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Digital watershed representation within the NewAge-JGrass system

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ABSTRACT

This paper describes the theoretical and technical architecture of a digital watershed model (DWM) that can be used as a basis for storing data relative to a river basin and to run a spatially distributed hydrological model that is directly representable in a GIS (such as uDig). The DWM deployment is based on the integration of geospatial modelling libraries (the Geotools) by means of which geographical information is encoded and becomes an integral part of the modelling process. Subsequently, the paper identifies a sequence of operations that have to be performed in order to obtain the desired DWM, and briefly describes the necessary programs. For the topological ordering of the network, a generalisation of the Pfafstetter ordering scheme is presented as well as a partitioning scheme based on the distances to the divides (namely Hack's Lengths).

These programs are stand-alone components which can be run in different ways by using: the uDig Spatial Toolbox interface, the user friendly Object Modelling System (OMS) console or by command line. The OMS console completes the work by allowing the connection of all parts to produce well-designed modelling solutions in which the components are connected and executed together. The tools presented have been applied to the Little Washita river basin (Oklahoma, US) and to the Piave river basin (Veneto, Italy).

Key words: digital watershed, geotools, Hack's Lengths, Pfafstetter ordering.

Representación digital de cuencas hidrográficas dentro del sistema NewAge-JGrass

RESUMEN

Este trabajo describe la arquitectura teórica y técnica de un modelo digital de cuenca (MDC) que puede utilizarse para almacenar datos relativos a una cuenca fluvial y ejecutar modelos hidrológicos espacialmente distribuidos que son directamente representables en un Sistema de Información Geográfica (como uDig). La estructura del MDC está basada en la integración de librerías de modelado geoespacial (los Geotools) por medio de las cuales la información geográfica es codificada para ser parte integral del proceso de modelado. Subsecuentemente el trabajo identifica una secuencia de operaciones que tienen que realizarse para obtener el MDC deseado, y describe brevemente los programas necesarios para obtenerlo. Para el ordenamiento topológico de la red, se presenta una generalización del esquema de ordenación de Pfafstetter así como un esquema de particionado basado en las distancia a las divisorias (las longitudes de Hack).

Estos programas son componentes independientes que se pueden ejecutar de varios modos: la interfaz Spatial Toolbox de uDig, el modo amigable de consola Object Modelling System (OMS) o por comandos en línea. La consola OMS completa el trabajo permitiendo la conexión de todas las partes para producir soluciones de modelado bien diseñadas en las que los componentes están conectados y se ejecutan juntos. Las herramientas presentadas se han aplicado a la cuenca fluvial Little Washita (Oklahoma, EEUU) y la cuenca del río Piave (Veneto, Italia).

Palabras clave: cuenca digital, geotools, longitudes de Hack, ordenamiento de Pfafstetter.

VERSIÓN ABREVIADA EN CASTELLANO

IIntroducción y metodología

La definición e implementación de modelos digitales de cuenca (MDC) está adquiriendo cada vez más importancia en hidrología, especialmente con la introducción de las dimensiones espaciales en el modelado hidrológico. Un MDC, como representación electrónica de las características hidrológicas espaciales y de series hidrológicas temporales, tiene que operar con diferentes tipos de datos: elevación, características del agua, uso del suelo, datos de observación puntual, y/o datos sobre una malla regular (imágenes de satélites, productos climáticos, …). En este contexto los datos están relacionados y son utilizables para investigaciones en un ambiente participatorio para promover una amplia colaboración entre muchos tipos de científicos e ingenieros (http://www.cuahsi.org).

Este trabajo presenta la arquitectura y la informática de un MDC capaz de almacenar datos relativos a una cuenca fluvial y ejecutarse sobre un modelo hidrológico espacialmente distribuido. Todos los elementos se pueden implementar y representar en un Sistema de Información Geográfica (GIS) de dominio público y código abierto, uDig que corre como cliente bajo diferentes plataformas (Windows, Mac OS/X, and Linux) y está orientado como servicio web.

El nuevo MDC es una malla especial sobre la que el usuario puede ejecutar el modelo hidrológico semi-distribuido NewAge-JGrass, un modelo continuo para predecir y modelar los recursos hídricos en general a escala de cuenca. Se integraron diferentes componentes hidrológicos en el sistema tales como diferentes tipos de algoritmos de interpolación meteorológica, balances energéticos de onda corta y onda larga, fusión de la nieve y modelado de la escorrentía. Por estas razones el modelo hidrológico semi-distribuido NewAge constituye un intento para representar y modelar todos los procesos hidrológicos. El diagrama de flujo de trabajo comienza con la delineación de subcuencas utilizando las herramientas disponibles en el SIG uDig y los JGrassTools. El sistema se basa en una partición geométrica del paisaje en base a laderas con enlaces. La unidad básica para la evaluación del balance de agua es la ladera, las cuales se tratan como cajas negras. Sin embargo, las laderas pueden diseccionarse todavía más dependiendo de los procesos a analizar. Cada ladera drena en un enlace simple asociado, en lugar de en celdas o píxeles. Los canales se describen como elementos vectoriales que están topológicamente interconectados en un grafo orientado simple. Además cada elemento de la red del río puede incluir estructuras antrópicas que regulan los regímenes de flujo, con lo que se hace posible simular entradas, gestión de presas, canales artificiales y extracciones de agua, por ejemplo para riego. Esta partición conceptual se desarrolló utilizando una informática con estructura vectorial para los canales y estructura ráster para las laderas.

El artículo ilustra el procedimiento completo que el usuario ha de llevar a cabo para obtener su propio MDC, esto es, la estructura ladera-enlace de la cuenca. Se ha esquematizado en la figura 1. Para el ordenamiento topológico de la red, se presenta una generalización del esquema del ordenamiento de Pfafstetter así como un esquema de particionado basado en las distancias a las divisorias (longitudes de Hack).

Las herramientas presentadas se han aplicado a dos casos de estudio, la cuenca del río Little Washita (Oklahoma, EEUU) y la cuenca del río Piave (Veneto, Italia) que presentan diferencias en tamaño y en complejidad topográfica.

Resultados y discusión

El trabajo discute el problema de la definición de un modelo digital de cuenca (MDC) en el contexto del sistema hidrológico NewAge-JGrass. El procedimiento para obtener el MDC se resume en dos pasos i) análisis geomorfológico de la cuenca con herramientas integradas en NewAge-JGrass y ii) ordenación y clasificación de las subcuencas. El flujo de trabajo del primer paso se presenta en la figura 2 e incluye: i) relleno de todas las posibles depresiones en algunos de los puntos del modelo digital de elevaciones; ii) cálculo de la dirección de drenaje; iii) extraer la red de canales de drenaje; iv) etiquetado utilizando el mismo número para cada canal y ladera que drena a dicho canal; v) cálculo del fichero shape que contiene información acerca de cada canal y enlace tal como: área, perímetros, elevación media, etc.

La segunda parte está relacionada con el ordenamiendo de canales y subcuencas de la cuenca vertiente. Una versión modificada del esquema de ordenamiento de Pfafstetter se implementó y chequeó en dos cuencas de diferente tamaño. El procedimiento para calcular el ranking de la red de canales incluye: i) el cálculo de la distancia de Hack (la distancia desde la cuenca a lo largo de la red procediendo aguas arriba a lo largo de la línea de máxima pendiente); ii) cálculo de cauces Hack que numera una red de canales comenzando por el canal principal y finalmente iii) aplicación de la metodología Pfafstetter. El algoritmo es capaz de gestionar y etiquetar de un modo apropiado tanto lagos como infraestructuras antrópicas en la cuenca fluvial como pantanos y derivaciones. Los resultados de cada uno de los programas para las cuencas fluviales de Little Washita y Piave se presentan en las figuras 4, 5 y 6. Los MDCs estructurados en laderas y enlaces serán la base de los componentes hidrológicos de NewAge-JGrass. Cada ladera y enlace se puede relacionar a ficheros CSV

conteniendo datos hidro-meteorológicos tales como lluvia media y temperatura media del aire para laderas, así como descarga media y velocidad media para canales. Sin embargo, está claro que el sistema se puede expandir para comunicarse fácilmente con la base de datos y servidores, de tal modo que se podrían escalar a situaciones operacionales reales donde tales sistemas son necesarios.

Las salidas de las herramientas es un modelo de datos implementado utilizando características simples OGC, esto es, ficheros shape e información conectada a ellos. Cada herramienta es un componente, de acuerdo a las definiciones en Sistema de Modelado de Objetos (SMO), esto es, un entorno de modelado basado en Java desarrollado para modelado por componentes. Se basan en Geotools, librerías geoespaciales por medio de las cuales se codifica información geográfica. Las herramientas se pueden ejecutar por ellas mismas o se pueden conectar fácilmente con otros componentes OMS que construyen una cadena de modelos.

Todos los programas presentados, así como los componentes NewAge, se pueden ejecutar de tres modos diferentes: la interfaz SpatialToolbox uDig, presentada en la figura 3, la consola amigable SMO o la tradicional línea de comandos. En los primeros dos casos, una interfaz gráfica de usuario facilita el procedimiento de entrada-salida para las aplicaciones de las herramientas y los resultados se pueden visualizar fácilmente en el SIG uDig mediente la selección y arrastre de mapas en el panel de vista. Es más, uDig es capaz de tomar geodatos servidos a través de estándares como el Web Feature Services (WFS), Web Map Services (WMS), y el Web Coverage Services (WCS). Esto posibilita el hecho de que la información topológica y geométrica relacionada con la cuenca fluvial se puede traducir muy fácilmente en tablas relacionadas de un geo-database SQL. Esta comunicación se realizó en una implementación piloto para la Autoridad de la Cuenca del Río Adige, donde se modelo la cuenca fluvial del río Adige.

Para concluir, el trabajo presenta las herramientas y el procedimiento para obtener un MDC que puede ser usado como dominio espacial para la ejecución de modelos hidrológicos. En particular la ordenación Pfafstetter de la red se modifica y se aplica en dos casos de estudio. Permite una fácil navegación a través de la red fluvial, ayuda al usuario a determinar si dos cauces de río están conectados y cómo están conectados y finalmente permite analizar la cuenca a diferentes escalas de resolución espacial de acuerdo al objetivo del análisis desarrollado.

Introduction

Even though highly remarkable results have been obtained in hydrological science by using just point models (e.g Rodriguez-Iturbe and Porporato (2005), Eagleson (1970)), introducing spatial dimension in hydrological modelling is the source of more physical realism and of new dynamical features. One of the goals of NewAge-JGrass (Formetta *et al.,* (2011)) is to advance this philosophy and to allow the construction of minimalist model solutions (MS) that are aware of the spatial information and its heterogeneity when they are used for predictions.

Using this modelling strategy however, it is necessary to conceptualise basin description in formal terms, usually called the digital watershed model (DWM). A DWM is an electronic representation of a watershed's spatial characteristics and time-series hydrologic information. "It can include elevation, water features, land use, point observation data, and/or gridded data, e.g. remote sensing, climate products, where the data are related and usable for investigations in a participatory environment to promote a broad collaboration among many types of scientists and engineers" (from: http://www.cuahsi.org). One of the most mature digital watershed designs of schematisation is the one initially encoded by Maidment (2002), and subsequently endorsed by the Consortium of Universities for the advancement of Hydrological Sciences (CUASHI), and described for instance by Goodall and Maidment (2009). It distinguishes the basic units that make up a watershed and identifies an appropriate data model and storage formats for them. For instance, Arc Hydro, Maidment (2002), distinguishes the following as part of the basin:

- the stream network subdivided in links
- the basins subdivided in sub basins
- the lakes and surface water bodies
- the monitoring points

The Arc Hydro data model also includes the groundwater features and dynamics (Strassberg *et al.,* (2011)) that are not covered here. DWMs are usually stored as simple features according to the Open GIS Consortium (OGC) standard that can be processed by all major GISs and have a corresponding storage format within all major database systems that manage geographic features.

The effective use of spatial information in models usually requires a further refinement, which is very much modelling dependent, and is usually based on the definition of the hydrologic response units (HRU) Ross *et al.,* (1979), Flugel (1995), Krause (2002) and Viviroli *et al.,* (2009).These are the elementary parts of the basins that are treated as black box units. Moussa *et al.,* (2007) represents an example of a detailed partition of a basin for agricultural use. Within the AGE model (Ascough II *et al.,* (1999)) sub-catchments are subdivided into many detailed functional parts which refer to the different treatments in soil use and/or land-cover which are thought to influence hydrological fluxes.

In this paper we describe the digital watershed model, i.e. the modern data model, used in the NewAge JGrass modelling system. The DWM is aimed to be a flexible and efficient description of the spatial features of a basin. It is needed to drive spatially explicit hydrological models (or model components) and is able to include human infrastructures inside the river basin description, in order to account properly for anthropic alteration of the hydrologic cycle. Section 2 introduces the hydrological components of the NewAge-JGrass model and explains how they fit into the digital watershed model implemented into the system. Sections 3 and 4 introduce the method and the tools available in the system for performing the basin geomorphologic analysis and the consequent watershed delineation according a suitable modification of the Pfafstetter ordering scheme. Finally, two applications of the method are presented

Concepts

In NewAge-JGrass (Formetta *et al.,* (2011), Formetta *et al.,* (2013), Formetta *et al.,* (2014a) and Formetta *et al.*, (2014b)), the basin is partitioned into a hillslope-link (HL) structure, where the hillslopes are the basic hydrologic response units (HRU) for all that concerns rainfall-runoff. Channels are described as vector features that are topologically interconnected in a simple, directed graph. For computational reasons, partitioning of the area is not usually designed to identify all the physical hillslopes present in the system, but to define the dimensions of small watersheds. In the applications shown in this paper, these are of 2-10 Km2 on average. HRUs can either be represented as vector features or rasters.

Within a model, any element of the river network can include anthropogenic structures that regulate the flow regimes, thus making it possible to simulate intakes, management of dams, artificial channels, and water abstractions, for example, for irrigation.

Hillslopes can be further dissected depending on the processes to be analysed. For instance, when temperature is the concern, each hillslope can be further subdivided into altimetric bands, each one with its own temperature, that could eventually be manipulated to obtain a single value for the whole hillslope, depending on the requirements of the case in study. Regarding the estimation of radiation, or snow, the specific model components of NewAge-JGrass can either use information at pixel scale, which is subsequently averaged, or information from selected representative points within the hillslope. Therefore, besides, a generic delineation of the basin, each module component relative to a process can use the data and the geometries it requires, and in general the HL partition is a key for interrogating and treating other informative layers. One critical issue is how single units exchange the main hydrological fluxes. MYDHAS [Moussa *et al.,* (2010)] and AGEs (Ascough II *et al.,* (1999). HRUs, for instance, exchange runoff and subsurface fluxes in multiple directions and therefore have procedures to manage this complexity. NewAge-JGrass, at the present stage, just allows one hillslope to discharge into its channel link. In any case, the river network constitutes a hierarchy in which sources flow into the internal links and these, in turn, into larger streams. To account for this hierarchical simulation various strategies can be used. The most advanced scheme is probably Liu *et al.,* (2013), which builds on the knowledge obtained by analyzing the Strassberg *et al.,* (2011) generalised Pfafstetter's scheme that is used here, and is described below.

Whatever the conceptualisation, the challenge is to deploy the ideas in a robust, correct code. This is accomplished in NewAge-JGrass by using the Geotools libraries and their implementation of the geographic features which seamlessly integrate with the Object Modelling System version 3 (OMS3) (David *et al.,* (2013) and uDig (http://udig.refractions.net/).

To obtain this hierarchical structure it is first necessary to process the raster data from a digital elevation model. For the scope of building the DWM, this paper also covers the description of the main tools for basins and channels (river networks), which are included in the Horton Machine Rigon *et al.,* (2006) and Abera *et al.,* (2014), and serve as foundations. These have been evolved during the last twenty years in parallel to other suites of programs such as Taudem (Tarboton (2005)) and RiverTools (Peckham (2003)). In contrast, the Horton Machine (HM) is consistently integrated in a GIS system through the uDig Spatial Toolbox. Formetta *et al.,* (2014a) describes in detail how each command can either work separately (from the command line or the OMS3 console) or by being connected to other commands through the functionalities offered by the OMS3 system, thus offering different possible operational modes.

Catchment analysis

The analysis of the catchment starts with the acquisition of a Digital Elevation Model (DEM) of the catchment, e.g. Wilson and Gallant (2000) and Peckham (2003). It is performed as illustrated in Figure 1 and summarized for the reader below.

The tools for basin characterization that the HM (Abera *et al.,* (2014)) offers are, amongst others:

- RasterReader: which imports raster maps (.asc, .grass, .geotifi) and converts them into GridCoverage, the object used in Geotools to store raster data.
- VectorReader: which imports vector files (.shp) and converts them into the Features Collection, the object used in Geotools to store vector data.
- Pitfiller (Tarboton (1997)): this tool fills the depression points in the DTM and assures that, for any point in the basin, except the outlet, there is a point lower, and so it allows the identification of the drainage directions at each point; the input for Pitfller is the DTM previously imported in the GIS. An example of the output is shown in Figure 2,a.
- FlowDir (O'Callaghan and Mark (1984) and Marks *et al.,* (1984)): it calculates the drainage directions with the method of the maximal steepest descent slope, selecting one out of 8 possible directions (D8); the input for the command is the output map of the Pitfiller component.
- DrainDir: this tool provides the drainage directions, minimising the deviation from the real flow. The deviation, calculated using a triangular construction, could be given in degrees (D8 LAD method) or as transversal distance (D8 LTD method), Orlandini *et al.,* (2003) and Orlandini *et al.,* (2012). The input raster maps are: the map in output from Pitfiller and Flowdir. The outputs are

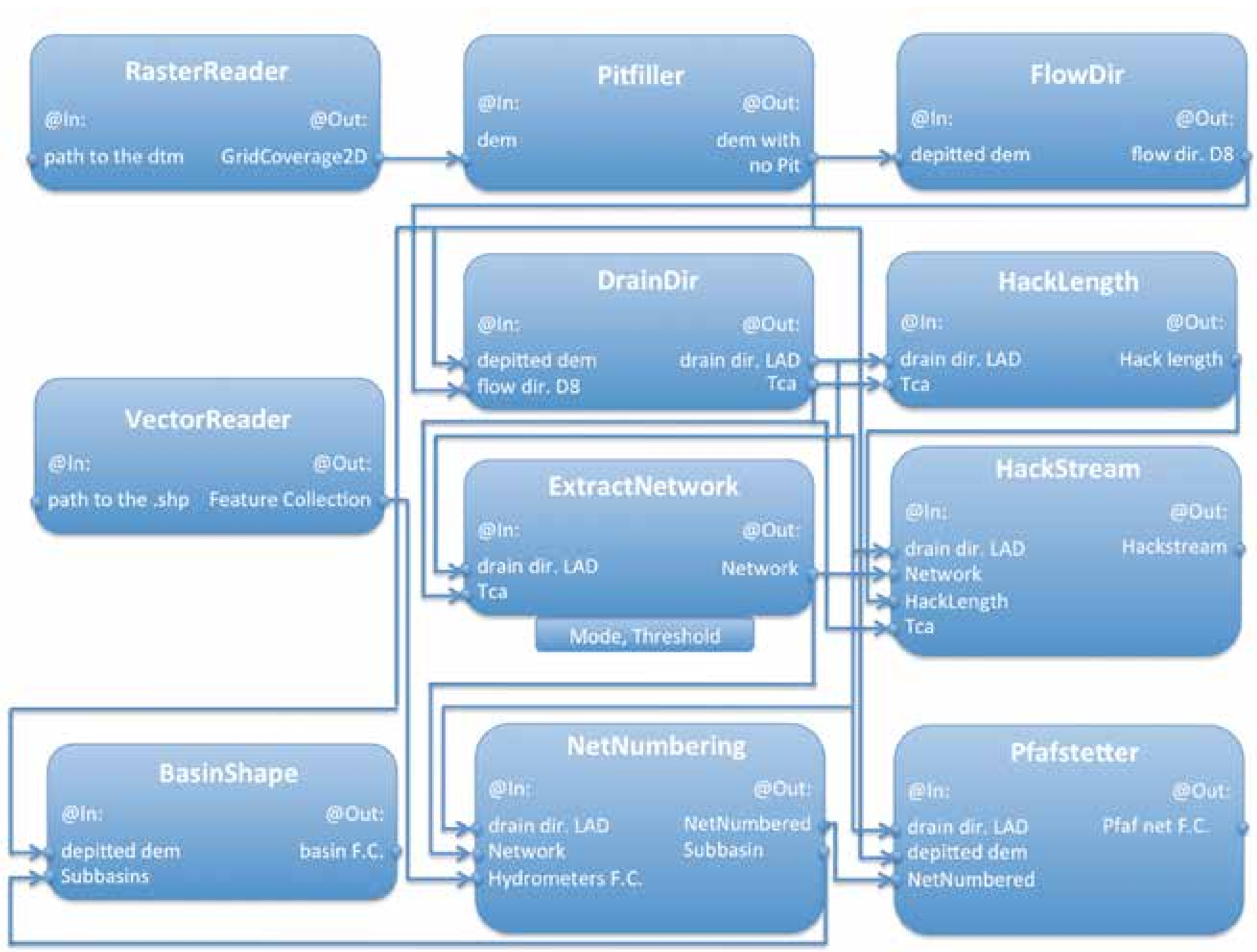

Figure 1. The workflow for basin characterization in NewAge-JGrass.
Figura 1. *El flujo de trabajo para la caracterización de cuencas en NewAge-JGrass.*

the raster maps of the drainage directions, (Fig. 2,b), and of the total contributing area, (Fig. 2,c).

- ExtractNetwork: it extracts the channel network from the drainage directions. Three operational modes are implemented. They differ in the way in which the start of the channel is modelled:
  1. mode 0: by using a threshold value of the contributing areas (then only the pixels with contributing area greater than the threshold are the channel heads);
  2. mode 1: by using a threshold value of the parameter: equivalent to a threshold value of the stress tangential to the bottom;
  3. mode 2: by using a threshold value on the stress tangential to the bottom;

  After identifying the beginning of a channel, the points downstream of it are considered as channel. If "mode 0" is used, the inputs of ExtractNetwork are the map outputs of Pitfiller and DrainDir (both drainage directions and TCA). The output will be the raster map and, if the user needs it, also a vector file an output of the river network, (Fig. 2,d).
- NetNumbering: it assigns different numbers to each network channel and labels it with the corresponding hillslope number, which is connected to the link. The input maps are: the file containing the flow directions (generated by DrainDir) and the map containing the channel network (generated by extractnetwork). There are two output raster maps: the network map with the numbered streams and the map containing the labelled sub-basins.
- BasinShape: it computes the shape file of the basin split into hillslopes. The BasinShape inputs are the map output of Pitfiller and the map containing

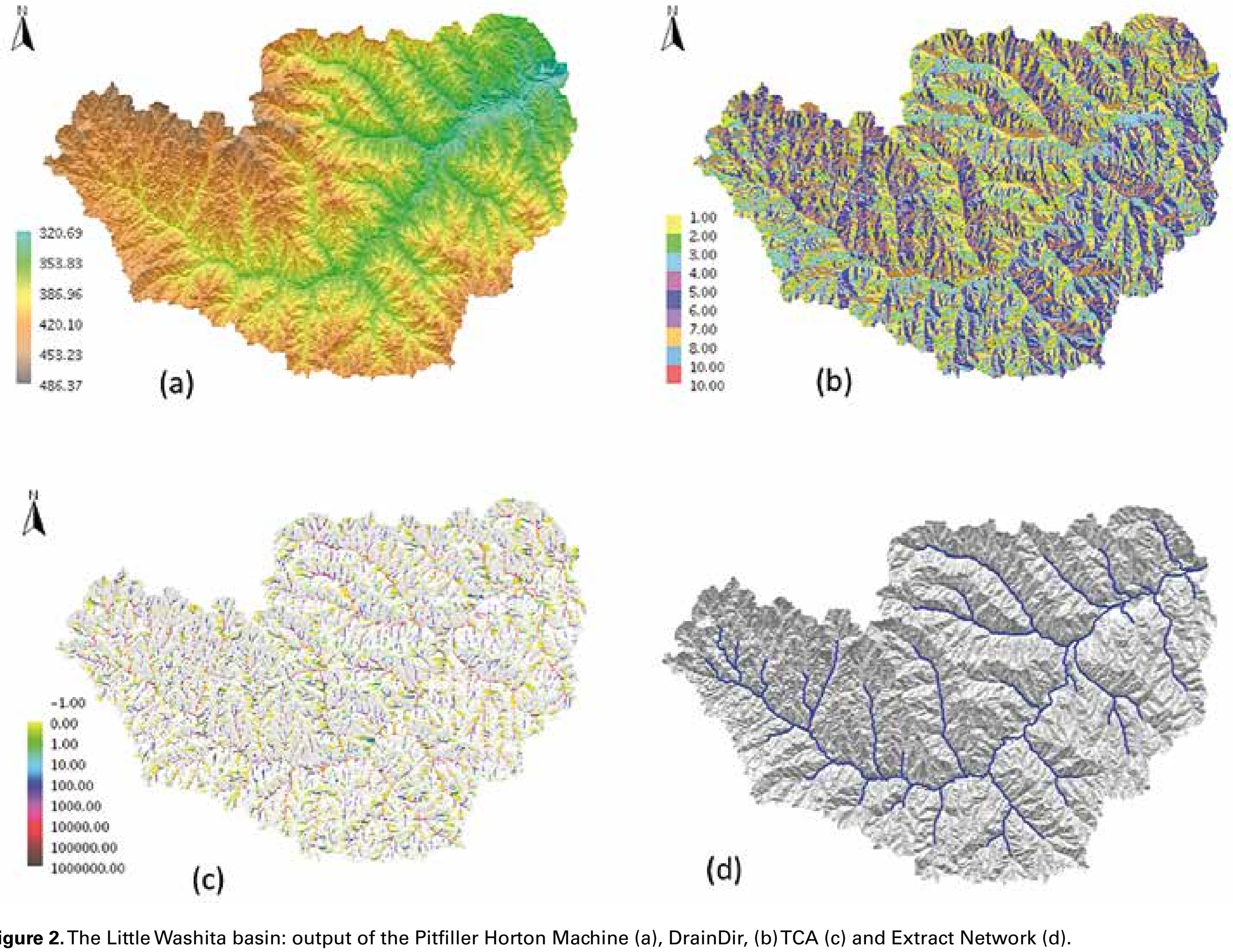

Figure 2. The Little Washita basin: output of the Pitfiller Horton Machine (a), DrainDir, (b) TCA (c) and Extract Network (d).
Figura 2. *La cuenca Little Washita: (a) salida de la Máquina Pitfiller Horton; (b) DrainDir; (c) TCA y (d) Extract Network.*

the labelled sub-basins (output of NetNumbering). The resulting shape file contains the basin split for each hillslope with some features such as:

- Area: the hillslope area [m2];
- Perimeter: the hillslope perimeter [m];
- Netnum: the hillslope ID;
- MaxZ: the hillslope maximum elevation [m];
- MinZ: the hillslope minimum elevation [m];
- AvgZ: the hillslope average elevation [m];
- Height: the hillslope centroid elevation [m];

Figure 3 presents a screenshot of the SpatialToolbox-uDig GIS interface. An example of basin partition in hillslopes is presented; for each hillslope the user is able to visualize the geomorphological features such as area, perimeter, mean elevation, etc.

Basin ordering and classification

In order to build the DWM it is necessary to assign a topology to the river network. In the past, a few methods for the topological ordering of the network were presented and the original historically was the Horton-Strahler [Horton (1945)]. This is the ordering method implemented in the HM.

Strahler ordering was used in the original paper about the geomorphologic unit hydrograph [Rodriguez-Iturbe and Valdes (1979)] but cannot be considered still functional to modern semi-distributed models, where the topography is assumed (and is) known in great detail. Another topological partition of the basin was based on magnitude ([Rodriguez-Iturbe and Rinaldo (2001)] and this is also implemented in the HM). However, magnitude was just a surrogate for the total contributing area, when such a quantity was difficult to estimate (on maps). More recent classifications of streams rely on other quantities, such as the length from any point to the divides (e.g. Rigon *et al.,* (1996) and Gangodagamage *et al.,* (2011)) and on the Pfafstetter numbering schemes [Verdin and Verdin (1999)].

The Pfafstetter numbering scheme (PNS) algorithm is defined as follows: starting from the outlet of the watershed, the main stream is delineated first. It uses the river streams extracted from the tree-like network of the drainage directions according to the algorithm presented in the previous section. This river network presents links (channel segments) separated by junctions, where tributaries meet. Each stream is characterized by a total upslope area, which is the total

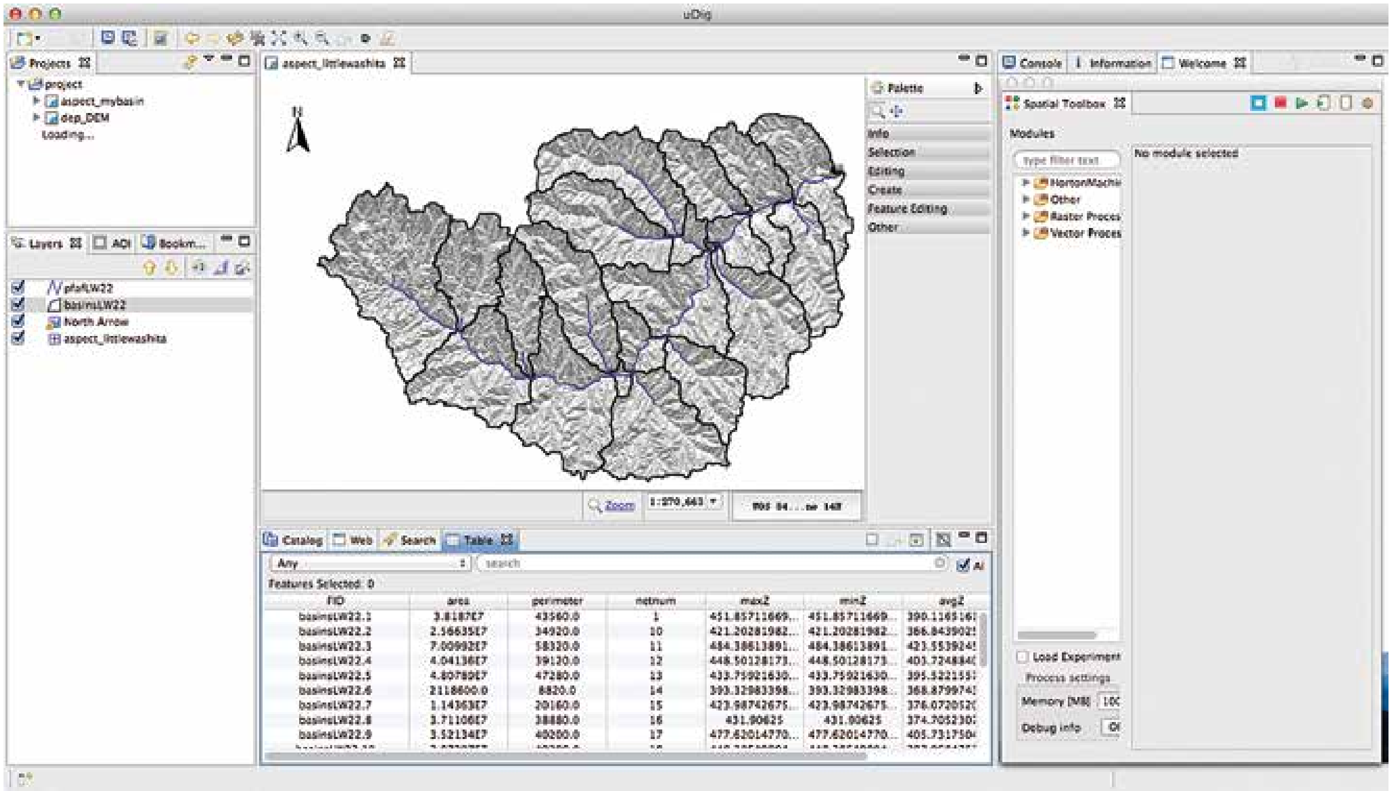

Figure 3. The Little Washita basin split into hillslopes by using the SpatialToolbox and uDig.
Figura 3. *La cuenca Little Washita dividida en laderas utilizando el SpatialToolbox y uDig.*

area of the basin flowing into that stream. The main stream is obtained by following the river network, starting from the outlet going upstream. When coming to a junction, the direction of the stream follows the channel link with the largest upslope area. In the case of equal areas a random direction is chosen. Each junction separates the main stream into links, which are numbered with a series of odd numbers starting with 1 at the outlet, (see Fig.5, below). Tributaries of the main stream are numbered with increasing, even, numbers while going upstream (assuming that two tributaries do not flow into the main stream

at the same point), Figure 5. This generalises the original Pfafstetter numbering where just 5 links and 4 tributaries were allowed to constitute the main river-network tree in order to limit the use to 9 digits to identify any link. Tributaries can have sub- tributaries. As shown in Figure 5, one tributary has sub-tributaries, and therefore a second order numbering is used, represented by two digits separated by a point. The main stream of 8 is split into links 8.1 and 8.3 and two order 2 headwater basins are delineated: 8.2 and 8.3, where 8.3 is thought to continue the main stream of the tributary.

The commands to obtain the partition of the catchment are therefore:

- Hack Length: at a given point in a basin, it calculates the distance from the watershed along the network proceeding upstream along the maximal slope length. The input raster maps are: the drainage directions map (obtained with DrainDir) and the contributing areas map. The output is the raster map of the Hack distances.
- Hack Stream: it arranges a channel network starting from the main stream. The main stream is of order 1 and its tributaries of order 2, the sub-tributaries are of order 3, and so on. The input raster maps are: the drainage directions map (obtai-

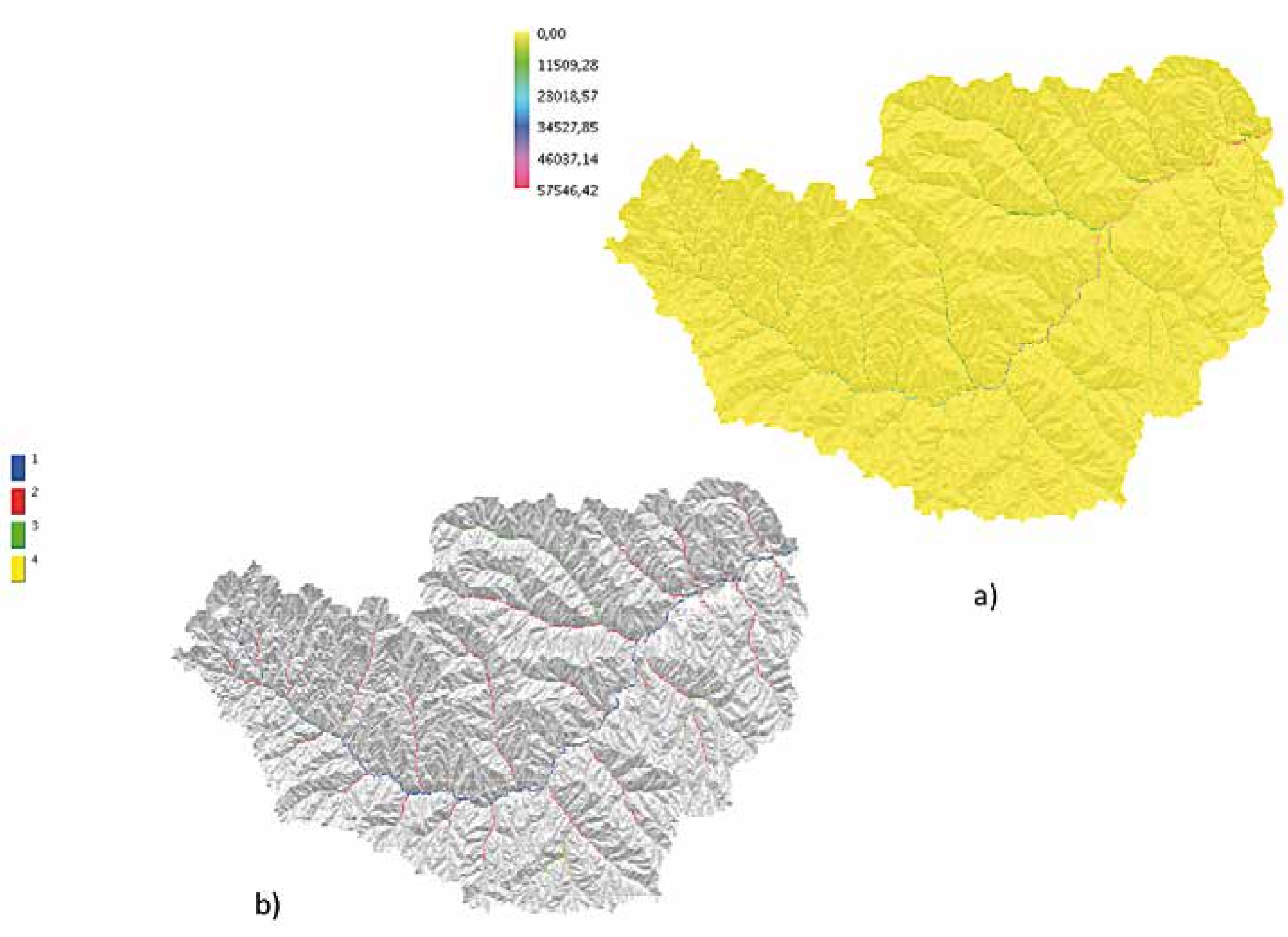

Figure 4. The Little Washita basin: output of HackLength, (a), and Hack Stream, (b).
Figura 4. *La cuenca Little Washita: (a) salida HackLength y (b) salida de Hack Stream.*

ned with DrainDir), the total contributing areas, the Hack length map (obtained with hack length), and the channel network (obtained with extract network).

- The Pfafstetter algorithm builds the topology of the network by numbering the river network structure according to a generalisation of the Pfafstetters numbering scheme (PNS) (e.g. Verdin and Verdin (1999), Furst and Horhan (2009)).

Once the river network has been numbered according to Pfastetter, it is naturally subdivided into parts, if each channel is associated with its hillslope, so that any part of the basin is uniquely identified. Besides, PNS uniquely identifies the watershed channels downstream of a point of interest (i.e. a droplet falling into the 8.3 sub-catchment is guaranteed to flow into links 8.1, 7, 5, 3, 1).

At the same time, it is known that, for instance, subcatchment 4.3 is neither upstream nor downstream of 8, but both merge into stream 3. A dense network ordering is presented in Figure 6, where the tools are applied for the Piave river basin (Italy).

Conclusions

The paper introduces a set of tools for analysis and ordering of channel networks from which a digital watershed model suitable for being used in spatially explicit hydrological modelling is obtained. The tool outcome is a data model implemented by using OGC simple features, i. e. shape files and information connected to them. The tools themselves are implemented as OMS version 3 components, to be used within the Spatial Toolbox of uDig. The conceptual core around which these tools were built is the use of a modified Pfafstetter numeration of the networks to account for the topology of the network and the basin. This is particularly useful because it allows: (i) an easy navigation through the river basin; (ii) to determine if two links are connected (for example a link 8.3 is the third link of the main stream of tributary 8); iii) to prune out the smaller channels to analyse the basin at different scales of resolution, therefore being able to deal with basins at multiple scales, according the scope of the analysis performed.

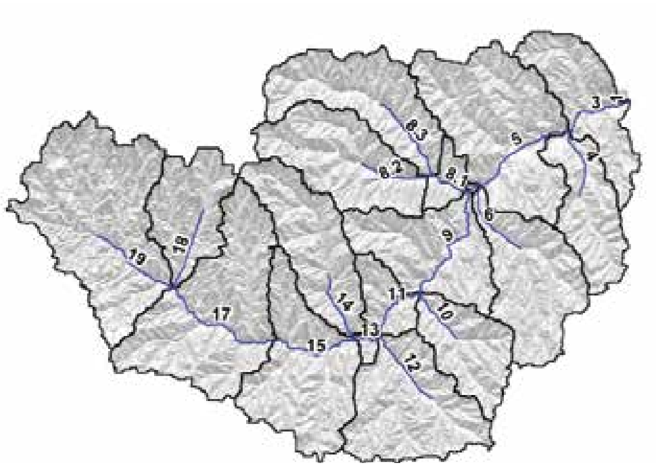

Figure 5. The Pfafstetter numbering scheme for the Little Washita watershed, Oklahoma (U.S.). The figure shows an example of the-Pfafstetter river-network numbering.
Figura 5. *El esquema de numeración de Pfafstetter para la cuenca vertiente de Little Washita, Oklahoma (EEUU). La figura muestra un ejemplo de la numeración de Pfafstetter para la red de drenaje.*

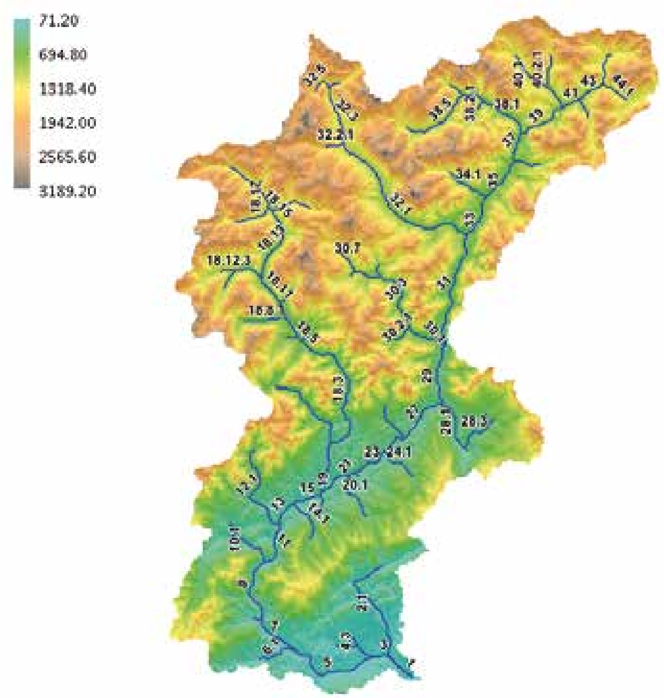

Figure 6. Pfafstetter numbering scheme for the Piave river basin (Italy). The figure shows an example of the Pfafstetter river-network numbering.
Figura 6. *El esquema de numeración de Pfafstetter para la cuenca del río Piave (Italia). La figura muestra un ejemplo de la numeración de la red de drenaje de Pfafstetter.*

The more important tributary numbering is presented. PNS, therefore, supplies the topological information that is otherwise missing in shape files representing the network.

Clearly, the above topological and geometrical information can easily be translated into interconnected tables of an SQL database, as shown in a prototype implementation for the River Adige Basin Authority. In fact, the DWM described has been successfully used in the JGrass-NewAGE model, of which a detailed reference can be found in Formetta *et al.,* (2011), Formetta *et al.,* (2014a), Formetta (2013) and Formetta *et al.,* (2013).

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