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A new approach to account for the spatial variability of drainage density in rainfall-runoff modelling

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ABSTRACT

Definition of drainage density as the inverse of twice the hillslope-to-channel length allows the creation of maps based on Digital Terrain Analysis that are able to clearly reveal the sharp contrast between neighbouring geologic provinces. This contrast, which is deeply correlated to the patterns of landscape dissection, also rules key hydrologic variables such as residence times, hydraulic conductivities, runoff coefficients and sediment yield. Traditional approaches in rainfall runoff modelling, based on the geomorphological derivation of the distribution of contributing areas as a function of the distance from the outlet (width function), are able to account for the effects of drainage density variability on the timing of the hydrologic response (direct effect). However, they neglect the indirect effects of drainage density in terms of runoff potential. We propose a new method to merge in a single function both the distribution of contributing areas and the runoff potential. Derivation of this function (which we define as the Drainage Density Weighted Width Function) is shown for a basin located in a region where geomorphological and hydrological contrast is paradigmatic: this is the border region between the geologic provinces of the High and Western Cascades in Oregon, USA.

Key words: drainage density, Western and High Cascades, width function, rainfall-runoff models.

Un nuevo enfoque para tener en cuenta la variabilidad espacial de la densidad de drenaje en el modelado precipitación-escorrentía

RESUMEN

La definición de la densidad de drenaje como el inverso de dos veces la longitud de la ladera-a-canal permite la creación de mapas, basados en Análisis Digital del Terreno, que son capaces de revelar claramente el marcado contraste entre provincias geológicas vecinas. Este contraste, que está profundamente correlacionado con los patrones de disección del paisaje, también gobierna variables hidrológicas fundamentales tales como tiempos de residencia, conductividades hidráulicas, coeficientes de escorrentía y producción de sedimento. Los enfoques tradicionales en el modelado precipitación-escorretía, basados en la derivación geomorfológica de la distribución de áreas de alimentación como una función de la distancia a la salida (función de amplitud), son capaces de tener en cuenta los efectos de la variabilidad de la densidad de drenaje en los tiempos de respuesta hidrológica (efecto directo). Sin embargo, no tienen en cuenta los efectos indirectos de la densidad de drenaje en términos de escorrentía potencial. En este trabajo se propone un nuevo método para combinar en una función única tanto la distribución de las áreas de alimentación como la escorrentía potencial. La obtención de esta función (que definimos como Función de Amplitud Ponderada de la Densidad de Drenaje) se muestra para una cuenca situada en una región donde el contraste hidrológico y geomorfológico es paradigmático: esta es la región situada en el límite entre las provincias geológicas de High y Western Cascades en Oregón, EEUU.

Palabras clave: dendidad de drenaje, función de amplitud, modelos precipitación-escorrentía, Western y High Cascades.

VERSION ABREVIADA EN CASTELLANO

Introducción y metodología

La densidad de drenaje dd se calcula convencionalmente dividiendo la longitud total de cauces en una cuenca por su área de drenaje A. Esta definición tradicional ha sido muy adecuada para la aplicación directa sobre mapas tradicionales (analógicos) pero tiene el inconveniente de implicar un proceso de promedios de las propiedades locales que no tiene en cuenta las variaciones locales de dd. La precisión y la escala de los mapas utilizados para su cálculo representan problemas adicionales todavía no resueltos. Algunos de estos inconvenientes se han atenuado adoptando una variable equivalente a la densidad de drenaje y que es la inversa de dos veces la distancia local al cauce más próximo. Esta definición alternativa se ha usado en el pasado para crear mapas de distancias de laderas que revelan la heterogeneidad espacial de dd en relación a las variaciones geológicas macro-escala. Además, a pesar del hecho de que esta definición se puede aplicar relativamente fácil mediante el uso de Sistemas de Información Geográfica (SIG), es sorprendente que sus aplicaciones han sido todavía limitadas. Entre estas se consideran en este trabajo la importancia de representar la heterogeneidad espacial en la variable dd junto con la organización intra-cuenca de la alimentación de la cuenca misma. De hecho, muchos trabajos resaltan como dd afecta a variables hidrológicas fundamentales tales como tiempos de residencia, conductividades hidráulicas, producción de sedimento y curvas de recesión. Pallard et al., (2009) clasifica los efectos de la densidad de drenaje en directos e indirectos. Entre los efectos directos se contabilizan la pequeña extensión de las longitudes de las laderas donde dd es alta, lo cual resulta en tiempos de escorrentía más cortos. Los efectos directos están intrínsecamente incluidos en los modelos geomorfológicos precipitación-escorrentía. Entre los efectos indirectos, los autores sugieren que valores altos dd están relacionados a laderas de roca impermeable y a laderas con fuerte pendiente: esto aumenta la generación de picos de avenida más pronunciados.

En zonas con alto dd, suelos someros y con baja permeabilidad previenen la infiltración de la lluvia, de modo que los volúmenes de escorrentía son grandes. En áreas de baja densidad de drenaje, se espera que las conductividades hidráulicas sean mayores, y las trayectorias hidrológicas están desarrolladas principalmente en el agua subterránea, donde el agua se "almacena" por tiempos más largos. A pesar de la evidencia de variaciones de la densidad de drenaje dentro de la cuenca, una esquematización fidedigna para tener en cuenta en un modelo simplificado tanto los efectos directos como indirectos, tal como su fuerte correlación con la permeabilidad, todavía no se ha formulado.

Muchos autores han encontrado que el ratio de escorrentía y la precipitación total están altamente correlacionados con la densidad de drenaje. En este trabajo se introduce una nueva función dependiente de la densidad de drenaje (a la que nos referiremos como DDWWF), similar a la conocida como Función de Amplitud geomorfológica, con el objetivo de combinar información sobre la heterogeneidad espacial de dd con la medida de la distancia desde el punto de salida. La habilidad de tener en cuenta las variaciones espaciales de permeabilidad es particularmente importante en la aplicación de modelos agregados de precipitación-escorrentía, ya que su enfoque tradicional no considera la variabilidad espacial de los coeficientes de escorrentía. Por el contrario, el enfoque novedoso que aquí se propone permite tener en cuenta de un modo sencillo los gradientes de permeabilidad dentro de la cuenca vertiente, a pesar de que se sigue manteniendo una estructura simplificada, lineal y agregada.

El área de estudio utilizada para la aplicación de DDWWF está situada en Cascade Range, Oregón, EEUU, (figura 1). Se eligió esta región porque su geología muestra diferencias sistemáticas entre dos sub-provincias geomorfológicas principales, a saber, i) Western Cascades que está dominada por lavas basálticas que se sitúan sobre rocas de baja permeabilidad más antiguas de edad Terciaria, y ii) High Cascades que siguen dominadas por estructuras volcánicas pero son representativas de un volcanismo constructivo más reciente de edad Cuaternaria (figura 2). Este contraste no se limita a los rasgos geomorfológicos, sino que está también bien documentado por las observaciones hidrológicas. Remarcamos como la red de drenaje evolucionó dentro de las dos provincias ramificándose caóticamente dentro de la Western y la High Cascades y muestreando aleatoriamente los diferentes caracteres de las dos provincias. Elegido un determinado punto vertiente que define los límites de una cuenca de drenaje, diferentes partes de su red de drenaje se pueden extender aleatoriamente en zonas que están sobreimpuestas las dos formaciones geológicas diferenciadas.

Resultados y discusión

Este contraste entre la High y la Western Cascades se reconoce con facilidad por inspección visual de los mapas tal y como se muestra en la figura 3, que representa la distribución espacial de distancias de ladera L_h *para la cuenca del río McKenzie en Clear Lake. Se obtuvo aplicando un análisis del terreno convencional a cada píxel de un Modelo Digital de Elevaciones (MDE) con espaciado de 10x10 metros.*

La figura 3a muestra claramente la alternancia de patrones de alta y baja disección del paisaje: colores naranja y rojo indican áreas donde la distancia ladera-a-canal es larga mientras azul y gris prevalece donde las laderas son cortas. Las áreas con alta densidad de canales de drenaje con fuertes pendientes, con valles y divisorias estrechas tienen prevalencia en Western Cascades; mientras que áreas sin canales aparecen típicamente en la meseta High Cascade. Esta alternancia espacial de L_h *está "muestreada aleatoriamente" por las diferentes etapas del desarrollo de una red de drenaje; los patrones de alternancia dependen completamente de la cuenca.*

La figura 3b se centra en la subcuenca "A" que está situada aguas arriba de la estación de aforos de Clear Lake en el río McKenzie. Su área de drenaje es de 36.4 km^2 *mientras que la longitud de su línea de flujo más larga es de 14.3 km. El alto valor del coeficiente de variación refleja la enorme variabilidad de la disección del paisaje que también emerge claramente en la inspección visual de la figura. Claramente sugiere que conforme uno se mueve aguas abajo, el curso del río principal encuentra sucesivamente el Western y después el High Cascades. Las áreas sin canales de colores naranja y rojizo indica que en la parte más baja de la cuenca la densidad de drenaje pasa a ser más pequeña que en la cabecera. Esta particularidad está bien reflejada en la figura 4, que representa el ordenamiento de la densidad de drenaje como una función de la distancia desde el punto vertiente de salida.*

Tanto los puntos grises (datos agregados) como los puntos negros (datos promediados en clases) muestran como la densidad de drenaje permanece baja para laderas situadas cerca del punto vertiente (aproximadamente 2×10^{-3} *y* 3×10^{-3} m^{-1}*) pero aumenta conforme la distancia al punto vertiente se incrementa (excediendo* 4×10^{-3} m^{-1}*).*

Se ha incluido esta marcada heterogeneidad espacial de la densidad de drenaje – reflejando la diferente tendencia de las áreas de alimentación dentro de la cuenca para producir escorrentía – en la teoría de la Unidad Hidrográfica Instantánea (IUH). Basicamente se adoptó el enfoque clásico de la Función Amplitud (FA), que se basa en medir el área de alimentación de la cuenca como una función de la distancia desde la salida (punto vertiente). En el enfoque ráster, donde las distancias se obtienen a partir de un MDE, esta "anchura" es proporcional al número de celdas a una distancia dada s normalizada por el número total de celdas; la figura 5 (línea discontinua) muestra la función de amplitud normalizada para la subcuenca "A".

La representación de la densidad de drenaje como en la figura 4 sugiere la aplicación potencial para combinar el enfoque FA clásico con la variabilidad espacial del coeficiente de escorrentía.

Basándose en resultados de la literatura científica sobre la alta correlación lineal entre el coeficiente de escorrentía y dd, se han introducido una Función de Amplitud revisada, que tiene en cuenta los valores heterogéneos de dd. Se obtiene mediante ponderación del área de cada celda del MDE por el inverso de dos veces la distancia ladera-a-canal.

Definimos esta función como Función de Amplitud Ponderada de Densidad de Drenaje (DDWWF) ya que representa una expresión nueva de la masa de la cuenca ponderada por el valor local de la densidad de drenaje, que se utiliza como un indicador de escorrentía potencial. Este enfoque es equivalente a considerar los coeficientes de escorrentía variables, y de esto modo se incorpora la heterogeneidad espacial en un modelo agregado. Hacemos notar que los modelos agregados basados con la teoría IUH tiene muchas ventajas y son todavía la herramienta más común en hidrología práctica: son de estructura simple y requieren un número de parámetros pequeño.

Es más, la asunción de correlación lineal entre el coeficiente de escorrentía y la densidad de drenaje puede relajarse fácilmente, aunque se mantiene sin cambios el esquema global.

La aplicación de este procedimiento al área de estudio (subcuenca "A") confirma que la DDWWF (línea negra continua de la figura 5) es capaz de representar de un modo sencillo las principales características de la cuenca: la contribución de las áreas relativamente cercanas al punto vertiente se reduce significativamente con respecto a la FA original. Esto es consistente con la alta permeabilidad de las áreas de la formación geológica High Cascades. Al contrario, el papel de las aguas de cabecera localizadas lejos de la salida en áreas de la formación Western Cascades se incrementa, como resulta de la alta contribución de la parte final de la DDWWF.

Esto tiene, por supuesto, importantes consecuencias en la evaluación del tiempo y forma de la respuesta hidrológica. El papel de áreas con un paisaje muy diseccionado (que es crucial especialmente para avenidas relámpago) está claramente considerado si se adopta el DDWWF; y al contrario, mucha de la información que se desprende de la geomorfología de la cuenca está recogida sólo de modo parcial en la FA tradicional.

Introduction

In an attempt to identify particular features of a basin which are instrumental for catchment classification and flood estimation, it is a common practice in hydrology to characterize mean geomorphological properties, such as average slope, average drainage density, relief ratio, longest flow path or drainage areas. Though these average properties are representative of the main metrics of a basin, they can neither take into account much of the information that can be derived nowadays through Digital Terrain Model analysis, nor represent the intrinsic spatial heterogeneity of a landscape.

Among these properties, drainage density, (*dd)* is conventionally computed by mapping the extension of channels within the basin, counting the total length l_c of streams and dividing it by the relative drainage area *A* (Horton, 1945).

The use of *dd* to discriminate the different morphological appearance of a catchment dates back to the works of Horton (1945), Schumm (1956) and Strahler (1964). In their pioneering works *dd* was related to other physiographic characteristics and used to describe and heuristically explain basin evolution stage and topographic implications of fluvial erosion. Imitating from their works, a huge body of literature has addressed the influence of *dd* on the hydrological behaviour of natural catchments, in combination with different climatic factors (see for a review Pallard *et al.*, 2009).

The original definition of *dd* proves to be a straightforward application and well fits the use of traditional maps. However, it implies an averaging process of local properties – only one value represents the dissection features for a given outlet; this involves some drawbacks both from a practical and theoretical point of view. First, it implies a loss of information on local variations of *dd* in different regions of the same basin, driven by geology, climate or vegetation cover (Gardiner and Gregory, 1982): different levels of complexity can be hidden in the averaging process (Gregory and Walling, 1968). We remark, additionally, that this approach results in a lack of knowledge on how, given a certain outlet, drainage density patterns combine with the spatial organization of the channel network itself. The latter can be easily represented, for example, by the Geomorphological Width Function (WF), which gives the relative portion of a basin area at a certain distance from the outlet (Mesa and Mifflin, 1986) and represents a broadly validated approach in rainfall-runoff modelling. The underlying idea of WF based models is that the distribution of a basin area with channel distance from the outlet can easily be transformed into a distribution of travel times, through the use of suitable hillslope and channel velocities (see, among others, Rinaldo *et al.*, 1995; Giannoni *et al.*, 2005; Grimaldi *et al.*, 2010; Kumar *et al.*, 2007; Noto and La Loggia, 2007; Volpi *et al.*, 2012). Research in this field in still extremely active and aimed at expanding the capabilities of WF models to include issues such as their application to small, ungauged or anthropogenic watersheds (e.g. Grimaldi *et al.*, 2012a; Grimaldi *et al.*, 2012b; Hallema and Moussa, 2013).

A second issue to be assessed when adopting the traditional definition for *dd* remains the scale at which this average should be computed and the accuracy of maps used for its derivation. This is evident when comparing values of *dd* obtained at different observation scales. Maintaining other controlling factors the same, both drainage densities and slopes tend to decrease with drainage area (Segura *et al.*, 2007). Thus, when considering basins of increasing size, the gap in drainage density quantification may derive from the scale dependence of the process and not from actual variations in geomorphology.

Some of those issues can be overcome by adopting a surrogate variable for drainage density, which is the inverse of twice the local distance to the channel head, i.d. . The physical interpretation for this definition is that *dd* is proportional to the distance a water drop has to move before meeting a channel. Tucker *et al.,* (2001) considered this quantity as a Random Space Function (RSF), which allows the investigation of higher moments and spatial correlation properties. Moreover, by introducing the assumption of isotropy and second-order stationarity, it is possible to explore the autocorrelation of *dd* with the geometric distance between points of a raster-based field. Tucker *et al.,* (2001) employed this technique diffusively, and created maps of hillslope-to-channel distances that revealed spatial patterns of variation of *dd* both related to valley-ridge alternation and to macro-scale geology variations.

Despite the fact that this technique can be applied relatively easily through the use of Geographic Information Systems (GIS), surprisingly its potential applications have been limited so far, and the link between drainage density and the metrics of the catchment has not been fully explored. The adoption of this raster-based surrogate variable has some additional potential which exceeds the drawing of spatially-continuous maps: it involves the derivation of statistical analysis of the distribution of *dd* and the derivation of specific arrangements where variation patterns of *dd* are described in combination with basin drainage structure.

The importance of representing heterogeneity in the field of *dd* coupled with the within-catchment organization of a basin derives from the control of *dd* on key hydrological processes and variables. Amongst them we account for: residence times (McGuire and McDonnell, 2006; Di Lazzaro and Volpi, 2011), flood potential expressed through runoff coefficient (Day, 1983; Humbert, 1990, Gregory and Walling, 1968, Gresillon, 1997, and Plaut-Berger and Entekhaby, 2001), hydraulic conductivities (Luo *et al.*, 2010), sediment yield (Grauso *et al.,* 2008), recession curve shapes

(Tague and Grant, 2004) and hillslope travel time distribution (Fiori *et al.*, 2009).

A comprehensive review can be found in Pallard *et al.,* (2009), who also propose an important classification of drainage density effects, considering both direct and indirect effects of drainage density. Among *direct* effects the relative smaller extension of hillslope lengths is accounted, where drainage density is high, which results in shorter corrivation times and therefore in higher flood peaks. This direct effect (we will call it "timing" effect) is already included in the rainfall-runoff models based on Width Function, provided that a reliable separation between hillslopes and channels is operated. Indeed, the metric of the catchment is used in these models as a key descriptor to derive the distribution of residence times for water particles along a river network. Even if early works on geomorphological models neglected hillslope-channel separation (Rodriguez-Iturbe and Valdes, 1979; Gupta *et al.,* 1980) the latter was soon included to correctly account for different time scale processes (Mesa and Mifflin, 1986; Rinaldo, *et al.*, 1991).

However, the review in Pallard *et al.*, (2009) also addresses important *indirect* effects of drainage density variability: the authors point out that high values of *dd* can usually be related to impervious rocky hillslopes and to steeper slopes: this imperviousness and steepness enhance short corrivation times generating potentially higher flood peaks. We will explain this point in detail since it is crucial for our application.

Areas with high/low values of *dd* identify zones where runoff generation in response to the rainfall input are ruled by different producing mechanisms. For example, generation of quick storm runoff is expected to be dominant in zones of higher drainage density. In these zones, shallow soils (Tague and Grant, 2004; Catani *et al.,* 2010) and low permeability (Luo and Stepinsky, 2008) prevent rainfall infiltration, so that runoff volumes are large. Rainfall is then rapidly conveyed to the channel network along short, steep hillslope pathways. This may be the triggering factor for the occurrence of flash floods (Grauso *et al.,* 2008). On the other hand, rapid storm flow is generally subdued in areas of low drainage density. In these zones hydraulic conductivities are on average expected to be of a higher order of magnitude (Luo *et al.*, 2010). Hydrological paths are mostly developed underground , where water appears to be "stored" for longer periods compared to zones of higher drainage density.

The efficiency of well drained areas in the generation of heavy storm runoff has been proven in many works (Gardiner and Walling, 1968; Gardiner and Gregory, 1982). Plaut-Berger and Entekhaby (2001) found that the ratio of runoff to total precipitation is highly correlated to drainage density; similarly, Humbert (1990) 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.,* (2011) proved that this correlation holds for the Thames river basin.

Among the significant effects of drainage-density variability we mention its relevance on sediment yield. Sediment yield is expected to be very productive on areas of higher drainage density, where erosion rates are typically much greater. Recently Grauso *et al.,* (2008) were able to find a strong correlation of the average yearly sediment yield (SSY) with the drainage density for a set of basins located in the Apeninne ridge (Italy). This means that sediment generation is enhanced in areas morphologically dominated by hilly ridges, steep slopes and narrow stream valleys – especially where vegetation coverage is scarce. Sediment yield may in some cases enhance high runoff potential, adding large volumes of solids. On the contrary, in areas with small drainage density (and generally smaller slopes) erosion rates and sediment production are generally subdued and the sediment balance is mainly ruled by suspended sediments being conveyed along the watercourse.

As the brief literature review above shows, effects of drainage density on the hydrologic regime have been broadly assessed in previous works, and are generally understood to be direct (i.e. they rule the timing of water arrivals) and indirect (volume of runoff). However, within-catchment variations of drainage density have received much less attention: a few works identified the importance of these variations on the timing of the hydrologic response (compare Di Lazzaro, 2008, 2009), whilst indirect effects of *dd* derived from its variability in space have not been considered so far. A reliable schematization which can take into account these indirect effects in a simplified model, such as its strong correlation with permeability and its overall control on the shape of basin hydrologic response, has not yet been formulated.

In this study we introduce a new drainage density-dependent function (which will be addressed as *DDWWF*), similar to the so-called geomorphological Width Function, in order to combine information on spatial variation patterns of *dd* with the measure of the distance from the outlet. As the geomorphological Width Function is able to account for the mass distribution of the basin area, arranged on the basis of the flow distance from a given outlet, this similar function is able to account for the heterogeneity of hillslope-to-channel lengths in a compact form.

This is particularly important in the application of lumped rainfall-runoff models, since their adoption neglects spatial variability of permeability. This novel approach, on the contrary, allows us to account for within-catchment permeability gradients in a simple form (represented through the drainage density weight) whilst still maintaining a simplified, linear and lumped framework.

Methods and materials

Study area

The study area is located in the western slopes of the Cascade Range, Oregon (USA) (Figure 1).

This region was specifically chosen because of its underlain geology, which shows strong, systematic differences between two major well-known geomorphological sub-provinces. The two provinces are, namely, i) the Western Cascades, which are dominated by basaltic and andesite lavas, and are underlain by older, low-permeability rocks of Tertiary Age and ii) the High Cascades, which are yet dominated by volcanic outcomes such as cinder, pumice and volcanic ash (Tague and Grant, 2004), but are representative of a much younger constructive volcanism originated in the Quaternary Age. Thus, the High Cascades represent a volcanic formation at its early stage of development (Figure 2).

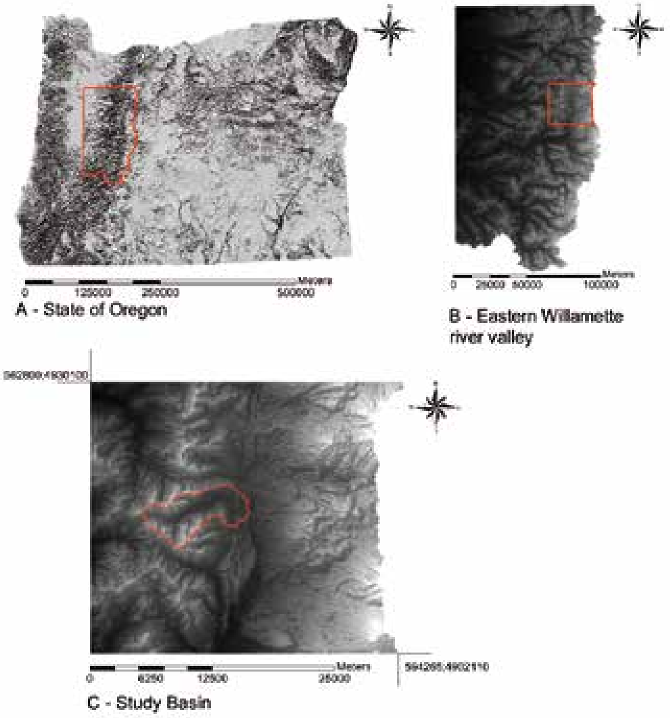

Figure 1. Geographical and topographic context of the study area (McKenzie river basin in the Willemette area - Oregon).

Figura 1. *Contexto geográfico y topográfico del área de estudio: cuenca del río McKenzie en el área Willemette, Oregon.*

Contrast between these two provinces can be easily recognized from a visual inspection of channel dissection as represented by maps, both of a traditional type and derived from Digital Terrain Analysis (compare Luo and Stepinsky, 2008). However, this contrast is not limited to their geomorphological features, but is well proved by hydrological observations, which support the hypothesis of strong differences in the overall hydrologic regime (e.g. Jefferson *et al.*, 2006).

Because of their sharp hydrological, geomorphological and geological contrasting characters the two zones have been extensively addressed in previous research (Luo and Stepinsky, 2008; Tague and Grant, 2004, Luo *et al.*, 2010). In particular, Tague and Grant (2004) performed an extensive analysis of the characters of recession curves for rivers mainly developed in one of the two geological provinces. Their analysis supports our knowledge of the different underlying hydrological processes that were described in the introduction, characterizing well drained versus poorly drained areas.

To sum up, from a geomorphological point of view the two provinces appear to be lithologically similar but geomorphically and age distinct: the Western Cascades appear very well dissected, as a result of erosion from fluvial, glacial or mass movement processes; the drainage system is therefore very well-organized and efficient in conveying water to the Willamette Valley. Overall drainage density is very high, and soils have limited depths.

On the other hand, the High Cascades completely differ both for their dissection patterns and their overall geomorphological appearance (Figure 1). Though they have been characterized by higher elevations (between 1500 and 3200 m) compared to the Western Cascades (between 1000 and 1800 m), they show much lower elevation gradients (i.e. small relief and gently sloped hillslopes). Drainage density is very low and the geological formations are associated with very high permeabilities.

From the hydrological perspective, the Western Cascades show a very high variability of discharge (Tague and Grant, 2004), characterized by large peak flows after heavy rainstorms and very low summer flows; on the contrary, the High Cascades show an almost constant and regular base flow throughout the year, while peak flows appear subdued. As far as the timing of the hydrologic response is concerned, the Western Cascades show much shorter corrivation ti-

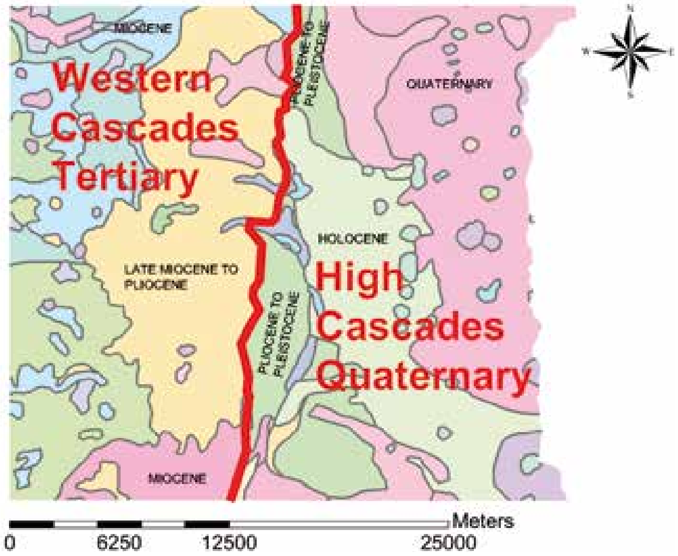

Figure 2. Geological context of the study area. The red line marks the divide between the older, well dissected Western Cascades and the younger, poorly drained High Cascades.

Figura 2. *Contexto geológico del área de estudio. La línea roja marca el límite entre el antiguo, bien diseccionado Wester Cascades y el más reciente, pobremente drenado High Cascades.*

mes compared to the delayed response of the High Cascades.

It is remarkable, however, how the contiguity of the two geological provinces and their position in space provides a unique framework for geomorphologists and hydrologists: it allows us to test the ability of mathematical models accounting for the effects of landscape on hydrologic regimes.

Within this framework we want to focus on a specific character. At a the large scale, most basins whose drainage network originates in the western slope of the Cascade Range show a common pattern, flowing toward western direction and feeding the Willamette River. But at the small scale, the drainage network of the whole region happens to evolve within the two provinces with quite irregular patterns, branching chaotically within the Western and High Cascades and randomly sampling the different characters of the two provinces. This means that, choosing a given outlet which defines the boundaries of a drainage basin, different parts of its drainage network may spread in zones which are overlain by the two contrasting geologic formations.

This intrinsic heterogeneity is well represented by the maps of hillslope-to-channel distance (Figure 3) which are derived according to the method described in the next section.

Method

The analysis which is described in the following section is mainly based on three stages: 1) derivation of hydrological pathways and of the geomorphological width function 2) computation and mapping of hillslope-to-channel distances and drainage density; 3) arrangement of drainage density as function of the distance to the outlet.

Drainage paths were derived applying a conventional terrain analysis to each pixel of a raster node (or cell), say *i*, of a Digital Elevation Model (DEM) with grid spacing of 10x10 meters.

This procedure can be synthesized in the following steps. i) Pit filling, resolved with the procedure described by Tarboton *et al.,* (1991), that assumes all sinks to be artefacts deriving from DEM generation. The elevation of each pit has been increased to the level of the lowest neighbouring grid cell until absence of residual pits was provided. ii) Flow direction assignment, operated according to the steepest downward slope (O'Callagan and Mark, 1984). This single drainage direction method was chosen in order to avoid numerical dispersion of area from a point to all the neighbouring lower cells. iii) Construction of a connectivity matrix of only Boolean (zero or unit) elements, defined as $w_{i,j}=1$ if cell *i* drains *j* and by $w_{i,j}=0$ otherwise, and resulting in a tree network connecting each point to the outlet (Rodruiguez-Iturbe and Rinaldo, 1997). The automatic DEM processing procedure defined by steps (i) to (iii) were performed through standard hydrological algorithms.

The operations previously defined result in a space-filling network, and a filtering procedure had to be applied in order to set a physical limit to the upstream development of the channel network. This filtering procedure is commonly based on two important scalar quantities defined for each site *i*: the total upstream contributing area and the local slope of the elevation field . They were used to determine whether a site belongs or not to the channelized part of the basin and play an important role on the resulting properties of the network (Gandolfi and Bischetti, 1997).

The total contributing area at the *i-th* site was computed by the equation , where

A_j is the contributing area at the site *j*, *a* is the elementary area of a pixel and $w_{i,j}$ is the element of the connectivity matrix. The local slope of the topographic field was calculated in discrete form, using the elevations of all the 8 neighbouring cells.

The channelization status of each cell was assessed through the definition of an automatic procedure. This is one of the most critical issues when deriving drainage networks from DEMs. Several criteria have been proposed involving threshold support-areas (Tarboton *et al.*, 1991), threshold slope-area values (Montgomery and Dietrich, 1992; Montgomery and Foufoula-Georgiou, 1993) or critical curvature (Howard, 1994). Combinations of the different methods have also been suggested (Tucker *et al.,* 2001).

Here a combination of the threshold slope-area and of threshold support area criteria was applied. The underlying hypothesis of the threshold slope-area criterion is that the actual shear stress at the *i-th* site, is proportional to its contributing area and local slope, say , and channels begin when the critical shear stress is exceeded. From an operational point of view, each drainage path is analyzed and the first downstream point *i* where the calculated scalar quantity exceeds a threshold value *k* identifies a channel head. In order to avoid unrealistic channel interruptions, each cell *j* draining a channel site *i* (directly or indirectly) is considered channelized, even if its local quantity is smaller than *k*. Moreover, an upper threshold to the maximum unchannelized contributing area was imposed, to avoid the appearance of unphysically large areas with no channelization, especially in flat regions.

An analysis of the drainage density, empirically seen through the observations of the blue lines, showed that a slope-dependent threshold equal to 4000 m^2 gave a good representation of the actual drainage network in the Western Cascades. For the poorly drained High Cascade, the area threshold was in most cases effective, with an upper limit for channelization equal to 0.5 km^2.

This method (slope-area threshold for well drained areas and area threshold for poorly drained ones) is supported by observations given by Jaeger *et al.*, (2007), who investigated both the dependence of the channel initiation process from geology and the variability of the source area for channel heads. They found that for some lithologies (and specifically when subsurface flow processes and underlying bedrock characteristics are controlling channel head locations) there was no dependence between the appearance of a channel head and the local slope.

Results

The inverse of the hillslope-to-channel distance L_h is used in the following as a surrogate variable of drainage density *dd*: thus, its main variations in space may be drawn by the variations of L_h. The spatial patterns of L_h are represented in Figure 3a for the McKenzie river basin. The McKenzie river is a tributary of the Willamette river from the left side; it drains a large portion of the east-facing side of the Western Cascades and of the west-facing portion of the High Cascades, west of the main drainage divide.

The map in Figure 3a clearly expresses the alternate patterns of high and low landscape dissection: orange and red colours indicate areas where hillslope to channel distance is large (eastern part of the McKenzie river), while blue and gray prevails where hillslopes are short (west of the McKenzie river).

This graphical representation of hillslope lengths suggests how steep, densely channelled areas with narrow valleys and ridges are predominant in the Western Cascades, whilst large, unchannelled areas typically appear in the High Cascade plateau. However, this spatial alternation of L_h – which follows a clear geographical arrangement stemming from the contrasting geology, is “randomly sampled” by the different branches of the developed drainage network, thus forming typical (though still random) patterns of alternation which are completely basin-dependent. This is, of course, a within-catchment variability of *dd*.

As a consequence of this randomness, it is evident that a fully “pure” basin (pure Western or pure High Cascades) becomes quite rare as the size of the basin exceeds a few km^2. Indeed, at the local scale we are able to observe hillslopes or small basins which are fully embedded in one of the two provinces and can be therefore considered homogeneous from the geomorphological perspective. When we move to larger watershed scales, the geologic contrast clearly emerges from the variations in pattern dissection and different zones can be easily detected, as for example by observing the map in Figure 3a. Since the geologic contrast is mainly east-west oriented, it appears that all the basins in the upper McKenzie river exceeding the length of about 10 km show a mix of the two contrasting landscapes.

For our study case we focus on a sub-basin “A” (Figure 3b), which is located upstream of the McKenzie river at the Clear Lake gauge station, and is a tributary of the McKenzie river from the right side. Its drainage area is 36.4 $km^{2,}$,while its longest flow path is 14.3 km. The average slope is 3.7%. The average drainage density is 0.00378 m^{-1} but local *dd* shows a high variability, with the standard deviation being 0.00427 m^{-1} and a coefficient of variation of 1.13. The high value of the variation coefficient reflects the huge variability of landscape dissection that also clearly emerges from visual inspection of Figure 3b; the latter shows the spatial distribution of hillslope lengths within the sub-basin “A”. In the same figure channels are also represented by black lines. It clearly suggests that the main river course succes-

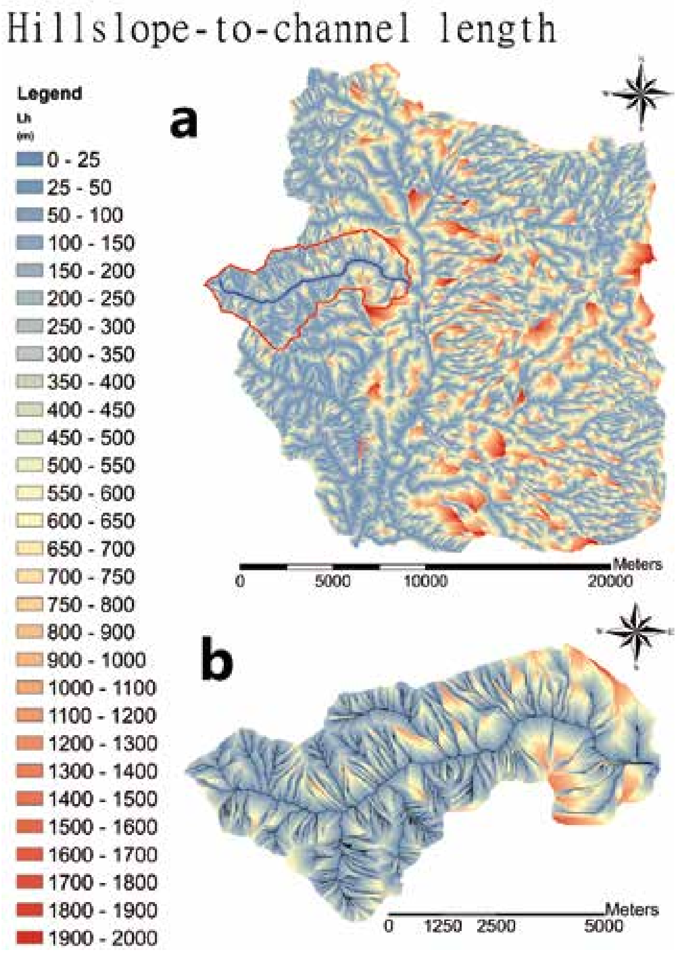

Figure 3. a: Hillslope-to-channel length L_h (m) for the McKenzie river; b: focuses on sub-basin "*A*", which represents the study case described in the text.

Figura 3. *a: Longitud ladera-a-canal* L_h *(m) para el río McKenzie. b: Detalle de la subcuenca "A", que representa el caso de estudio descrito en el texto.*

sively encounters the two distinct provinces. The main headwaters are located in the Western Cascades where, as shown in Figure 3b, drainage density is very high (blue-grey areas indicate well dissected zones) and the channel network is dense. On the contrary, contributing areas at a short distance from the outlet are underlain by the High Cascades geologic type. Thus, as we move downstream, we find a clear pattern of change in the spatial distribution of hillslope-to-channel lengths; the maximum rate of variation in drainage density occurs about 6 km from the outlet. Orange and red-coloured unchannelled areas indicate that in the lower part of the basin drainage density becomes very small, where large hillslope paths prevail and in some cases may exceed 1 km in length.

This feature is definitely expressed by Figure 4, which represents the general behaviour of drainage density as a function of the distance from the outlet.

Grey points are obtained according to a binning procedure which was performed as follows: i) for each cell of the DEM drainage density is calculated according to the 1/2 L_h definition; ii) values of drainage density are divided into equally spaced classes on the base of their distance from the outlet; iii) within each class, 500 values of local drainage density have been binned to obtain a single point in the figure; both the distance and the drainage density of each point are calculated averaging over all the cells of the bin. The procedure is quite standard in quantitative geomorphology and it is often applied for the classification of large numbers of raster-based data (Rodruiguez-Iturbe and Rinaldo, 1997).

The black points in the same figure are simply obtained by dividing the whole set of raster based *dd* values in classes as a function of the distance from the outlet *s*, and taking the average of all the values found within a class.

Both the grey dots and the black points show how drainage density remains low for hillslopes located near the outlet but increases as the distance from the outlet becomes greater. Approximately, the drainage density is between 2×10^{-3} and 3×10^{-3} up to a distance of 5 km from the outlet (where the High Cascades prevail); it is between 3×10^{-3} and 4×10^{-3} up to a distance of 7.5 km and is greater than 4×10^{-3} for greater distances (the Western Cascades prevailing).

According to the literature, both permeability and runoff coefficients show a very high correlation with drainage density (see e.g. Plaut-Berger and Entekhaby, 2001 and Gresillon, 1997). We argue that the spatial heterogeneity of drainage density must reflect the tendency of different contributing areas within the basin to produce runoff, which is a typical indirect effect of landscape dissection variability.

We remark that under the assumptions of the classic Instantaneous Unit Hydrograph (IUH) theory this heterogeneity is hardly considered: only when adopting a distributed model for soil infiltration is it possible to conveniently represent the spatial variability of the process. However, lumped models based on the IUH theory have many advantages that make them the most common tool in practical hydrology: they are simple in structure and require a small number of parameters. This often matches the availability of observed data.

Within the IUH theory, a validated approach is that of measuring the contributing area of the basin as a function of the distance from the outlet; this yields the so-called Width Function (WF). The underlying idea for this approach is that the "width" of the basin at a given distance *s* is proportional to the contributing fraction of the basin located at the same distance *s*, in response to a uniform and instantaneous injection of rainfall (Mesa and Mifflin, 1986; Rodriguez-Iturbe and Rinaldo, 1997). In the raster-based approach where distances are obtained from a DEM, this "width" is proportional to the number of cells at a given distance *s* normalized by the total number of cells; Figure 5 (dashed line) shows the normalized width function for sub-basin "A".

The representation of drainage density as in Figure 4 yields a potential application to combine the classic WF approach based on the IUH theory with the spatial variability of the runoff coefficient.

Based on the results of Day (1983) and Humbert (1990) we introduce a revised Width Function which accounts for very heterogeneous values of drainage density. It is obtained as follows: i) for all DEM cells the distance from the outlet and the drainage density are calculated according to the procedure described in the Methods and Materials section; ii) the area of each DEM cell is attributed a weight which is proportional to the local drainage density *dd*; iii) the weighted DEM cells are re-sampled on the basis of their distance from the outlet.

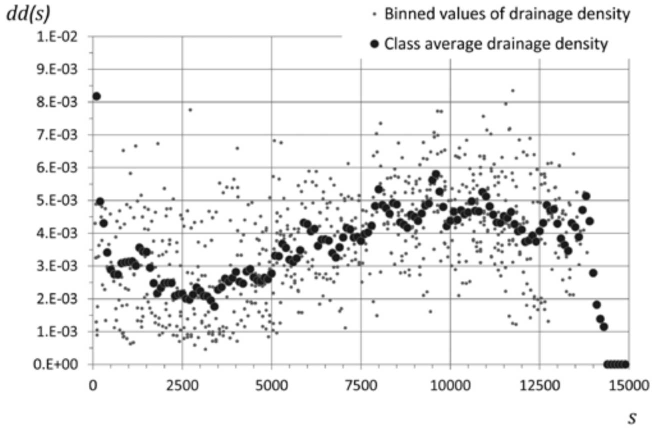

Figure 4. Behaviour of drainage density as a function of the distance from the outlet *s*. Grey points represent the values of drainage density obtained by averaging over at least 500 cells of the DEM; the black points are the drainage density obtained by averaging over all the points within a given class of *s*. Distances *s* are in [m], *drainage density* in [m^{-1}].

Figura 4. *Densidad de drenaje como una función de la distancia al punto vertiente s. Los puntos grises representan los valores de densidad de drenaje obtenidos por promedio de al menos 500 celdas del MDE; los puntos negros son la densidad de drenaje obtenida por promedio sobre todos los puntos dentro de una clase data s. Las distancias s están dadas en metros [m], la densidad de drenaje en [m^{-1}].*

We define this function as Drainage Density Weighted Width Function (*DDWWF*) as it represents a revisited expression of the mass of the basin weighted by the local value of drainage density, which is used as an indicator of runoff potential. This approach is equivalent to using different runoff coefficients for different parts of the basin, thus incorporating heterogeneity in the lumped model. Note that the assumption of linear correlation between runoff coefficient and drainage density may be easily relaxed, though keeping the global framework unchanged.

The application of this procedure to the study case (sub-basin "A") hints that the *DDWWF* (which is represented by the black line in Figure 5) is able to represent the main features of the basin in a simple manner: the contribution of areas relatively close to the outlet is significantly reduced with respect to the original WF. This is consistent with high permeability of areas underlain by the High Cascades geological formation. On the contrary, the role of the headwaters located far away from the outlet, in areas underlain by the Western Cascades, is enhanced, as it results from the high contribution of the final part of the *DDWWF* (i.e. for network distance that is greater than 7500 m).

This of course has significant consequences for the evaluation of the timing and shape of the hydrologic response. The role of areas with a very dissected landscape (which is crucial especially for flash floods) is clearly highlighted by adopting the *DDWWF*; on the contrary, much of the information content that can be read in the geomorphology of the basin is only partially encapsulated in the traditional WF.

The *DDWWF* can be straightforwardly applied in rainfall-runoff modelling: for example, with this technique it is possible to use an average runoff coefficient to determine the net rainfall over the basin (on the basis of total runoff volume), but still accounting for the variability of the runoff coefficient itself, since it is directly embedded in the *DDWWF*.

Moreover, this technique can be extended to other applications depending on the controlling factors of the process considered each time: this may be obtained by just changing the relationship between controlling factors and the drainage density. For example, a straightforward extension of the method is that the *DDWWF* can be considered as the description of timing for sediment yield (Sedimentograph), since the latter is still dependent on drainage density, but with a relationship which has not been proved linear (Grauso *et al.,* 2008). Another example is given by the analysis of the timing of base flow, which is generated in areas of low drainage density; in this

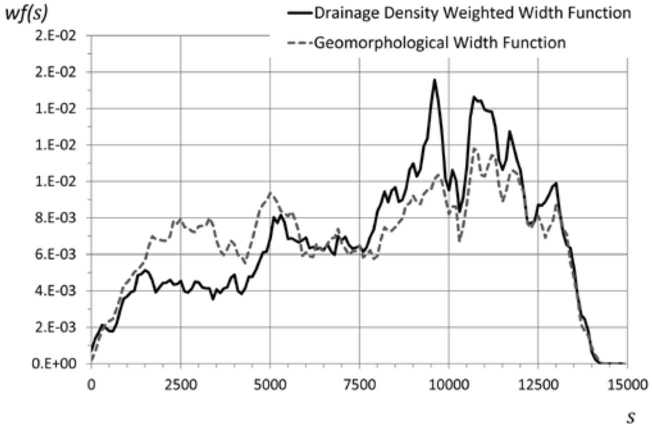

Figure 5. Drainage Density Weighted Width Function (DDWWF) compared to the normalized Width Function (WF) for sub-basin “A.” Distances *s* are in [m], *drainage density* in [m^{-1}].

Figura 5. *Función de Amplitud Ponderada Densidad de Drenaje (DDWWF) comparada con la Función de Amplitud (FA) normalizada para la sub-cuenca “A.” Las distancias s están en metros [m], y la densidad de drenaje en [m^{-1}].*

latter case, the weighting function should be inversely proportional to *dd*.

Conclusions

The main conclusions of this work are summarised in the following points.

- The definition of drainage density as twice the inverse of local distance to the channel allows us to draw raster-based maps which are able to clearly reveal the spatial heterogeneity of drainage density as a function of the underlying geology.
- Spatial heterogeneity of drainage density rules the timing of the hydrologic response. Moreover, it intrinsically implies the variability of a large number of other hydrologic variables which are indirectly affected by landscape dissection; they include (but are not limited to) runoff coefficients, hydraulic conductivities, and sediment yield. These variables are able to heavily determine the hydrologic behaviour of the basin in terms of runoff production.
- We highlight how the classic Width Function (WF), which keeps the benefits of a linear, convolution based approach, only accounts for the direct effects of drainage density variability. WF is indeed a powerful tool for deriving the timing of basin response to an instantaneous input of rain, but neglects much of the information which is embedded in the geomorphology of the catchment, especially related to runoff potential.
- We propose a new method for accounting in a combined form for the distribution of contributing areas within the basin and drainage density: these features are both expressed through a newly derived Drainage Density Weighted Width Function (DDWWF) which synthesizes the role of provinces with different runoff potential and combines it with their position within the basin, measured through their distance from the outlet. We show how this WF and DDWWF much significantly differ in shape for a case study.
- This method allows us to easily account for runoff coefficient variability in space, accounting for different parts of the basin to contribute with different weights; notwithstanding, it still maintain the benefits of a linear approach: this avoids recurring to distributed models for infiltration and routing, which generally require much more data and time-consuming computations.
- Additionally, we remark that the procedure which is proposed here has been developed by applying standard procedures for DEM analysis. It can therefore be easily implemented in hydrologic routines for hydrologic analysis within a GIS framework.

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