and, in a few cases, also for several years in a row, and have water flowing in the channel only in response to sporadic heavy rainfalls. Also, distributive systems naturally or artificially laterally

confined or affected by human installations or infrastructures were not considered.

For each distributive system, the following parameters were measured on Google Earth Pro® images: distributive system area (A), average length of radius (R_d), average slope (S) and apex angle (α) (Fig. 1f). A minimum number of three radii were traced on the distributive body (Fig. 1f) and their length averaged to obtain R_d . The distributive system slope (S) is the average of the slopes of the individual radii traced to calculate R_d and the apex angle was measured after tracing the distributary system external borders (the dotted line in Figure 1f). A summary of the data measured is reported in Table 1.

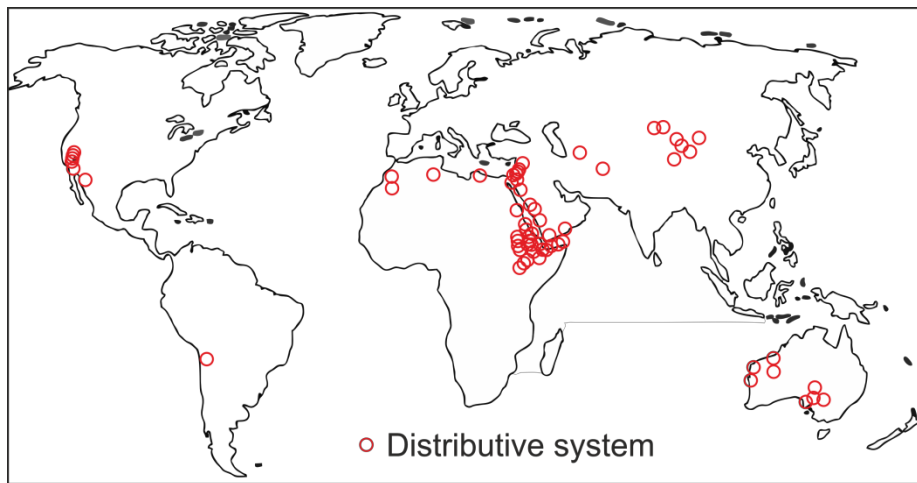


Figure 2 Location map of the distributive systems selected

In this study, the upstream catchment area was not considered for the following reasons:

i) Several papers dealt with the control of catchment area on fan size and slope (e.g., Blair and McPherson, 1994; Viseras et al., 2003; Harvey, 2011; Mokarram et al., 2014) and several power functions with different coefficients and exponents were presented. Their general forms are:

$$A = cA_c^b, \quad (1)$$

$$S = qA_c^k, \quad (2)$$

in which A is fan area, A_c is catchment area, S is fan slope, c and q constants and b and k exponents. According to the extensive work of Harvey (2011), who considered several published data of dryland alluvial fans, c varies between 0.1 and 2.1, b varies between 0.7 and 1.1, q between 0.03 and 0.17 and k

between -0.15 and -0.35. However, if we consider other studies (e.g., Marchi and Tecca, 1995; Viseras et al., 2003; Mokarram et al., 2014; Zhang and Lu, 2014), the ranges are even wider: $c = 0.08 - 3.83$; $b = 0.11 - 3.33$; $q = 0.03 - 1.90$; $k = -0.10 - -0.53$. Harvey (2011) attributes such a large variability to regional differences in fan age, catchment geology and sedimentary processes. For Nevada and California fans, in fact, Lecce (1991) found an inverse relationship between basin erodibility and fan size.

ii) In their study on distributive fluvial systems in the drylands of northern Patagonia, Bilmes and Veiga (2016) found that the catchment area is not the only factor controlling the size of the distributive systems as the accommodation space may also play an important role. The role of accommodation space is also emphasized by Hartley et al. (2010). Viseras et

al. (2003) found that in southern Spain there is no relation between fan slope and catchment area, under conditions of base-level rise.

iii) De Chant et al. (1999) concluded that the fan morphology is predominantly controlled by channel processes rather than environmental variables (climate, lithology). Their model deliberately does not include the sediment influx (which is very difficult to quantify) and it is synthesized by the following equation:

$$V = 0.28[(\alpha/360)\pi R_d^2 h] , \quad (3)$$

in which V = fan volume; α = fan apex angle (Fig. 1e); R_d = the fan radius; h = the total height at the fan head with respect to the fan fringe.

iv) With the exception of estuarine deltas, the size and shape of sea deltas are largely controlled by the action of the waves, the distance of the river basin mountain portion from the coast, the depth of the nearshore water and the tide range (Woodroffe and Saito, 2011). Though for lacustrine deltas, the relationship between catchment size and delta area seems obvious, for sea deltas, it is not so straightforward.

Given the limited control that catchment area may or may not have on the area of distributive systems, it seems preferable not to consider this parameter in the attempt to discriminate the different types of distributive systems mainly on the basis of geomorphic parameters. Moreover, the role of the catchment area has already been widely investigated for alluvial fans, though with large uncertainties and often with unsatisfactory correlation coefficients, the investigation of which is beyond the scope of this study. Following the results of De Chant et al. (1999) and the work of Viseras et al. (2003), it is evident that the shape of the distributive system is largely influenced by the depositional processes and the accommodation space characteristics (Hartley et al., 2010), rather than the catchment characteristics. For these reasons, the characterization and discrimination among the different types of distributive systems were carried out through the analysis of the four parameters, defined above and outlined in figure 1f, that can be used to describe the geometry of any type of distributive system.

4. Results

Mean and range values of the distributive system geometry parameters are reported in Table 1. From these data, some main preliminary differences among the types of distributive systems are evident. For instance, lacustrine and sea deltas have the smallest slopes, whereas the distributary systems have the smallest apex angle and the lacustrine deltas the widest.

One of the main aims of this study was to verify if distributary systems are simply relict lacustrine deltas as proposed by a few authors (e.g., North and Warwick, 2007), rather than a depositional body with distinctive geomorphic characteristics. The plot diagram of distributive area versus slope (Fig. 3a) clearly shows a distinction between inland distributary systems and lacustrine deltas, with the latter and the former data plotting above and below, respectively of the discriminating function, expressed by the following power equation:

$$S = 0.0109 \times A^{0.508} , \quad (4)$$

Additional evidence of the geomorphic differences between distributary systems and lacustrine deltas was obtained by bivariate diagrams considering the combination of the distributary radius, slope and area vs. the apex angle (Fig. 3b, c and d). In Figure 3b to d, however, the discriminating function is not derived by correlation analysis, as in figure 3a, but it is traced by eye and its aim is simply to emphasize the distinction between the two data sets that plot in different areas of the diagrams.

The data of Table 1 indicate that both alluvial fans and fan deltas have very similar characteristics in terms of slope and area, but they are well distinguished from lacustrine and sea deltas. This observation is also confirmed by the diagram of Figure 4 in which the distributive system area is plotted against the slope. In Figure 4, in fact, alluvial fan and fan deltas are very close and take up the upper portion of the diagram, whereas lacustrine and sea deltas are mixed up and stand in the lower portion with distributary systems in an intermediate position. The constant, the exponent and the correlation coefficient of the equation,

$$S = qA^k , \quad (5)$$

are reported in Table 2.

The k exponent of alluvial fans, fan deltas and lacustrine deltas is very similar, whereas that of

distributary systems and sea deltas are the largest and lowest, respectively.

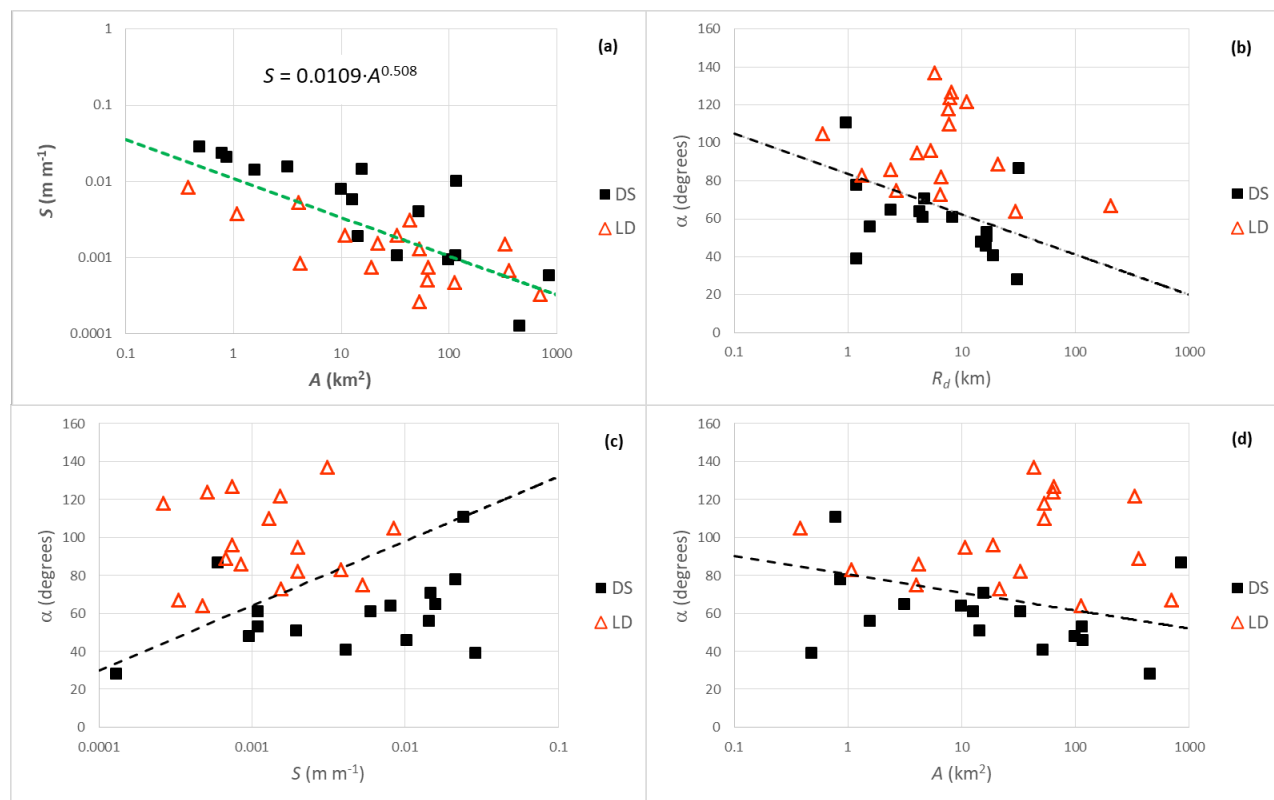


Figure 3 Bivariate diagrams to discriminate between distributary systems (DS) and lacustrine deltas (LD): a) distributive system area (A) vs. slope (S); b) radius (R_d) vs. apex angle (α); c) slope (S) vs. apex angle (α); d) area (A) vs. apex angle (α)

Table 1 Summary of the geomorphic parameters measured: A = area; R_d = radius; S = slope; α = apex angle (see Fig. 1f); cv = coefficient of variation

		Distributary systems	Alluvial fans	Fan deltas	Lacustrine deltas	Sea deltas
A (km^2)	mean	110.90	374.79	100.00	110.14	279.46
	max	852.34	2176.29	1273.37	700.47	2157.24
	min	0.48	1.58	0.02	0.38	0.26
	cv	0.49	0.54	0.31	0.58	0.47
R_d (km)	mean	10.92	14.87	6.21	19.46	12.11
	max	31.88	50.42	45.00	203.00	56.38
	min	0.96	1.51	0.18	0.60	0.58
	cv	1.06	0.90	0.50	0.39	0.72
S (m m^{-1})	mean	0.0095	0.0350	0.0687	0.0020	0.0042
	max	0.0288	0.1090	0.1833	0.00845	0.0119
	min	0.0001	0.0051	0.0024	0.0003	0.0005
	cv	1.03	1.08	1.10	0.89	1.20
α (degrees)	mean	60	86	79	97	81
	max	111	121	108	137	126
	min	28	32	36	64	38
	cv	2.97	3.56	4.10	4.23	3.53

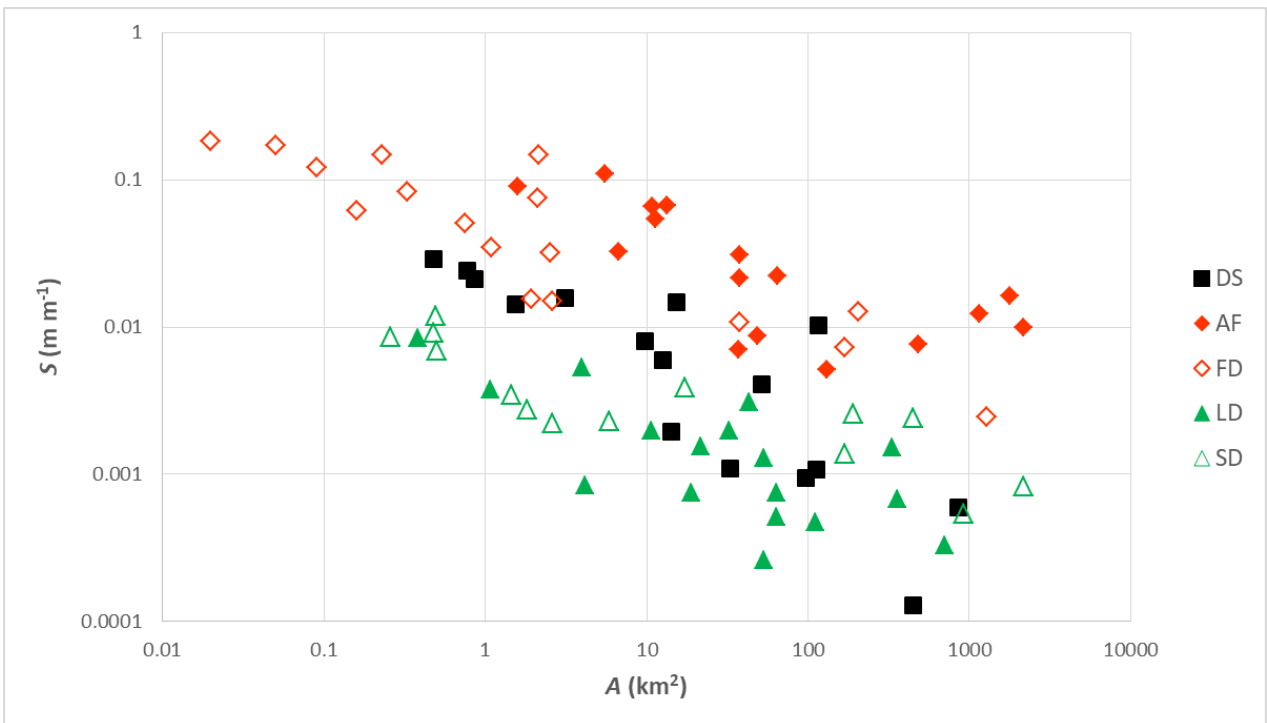


Figure 4 Plot diagram of distributive area (A) vs slope (S). The five types of distributive systems are clearly distinguished; DS = distributary systems; AF = alluvial fans; FD = fan deltas; LD = lacustrine deltas; SD = sea deltas

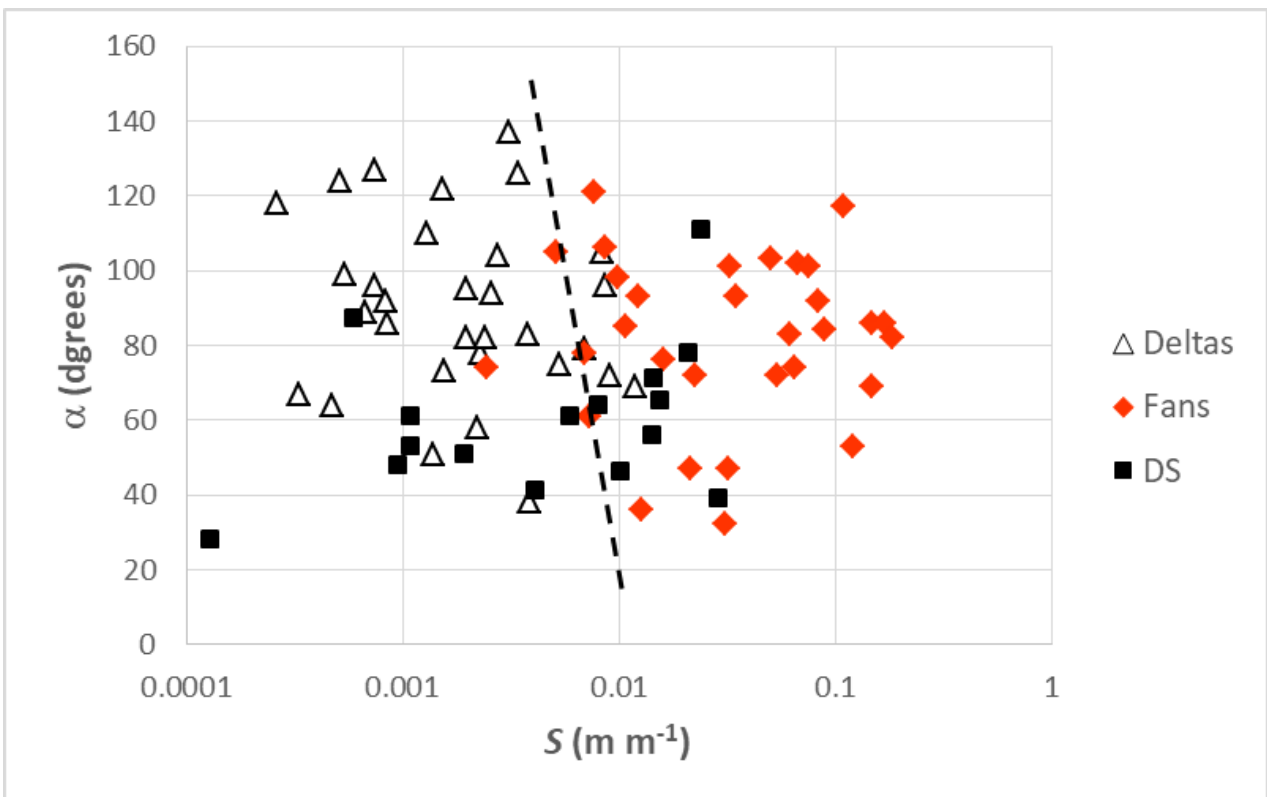


Figure 5 Plot diagram of distributive system slope (S) and apex angle (α). Deltas and fans take up different parts of the diagram. The discriminatory line (dashed line) is not an interpolation line and it is traced by eye

Other non-spurious correlations, such as that between slope and apex angle, are not significant, but if we group the data into the three main types of distributive systems, i.e., deltas, distributary systems and fans, a clear distinction is evident between deltas and fans, whereas distributary systems, yet occupy and intermediate position (Fig. 5).

Table 2 Constant, exponent and correlation coefficient of equation (5) (DS = distributary systems; AF = alluvial fans; FD = fan deltas; LD lacustrine deltas; SD = sea deltas)

Dist. Syst.	q	k	R^2
DS	0.0220	-0.588	0.72
AF	0.0845	-0.329	0.52
FD	0.0490	-0.370	0.80
LD	0.0040	-0.347	0.51
SD	0.0054	-0.241	0.72

The shape of a distributive system depends on many factors, but sediment diffusion and channel processes are probably among the most important, as suggested by De Chant et al. (1999). In fact, if no later constraint is present, the rate of channel shifting, avulsions and bifurcation are expected to result in wider and gentler distributive systems.

To explore this issue, a cone shape parameter $Y = \alpha \times S$ is introduced. The plot diagram of area and Y (Fig. 6) clearly shows that distributary systems, fans and deltas have different shapes. The respective interpolating functions are:

- Deltas: $Y = 112.2 \times A^{1.069}$, ($R^2 = 0.94$) (6)

- Fans: $Y = 1391 \times A^{0.2868}$, ($R^2 = 0.59$) (7)

- Distributary systems: $Y = 2869 \times A^{0.5404}$, ($R^2 = 0.69$) (8)

Small deltas have the lower values of the $\alpha \times S$ product, i.e., narrow and flat bodies, but large deltas have the largest $\alpha \times S$ product and, since an increase in delta gradient is not realistic and increase in apex angle has to be expected. Small distributary systems

have the largest values of the $\alpha \times S$ product implying comparatively steeper body slope, but for large distributive areas are similar to the deltas. Fans have an intermediate behavior with a lower rate of change with increasing the fan area.

5. Discussion

Hartley et al. (2010) have shown that the geometry of inland distributive systems is controlled by a number of parameters, the most important of which are climate, discharge, sediment supply and accommodation space. This study focused only on dryland rivers, therefore, the climate variable can be neglected. In this study, however, also lacustrine and sea deltas were considered as part of the family of distributive depositional bodies. Deltas are also controlled by discharge, sediment and accommodation space, but especially the geometry of sea deltas and fan deltas is also influenced by the wave action. Furthermore, the fluvial and depositional processes are different for distributary systems, alluvial fans, fan deltas and deltas and the confined size characteristics of the deposited material may also play an important role. Notwithstanding such a complex interaction of factors, acting at different rates and with different intensities, yet it is possible to discriminate the geometry of the main types of distributive systems on the base of simple geomorphic parameters (Figs. 4, 5 and 6). Hartley et al. (2010) have produced a huge, planet-wide data set on large distributive fluvial systems, but they recognized six main planforms types based on the number, morphology and downstream changes of the river channels, thus stressing the role of fluvial processes in determining the distributive system characteristics. However, Hartley et al. (2010) included in their analysis any kind of distributary system that corresponded to their definition of a "deposit of a fluvial system which in planform displays a radial, distributive channel pattern". In this regard, this study, though restricted only to arid land distributary systems and based on a smaller data set, may be seen as a partial development of Hartley et al. (2010) work.

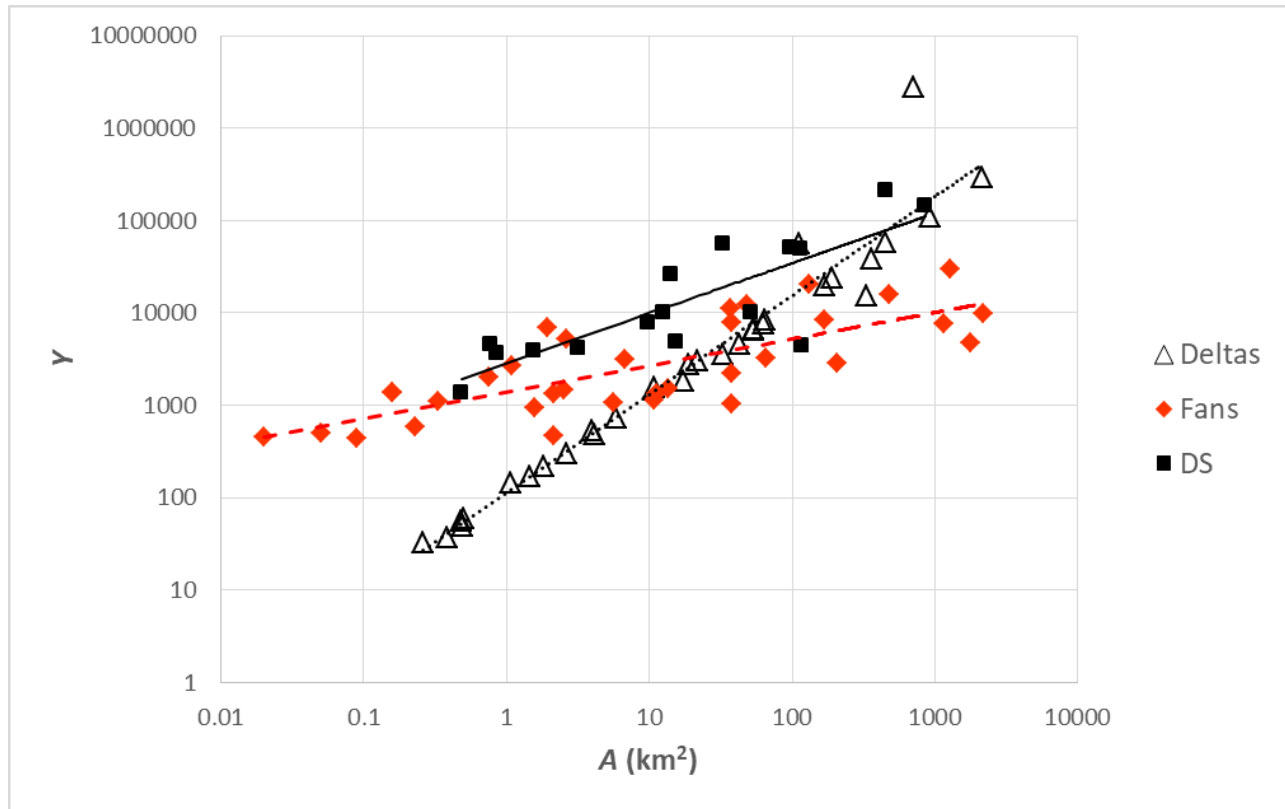


Figure 6 Plot diagram of distributive system area (A) vs. a distributive geometry parameter $Y = \alpha \times S$, where α is the apex angle and S is the slope

A few authors (e.g., North and Warwick, 2007) are convinced that distributary systems are lacustrine deltas inherited from wetter times. According to these authors, modern distributary systems were originally lacustrine deltas and, as the lake dried up, they became entirely subaerial and maintained the distributive geomorphology. This interpretation is based on the occurrence of lacustrine deposits interbedded with ephemeral stream deposits. Though the lacustrine distributary system model evolution may find some correspondence in the world, in many arid and semiarid endorheic, structural basins distributary systems, they have no relation with a former lacustrine delta simply because no lacustrine deposit is present and no lake or swamp ever formed in the past. This setting is quite evident in the Raya graben in northern Ethiopia, where almost all rivers form distributary systems, but no lacustrine deposit was identified by both surface and subsurface drilling investigations (Ethiopian Government, 1977; Billi, 2007).

In the present study, in the lacustrine deltas category, deltas of former lakes, now desiccated, were included as well, but the diagrams of Figure 3 clearly show that distributary systems and lacustrine deltas occupy separate parts of the plot area, with very limited overlapping. In fact, for a comparatively similar area, distributary systems have a steeper slope than lacustrine deltas and for comparatively similar radius length, lacustrine deltas have a much wider apex angle. In other words, distributary systems are steeper and narrower than lacustrine deltas. Such a difference can be accounted for by the different depositional processes that, in the case of the delta, are influenced by the frontal constraint of the water body, whereas in the distributary systems, channels are free to prograde, provided their water and sediment discharge is properly sustained from upstream. Moreover, seasonal or inter annual lake level fluctuations may favour the lateral, longshore redistribution of sediment, resulting in a wider apex angle.

The wave action seems to have less influence on fan deltas, probably because they are made up of coarser material. Alluvial fans and fan deltas have very similar geomorphic characteristics as do lacustrine and sea deltas, though these two groups of distributive systems are clearly distinct. Deltas have comparatively lower slopes than fans (alluvial and fan deltas) but comparable apex angles. This likely implies higher depositional rates at the fan apex, but also some influence of apex bedrock topography and tectonic displacement effect cannot be excluded.

Distributary systems appear to have intermediate characteristics between fans and deltas, but they maintain their unicity in terms of fluvial processes and geomorphic characteristics. Bifurcation and avulsion are common channel processes in distributary systems, with main flood flows often shifting from one distributary channel to the other, but multiple active channels, like those observed on fans, are absent and in deltas, the rate of bifurcation is higher. Deltas, in fact, have the lowest gradient and, though the bedload flux may be less than in distributary systems, the frontal confinement imposed by the water body and the smaller stream power may result in high sedimentation rates and, consequently, in high bifurcation rate.

The prevalence of factors such as accommodation space characteristics, fluvial processes and sediment supply in shaping distributive systems was pointed out by Hartley et al. (2010), who also stressed the importance of local geological and structural settings. The clear distinction of the different kinds of distributive systems highlighted in this study by means of bivariate diagrams including only geomorphic parameters seems to support the conclusions of Hartley et al. (2010) and the approach presented by De Chant et al. (1999). These authors derived a simple equation to calculate the volume of alluvial fans as a function of the apex angle (α), the radius (R_d) and the elevation of the apex with respect to the fan fringe (h) (eq. 3 of this paper). In the present study, it was not possible to measure h , which would require extensive field inspection to determine the elevation of the bedrock under the fan apex and the main focus was instead on distributive system area. Moreover,

distributary systems and deltas have lower gradients than fans and allow to remove h from eq. 3 and to define a geometry parameter Y as the product of apex angle and slope. The plot of area vs the shape parameter Y , confirms that distributary systems, deltas and fans have distinctive shapes (Fig. 6). Deltas and fans have the highest and the lowest correlation coefficient ($R^2 = 0.94$ and 0.59 , respectively), probably because they are the flattest and have the thickest bodies, respectively. Unlike deltas and fans, the distributary systems of this study are all unconfined and this may be an important factor of distinction. Nevertheless, these results indicate that for fans h is an important parameter and indirectly confirms the approach of De Chant et al. (1999).

6. Conclusions

A total of 81 ephemeral streams distributive systems were selected from different arid lands in the world. They were included into five categories: distributary systems *sensu stricto*, alluvial fans, fan deltas, lacustrine deltas and sea deltas. The data show that distributary systems have geomorphic characteristics different from those of lacustrine deltas and no relations seem to exist with former lacustrine deltas of wetter climate as instead advocated by North and Warwick (2007).

Alluvial fans and fan deltas have similar fan geometry and very similar are also the geomorphic characteristics of lacustrine and sea deltas. Distributary systems have intermediate geomorphic characteristics between fans and deltas. Fan deltas seem to be less influenced by wave action than deltas, likely because the former are composed of coarser sediment. Distributary systems have a smaller apex angle and are steeper than deltas. The lower gradient of the latter favours the formation of multiple channels and hence a wider apex angle. All these results confirm the convincement of De Chant et al. (1999) that the shape of distributive systems is mainly controlled by sediment diffusion, channel processes and accommodation space characteristics rather than catchment area.

Acknowledgments

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References

- Bhattacharya JP. 2006. Deltas. In: *Facies Models Revisited*. SEPM Special Publication, No. 84, Tulsa, 237–292.
- Billi P. 2007. Morphology and sediment dynamics of ephemeral streams terminal reaches in the Kobo basin (northern Welo, Ethiopia). *Geomorphology* **85**: 98–113. DOI: 10.1016/j.geomorph.2006.03.012
- Bilmes A., Veiga GD. 2016. Linking mid-scale distributive fluvial systems to drainage basin area: geomorphological and sedimentological evidence from the endorheic Gastre Basin, Argentina. In: Ventra D, Clarke LE. (eds.), *Geology and Geomorphology of Alluvial and Fluvial Fans: Terrestrial and Planetary Perspectives*. Geological Society Special Publications No. 440, The Geological Society, London, 1–15. DOI: 10.1144/SP440.4
- Blair TC, McPherson JG. 1994. Alluvial fan processes and forms. In: Abrahams AD, Parson AJ. (eds.), *Geomorphology of Desert Environments*. Chapman and Hall, London, 354–402.
- Bristow CS, Skelly RL, Ethridge FG. 1999. Crevasse splays from the rapidly aggrading, sand-bed, braided Niobrara River, Nebraska: effect of base-level rise. *Sedimentology* **46**: 1029–1047. DOI: 10.1046/j.1365-3091.1999.00263.x
- Charlton R. 2008. *Fundamentals of fluvial geomorphology*. Routledge New York. 264 p.
- De Chant LJ, Pease PP, Tchakerian VP. 1999. Modelling alluvial fan morphology. *Earth Surface Processes and Landforms*, **24**(7): 641–652. DOI: 10.1002/(SICI)1096-9837(199907)24:7<641::AID-ESP979>3.0.CO;2-3
- Donselaar ME, Cuevas Gozalo MC, Moyano S. 2013. Avulsion processes at the terminus of low-gradient semi-arid fluvial systems: Lessons from the Río Colorado, Altiplano endorheic basin, Bolivia. *Sedimentary Geology* **283**: 1–14. DOI: 10.1016/j.sedgeo.2012.10.007
- Ethiopian Government 1977. Kobo–Alamata agricultural development program. Volume II: Annexes pedology and water development. German Agency for Technical Co-operation, unpublished.
- Fisher JA, Nichols GJ, Waltham DA. 2007. Unconfined flow deposits in distal sectors of fluvial distributary systems: Examples from the Miocene Luna and Huesca Systems, northern Spain. *Sedimentary Geology* **195**: 55–73. DOI: 10.1016/j.sedgeo.2006.07.005
- Galloway WE. 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In: Broussard ML (ed.), *Deltas: Models for Exploration*. Houston Geological Society, Houston, 87–98.
- Hartley AJ, Weissmann GS, Nichols GJ, Warwick GL. 2010. Large distributive fluvial systems: characteristics, distribution, and controls on development. *Journal of Sedimentary Research* **80**: 167–183. DOI: 10.2110/jsr.2010.016
- Harvey A. 2011. Dryland alluvial fans. In: Thomas DSG. (ed.): *Arid Zone Geomorphology: Processes, Form and Change in Drylands*. Wiley, New York, 333–371. DOI: 10.1002/9780470710777.ch14
- Jones LS, Schumm SA. 1999. Causes of avulsion: an overview. In: Smith ND, Rogers J (eds.), *Fluvial Sedimentology VI*. Special Publication No. 28 of the International Association of Sedimentologists, Blackwell Science, 171–178. DOI: 10.1002/9781444304213.ch13
- Kelly SB, Olsen H. 1993. Terminal fans – a review with reference to Devonian examples. *Sedimentary Geology* **85**: 339–374. DOI: 10.1016/0037-0738(93)90092-J
- Lecce SA. 1991. Influence of lithologic erodibility on alluvial fans area, Western White Mountains, California and Nevada. *Earth Surface Processes and Landforms* **16**: 11–18. DOI: 10.1002/esp.3290160103
- Marchi L, Tecca PR. 1995. Alluvial fans of the Eastern Italian Alps: morphometry and depositional processes. *Geodinamica Acta* **8**(1): 20–27. DOI: 10.1080/09853111.1995.11105270
- Mikhailova MV. 2015. Morphometry of river deltas. *Water Resources* **42**(1): 52–62. DOI: 10.1134/S009780781501008X
- Mokarram M, Seif A, Sathymoorthy D. 2014. Use of morphometric analysis and self-organizing maps for alluvial fan classification: case study on Ostorankoo altitudes, Iran. *IOP Conference Series: Earth and Environmental Science* **20**: 012003. DOI: 10.1088/1755-1315/20/1/012003
- Mukerji AB. 1976. Terminal fans of inland streams in Sutlej–Yamuna plain, India. *Zeitschrift für Geomorphologie* **20**: 190–204.
- Nichols GJ, Fisher JA. 2007. Processes, facies and architecture of fluvial distributary system deposits. *Sedimentary Geology* **195**: 75–90. DOI: 10.1016/j.sedgeo.2006.07.004
- North CP, Warwick GL. 2007. Fluvial fans: myths, misconceptions, and the end of the terminal-fan model. *Journal of Sedimentary Research* **77**: 693–701. DOI: 10.2110/jsr.2007.072

- Olariu C, Bhattacharya JP. 2006. Terminal distributary channels and delta front architecture of river-dominated delta systems. *Journal of Sedimentary Research* **76**: 212–233. DOI: 10.2110/jsr.2006.026
- Schumm SA. 1977. *The fluvial system*. New York Wiley. 338 p.
- Stainstreet IG, McCarthy TS. 1993. The Okavango fan and the classification of subaerial fan systems. *Sedimentary Geology* **85**: 115–133. DOI: 10.1016/0037-0738(93)90078-J
- Syvitski JPM, Saito Y. 2007. Morphodynamics of deltas under the influence of humans. *Global and Planetary Change* **57**: 261–282. DOI: 10.1016/j.gloplacha.2006.12.001
- Ventra D, Clarke LE. 2018. Geology and geomorphology of alluvial and fluvial fans: Current progress and research perspectives. In: Ventra D, Clarke LE (eds.), *Geological Society Special Publications No. 440*, The Geological Society, London, 1–21. DOI: 10.1144/SP440.16
- Viseras C, Calvache ML, Soria JM, Fernandez J. 2003. Differential features of alluvial fans controlled by tectonic or eustatic accommodation space. Examples from the Betic Cordillera, Spain. *Geomorphology* **50**: 181–202. DOI: 10.1016/S0169-555X(02)00214-3
- Woodroffe CD, Saito Y. 2011. River-Dominated Coasts. In: Wolanski E, McLusky DS (eds.), *Treatise on Estuarine and Coastal Science*. Vol. 3, Elsevier-Academic Press, Waltham, 117–135. DOI: 10.1016/B978-0-12-374711-2.00306-5
- Zhang H, Lu Y. 2014. Geomorphometric features of the alluvial fans around the Chaka–Qinghai Lake in the northeastern Tibetan Plateau. *Journal of Earth Science* **25**(1): 109–116. DOI: 10.1007/s12583-014-0404-z