Geomorphology 295 (2017) 16–27

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Self-dissimilar landscapes: Revealing the signature of geologic constraints on landscape dissection via topologic and multi-scale analysis

Mohammad Danesh-Yazdi[a,*], Alejandro Tejedor[b], Efi Foufoula-Georgiou[b]

[a] Department of Civil, Environmental, and Geo-Engineering, St. Anthony Falls Laboratory, National Center for Earth-Surface Dynamics, University of Minnesota, Minneapolis, MN, USA
[b] Department of Civil and Environmental Engineering, University of California, Irvine, CA, USA

ARTICLE INFO

Keywords:
Self-dissimilarity
Landscape topography and river network topology
Wavelet multi-scale analysis and synthesis
Spectral gap

ABSTRACT

Climatic or geologic controls, such as tectonics or glacial drainage, might impose constraints on landscape self-organization resulting in spatial patterns of rivers and valleys which do not obey the typical self-similar relationships found in most landscapes. The goal of this study is to quantify how such geologic constraints express themselves on channel network topology, spatial heterogeneity of drainage patterns, and emergence of preferred scales of landscape dissection. We use as an example a basin located in the Upper Midwestern United States where successive glaciations over the past thousand years have led to a pronounced spatially anisotropic channel network structure which defeats most scaling laws of fluvial landscapes. This is contrasted with another river basin in the North-Central U.S. which has been organized under the absence of major geologic influences and follows a typical self-similar channel network organization. We show how the geologic constraints have imposed a competition for space which is captured in the slope–local drainage density probabilistic structure, in the failure of self-similarity in basin-wide river network topology, and in the length-area scaling relationship being not typical of fluvial landscapes. Via a two-dimensional wavelet analysis and synthesis, we demonstrate the occurrence of a gap in the power spectrum which corresponds to the presence of preferred scales of organization, and characterize them through multi-scale detrending. The developed methodologies can be useful in advancing our geomorphologic understanding of how external controls might manifest themselves in creating a landscape dissection that is outside the norm and how this dissection can be studied objectively for understanding cause and effect.

1. Introduction

Landscape self-organization driven by the movement of water and sediment, and the emergence of river networks that exhibit a hierarchical structure across a range of scales have been the subjects of intensive research over the past decades (e.g., see Rodriguez-Iturbe and Rinaldo, 2001 and references therein). Recently, Zanardo et al. (2013) studied 408 river networks from 50 basins with different geographic location and climate across the United States to assess if the majority of the river networks exhibit self-similarity (SS) in their topological structure. Through a rigorous statistical testing of the Hortonian and Tokunaga self-similarities (see Zanardo et al., 2013 for a detailed representation of these tests), they concluded that 96% of the river networks overwhelmingly exhibited Hortonian Self-Similarity (HSS), while 80% of them followed a topological hierarchical structure that can be characterized successfully by Tokunaga Self-Similarity (TSS). Despite the wealth of studies on landscapes drained by river networks that exhibit HSS, detailed studies of those 20% basins that break the stricter TSS are lacking. The goal of this work is to explore such "outlier basins" which we call "self-dissimilar" and propose methodologies that can probe into their structure in ways that are able to reveal spatially heterogeneous organization and preferential scales of dissection, which then can be related to the underlying controls of, e.g., climate or geology.

Fig. 1a illustrates an example of such basins corresponding to the 43,400 km^2 Minnesota River Basin (MRB) located in the Upper Midwestern Unites States. The geologic history of the MRB (Ojakangas, 1982; Nicollet, 1993) reveals that successive glaciations around 100,000–10,000 BP and the draining of glacial Lake Agassiz in 13,400 BP drastically carved this landscape (Clayton and Moran, 1982; Belmont et al., 2011). While glacial lobes draining over most of this basin left behind a flat and lake-punctuated landscape in the central-

* Corresponding author at: Department of Civil, Environmental, and Geo-Engineering, St. Anthony Falls Laboratory, National Center for Earth-Surface Dynamics, University of Minnesota, Minneapolis, 2 Third Ave SE, Minneapolis, MN 55414-2196, USA.
E-mail address: dane0049@umn.edu (M. Danesh-Yazdi).

http://dx.doi.org/10.1016/j.geomorph.2017.06.009
Received 21 September 2016; Received in revised form 11 June 2017; Accepted 11 June 2017
Available online 21 June 2017

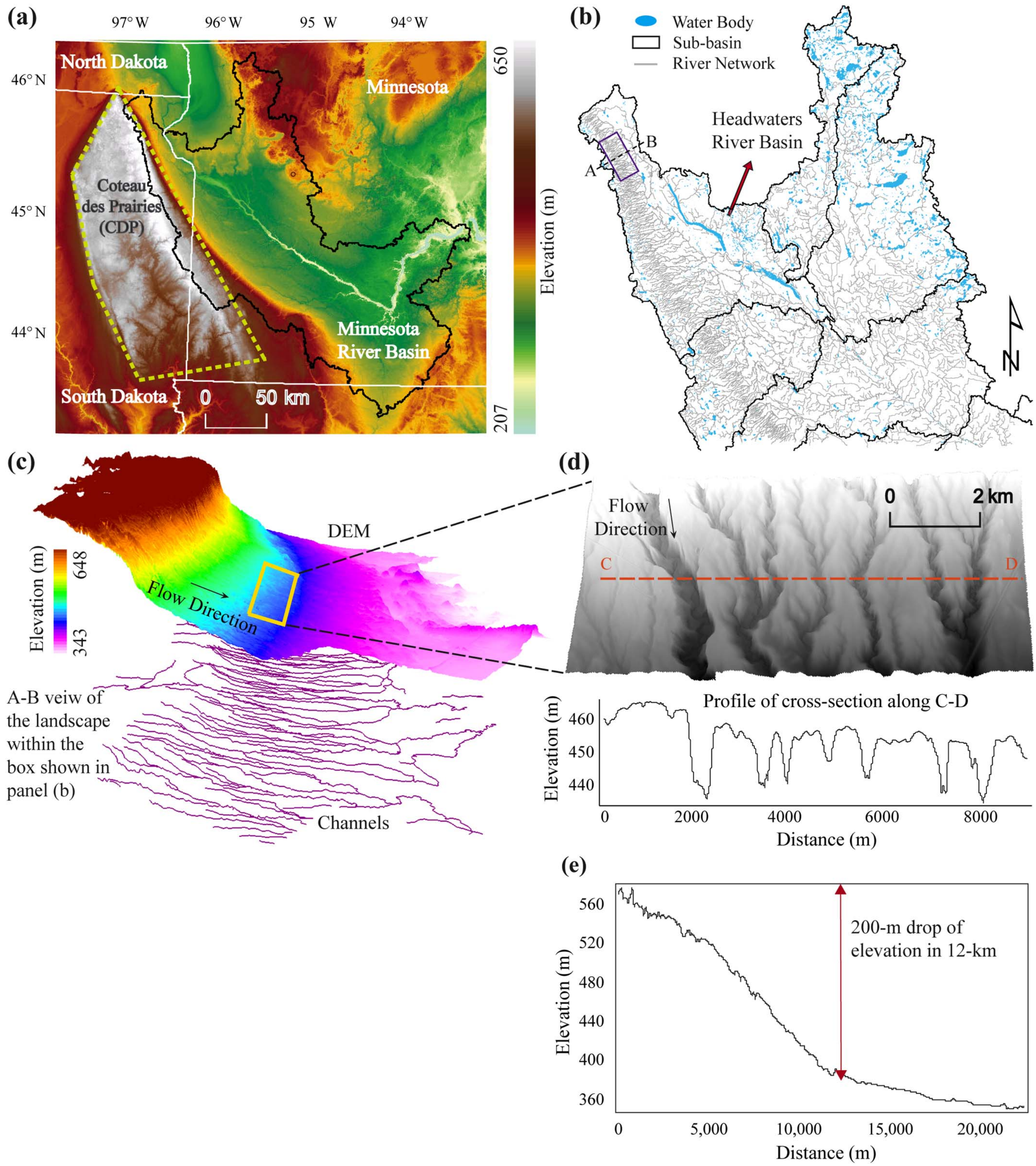

Fig. 1. Illustration of the Minnesota River Basin (MRB) and the Coteau des Prairies (CDP) region. (**a**) Elevation map of the MRB and the CDP residing along the South Dakota border and extending to the Northwestern part of the MRB. (**b**) River network topology of the Northern part of the MRB, including the Headwaters sub-basin which encompasses a portion of the CDP. (**c**) 3D view of the Headwaters landscape delineated by the box shown in (b), showing the presence of a dense number of fairly parallel channels. (**d**) Hillshade of the DEM corresponding to a 70 km^2 patch in the high slope region, depicting quasi-periodic ridges and valleys in this part of the landscape. (**e**) Longitudinal profile of the cross section A–B within the box shown in (b), indicating a 200 m drop in elevation within a 12 km horizontal distance.

eastern part, the western bedrock part was not eroded (Fig. 1b). Instead, repeated glacial cycles covered that bedrock with glacial till deposits and formed the 320 km long, 160 km wide geological feature called Coteau des Prairies (CDP) residing along the South Dakota border and extending to the northwestern part of the MRB. At the edge of the CDP (Fig. 1c,d) there is a pronounced difference in the fluvial dissection compared to the rest of the basin, expressed by the presence of a dense number of steep channels and quasi-periodic ridges and valleys. This high slope region (HSR) includes channels with slope larger than 0.01 m m^{-1} and maximum elevation less than 500 m. A cross-section