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Terrain representation impact on periurban catchment morphological properties

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SUMMARY

Modelling the hydrological behaviour of suburban catchments requires an estimation of environmental features, including land use and hydrographic networks. Suburban areas display a highly heterogeneous composition and encompass many anthropogenic elements that affect water flow paths, such as ditches, sewers, culverts and embankments. The geographical data available, either raster or vector data, may be of various origins and resolutions. Urban databases often offer very detailed data for sewer networks and 3D streets, yet the data covering rural zones may be coarser. This study is intended to highlight the sensitivity of geographical data as well as the data discretisation method used on the essential features of a periurban catchment, i.e. the catchment border and the drainage network. Three methods are implemented for this purpose. The first is the DEM (for digital elevation model) treatment method, which has traditionally been applied in the field of catchment hydrology. The second is based on urban database analysis and focuses on vector data, i.e. polygons and segments. The third method is a TIN (or triangular irregular network), which provides a consistent description of flow directions from an accurate representation of slope. It is assumed herein that the width function is representative of the catchment's hydrological response. The periurban Chézine catchment, located within the Nantes metropolitan area in western France, serves as the case study. The determination of both the main morphological features and the hydrological response of a suburban catchment varies significantly according to the discretization method employed, especially on upstream rural areas. Vector- and TIN-based methods allow representing the higher drainage density of urban areas, and consequently reveal the impact of these areas on the width function, since the DEM method fails. TINs seem to be more appropriate to take streets into account, because it allows a finer representation of topographical discontinuities. These results may help future developments of distributed hydrological models on periurban areas.

1. Introduction

Correlating the hydrological response of a catchment with its geomorphological features has proved to be beneficial and successful in the field of hydrology. Many authors have focused on the role of morphological features on hydrology, including the shape, size, and land use distribution of the catchment, as well as drainage network geometry. The main body of literature supporting this premise has dealt with the geomorphological identification of the Unit Hydrograph (UH) or the use of isochrones (Gupta et al., 1980; Pilgrim, 1977; Rodriguez-Iturbe and Valdes, 1979). Behind these initial works, many studies have been initiated: Maidment et al. (1996) have used the geomorphic features of a rural catchment in order to estimate the UH by generating a spatially-distributed velocity field. More recently, Gironás et al. (2009) have revisited the initial GIUH (Geomorphological Instantaneous Unit Hydrograph) concept and defined the IUH as the probability density function of the travel time in an urban area, based on the flow path extraction and a spatially-distributed travel time method, following similar efforts done by Melesse and Graham (2004). The availability of morphological features, such as contributive area and width function (Rodriguez-Iturbe and Rinaldo, 1997) has been simplified through the use of geographic databases and GIS processing tools, along with a generalisation of digital terrain models (DTMs). The corresponding data can assume different forms: digital line graphs, triangular irregular networks (TINs) and raster digital elevation models (DEMs). DEMs are frequently employed to derive basic topographical characteristics or features (river network extraction, catchment delineation, etc.) (Band, 1993; Da Ros and Borga, 1997; Lee and Yen, 1997) thanks to the incorporation of numerous algorithms (Desmet and Govers, 1996) into commercial or public license GIS. DEMs introduced with regular grid model can be accomodated quite easily. However, with such a regular representation, elevation may be undersampled in more rugged areas and

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oversampled in smoother areas. Since TINs use variable size elements, they do not encounter this problem. The benefits of TINs in the study of runoff water pathways have already been discussed by several authors (Bocher, 2005; Tucker et al., 2001; Vivoni et al., 2004). The use of variable size elements allows for both a consistent description of multiple flow directions due to an accurate slope representation and an appropriate description of anthropogenic obstacles in the surface water flow. TINs better capture abrupt changes in terrain (Djokic and Maidment, 1991).

Moreover, recent works have underscored the need to improve the extraction of pertinent morphological features, independently of the geographical data resolution used (Bendjoudi and Hubert, 2002; Moussa, 2003). This type of analysis, based on the hydrologic interpretation of morphometric properties of catchments, has significantly raised the level of knowledge of ungauged catchment hydrology and has become routinely applied to natural catchments as well (Ogden et al., 2011; Smith et al., 2002). The applicability of such approaches to urban catchments is a new challenge, due to the availability of geographical data on such areas. Very few urban catchments are actually gauged, yet modelling their behaviour is still necessary for any project involving storm sewer systems. Water management problems such as flooding and pollution control require improving as well as adapting hydrological modelling practices. The morphology of an urban environment evolves quickly over time due to the constant expansion of urban areas. New neighbourhoods increase the density and the extension of both the street and sewer networks, and moreover generate disturbances on the original river and stream network, like erosion or incision (Holman-Dodds et al., 2003; McBride and Booth, 2005). Urban areas seem to be well adapted to a modelling approach that is able of taking the catchment morphological features into account. Cities are continuously revising the documentation on their environment, through the development of urban databases. This documentation, while primarily devoted to pursuing management goals, offers a highly detailed representation of the city's main elements (Laurini, 2001; Sui, 1998). The available data currently encompass the land use of property blocks and topographical maps of streets and the sewer system. Interpretation of the geographical data available from cities allows generating an explicit model of water flow on urban catchments (Rodriguez et al., 2003, 2005).

The extraction of morphological features of urban or periurban catchments is nevertheless yet infrequent; few studies dealing with this topic. Jankowfsky et al. (in press) did a good review of the methods used in "periurban" catchments: the word "periurban" will refer in this study to catchments made of mixture of natural or agricultural areas and urbanised areas, as suggested by Braud et al. (in press). The difficulty with these approaches to periurban catchments is caused by the heterogeneity of the drainage network elements encountered within the given environment: ditches, sewers, rivers and dams, whose sizes and scales may be quite different. Handling these man-made hydraulic features is difficult (Choi and Park, 2011). Stream burning is a classical approach employed in urban areas described with DEM data. This method, developed by Zech et al. (1994) forces the runoff water to follow the sewer network and facilitates the transposition of methods used in natural catchments (Duke et al., 2003 for roads and ditches; Gironás et al., 2010). Yet, TINs may also simplify the representation of the various links in a drainage network, including man-made structures (pipes and channels), and overland flow streams, as described by Djokic and Maidment (1991) for a specific urban application.

The representation of periurban catchments depends on the format chosen to depict the drainage network and hydrological features of a catchment, which alternates between different methods, depending on the specific type of data. This study focuses on the geomorphological features of a periurban catchment, by means of analysing drainage network properties. The first objective of this study is to investigate the sensitivity of a periurban catchment's morphological features to both the geographical data used and the corresponding analysis method. The second objective consists of issuing some distributed hydrological modelling guidelines from this investigation, with concerns to the mode of representation of periurban areas. Are the available data in periurban zones well adapted to the terrain representation of spatially distributed hydrological models? Are classical DEM analysis algorithms available in GIS tools relevant for catchment delineation and drainage network determination in these areas? Three methods have been implemented as part of this work programme; they will be called 'DEM gridded data', 'OBJects', and 'TIN', the capitals indicating the acronym employed further. The case study of the Chezine River, located in the Nantes metropolitan area (France) provides the suitable application.

The second section of this study presents (i) the case study of the Chezine River catchment (30 km^2), (ii) the various segmentation methods implemented during this study and (iii) the determination method of the width function, which captures the essential features of a catchment's response (Moussa, 2008). The morphological features deduced from these methods are discussed in the third section, along with an analysis of the sensitivity of these features to the chosen methodology. The case study width functions are analysed in the fourth section, which also proposes a number of hydrological interpretations. The article closes by drawing conclusions and perspectives from the present set of results.

2. Material and methods

2.1. Study case

The Chezine River (Fig. 1) is located in the north-western suburb of Nantes (western France); it follows a south-easterly course, flowing over a distance of 15 km from source to confluence with the Loire River. The area is relatively flat, with a maximal altitude difference of 80 m. The catchment is highly urbanised downstream, where it includes part of the city of Nantes. A residential area (town of Sautron) is located in the middle part of the basin. According to the land-use map drawn in 2006 and from a Corine Land Cover database estimation (European Environment Agency, 2007), 40% of the basin is located within urbanised areas and 60% consists of rural or natural areas. The estimation of impervious areas provided by the urban cadastral map (Rodriguez et al., 2003) leads to a built ratio of 7% and a road ratio of 14% on the entire catchment area. The road ratio is probably excessive due to road width overestimation in the considered databank, although this area is indeed crossed by three highways that would contribute to such a high ratio.

Two main kinds of geographical data sources were available in this study (Table 1). The Nantes Metropolitan authorities (Nantes Metropole) supplied a range of data from their urban databanks (UDBs), i.e. cadastral parcels, roads, buildings, sewer networks and river networks. The French National Geographic Institute (IGN) provided topographical data, plus road and river lines. These two different data sources led to some discrepancies: data from both sources did not always match, which in some cases complicated data integration.

A field survey yielded an inventory of ditches in the Sautron Basin in the rural upper part of the study basin (Fig. 2) in order to document water pathways and the anthropogenic elements potentially affecting these pathways (Guilbaud, 2007). The basin was cut in 21 sections with an area ranging between 0.15 and 0.65 km^2. A 2 people team was affected to each section all over which they walked. Each ditch, pipe or river was drawn on a detailed map