Urban and peri-urban drainage network representation using Geo-PUMMA in the Mercier (France) and El Guindo (Chile) catchments

Représentation du réseau d'assainissement urbain et péri-urbain par l'utilisation de Geo-Pumma dans les bassins versants du Mercier (France) et de l'El Guindo (Chili)

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RÉSUMÉ

Les processus hydrologiques dans les zones urbaines et péri-urbaines sont significativement affectés par des éléments artificiels comme les canaux, les tuyaux, les rues et les réseaux d'eau pluviale. Nous présentons Geo-PUMMA, un ensemble d'outils SIG en Python pour GRASS qui représentent explicitement les différentes composantes des zones périurbaines par un maillage vectoriel irrégulier. Geo-PUMMA rassemble informations spatialisées telles que le cadastre, les types de sols, la géologie et des modèles numériques de terrain. Geo-PUMMA fournit des Unités de Réponse Hydrologique (HRUs) et des Eléments Hydrologiques Urbains (UHEs) et permet d'améliorer le maillage initial pour une meilleure représentation des chemins de l'eau. Geo-PUMMA permet également l'extraction de propriétés morphologiques du bassin telles que la fonction largeur, aire drainée ou d'imperméabilisation. Geo-PUMMA est appliqué à deux bassins péri-urbains: le Mercier (10% d'urbanisation) situé près de Lyon, France, et El Guindo (40% d'urbanisation) situé dans la région du piémont andin, Chili. La comparaison des fonctions largeur et aire drainée entre les maillages initiaux et finaux montre une amélioration de la représentation de réseau de drainage à petite et moyenne échelle (120-150 m pour El Guindo et 80-150 m pour le Mercier).

ABSTRACT

Hydrological processes in urban and peri-urban areas are significantly affected by artificial elements like channels, pipes, streets and storm water networks. We present Geo-PUMMA, a set of GIS tools programmed in Python for GRASS that uses irregular vectorial meshes to explicitly represent the components of the peri-urban terrain. Geo-PUMMA gathers spatial information maps (e.g. cadastral, soil types, geology and digital elevation models) to produce Hydrological Response Units (HRU) and Urban Hydrological Elements (UHEs), and to improve the mesh for a better representation of water pathways. Geo-PUMMA also allows the extraction of basin morphologic properties such as the width-function, the area-function and the imperviousness-function. Geo-PUMMA was applied to two peri-urban catchments: the Mercier catchment (10% urbanized) located near Lyon, France, and the El Guindo catchment (40% urbanized) located in the Andean piedmont in the Maipo River, Chile. The comparison of width and area functions between the initial and recommended meshes shows that the drainage network representation is particularly improved at small to medium spatial scales (i.e. 120-150 m for the El Guindo catchment and 80-150 m for the Mercier catchment).

KEYWORDS

Peri-urban catchments, Drainage extraction, Computer-assisted mesh generation, GRASS-GIS

1 INTRODUCTION

Urban development and associated increase of soil imperviousness has significantly changed the urban hydrology cycle and modified the drainage network in non-natural areas. This change also affect peri-urban basins, characterized by a high level of heterogeneity, a mixture of natural, rural and urban areas (Braud et al., 2013). In this type of basins, typical elements or infrastructures can modify the direction of the superficial and sub-superficial flows, generating complex environments and increasing the types of connectivity between pervious and impervious areas that must be represented.

Several GIS tools have been developed to represent and visualize landscapes and extract information from them.. Most of these tools were developed to represent regional and medium size areas, and do not consider urban and peri-urban elements. Classical methodologies of drainage extraction and basin delineation use flow direction algorithms such as the D8 and Multiple Flow Directions (MFD), which consider Digital Elevation Models (DEM). These algorithms give good results in natural and non-flat areas at regional or median scales, but are not suitable for urban and peri-urban typical scales (<0.1-10 km^2) where surfece and subsurface infrastructure can modify the natural flow directions dramatically, and even change substantially the limits of urban and suburban basins. Thus to the best of our knowledge, a specific tool that allows creating a hydrological model mesh in urban and peri-urban catchments is still not available. In this work we develop Geo-PUMMA, a GIS tool that allows generating a good quality mesh for realistic urban and peri-urban hydrological connectivity and water pathways representation.

Geo-PUMMA uses a vectorial approach that preserves the principal physiographic units of urban and peri-urban basins, defined as polygons with irregular shape. Geo-PUMMA allows perparing urban and peri-urban terrain for semi-distributed or distributed hydrological models.Thus, it is possible to consider explicitly the infrastructures encountered in this complex environment (e.g. works of arts, retention infrastructures, aqueducts, piping, and streets or avenues). The representation of urban areas is based on Urban Hydrological Elements (UHE) (Rodríguez et al., 2008), while the rural and peri-urban areas are depicted using Hydrological Response Units (HRU) (Flügel, 1995).

We apply Geo-PUMMA to the Mercier catchment (close to Lyon in France), and the Estero El Guindo catchment, a piedmont catchment located in Santiago, Chili. These two catchments differ in their landscape and climate conditions.

2 MATERIALS AND METHODS

2.1 Geo-PUMMA presentation

Geo-PUMMA was initially developed to prepare the geospatial information for the PUMMA hydrological model (Jankowfsky et al., 2014), but can also be used for any distributed hydrological model based on irregular modelling units. Thus previous work was put together in a set of tools programmed in Python language (python.org) using the GRASS platform (grass.osgeo.org) and QGIS (www.qgis.org). A methodology is proposed for helping in the spatial pre-processing of the HRUs and UHEs

The proposed methodology has four steps. Step 1 corresponds to data collection, digitalization and quality improvement of all the geospatial maps of relevance for hydrological processes in urban and peri-urban areas. Step 2 corresponds to the representation of the urban area, in which all the UHEs are delineated and characterized using attributes such as average height, area, imperviousness, green area, and distance from the centroid of each unit to the closest sewer or street. In step 3 we improve the initial HRUs segmentation to address geometric constraints and insure accurate numerical modelling. To do this we use a triangulation and dissolution process based on geometrical indicators. In this step, the HRUs can be process to obtain more homogeneous properties such as slope, topographic index, aspect or other topographic parameter of interest that can be obtained from high resolution digital terrain models. Finally, in Step 4 the drainage network is extracted after accounting for the hydrological connectivity between the different units, using a recursive algorithm for identifying surface flow directions. This drainage network is composed of channelized and non-channelized elements. Finally, we describe and assess the obtained drainage networks by means of geomorphologic properties.

2.2 Case studies, meshes generation and comparison

The Mercier catchment is part of Yzeron peri-urban watershed (150 km^2) located southwest of Lyon, France. The catchment has an area of 7 km^2 and is covered with forests, crops and urbananization (about 10%), although a significant portion is rural. The peri-urban Estero El Guindo basin (6.5 km^2) is located in the foothills of Santiago, Chili, in a location where urban sprawl is taking place quite rapidly. The natural area is covered by native vegetation (3.3 km^2) and the urban area (3.2 km^2) it is distributed along and close to the Estero El Guindo.

We applied Geo-PUMMA to the Mercier and El Guindo catchments. We generated three meshes to identify geometrical indices that allow getting the best representation drainage network, keeping the number of elements as low as possible to limit computing cost. The different maps were created using different values of 2 geometrical indices: the Convexity Index (CI) and Form Factor (FF). The first index measures the level of convexity of each element, and the second one measures how thin and needle-shaped elements are. The three meshes developed include the **Initial Mesh** (i.e. the mesh coming directly from the intersection of the land use, soil type, subbasins and geology layers), the **Reference Mesh** (a extremely dense mesh to represent the terrain as much as possible, which is created using high values of the geometric indices, i.e. CI = 0.975; FF = 0.50, and a maximum polygon area of 0.2 ha), and the **Recommended Mesh** (i.e. a mesh that compromise the initial and reference meshes, which is obtained using geometric indices that do not greatly increase the number of HRUs, but improve the water pathways representation to a large extent). Indeed, in this study we attempt to identify threshold values for the geometric indices to obtain this realistic yet simple representation of the terrain. After a process of trial and errors we obtained values of CI = 0.75 and FF = 0.2, and a maximum polygon area of 2 ha.

To analyze and compare the drainage network extracted from each mesh, the width-function, *W(x)*, and area-function, *A(x)* were used (Shreve, 1969; Rodriguez-Iturbe y Rinaldo, 1997). These properties describe the flowpath organization and drainage contribution at different locations from the outlet *x*, which allows reducing a 2D drainage structure to a 1D mathematical function. These functions and the corresponding Cross Spectral Density (CPSD) functions were used to compare the results obtained using the various meshes.

3 RESULTS AND DISCUSSION

Figure 1 presents the results of the application of Geo-PUMMA to the two basins: the Mercier (left) and El Guido (rigth) in terms of model mesh and drainage extraction. The figure presents the three drainage networks corresponding to the three kinds of meshes described above. For both catchments, major changes are observed in the upper part of the catchments, where natural (resp. forest) land use were present and were initially digitized with larger polygons. These are the areas which were further segmented to get more representative water pathways. The mesh improvement in those areas at the largest distance from the outlet is visible in Figure 2 (top) with a large increase of *NS* from the initial to the recommended mesh (except for the area function of El Guindo). The increase in *NS* is larger for the width function than for the area function. The CPSD (Figure 2, bottom) applied to the width-function allows comparing the spatial similarity between the reference width-function and area-function versus the recommended and initial drainage network. Figure 2 shows improvement from 80 m to 60 m for CPSD of *W(x)* of the Mercier catchment and from 120 m to 60 m for CPSD of *W(x)* of El Guindo catchment. In the case of the area-functions, Figure 2 shows improvement from 150 m to 55 m for CPSD of *A(x)* of the Mercier and from 150 m to 100 m for CPSD *A(x)* of El Guindo. For both functions, *NS* is greatly improved when moving from the initial to the recommended mesh, expect for the area function of El Guindo, which requires further analysis. Generally, we find that the performance of the recommended mesh is satisfactory in terms of water pathways representation.

To conclude, the results show that Geo-PUMMA allowed getting the drainage network considering the main physiographic units of the natural and urban. The output layers and their corresponding databases provide useful information for any distributed hydrological model that requires a detailed representation of the conditions of land use and the hydrological connectivity. Our results show that it is not necessary to use the reference mesh as input for modeling, and that the recommended mesh can be used safely without increasing heavily the final number of HRUs to represent the topography and to obtain a realistic drainage network. The current version of Geo-PUMMA was carried out in GRASS 6.4 in a virtual machine with Ubuntu 14 (64b). The use of Geo-PUMMA and its methodology is recommended to users with spatial and hydrological modelling knowledge, which allow taking decisions when making simplifications on the HRU.

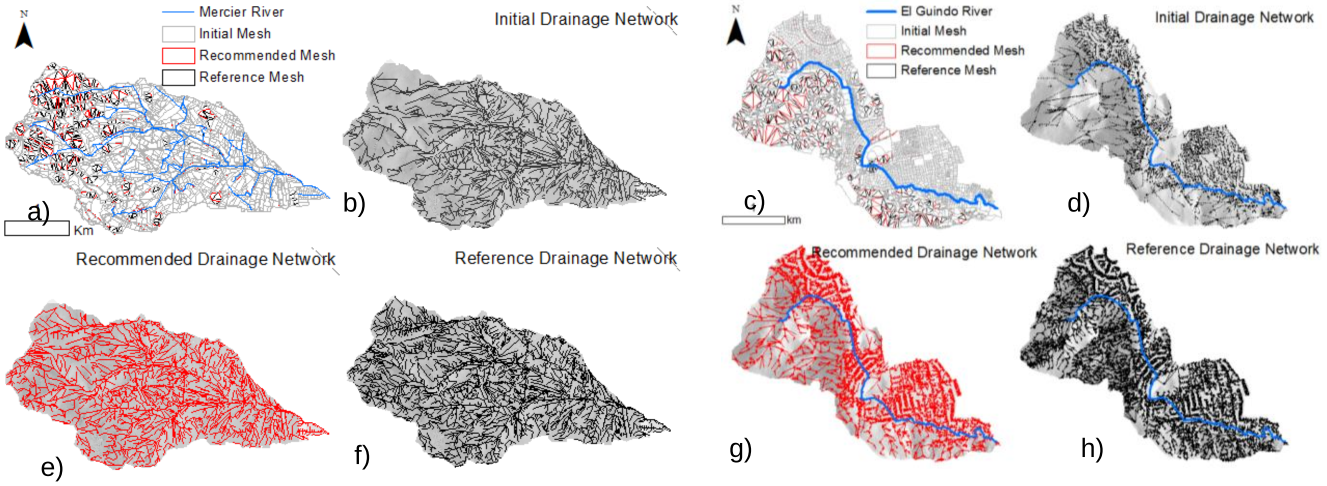

Figure 1, Initial, Reference and Recommended Mesh for Mercier (a) and El Guindo (c). Drainage Network from Initial (b), Recommended (e) and Reference (f) Mesh for Mercier and Drainage Network from Initial (d), Recommended (g) and Reference (h) Mesh for El Guindo.

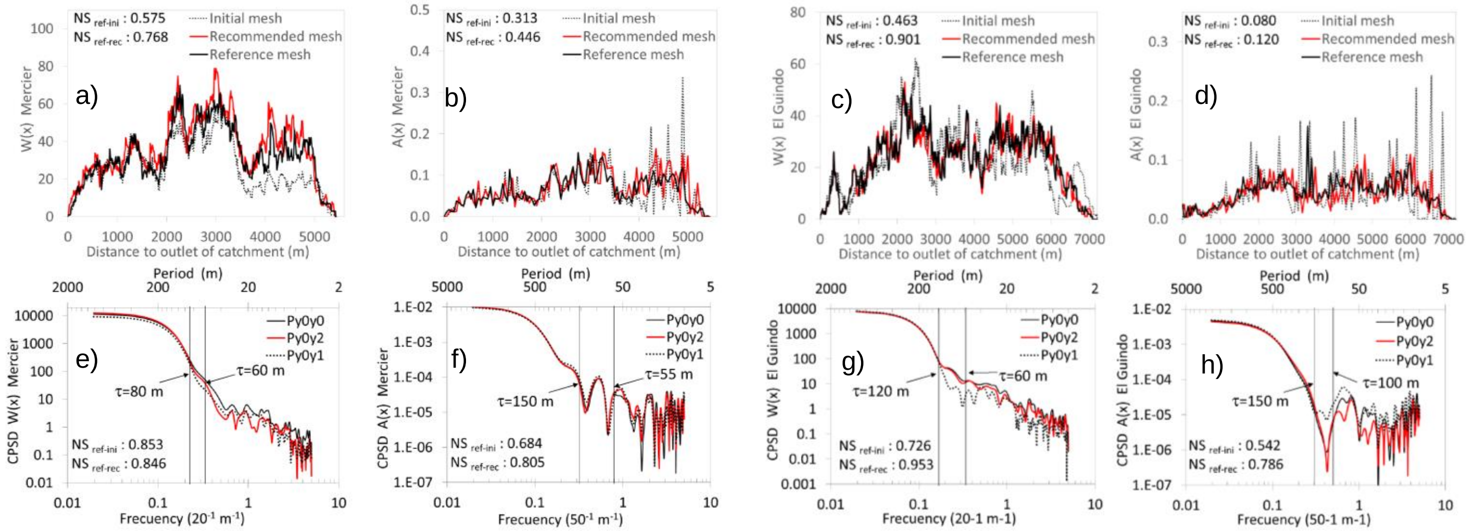

Figure 2: (a) Width-Function, W(x), and (b) Area-Function, A(x), of three meshes of Mercier. (ca) Width-Function, W(x), and (d) Area-Function, A(x), of three meshes of El Guindo. In both drainage networks came from initial mesh (segmented gray line), recommended mesh (red) and reference (black). (e) CPSD of Width-Function and (f) CPSD of Area-Function of Mercier. (g) CPSD of Width-Function and (h) CPSD of Area-Function of El Guindo. In both cases, comparing reference vs reference (Py0y0, black line), reference vs initial (Py0y1, gray segmented line) and reference vs recommended (Py0y2, red line). At six figures, NS coefficients are indicated.

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LIST OF REFERENCES

Braud, I., Fletcher, T.D., Andrieu, H., 2013. Preface: Hydrology of peri-urban catchments: processes and modelling, Journal of Hydrology, 485, 1-4.

Flügel, W.A., 1995. Delineating hydrological response units by geographical information system analyses for regional hydrological modeling using PRMS/MMS in the drainage basin of the River Bröl, Germany. Hydrological Processes 9, 423-436.

Jankowfsky, S., Branger, F., Braud, I., Rodriguez, F., Debionne, S., Viallet, P., 2014. Assessing anthropogenic influence on the hydrology of small peri-urban catchments: development of the object-oriented PUMMA model by integrating urban and rural hydrological models. Journal of Hydrology, 517, 1056 - 1071.

Rodriguez, F., Andrieu, H., and Morena, F. (2008). A distributed hydrological model for urbanized areas - model development and application to case studies. Journal of Hydrology, 351:268–287.

Rodriguez-Iturbe I., Rinaldo A., (1997). Fractal River Basins: Chance and Self-organization. Cambridge University Press, New York, pp. 1-6.

Shreve R.L., (1966). Statistical Law of Stream Numbers, J. Geology, Vol (74), pp. 17-37.