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MATLAB-BASED TOOL FOR DRAINAGE NETWORK ORDERING BY HORTON AND HACK HIERARCHIES

HERRAMIENTA DISEÑADA EN MATLAB PARA LA ORDENACIÓN DE REDES DE DRENAJE POR LAS JERARQUÍAS DE HORTON Y HACK

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Abstract:

This work presents a new MATLAB-based tool designed for network extraction and drainage network orderings by Horton and Hack hierarchies. Most GIS software offers only topological network orderings, based on joining segments, such as Stahler or Shreve, providing segments between junctions but not entire streams. Differently, Hack and Horton orderings allow organizing a drainage network in a hierarchy, identifying the parent segment over the child segment, giving as a result a drainage network where the value of a river remains unchanged from the mouth upstream to the headwater, allowing extracting entire streams. Horton and Hack hierarchies ease the interpretation of a drainage system compared to Strahler and Shreve. To extract the drainage network, this tool uses TopoToolbox 2 functions, to compute the prior steps of the channel network extraction and channel network ordering processes, and develops new functions. To sort a network, this tool allows selecting the parameter that defines the network hierarchy. This parameter is the so-called hierarchy attribute and could be the distance upstream, which refers to the distance between a junction upstream to the headwater, or the upstream accumulation, which is the accumulation at the junction. In addition to these mandatory parameters, the tool offers a set of optional parameters which turns it into a competitive alternative to generate a highly tailored ordered drainage network. The continuous channel network provided by the tool facilitates the use of other multiple applications for landscape analysis, such as the extraction longitudinal profiles or basin analysis through geomorphic indices.

Key words: Hydrology, Fluvial hierarchies, Drainage network, Horton, Hack, MATLAB

Resumen:

Este trabajo presenta una nueva herramienta diseñada en MATLAB para la extracción y ordenación de redes de drenaje por las jerarquías de Horton y Hack. La mayoría de software GIS ofrece sólo ordenaciones topológicas de redes, basadas en la unión de segmentos, como las ordenaciones de Stahler o Shreve, que proveen segmentos entre puntos de confluencia pero no canales completos. En cambio, las ordenaciones de Hack y Horton permiten organizar una red de drenaje en una jerarquía, identificando el segmento primario sobre el segmento secundario, dando como resultado una red de drenaje donde el valor de un río permanece inalterado desde la desembocadura aguas arriba hasta la cabecera. Las ordenaciones de Horton y Hack facilitan la interpretación de un sistema de drenaje comparado con Strahler y Shreve. Para extraer la red de drenaje, esta herramienta utiliza funciones de TopoToolbox 2 para calcular los pasos previos de los procesos de extracción y ordenación de la red y además desarrolla nuevas funciones. Para ordenar la red, esta herramienta permite seleccionar el parámetro que define la jerarquía de la red. Este parámetro es el llamado atributo de jerarquía que puede ser la distancia aguas arriba, que se refiere a la distancia desde el punto de confluencia a la cabecera, o la acumulación ascendente, que es la acumulación en el punto de confluencia. Además de estos parámetros obligatorios, la herramienta ofrece un conjunto de parámetros opcionales que la convierten en una alternativa competitiva para generar una red de drenaje ordenada personalizada. Esta herramienta permite generar de una red fluvial continua que es requerida en otras múltiples aplicaciones como puede ser para la extracción perfiles longitudinales y/o el análisis de cuencas a través de índices geomórficos.

Palabras clave: Hidrología, Jerarquías fluviales, Red de drenaje, Horton, Hack, MATLAB

1. Introduction

In the last three decades advances in modelling Earth's surface have been made thanks to the development of algorithms and computer simulation models (Refice *et al.* 2012). Land surface analysis, hydrology and hydrogeology assessment, drainage network analysis, etc., they all have had an extensive development since the 1980s (O'Callaghan and Mark 1984; Jenson 1985) and keep developing today. Regarding hydrology analysis, many flow-related algorithms have been developed, such as flow direction (Lindsay 2003;

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O'Callaghan and Mark 1984), flow accumulation, flow length, stream order, among others.

Most of the mentioned flow-related algorithms are implemented in GIS software. Although, many of these flow-related algorithms have also been developed for non-spatial software, such as MATLAB (MathWorks 2012) or Octave (Eaton *et al.* 2014). These software allow non-GIS users to perform different drainage analysis in a non-spatial environment.

Nowadays, there are numerous geomorphologic indices and other quantitative analysis based on the fluvial network which provide information on landscape evolution (Kirby and Whipple 2001; Tucker and Hancock 2010; Anton et al. 2015; Antón et al. 2012; Whipple et al. 2003). Based on streams characterization, those analysis help to understand fluvial systems and landscape responses to external drivers such as climate, tectonics, human actions, etc. (Font *et al.* 2010; Shugar *et al.* 2017; Pedrera *et al.* 2009; Antón *et al.* 2014, Mather and Hartley 2006; Anton and Munoz 2007).

Although numerous authors developed software to facilitate fluvial extraction and indices calculation (Schwanghart and Kuhn 2010; Pérez-Peña *et al.* 2009) attaining a suitable channel network to tackle the automatic calculation of indices is still a quite time consuming process as most software extracts independent channel stretches instead of a continuous channel from headwater to mouth. While an entire channel is required to tackle stream long profile analysis (Jiménez-Cantizano *et al.* 2017) and most of geomorphic indices.

The aim of this paper is to present a new MATLAB-based tool for channel network ordering by Horton and Gravelius/Hack hierarchies. This tool works with MATLAB-based TopoToolbox 2 toolkit (Schwanghart and Kuhn 2010; Schwanghart and Scherler 2014) to calculate the flow direction, flow accumulation and flow length matrices, which are the prior flow maps required in the drainage network extraction process.

2. Flow-related concepts

A Digital Elevation Model (DEM) grid is a rectangular matrix of floating or integer values representing elevations of the terrain above a common base level. Each matrix element is a cell. Grids are common because they are simple, and because data is readily available in this form (Toma *et al.* 2001). Flow-related maps are normally derived from the DEM. Flow-related matrices are the following: Flow direction, normally computed with the Single Flow Direction (SFD) or Deterministic-8 (D8) algorithm, introduced by O'Callaghan (1984). SFD assigns flow from each cell to one of its eight neighbors, either adjacent or diagonal, in the direction with steepest downward slope. Another flow-related matrix is the flow accumulation, which quantifies the amount of water that flows through each cell of the terrain, if water was poured uniformly onto the terrain (Moore *et al.* 1991). Most of flow accumulation algorithms depend on flow directions. Another flow-related matrix is flow length. It can be computed upstream, which is the length from each cell up to the headwaters, or downstream, which refers to the length down to the confluence or mouth of the basin. These matrices are the previous steps in the process to sort a channel network.

Normally a channel network can be idealized as a planar tree where a channel is a branch and the master channel is the tree trunk. The furthest point downstream is the channel network outlet or mouth. Points furthest upstream, are called stream heads or headwaters. The points where two channels join are called junctions or confluences.

2.1. Drainage network ordering

Drainage network ordering refers to the method to sort a channel network. There are multiple methods to order a drainage network. The most common ordering methods included in conventional GIS software are the Strahler method (Fig. 1.A) and Shreve method (Fig. 1.B). In addition to these sorting hierarchies, there are other network orderings, such as: Original Horton hierarchy (1945) (Fig. 1.C) and normal stream hierarchy proposed by Gravelius (1914) also known as Hack's main streams (1957) (Fig. 1.D).

Gravelius proposed one of the first attempts to classify drainage networks on the basis of branching (Gravelius 1914; Hack 1957). In this system, the main stream is designated as order 1 and smaller tributary streams are designated with increasingly higher orders, from the stream confluence upstream to the headwaters. When a parent channel of order *n* meets a junction, ascribes order *n* + 1 to the joining tributary (Fig. 1.D). Horton, in the inverse of which was Gravelius hierarchy, considering that the main stream should be the one with the highest order and that unbranched finger-tip tributaries should always be designated by the same ordinal, used a system where unbranched finger-tip tributaries are always designated as order 1. Tributaries of second order receive only tributaries of first order, third order tributaries receive tributaries of second order but may also receive first order tributaries, and so on (Horton 1945) (Fig. 1.C). To determine which the parent segment is and which is the child segment in a junction, Horton considers that the stream that forms the greatest angle with the parent is of lower order. If both joining streams form the same angle with the parent, the shorter stream is taken as of the lower order.

Strahler system slightly modifies Horton hierarchy, which fixes the ambiguity of Horton's ordering. Strahler remains to an idealized topological model, where the stream order changes from the basin mouth point up to the stream head (Strahler 1957). In Strahler hierarchy, the starting points are the headwaters. The smallest finger-tip tributaries are designated with order 1. When two segments of the same order *n* join, a segment of order *n* + 1 is formed. When two segments of different order meet, they form a segment of maximum order of both (Fig. 1.A). The master stream is therefore the segment of highest order. Shreve hierarchy is similar to Strahler hierarchy. Finger-tip streams are of order 1. When two segments join, the resultant segment downstream order is the sum of the segments' order joining. Hence, the magnitude of a segment is equal to the total number of stream heads ultimately tributary to it (Shreve 1967) (Fig. 1.B). Both hierarchies, Strahler (1957) and Shreve (1967) are purely topological hierarchies, where the interconnected segments between junctions do not involve lengths, shapes, accumulation rates or orientations of the segments comprising the channel network.

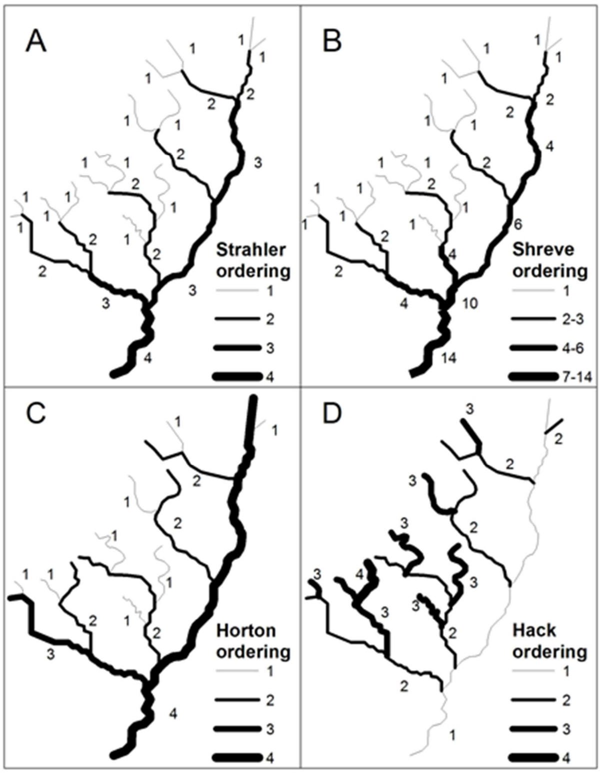

Figure 1: Stream network orderings: (A) Strahler (Strahler 1957), (B) Shreve (Shreve 1967), (C) Horton (Horton 1945), (D) Hack (Hack 1957).

3. Methodology

3.1. Tool-related concepts

In this tool, the furthest point downstream of the channel network is called outlet. The points where two channels join are called junctions and the last point of a channel before joining in a confluence with another channel is called pour point.

3.2. Parameters

The tool requires setting a set of input parameters values prior to its execution. They are of two types: mandatory and optional. The mandatory parameters should be fulfilled to execute the tool, otherwise the tool will show up an error message. Mandatory parameters are the following: name of the DEM file in ASCII format; the sorting hierarchy: Horton or Hack; and the hierarchy attribute which defines the hierarchy of a segment over another when two or more segments converge in a confluence: upstream accumulation or upstream distance.

Upstream accumulation represents the amount of water a tributary carries along its route from the headwater down to the junction. Upstream distance represents the cumulative length from the headwater to the junction. The tool gives the greatest order to the branch with higher hierarchy attribute value in the pour point. If two channels have same hierarchy attribute value, elevation is compared as a second attribute. The branch with highest elevation in the pour point will be given the highest order (Jasiewicz and Metz 2011). Upstream accumulation and upstream length replace Horton's previous idea to give the greatest order to the branch that has a smaller angle with respect to the parent branch (Horton 1945). This idea was discarded because this parameter leads to hierarchy systems that do not represent realistic drainage structure (Ai 2007).

Added to the set of mandatory parameters, there is also the set of optional parameters. Optional parameters can be used to obtain a more customized sorted channel network. If these parameters are left empty, a default value for each parameter will be set. These parameters are the following: The maximum tributary order, which is the '-ith' order up to which the channel network will be sorted. If user sets a value, only tributaries of equal or lower order to the value set will be sorted. Otherwise, if no value is set, the entire drainage network will be sorted.

Another optional parameter is the minimum drainage area, which refers to the minimum drainage area of a channel to be sorted. This parameter should be dimensioned in relation to the DEM size and spatial resolution. If user sets a value, only channels with equal or higher drainage area than the value set will be sorted. The rest of the cells will appear as no-data. In contrast, if this parameter is left as empty, the default value will be set to the 0.01% of the DEM watershed area in square meters. The last two optional parameters are the name for the resultant sorted channel network in ASCII format, and the name for the resultant ASCII file with the pour points. Both names have to be written with the extension '.asc' or '.txt' at the end of the name. If no names are given, the resultant names will be built by adding to the DEM name, the values set in the parameters joined by an underscore.

3.3. Extraction and sorting processes

The process of this tool is shown in Figure 2 workflow which illustrates the process on a whole (Fig. 2.A) and the logical scheme of find_next_river_cell and find_junctions functions (Fig. 2.B).

The extraction of the drainage network is upstream. The initial point is the mouth of the basin. From that point, the drainage network skeleton is delineated upstream, finding junctions until reaching the head of the channels.

To initially generate the flow direction, flow accumulation, upstream distance and Strahler matrices, functions from the TopoToolbox 2 (Schwanghart and Scherler 2014) are used in *build_streams_map* function. In *build_streams_map* function the DEM is converted to GRIDobj format. A process of filling is applied to the DEM matrix to fill sinks or atopic peaks, using *fillsinks* function on the GRIDobj variable. Negative values and zeros are replaced with 'NaN' values. Flow direction is then computed applying *FLOWobj* function on the filled DEM, selecting 'preprocess' and 'fill' as options. Flow accumulation matrix is computed applying *flowacc* function on the flow direction object (FD). Finally, the upstream length matrix is computed applying *flowdistance* function on a stream object (STREAMobj). If Horton hierarchy is selected, Strahler downstream matrix is also computed within these prior steps, using *streamorder* function.

Figure 2: Workflow of the processes for the extraction and ordering by Horton or Hack hierarchies: A) Complete workflow; B) Schemas of find_next_river_cell and find_junctions functions.

Once all flow-related matrices have been computed, two rows and columns with ‘NaN’ values are added to all of the matrices in order to analyze the edge cells.

The initial point from which the channel network skeleton will be delineated is the watershed outlet. In the *build_channel_network* function four empty arrays are created to store channel network information while it is extracted. The *xy_channel_array* variable, stores the indices of a channel; *order_channel_array* variable stores the hierarchical order of each extracted cell. For an index in the *xy_channel_array*, its order value will be the one that is in the same index in the *order_channel_array*. Similarly, *xy_junction_array* stores the indices of the pour points cells and their corresponding orders are stored in the *order_junction_array*.

The *build_channel* function extracts a channel. The first channel cell to assess is the basin mouth. To assess a channel cell, a 3x3 auxiliary window matrix is created around it. Six empty arrays are created, and each array is filled with neighboring cells values of the following matrices: elevation, flow direction, flow accumulation, flow distance, Strahler (only for Horton hierarchy) and also neighbours’ linear indices. All these variables are described in Table 1. Once the auxiliary arrays are filled, *find_next_river_cell* function finds the neighbor, which will become the next channel cell of the channel and so the next cell to be addressed. If upstream accumulation is chosen as the hierarchy attribute, the array to assess is *flowacc_neighbors*. Instead, if upstream distance is chosen as the hierarchy attribute, the array to consider is *flowdist_neighbors* (Fig. 2.B).

The selection process of the next channel cell is different depending on the hierarchy. For Horton hierarchy, the first step is to find the neighbor that flows into the channel cell and has equal Strahler value than the channel cell. If there is a neighbor that meets both conditions, this neighbor’s index will be stored in the *xy_channel*. On the other hand, if there is no neighbor meeting these previous conditions, the neighbor that has the highest hierarchy attribute value will be taken as the next channel cell and its index will be stored in *xy_channel*. If several neighbors have the same hierarchy attribute value, elevation is prioritized. The highest elevated neighbor will be the next channel cell in the channel.

For Hack hierarchy, the first step is to find a neighbor which flows into the channel cell and has the highest hierarchy attribute value. If there is only one neighbor that meets both conditions, this neighbor’s index will be stored in the *xy_channel*. Else, if there is more than one neighbor with equal hierarchy attribute value, elevation will be taken into account and highest elevated cell will be chosen as the next channel.

The last step in the channel network extraction process is to identify the pour points that will be the initial points to delineate tributaries. The *find_junctions_cells* checks the value of the minimum basin area parameter. If no value has been set for this parameter, minimum basin area is set to 0.01% of the DEM drainage area as default. Only the neighbors flowing to the channel cell with equal or higher basin area than the value computed, except for the neighbor already identified as the parent channel, will be considered as pour points and its linear index will be stored in the *xy_junction* array (see Table 1 and Fig. 2.B).

The *build_channel* function continues to loop until it finds the headwater of the channel. Then it returns *xy_channel*, *order_channel*, *xy_junction* and *order_junction* arrays to the *build_channel_network* function and starts looping over the newly found pour points to begin a new process of channels extraction. This process keeps on looping until *stream_matrix* and *junction_matrix* are successfully generated in the *build_streams_map* function. Finally, *stream_matrix* and *junction_matrix* are copied into two separate ASCII files, one ASCII is for the sorted channel network and the other ASCII contains the pour points. The function to convert a matrix into an ASCII file is from TopoToolbox 2. Each ASCII file receives the name set in *output_name_streamnetwork* parameter and *output_name_junctions* parameter. Additionally, both matrices are represented in MATLAB in separated figures.

Table 1: Variables definition

Variable	*Definition*
elevation_neighbors	Stores neighbours elevation values
flowacc_neighbors	Stores neighbours flow accumulation values
flowdir_neighbors	Stores neighbours flow direction values
flowdist_neighbors	Stores neighbours flow length values
strahler_neighbors	Stores neighbours Strahler values
coord_xy_neighbors	Stores neighbours coordinate linear indices
xy_channel	Stores coordinate linear indices of a channel or channels
order_channel	Stores order values of the correspondent channel cells
xy_junction	Stores coordinate linear indices of pour points
order_ junction	Stores order values of their correspondent pour points
stream_matrix	Matrix with the extracted channel network
junction_matrix	Matrix containing the pour points of the channel network

3.4. Case of study

The case of study is located in the Pisuerga watershed (Fig. 3). Pisuerga river belongs to Duero watershed in the Iberian Peninsula. Duero watershed is one of the main hydrological systems in Iberia. Duero river is approximately 900 km in length, spans over an area of 97,300 km^2 and has 22,000 hm^3 year^{-1} of water contribution (Morán-Tejeda *et al.* 2011). Duero river is a transboundary river that flows westward through Spain to Portugal, ending in the Atlantic Ocean. Pisuerga river is one Duero’s main tributaries. The Pisuerga–Carrión Unit is surrounded to the north by the Cantabric System and to the northeast by the Iberian System (Pastor-Galán *et al.* 2014). Pisuerga river is 270 km in length with a watershed of 15,700 km^2. Two of its main tributaries are Arlanza river, on the left side, and Carrion river, on the right side. Pisuerga DEM is derived from the Shuttle Radar Topography Mission (SRTM) (Rabus *et al.* 2003) version 4.1 of 90 m of spatial resolution. ArcGIS 10.3 (ESRI) (Refice *et al.* 2012) software was used to delineate Pisuerga's watershed.

The tool has been applied to the Pisuerga basin. For all the cases shown in Figure 4, optional parameters were left as empty. The objective was to sort the entire drainage network, ordering it from the main channel up to the tributaries with smaller drainage area. Hack hierarchy, was sorted by upstream distance as the hierarchy attribute (Fig. 4.A) and by upstream accumulation (Fig. 4.B). For Horton hierarchy, channel networks were extracted by upstream distance (Fig. 4.C) and by upstream accumulation (Fig. 4.D). To represent the results, drainage networks in ASCII format appear on the left side in each of the subfigures in Figure 4. On the right side of each subfigures, networks were transformed to vector format, to observe the hierarchy of the main rivers, for what the flow direction matrix generated internally in the extraction process was used. For the subfigures representing data in vector format, the colored rivers are the rivers identified as the master channel and main tributaries: Carrion, Valdivia, Odra, Arlanza and Arlanzon.

4. Results and discussion

Four channel networks with approximately 2,700 rivers have been obtained and the most important first-order tributaries with lengths greater than 67 km have been filtered and converted to vector format. Also the Arlanzón second-order tributary has been filtered because some hierarchies have considered it as part of the master channel (Figs. 4.B and 4.D). These rivers are equivalent to the tributaries of Carrión, Valdivia, Odra, Arlanza and Arlanzón recognized as main tributaries by the Confederación Hidrográfica del Duero (CHD) and by the Instituto Geográfico Nacional (IGN). The CHD vector channel network, scale 1: 50,000, was also filtered using the same criteria to compare the results. In general, the trajectories of the rivers obtained with the tool coincide with the channels provided by the CHD and IGN.

For the cases in which the upstream distance has been the hierarchy attribute, the river identified as the main channel follows the Pisuerga path recognized in the topographic maps of the IGN (Figs. 4.A and 4.C). In addition to this, in Hack hierarchy (Fig. 4.A), tributaries of Carrion, Valdivia, Odra and Arlanza have been identified as first order tributaries, and Arlanzon river as second order tributary, resembling the the CHD and IGN channel networks for the Pisuerga watershed.

However, the two channel networks that have been ordered by upstream accumulation (Fig. 4.B and 4.D), have identified Arlanzon River as part of the main river, turning the Pisuerga upper reach into a tributary of this one. In these two networks, Arlanzon river, accumulates more water at the pour point than Pisuerga upper reach. This is due to the fact that the gradients of the slopes, especially at the upper reach of Arlanzon river, are more pronounced than those slopes in the upper reach of the Pisuerga river, which causes Arlanzon's flow accumulation cells, derived from the direction model, compute higher accumulation value at the confluence of both rivers.

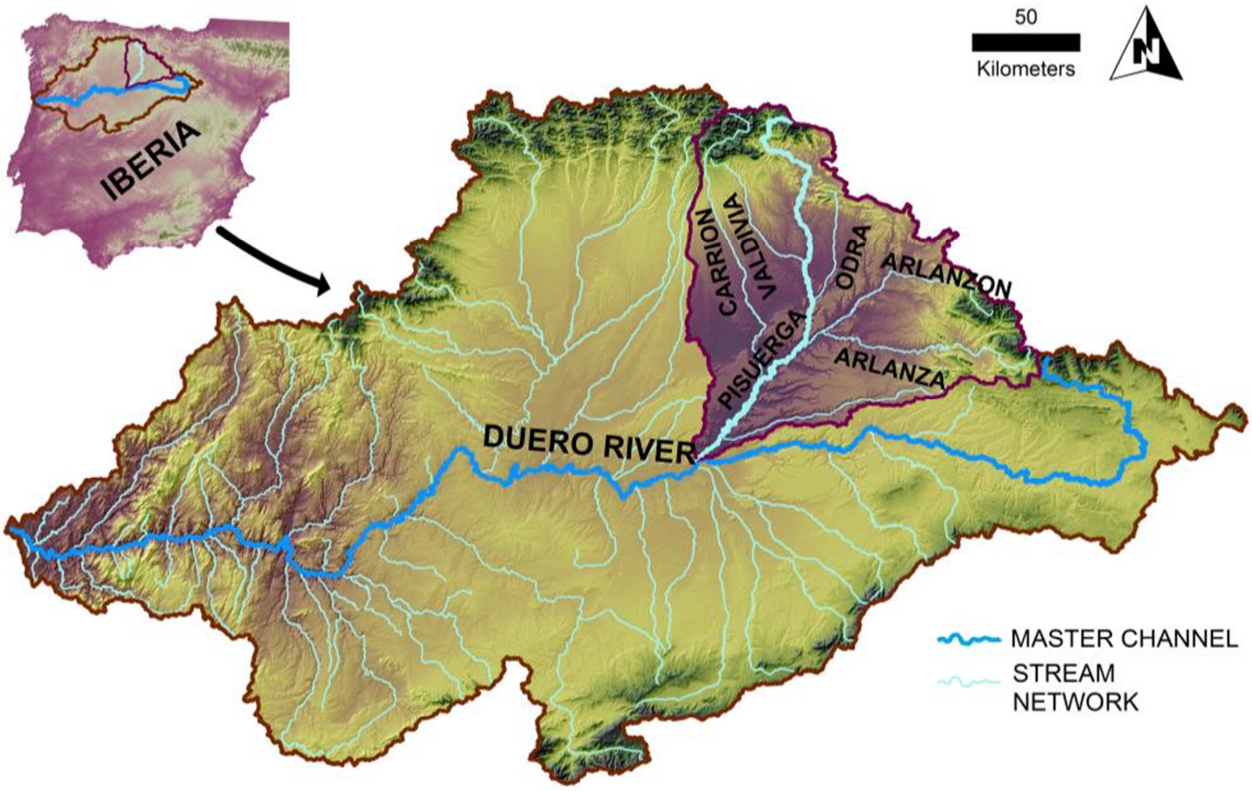

Figure 3: Duero basin SRTM v.4.1 DEM showing the master channel and main tributaries areas, Pisuerga watershed and main tributaries in Pisuerga catchment: Carrion, Valdivia, Odra rivers and the Arlanza-Arlanzon system.

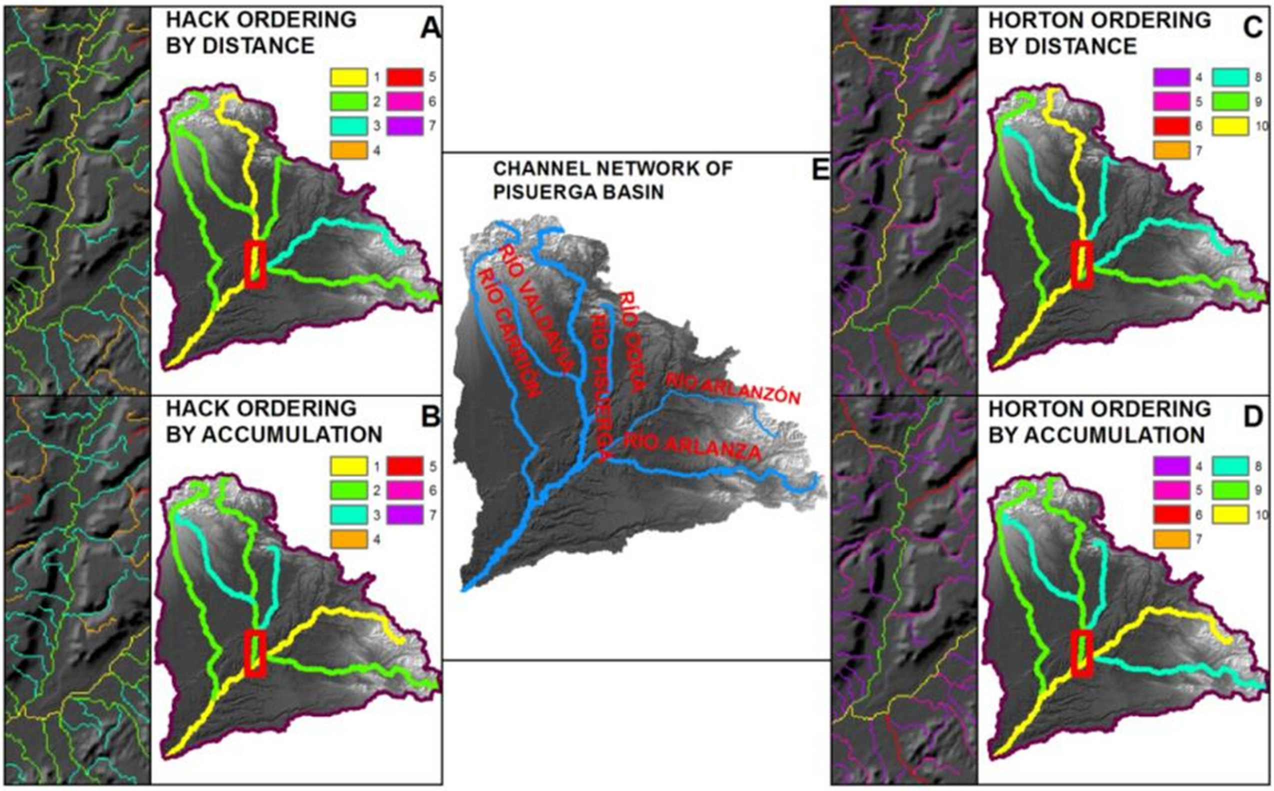

Figure 4: The networks represented in the subfigures were extracted from the DEM SRTM V.4.1 90 m, for the Pisuerga watershed using the following combination of parameters: (A) Network ordered by Hack hierarchy using upstream length as hierarchy attribute. (B) Network ordered by Hack hierarchy using upstream accumulation as hierarchy attribute. (C) Network ordered by Horton hierarchy using upstream length as hierarchy attribute. (D) Network ordered by Horton hierarchy using upstream accumulation as hierarchy attribute. (E) Official hydrological network from the Confederación Hidrográfica del Duero at 1: 50,000 scale.

The combination of factors that in the past determined the hierarchy and the headwaters location of a drainage network varies depending on the place. These historical reasons determine the fluvial networks presented in nowadays topographic maps. A characteristic of the Arlanza-Arlanzon hydrologic unit is that it is not clear which river is tributary of the other, since its flows rates are similar.

Drainage networks that are extracted using this tool, do not totally represent the official drainage network of a watershed, although they represent a way to sort a continuous channel network. If willing to work with official geospatial data, it is necessary to obtain it from services that provide official geographic data. This tool provides a sorted channel network and also information of the drainage watershed from which can be inferred other information such as the topography and geomorphology of the terrain. In addition, a sorted network by one of these two hierarchies, eases the following steps in the analysis of a basin, for instance facilitates the automation of geomorphological indices, such as Valley Height-Width Ratio (Vf), Stream Length-Gradient Index (SL), basin asymmetry factor (Antón *et al.*, 2014), etc., which require a continuous channel network previously extracted from the DEM. These indices give a more extensive knowledge of the characteristics and properties of a watershed, and the combination these indices provides very significant information on fluvial morphology useful to understand landscape evolution in terms of tectonics, climate change or geomorphological processes.

5. Conclusions and further work

In this paper, we present a new MATLAB-based tool for drainage network ordering in a non-spatial environment. The tool works along with TopoToolbox 2 toolkit, to generate the flow-routing maps previous to the channel network extraction and ordering. The tool offers two ordering hierarchies, Hack and Horton. This tool is applicable to any DEM, with low time-consumption on small-size DEMs. The tool was applied to the Pisuerga basin, a subbasin of the Duero river, and the differences in the results derived from the different combination of parameter values support its robustness.

Up to our knowledge, nowadays no tool was available for conventional GIS or non-spatial software that allowed the ordering of stream networks by Hack and Horton hierarchies. In addition to this, this tool allows choosing the hierarchy attribute to lead the sorting process, between upstream accumulation and upstream distance. Also, the high number of optional parameters enables to attain a high tailored sorted drainage network which may best suites the user's requirements, such as selecting the maximum order of tributaries instead of extracting a complete network.

Horton and Hack hierarchies provide a continuous drainage network, as each channel retains the same value from its mouth to the header. Unlike nodes graphs, this type of ordering eases the analysis of terrain properties that can be inferred from them. A channel network sorted by one of those hierarchies are necessarily the starting point of other terrain analyzes, such as the extraction of longitudinal profiles or the calculation of other geomorphometric indices. Geomorphological indices are used to quantify properties of the terrain and allow inferring characteristics of it in a quantitative format. Not only by interpreting the information each of these geomorphological indices gives, but also combining several indices, increases the information about the terrain characteristics and enables to provide geological and geomorphological interpretations.

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