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Meander hydromorphology of ephemeral streams: Similarities and differences with perennial rivers

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ABSTRACT

The geomorphology, hydrology and processes of ephemeral streams are poorly known and studies on the geomorphic characteristics of ephemeral meandering streams (EMS) are even less investigated. We collected geomorphic data (namely, channel width, sinuosity, wavelength and curvature radius) from 107 EMS reaches in different drylands of the world from GoogleEarth Pro® satellite images. Geomorphology features/processes, such as neck cutoffs, point scrolls and chute cutoffs, were also assessed. The main aim of this paper is to investigate similarities and differences between EMS and perennial counterparts of more humid areas (on which almost all hydrogeomorphic models are based) for the purpose of explaining why meandering rivers form in environments where the lack of vegetation, sporadic flows and a high sediment supply should favour the development of braided rivers. EMS showed both geomorphological similarities and differences with perennial rivers. Point bar chute cutoffs and point bar scrolls are the most common geomorphic features of EMS, suggesting a certain stability of meander behaviour, though within a continuous process of changes towards the most probable form, similarly to perennial streams. The bimodal distribution of curvature ratio values departs substantially from that of perennial rivers that are commonly in the 2–3 range. Data from the rivers in this study indicate that their channel pattern is well described by the same sine generated function used for perennial rivers. Wavelength to channel width ratio and bankfull discharge to streambed gradient of EMS unexpectedly plot in different areas of classical diagrams developed for perennial rivers. We interpret such differences in terms of excess energy expenditure for high sediment load transport. We also propose a new function to discriminate the meandering from the braided pattern of ephemeral streams, and present a conceptual model of meander formation in ephemerals streams based on an autogenic process of bank collapse and bar deposition.

1. Introduction

In the scientific literature, papers dealing with the geomorphology, hydrology and processes of ephemeral streams are scarce compared to those on perennial rivers. A few of these papers, however, include some consideration of the differences between ephemeral streams and their perennial counterparts of more humid areas (e.g., Knighton and Nanson, 1997; Billi, 2008; Powell, 2009). Some authors think that ephemeral and perennial rivers are governed by the same geomorphic processes, and that the former are just end-members in the river hydromorphology continuum, though under the extreme condition of a climate-driven lack of precipitation (e.g., Bridge, 2003). Others consider ephemeral streams as unique and deserving to be investigated as a distinctive, unique case (Tooth, 2000; Vyverberg, 2010). Most authors, however, recognize that ephemeral streams have characteristics that may differ from perennial rivers, though not all are specific of dryland rivers:

1. Intermittent flows, in response to sporadic heavy rainfall.
2. Larger flood magnitudes compared to rivers of more humid regions. According to Osterkamp and Friedman (2000), rare high unit peak flows in drainage basins smaller than 1000 km^2 are more common in semi-arid areas than elsewhere. This does not depend solely on high intensity precipitation, but also on more cohesive, compacted, poorly developed soil (Osterkamp and Friedman, 2000) due to sparse vegetation and scarce organic matter (Baker, 1977; Knighton and Nanson, 1997).
3. Downstream transmission losses (Dunkerley, 1992).

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4. High sediment supply due to the sparse vegetation (Reid and Laronne, 1995).
5. High transport rates of both bedload and suspended load (Reid and Laronne, 1995; Tooth, 2000; Billi, 2011).
6. High depositional rates, favoured by the high sediment supply and the reduced sediment transport capacity due to water infiltration and transmission losses, which lead to wide channels with large width/depth ratios.
7. Flat bars (especially in braided channels) and a predominance of horizontal lamination in sand bed rivers, which are commonly devoid of other kinds of bedforms (Frostick and Reid, 1977; Billi, 2008; Li et al., 2015).
8. Predominance of straight braided channels (Tooth, 2000) due to sparse (or absent) riparian vegetation and a lack or very scarce presence of clay, resulting in poor bank stabilization and cohesion, which favour channel widening (and thus braiding) during floods (Powell, 2009).

In ephemeral streams, the lack of riparian vegetation, the ease with which non-cohesive banks are eroded, and the instability of bedload transport in wide channels (Parker, 1976) are strong arguments in support of a high probability for ephemeral streams to assume a braided configuration rather than a meandering pattern. According to Tal and Paola (2007), rooted vegetation plays an important role in the formation of meanders, and that seems to be supported by the analysis of Gibling et al. (2014, their Fig. 1) who pointed out the lack of meandering rivers in pre-Devonian deposits (i.e., prior to the advent of well developed, rooted vegetation). Nevertheless, braided channels are considered the most common in arid lands (Tooth, 2000; Levick et al., 2008), but ephemeral meandering streams (EMS) do exist as well, although Graf (1988) speculates that the latter are quite rare in drylands. Additional evidence that meandering channels can form in the absence of vegetation is provided by the meanders observed in the Aeolis Dorsa region on Mars studied by Matsubara et al. (2015), although gravity and hydrological conditions on Mars are totally different from those of modern EMS on Earth. The results of flume experiments on the role of a cohesive floodplain also led van Dijk et al. (2013a) to conclude that “a meandering river can develop without having an initial cohesive bank”.

A proportion of EMS are entrenched into the bedrock or relatively recent cohesive fluvial/lacustrine deposits, and therefore likely inherited their present meandering pattern from Late Pleistocene-Early Holocene wetter climate conditions. However, alluvial EMS also can be found in several arid areas of the planet (Figs. 1 and 2).

Very little is known about this latter kind of rivers (Tooth, 2000), though in dryland countries they are a resource as well as a threat to infrastructure. The literature on ephemeral streams in general is not rich, and only one paper by Li et al. (2015) was found to deal specifically with a modern example of ephemeral meandering river. These authors investigated sediment dispersal within an ephemeral meandering system in the semi-arid Highland Basin of the Bolivian Cordillera and provided very limited information about geomorphological features other than the longitudinal profile and some qualitative description of channel morphology (their Figs. 7, 11, 12 and 13).

Field and laboratory data indicate that channel morphology is mainly controlled by discharge (specifically bankfull discharge) and slope (Lane, 1957; Leopold and Wolman, 1957), bed material grain size, flow energy (namely potential unit stream power, van den Berg, 1995), particle size and quantity of sediment supply, roughness, sediment transport and sedimentation (Dade, 2000; Church 2006).

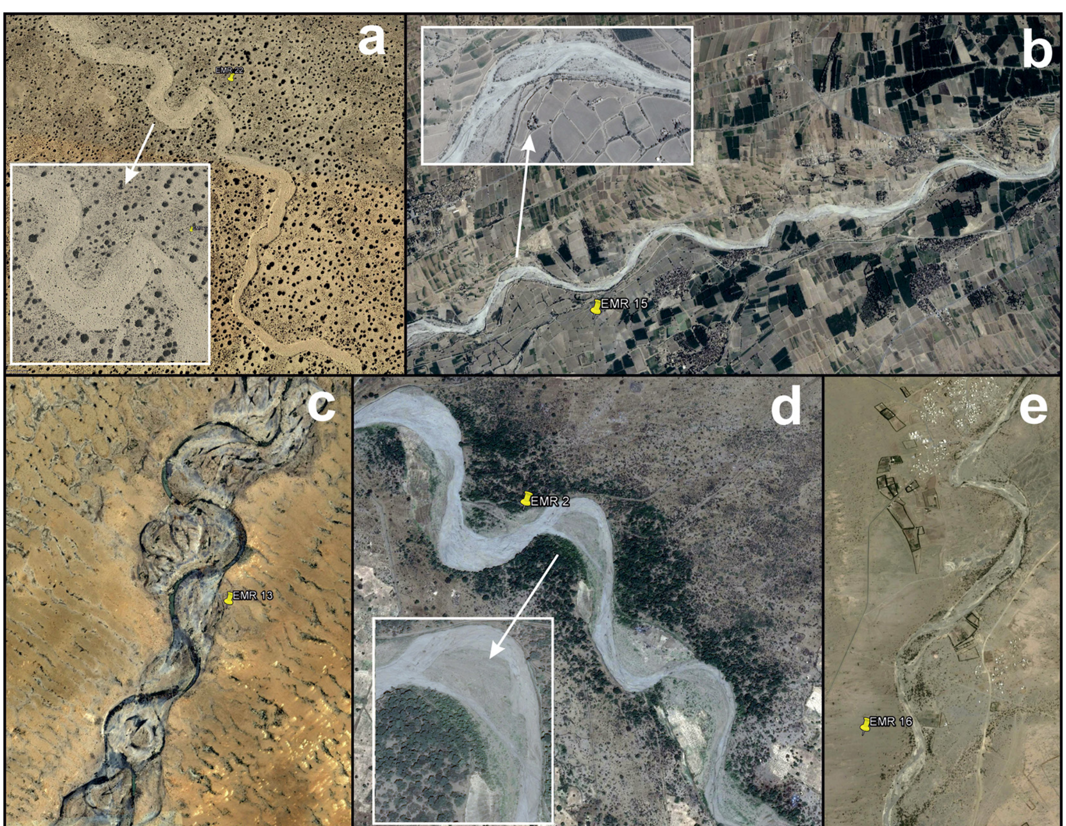

Fig. 1. Examples of EMS reaches considered in this study: (a) reach 22 - south of Paita, northern Peru coastal plain; (b) reach 15 - Red Sea coastal plain of western Yemen; (c) reach 13 - western Chad, near Lake Chad; (d) reach 2 - southern Ethiopia, near Konso; (e) reach 16 - southern Red Sea coast of Saudi Arabia (see the KML file online for location of all study sites). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)