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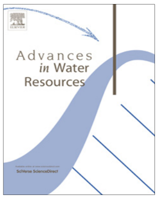

Hydrological effects of within-catchment heterogeneity of drainage density

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ABSTRACT

Local drainage density (*dd*) has been traditionally defined as the inverse of twice the distance one has to walk before encountering a channel. This formalization easily allows to derive raster-based maps of *dd* extracted straight off from digital elevation model data. Maps of local *dd*, which are continuous in space, are able to reveal the appearance of strong heterogeneities in the geological and geomorphological properties of natural landscapes across different scales. In this work we employ the information provided by these spatial maps to study the potential effects of the within-catchment variability of *dd* on the hydrologic response. A simple power law relationship between runoff yield at the local scale and the value of *dd* has been adopted; the hypothesis is supported by a large number of past empirical observations and modeling. The novel framework proposed (*ddRWF*) embeds this spatially variable runoff weight in the well-known Rescaled Width Function (*RWF*) framework, based on the more general geomorphological theory of the hydrologic response. The model is applied to four sub-basins in the Cascade Range Region (Oregon, USA) where strong contrasts in dissection patterns due the underlain geology have been broadly addressed in previous literature. The *ddRWF* approach is compared with the classic *RWF* in terms of shape, moments and peak of the simulated hydrograph response. Results hint that the variability of runoff yield due to the heterogeneity of *dd* (i.e. of hillslope lengths) determines a more rapid concentration of runoff, which implies shorter lag times, larger skewness and higher peak floods, especially in the case hillslope velocity is much smaller than channel velocity. The potential of the proposed framework relies on accounting for spatially variable losses related to geomorphologic heterogeneity in lumped rainfall–runoff models, still keeping the simple and robust structure of the IUH approach.

1. Introduction

The definition of drainage density *dd* stems from the extent to which streams dissect a topography; it represents a measure of the degree of development of a river network in space [18]. The evolution of *dd* can be viewed as the result of many environmental factors which combine to determine a balance between propensity of streams to erode and landscape's ability to counteract erosion [6]. This balance is known to be mainly ruled by processes taking place at the hillslope scale, such as diffusive–advective transport of sediments, erosion, landsliding and runoff production through saturation excess over flow [45]. While at the local scale each of these processes is known to leave a specific "fingerprint" on landscape morphology, at the basin scale they usually combine and overlap, so that a predominant geomorphic regime may not be distinguished; nonetheless, strong heterogeneities in the visual appearance of landscape as well as in the values of *dd* are well documented across the world [26]. Underlying geology and lithology [24], climate [15], vegetation [27], topographic relief and slope [29,33,41] are generally acknowledged to be the main controlling factors for the spatial and temporal evolution of *dd*. In general terms, high values of *dd* are typical of highly efficient drainage systems and can be associated to the presence of impermeable hillslopes and narrow valleys, especially in semi-arid climates. Low values of *dd* are mostly associated to weathered bedrocks, highly permeable fluvial deposits, karst areas or regions where vegetation impedes runoff [34].

Since early works on quantitative geomorphology [18,19] *dd* has been often used as a specific basin-averaged parameter to compare basins with different properties, for regionalization studies, or in multivariate analysis [1,36]. Recent works highlighted that variations of *dd* are continuous in space and also show intra-catchment variability which is related to the spatial heterogeneity of the local density of channel heads, or stream sources [7,29,46]. This variability may emerge at different scales of observation: at the large scale

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it can be related both to the intrinsic heterogeneity of specific factors such as variations in the underlain geology or strong gradients in precipitation height or intensity [25]. In some cases this variability can also be the result of classic geomorphologic properties, e.g. those deriving from the decrease of slope with increasing drainage area. At a smaller scale it may simply stem from valley to ridge alternation in space.

In geomorphology, the traditional measure of *dd*, dating back to Horton [18], is obtained as the ratio of the total length of streams in a watershed over its contributing area. So defined, *dd* is not able to reveal changes in dissection density within a basin (or domain) of area *A*. Later Horton [19] gave a different definition of *dd* as the inverse of twice the distance one has to walk before encountering a channel, i.e. $dd \propto 1/2L_h$, and directly related its local value to the infiltration capacity. The latter definition, in particular, is suitable for the derivation of continuous, raster-based maps which can be obtained directly from gridded elevation data (see, e.g. [26,47]).

From the hydrological perspective, the effects of drainage density on flood response have been broadly divided into direct and indirect (see e.g. [2,34]). Among direct effects it is generally accounted the role of relatively smaller extension of hillslope lengths where drainage density is high: since, for hillslope-dominated catchments, corrivation times can be considered directly related to hillslope lengths, shorter hillslope paths will in general result in shorter travel times - and therefore higher flood peaks [11]. This direct effect (we will call it “timing” effect) is well represented in rainfall–runoff models which rely on a metric description of the catchment, such those based on a geomorphologic derivation of the distribution of residence times[9,28,37,38,48,49].

However, important indirect effects of drainage density variability have been also addressed: in particular, high values of *dd* are usually related to impervious hillslopes and to steeper slopes, and this not only affects the timing of the response, but also enhances the generation of potentially larger runoff volumes and peaks. Moreover, shorter corrivation times implies smaller potential for water to infiltrate. In general terms, regions with less permeable surface materials are often associated with higher drainage density and higher runoff potential; Luo et al. [25] have shown that the boundaries of geologic formations and the spatial distribution of estimated hydraulic conductivities *K* (by orders of magnitude) are highly correlated in space with the values of drainage density obtained through a geomorphologic analysis for the Cascade region in Oregon, USA.

Additionally, areas with high/low values of *dd* identify zones with geomorphic contrasting characters where runoff generation in response to the rainfall input is supposed to be ruled by different producing mechanisms. For example, generation of quick storm runoff is expected to be dominant in zones with higher drainage density, where shallow soils [5,42] and low permeability [26] prevent rainfall infiltration, so that surface runoff volumes are large. Rainfall is then rapidly conveyed to the channel network along short, steep hillslope pathways. On the other way quick stormflow is generally subdued in areas of low drainage density. In these zones hydraulic conductivities are expected to be significantly higher on average, with hydrological paths that are mostly developed subsurface; hence water volumes are stored for larger times before being injected in the channel network, implying smaller potential for peak runoff.

Indeed the efficiency of well drained areas in the generation of heavy storm runoff has been proven in many works both through observations and conceptual models [12,16]. Plaut-Berger and Entekhaby [36] found that the ratio of runoff to total precipitation is highly correlated to *dd*; similarly, Humbert [20] obtained a good linear correlation between the runoff coefficient of flood event and the drainage density for a group of 45 French basins. Bloomfield et al. [1] proved that this correlation holds for the Thames River basin. In a similar way sediment yield has been found larger than expected in areas of higher drainage density, where erosion rates are typically much greater (see, e.g., [14]). This means that both runoff and sediment generation are enhanced in areas morphologically dominated by hilly ridges, steep slopes and narrow stream valleys – especially where vegetation coverage is scarce.

Given these premises we believe that the raster-based approach for the derivation of *dd*, which embeds a proper representation of its morphological variability in space, have some unexplored research potential. In particular, there has been a lack of attention in trying to combine these continuous *dd* maps with the metric of the drainage structure, in an effort to better define how basins respond to intense rainfall forcing.

In this paper we will specifically focus on the hydrological effects of *dd* spatial heterogeneity. Our goals are (i) to introduce a novel conceptual framework based on drainage-density weighted width function, and (ii) to provide a numerical analysis of the effects of drainage density variability on the moments of the simulated unit hydrographs. To these aims, we adopt the raster-based approach for *dd* description in order to embed the effects of its spatial variability in rainfall–runoff modeling, still keeping a simplified and robust lumped approach typical of geomorphological models. We will investigate how direct and indirect effects of drainage density combine with the drainage network structure to control the hydrologic response. These effects will be described adopting the general framework of the Geomorphological Instantaneous Unit Hydrograph (GIUH) theory, thus keeping the assumptions of linearity and time-invariance. Given the focus of the work, we will keep hillslope velocity uniform in space, and will not consider the contribution of other kinematic dispersive effects such as those described by Botter and Rinaldo [3] and Saco and Kumar [40]. The paper is organized as follows. We will first introduce in Section 2 the conceptualization of the indirect effects of *dd* deriving a mathematical scheme to directly link the spatial variability of runoff potential to the heterogeneity of hillslope lengths (or local drainage density values). This framework is then applied to four study basins, for which we obtain a new distribution of lengths and times. The four study cases proposed are selected among a few sub-catchments of the McKenzie River Basin, Oregon, USA, for which previous studies have shown in detail the existence of strong geomorphological heterogeneities. Details about the methodologies adopted are given in Section 3, while in Section 4 we present the derived distribution of arrival times as function of the ratio between hillslope and channel velocities, in terms of moments and peaks. A Conclusion Section closes the paper.

2. Mathematical framework

2.1. Width function approach

The approach adopted herein relies on the GIUH theory, where the basin is schematized as a collection of paths. Each path is connected to the outlet and composed by two components: the first one represents all processes taking place at the hillslope scale, and it is modeled as a hillslope of length L_h where water particles travel at constant velocity u_h; the second one, representing channelized flow, has length L_c and water particles travel at constant velocity u_c. Thus, the total path length is given by $L = L_h + L_c$.

Once paths from each point of the basin to the outlet are derived on the base of topographic gradients (see next Section), the frequency distributions of hillslope, channel and total path lengths are known. Since in the raster-based approach each path i drains an equal area A_i, the probability density function (pdf) of path lengths $f(L)$ is conceptually corresponding to the Width Function $WF(L)$