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Controls of climate, topography, vegetation, and lithology on drainage density extracted from high resolution topography data

Harish Sangireddy [a], Richard A. Carothers [a], Colin P. Stark [b], Paola Passalacqua [a,*]

[a] Department of Civil, Architectural and Environmental Engineering, and Center for Research in Water Resources, The University of Texas at Austin, Austin, TX, USA
[b] Lamont-Doherty Earth Observatory, Columbia University, USA

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S U M M A R Y

Mark Melton in 1957 found that climate, basin morphometry, and surficial variables control drainage density (D_d), but differences observed between field surveyed channels and those mapped on topographic contours or blue lines left doubts on these results. Later, several landscape evolution model and observational studies analyzed the behavior of D_d. However, only a few studies have been performed over a large number of landscapes of different characteristics and have relied on high resolution topography data.

We revisit Melton's hypothesis by using meter-resolution digital terrain models (DTMs) in 101 sub-basins in the USA. We first propose a dimensionless drainage density (D_{dd}) metric based on the ratio of likely channelized pixels to total number of basin pixels, which has the advantage of eliminating the computation of the channel network. Our analysis shows that D_{dd} is a weak scaling function of the input DTM resolution compared to the classic dimensional D_d metric (ratio of total channel length to total basin area). We analyze the correlation of D_{dd} and mean annual precipitation (*MAP*) with a Gaussian mixture model which identifies two sub-groups displaying different correlation; negative in arid and semi-arid environments, and positive in humid environments. The transition in correlation is around 1100 ± 100 mm/yr of *MAP* and is accompanied by the occurrence of thick soil layers and high available water capacity that promote dense vegetation cover (V_{cov}) and low D_{dd}. While small variation in D_{dd} is observed across vegetation types, increasing V_{cov} corresponds to decreasing D_{dd}. We also explore the relationship between D_{dd} and relief R, and D_{dd} and lithology. D_{dd} and R are weakly correlated in arid and semi-arid environments, while they have strong positive correlation in humid environments. No significant correlation is found between D_{dd} and lithology although the results are likely affected by our sample choice.

1. Introduction

As a unique property of the landscape, drainage density (D_d) relates the underlying geomorphic processes acting in a catchment to its topography (Moglen et al., 1998). Usually expressed as the ratio of total channel length to total catchment area (Horton, 1932), D_d is controlled by local lithology (Carlston, 1963; Kelson and Wells, 1989; Melton, 1957; Talling and Sowter, 1999), topography (Tucker and Bras, 1998; Oguchi, 1997a), vegetation (Luoto, 2007; Chorley, 1957; Moglen et al., 1998; Melton, 1957; Collins and Bras, 2010; Istanbulluoglu and Bras, 2005) and regional climatic patterns (Melton, 1957; Abrahams, 1984, 1972b; Daniel, 1981; Gregory and Walling, 1968; Madduma Bandara, 1974; Chorley, 1957; Moglen et al., 1998; Smith et al., 2013; Chadwick et al., 2013).

Field studies and modeling efforts have been used to isolate and understand the controls of climate, topography, vegetation, and lithology on D_d. One such extensive field study was conducted by Melton (1957) over 90 basins in Arizona, Colorado, New Mexico and Utah. Topographic contour maps [1:24,000] were used to measure catchment slope, relief (R), and D_d. The Thornthwaite precipita tion–evaporation (P–E) index (Thornthwaite, 1931) was used to represent regional climatic patterns, while relative infiltration capacity, soil strength, and percent bare ground were used to represent soil and vegetation characteristics. Through multivariate regression and correlation analysis, Melton (1957) observed that D_d increased with increasing percent bare ground and runoff (I), but decreased with increasing P–E index and infiltration capacity. Some variation

* Corresponding author at: Department of Civil, Architectural and Environmental Engineering and Center for Research in Water Resources, The University of Texas at Austin, 301 E. Dean Keeton St., Stop C1700, Austin, TX 78712-2100, USA.
E-mail address: paola@austin.utexas.edu (P. Passalacqua).

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in D_d by lithology type was also observed; average D_d for shale and schist was well above the observed mean D_d, whereas the values for limestone and acidic volcanic rocks were well below mean D_d.

Abrahams (1984) extended this analysis over a wider range of P–E index and observed that D_d varied inversely with P–E index in semi-arid regions while increased with increasing P–E index in humid environments. This reversal in trend was attributed to the local vegetation cover (V_{cov}). The dueling control of vegetation and runoff over D_d with increasing mean annual precipitation (*MAP*) was also studied by Istanbulluoglu and Bras (2005) who showed with numerical experiments that contrasting differences existed between drainage networks in landscapes with and without vegetation cover. For no V_{cov} their simulations generated low-relief highly dissected landscapes, while a static V_{cov} produced a less dissected landscape. Collins and Bras (2010) later summarized the feedback of vegetation and runoff under varying *MAP* in a schematic representation showing an initial increase in drainage density in arid areas, followed by a decrease in semi-arid regions, and an increase in humid environments.

Drainage density (D_d) is defined as the ratio of total channel length in a catchment to total catchment area (Horton, 1932). Computation of D_d needs prior knowledge of channel head locations followed by a robust method for channel centerline extraction. Coarse resolution digital elevation models (DEMs) fail to capture first order channels which are essential for the transport of runoff and sediment from hillslopes to valleys. The inability to accurately detect channel networks in coarse resolution DEMs affects the computation of D_d causing strong discrepancy with field mapped results (Morisawa, 1957; Morisawa, 1961; Schneider, 1961; Li and Wong, 2010; Goulden et al., 2014). With the recent availability of high resolution topography (HRT) data, we have the opportunity to analyze drainage density at spatial resolutions commensurate with the underlying process regimes. HRT data have changed the way landscapes are analyzed and have increased our ability to infer processes from landscapes and extract landscape features at scales comparable to the underlying catchment processes (Lin and Oguchi, 2004; Roering et al., 2013; Glennie et al., 2013; Passalacqua et al., 2014; Tarolli, 2014; Harpold et al., 2015; Passalacqua et al., 2015).

Channel networks and channel heads can be automatically and objectively extracted from HRT data (Lashermes et al., 2007; Tarolli and Dalla Fontana, 2009; Passalacqua et al., 2010b; Passalacqua et al., 2010a; Pelletier, 2013; Sangireddy et al., in review) opening up the possibility of measuring D_d objectively and revisiting the Melton (1957) hypothesis. Similarly, processes such as tree throw and root decay, which control sediment generation in a basin and indirectly influence the extent of landscape dissection, can be inferred successfully from HRT data (Gabet et al., 2003; Roering et al., 2004; Gabet and Mudd, 2010). Vegetation properties such as mean tree height, canopy density, above-ground biomass (AGB) can also be computed from these datasets (Nilsson, 1996; Clark et al., 2011; Pelletier et al., 2011; Hurst et al., 2013).

Basin lithology affects the extent of landscape dissection. *MAP* and available water capacity (*AWC*) are important factors influencing rock weathering and soil thickness (*THICK*). By analyzing the behavior of soil parameters, relief (R), and vegetation cover (V_{cov}) with increasing *MAP* we can capture how climate controls these variables and how these variables affect the correlation of D_d and *MAP*. Also, soil physical properties such as porosity, thickness, and pore size are controlled indirectly by climate (Chadwick et al., 2013) and determine water supply that strongly influences plant growth. Similarly, the correlation between topographic relief and D_d is of particular interest as it helps understand the relationship between erosion rates and patterns of channelization critical for testing eco-geomorphic landscape evolution models (Oguchi, 1997a; Howard, 1998; Tucker and Bras, 1998).

Melton's hypothesis has been cited numerous times in the literature. However, to our knowledge, his hypothesis has not been investigated using high-resolution lidar data and new technologies for data processing and methods for channel identification. Here we present a new non-dimensional metric of drainage density, illustrate its robustness with respect to data resolution, and use it for analyzing the relationship between drainage density and its controlling factors. In particular, the goals of our study are to: (i) propose a dimensionless measure of drainage density D_{dd} based on the number of likely channelized basin pixels, eliminating the need for computation of the channel network and reducing the resolution dependence of drainage density, and (ii) by using a large high resolution data set across the USA, revisit Melton's hypothesis and examine the controls of climate, topography, vegetation, and lithology on drainage density. The underlying hypothesis of our study is that drainage density carries strong, codependent signatures of *MAP*, R, V_{cov}, vegetation type, lithology, and rock strength. Such signatures can be objectively determined by analyzing HRT data.

We test this hypothesis by mapping drainage density over meter-resolution datasets with the GeoNet method (https://sites.google.com/site/geonethome, Passalacqua et al., 2010b; Sangireddy et al., in review) in 101 subbasins across 13 states in the USA in combination with best-available spatial resolution maps of precipitation, soil, geology, and land cover. The choice of the subbasins was constrained by the availability of HRT data and the need to cover a wide range of climatic regimes. The availability of spatial maps of precipitation, soil, geology, and land cover was also considered. In addition, we focused our analysis on basins that are not severely urbanized, enforcing this criterion through visual inspection of aerial imagery.

The paper is organized as follows. After introducing the datasets used in this work (Section 2), we propose a dimensionless drainage density metric and analyze its behavior through scales, followed by an explanation of the method used to estimate canopy cover (Section 3). We analyze the correlation between drainage density and several climatic, topographic, vegetational, and geologic parameters (Section 4), followed by a discussion of the results (Section 5). Finally, we state the conclusions of this work (Section 6).

2. Study areas and data description

We analyze a total of 101 subbasins located across 13 states (Fig. 1). HRT data were obtained from OpenTopography (http://www.opentopography.org/) at 1 m resolution (airborne lidar), except for four basins in Arizona and four basins in Utah, for which HRT data were obtained from the National Elevation Dataset (NED) at 3 m resolution and re-sampled to 1 m resolution by using the nearest neighbor method. The eight basins from NED were included in our analysis as these regions were analyzed by Melton (1957). Lidar point density varied considerably over the basins depending on the date of the lidar survey as well as the local ground cover. Rasters were generated from the lidar point clouds by creating a TIN (Triangulated Irregular Network) with an interpolation algorithm called TIN streaming (http://www.cs.unc.edu/isenburg/tin2dem/).

As explained in Section 3.3, the estimation of vegetation density relies on lidar data classified into ground returns (bare earth DTMs) and non-ground returns (Digital Surface Models DSMs). The ground and non-ground returns are only available for the datasets obtained from OpenTopography.

The subbasins analyzed are all of size 0.12 km^2. A larger box of data of size 2 km^2 was cut around each subbasin to perform operations such as filtering and computation of topographic attributes without creation of edge effects at the subbasin boundary.