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Geo-MHYDAS: A landscape discretization tool for distributed hydrological modeling of cultivated areas ☆

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ABSTRACT

The representation of landscape variabilities by means of an adequate landscape discretization is of major importance in distributed hydrological modeling. In this paper, we present Geo-MHYDAS, a landscape discretization tool that allows explicit representation of landscape features, particularly man-made ones, that are known to have a great impact on water and mass flows across the landscape. The landscape discretizations that are produced include user-controlled delineated irregular, linear or areal units connected to each other along a tree-like structure.

Geo-MHYDAS includes three steps: (i) processing (i.e., the importation or the creation), followed by the modifications of the geographical objects, the limits of which are considered in the modeling as hydrological discontinuities, (ii) creation of the areal and linear units for hydrological modeling by a "selective cleaning" procedure after overlay that preserves, as much as possible, the object limits defined in the previous step, while having sizes and shapes that remain compatible with the application of the water flow functions of the hydrological model and (iii) building an oriented topology between irregularly shaped areal and linear units that allows the routing of the simulated water flows across the landscape. Geo-MHYDAS was developed using the open source free Geographic Information Systems (GIS) software GRASS.

The use of Geo-MHYDAS was illustrated by running the hydrological model MHYDAS for different scenarios of man-made features, their presence and spatial organization within a small vineyard catchment located in the south of France (the Roujan catchment). Comparisons with hydrological modeling performed with usual landscape discretizations showed significant differences in the simulated hydrograms. This comparison illustrates well the strong impact of landscape discretizations on hydrological modeling, specifically on the man-made landscape features represented in Geo-MHYDAS.

1. Introduction

Distributed hydrological models provide effective simulation tools for exploring basin hydrological processes and predicting the effects of changes on catchment response. Each model has its own method to represent landscape variabilities, which strongly influences its performance and often limits its use. Therefore, it is important to provide adequate spatial discretizations of landscapes that could be coupled with physically based representations of hydrological processes. This is all the more true in cultivated landscapes, where the number of man-made features (e.g., ditches, field boundaries, benches or hedges), recognized as strongly influencing water flows, must be taken into account (Louchart et al., 2001; Carluer and De Marsily, 2005).

Grid-based segmentation of the landscape is commonly used by hydrological distributed model because grid-based Digital Elevation Models (DEM) are the most commonly available, the methods of analysis are computationally efficient and simple and the structure is compatible with remote sensing techniques and GIS. Furthermore, the coupling with the equations that represents hydrological processes is straightforward. Some examples of models based on this structure include the Areal Nonpoint Source Watershed Environment Response Simulation model (ANSWERS) (Beasley et al., 1980), the Système Hydrologique Européen model (SHE) (Abbott et al., 1986a, b), the TopModel (Beven et al., 1987), the Agricultural Non-Point Source pollution model (AGNPS) (Young et al., 1989) or the Limburg Soil Erosion Model (LISEM) (De Roo and Offermans, 1995). However, the elementary pixels considered by grid-based landscape representations do not correspond to real landscape features as recognized by landscape surveyors, which results in unsatisfactory solutions for representing irregularly sized landscape features and gradients. This is all the more true in cultivated landscapes where many human-made features are to be considered as hydrological

☆ Code available from authors' web site www.umr.lisah.fr/openfluid and on server at http://www.iamg.org/CGEditor/index.htm.

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discontinuities. To take into account these small-sized features (often less than 1 m width), one would need to define very fine grids, resulting in a very large number of parameter values, which raises the problem of over-parameterization and calculation time as stated by Beven (1989).

In order to reduce the number of cells and represent more realistically some real landscape features, cell-based, contour-based or TIN-based segmentations of landscapes can be used. Cell-based segmentations consist of a finite number of cell units, such as sub-catchments as in KINEROS (Woolhiser et al., 1990), WEPP (Laflen et al., 1997), CELMOD (Karnieli et al., 1994) and HYDROTEL (Fortin et al., 1995), interconnected elements bounded with a pair of flow trajectories and upper and lower contours in TOPOG (Vertessy et al., 1993; Zhu et al., 1999), or rectangular cases in the Quasi-Physically Based Rainfall–Runoff Model (QPBRRM) (Loague, 1992). TINs have also been used for dynamic hydrologic modeling (Maidment et al., 1989; Palacios-Velez and Cuevas-Renaud, 1991; Vieux, 1991) and are well adapted to finite-element resolution of runoff equations. Other models, such as THALES (Grayson et al., 1992), use a contour-based method of terrain analysis (Moore et al., 1988; Moore and Grayson, 1991) that divides the catchment into elements based on the way water flows over a surface. However, these landscape discretizations take into account only landscape features related to relief, i.e., that can be derived from a Digital Elevation Model. An apparent exception is SWAT (Arnold et al., 1994), in which sub-catchments are further subdivided into Hydrologic Response Units (HRU) that allow us to consider multiple combinations of soil and land use. However, the HRUs are not delineated and do not allow us to explicitly take into account their spatial distributions within the sub-catchments. Finally, none of these landscape segmentations explicitly take into account the man-made landscape features that cause hydrological discontinuities, since these features do not systematically follow the steepest slopes or contour lines and therefore, the delineated cell boundaries.

A more sophisticated landscape representation is considered in MHYDAS, a physically based catchment model specifically designed for agricultural catchments (Moussa et al., 2002) which has been applied in various contexts. MHYDAS considers a discretization of catchments into irregularly sized and shaped areal and linear topographically connected hydrological units that account for a great number of natural and man-made hydrological discontinuities that can be encountered in farmed catchments. This paper presents Geo-MHYDAS, the GIS tool that helps users of MHYDAS – and possible similar models – to perform this complex landscape discretization prior to running the model. This landscape discretization has the following characteristics:

1. Takes into account both natural and man-made landscape features of various sizes, e.g., sub-catchments, soil units and land use units, but also ditch networks and field boundaries.
2. Provides both linear and polygonal hydrological units by a specific selective cleaning procedure that performs a user-controlled filtering of the small and/or badly shaped units.
3. Builds a topology that connects all the areal and linear hydrological units along an oriented tree to enable the routing of the simulated flows.
4. Enables multiple discretizations for sensitivity analysis of geographical input data through a full automation of the discretization process.

Geo-MHYDAS can be compared to other GIS tools that were developed by hydrological model editors to help users in running the models, for example, geoWEPP (Renschler, 2003), AVSWAT (Di Luzio et al., 2004) or AGWA (Miller et al., 2007). These tools include a landscape discretization based on DEM-derived sub-catchments only. The peculiarity of Geo-MHYDAS is the implementation of a more complex discretization by handling a great variety of landscape features that are not all ordered along the slope. In addition, the parameterization step, i.e., the estimation of hydrological model parameters for each hydrological unit from the current landscape database, remains local-specific in this presented version of Geo-MHYDAS.

In the following section, the spatial segmentation steps of Geo-MHYDAS are presented, namely creating/importing geographical objects, building hydrological units and creating oriented topologies. The use of Geo-MHYDAS is then illustrated by a MHYDAS modeling of discharge at the outlet of an intensively cultivated vineyard catchment located in the south of France (the Roujan catchment). This modeling is evaluated against alternatives using classical cell-based landscape discretizations with regard to its ability to represent the hydrological consequences of possible changes in the spatial distribution of man-made landscape features within the catchment.

2. The procedure of spatial discretization

2.1. General principles

The general principles of the proposed landscape discretization are illustrated in Fig. 1. The first step of the procedure is the processing of geographical objects whose limits are considered in the modeling as hydrological discontinuities. These limits can be either natural, like sub-catchment (crests), soil or geology limits, or man-made, like field boundaries or ditches. There is no restriction in the number of limit types that can be considered at this step. The second step (Fig. 1) is the creation of the hydrological units that will be considered in the MHYDAS modeling. These hydrological units must take into account the object limits defined in the previous step while having sizes and shapes that remain compatible with the application of the water flow functions of the hydrological model. This compromise is obtained by a specific procedure of ‘‘selective cleaning after overlay’’ that removes the overlay-produced units considered too small (for linear or areal units) or badly shaped (for areal units only) according to user-fixed quantitative thresholds. These units are removed according to a pre-defined order of geographical object importance that orients the choice of the limits that must be removed for merging the deleted units with their neighbors. This selective overlay procedure allows the modeler to maintain control of the discretization process and to test several possible landscape discretizations. The third step of the procedure is the building of an oriented topology that allows the routing of the simulated water flows across the landscape. An oriented tree is built from areal to linear units. This tree is defined by computing a flow direction for each couple of hydrological units: linear to linear units, areal to areal units, then areal to linear units.

Geo-MHYDAS was developed using GRASS (Geographic Resources Analysis Support System) version 6.3, open source, free GIS (Geographical Information System) software (GRASS Development Team, 2008). GRASS was originally developed by the U.S. Army Construction Engineering Research Laboratories and is now widely used in scientific research. GRASS provides for the management of topological vector data and support for vector network analysis in an open source environment with the ability to create geomatic algorithms.

The Geo-MHYDAS procedure is divided into several independent GRASS scripts that were developed under Shell and Perl languages (Table 1). These scripts are launched under an interactive graphical mode that allows the user to select the optimal sequence of scripts and visualize the intermediate results. A batch