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Improvement of surface flow network prediction for the modeling of erosion processes in agricultural landscapes

Alain Couturier [a,*], Joël Daroussin [a], Frédéric Darboux [a], Véronique Souchère [b,c], Yves Le Bissonnais [d], Olivier Cerdan [e], Dominique King [a]

[a] INRA, UR0272 Science du sol, Centre de recherche d'Orléans, CS 40001, 45075 Orléans Cedex 2, France
[b] INRA, UMR1048 SADAPT, B.P. 1, 78850 Thiverval Grignon, France
[c] AgroParisTech, UMR 1048 SADAPT, F-75005 Paris, France
[d] INRA, LISAH (Laboratoire d'étude des Interactions Sol. Agrosystème, Hydrosystème), Unité Mixte de Recherche INRA, IRD, SupAgro Montpellier, Campus AGRO, Bat. 24, 2 place Viala, 34060 MONTPELLIER Cedex 1, France
[e] BRGM, ARN, 3 av. Claude Guillemin, BP 6009, 45060 Orléans, France

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ABSTRACT

The modeling of soil erosion by water supposes an accurate and thorough understanding of the hydrology. Thus, it is critical to have a good delineation of the surface flow path. The flow network data are critical for important uses such as flood forecasting and watershed management. Geographic Information System (GIS) functions are able to compute a flow network directly from the digital elevation models. Because the flow directions are only based on the topography, the other factors controlling the flow directions are overlooked. In the agricultural areas, work such as tillage can have a large impact on the flow direction. We propose a 5-step procedure to account for such man-made features. The use of this procedure clearly improves the quality of the computed flow network. This procedure has been successfully implemented in a GIS and improves the prediction of surface flow and therefore improves water erosion modeling at the watershed scale.

1. Introduction

The modeling of overland flow and soil erosion requires a good knowledge of surface water flow paths. Previous works have demonstrated that one of the main factors that explains the initiation and location of erosive phenomena is the area contributing runoff (Thorne and Zevenbergen, 1990; Auzet et al., 1995). Govers et al. (2000) and Le Bissonnais et al. (2005) found that the occurrence of erosion phenomena is strongly related to the runoff-generation process. It has also been shown that the flow paths and flow concentration processes inside a watershed are important (Takken et al., 2005). In fact, erosion caused by overland flow is a threshold phenomenon for which triggering occurs at specific times and locations (Boiffin et al., 1988; Papy and Boiffin, 1989; Ludwig et al., 1995; Le Bissonnais and Gascuel-Odoux, 1998). So, even if runoff models predict correctly the water flux at the outlet of a catchment using a standard flow direction algorithm, they may be not adapted for modeling erosion and simulating the effect of anti-erosion management schemes (Souchère et al., 2005; Furlan et al., 2012).

For more than ten years, several studies have been performed to determine and model the location and the size of areas contributing to runoff within catchments, including their changes under the combined effect of farming operations and meteorological conditions (Ludwig et al., 1995; Desmet and Govers, 1997; Souchère et al., 1998; Govers et al., 2000; Takken et al., 2001). These studies demonstrated that furrows created by tillage operations could affect the flow directions as much as the topographic slope. However, most current hydrologic models, such as the WEPP (Flanagan and Nearing, 1995), AGNPS (Bingner and Theurer, 2007) and EUROSEM (Morgan et al., 1998) consider the topographic slope to be the only factor controlling the water flow path. Thus, even if these models include sophisticated water routing algorithms and up-to-date finite difference schemes to compute water fluxes, they cannot properly model the actual flow paths in agricultural watersheds.

Orlandini et al. (2003, 2011) developed methods to improve the classical D8 flow network calculation from Digital Elevation Model (DEM) (Tarboton, 1997). The path-based D8-LAD and D8-LTD reduced the flow drift without the inconvenience of introducing dispersive flow. However, they were tested in mountainous areas where steep slopes constrain the flow direction whatever the surface roughness and anthropogenic landscape features. Bailly et al. (2008) designed an approach for automated ditch network detection from LiDAR data in vineyard landscapes. This methodology appears transposable to other

* Corresponding author.
E-mail address: Alain.couturier@orleans.inra.fr (A. Couturier).

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linear anthropogenic features under the condition that they are located on field boundaries and that they correspond to a sufficient elevation discontinuity so that they can be identified in LiDAR profiles. In addition, since it is based on the availability of LiDAR data, there is still a need for improving flow network determination in the case of low slope agricultural landscapes, taking into account more easily accessible tillage direction and roughness information. A predictive erosion model at the watershed scale was developed with the aim of balancing the amount of data required, the cost of their acquisition, and the description of fundamental erosion processes. This model, named STREAM, is based on the understanding and parameterization of prevailing factors at local scales from experimental results and on the specific features at the watershed scale (Cerdan et al., 2002a,b; Le Bissonnais et al., 2005). In this paper, we present the 'flow network' module implemented in the STREAM model. This module allows the model to account for the effect of the tillage operations on the directions of the surface water flow. The method in use is based on the modification of a regular model of the surface water flow network (i.e. a flow network model based on the topography only). From this topographic flow network, a flow network accounting for the tillage directions and preferential flow paths is built. The processing is raster-based (i.e. cell-based) and makes use of Geographic Information System (GIS) capabilities to analyze the soil surface water movement according to the terrain morphology, tillage direction, and preferential flow paths. The first part of this paper presents the 'flow network' module and the methodological developments required to introduce preferential flow paths in a regular DEM. In the second part, we apply the model to a test watershed, and we analyze and discuss the relevance of the results based on the methodological and hydrological standpoints. We then emphasize the main achievements and perspectives for future improvements of the 'flow network' module.

2. Material and methods

The 'flow network' module creates a network of flow directions for every point of the studied area, usually a watershed. The watershed is the reference unit for water and erosion management. Many algorithms have been published to compute a flow network on a grid DEM (e.g., O'Callaghan and Mark, 1984; Tarboton, 1997; Orlandini et al., 2003). The most sophisticated can define several flow directions for each cell, such as the "multiple flow direction" of Quinn et al. (1991). For our purpose of demonstrating the importance of taking into account the agricultural features for constructing an accurate flow network, we decided to use a simple "single flow direction" algorithm close to the well-known D8 algorithm (O'Callaghan and Mark, 1984). In our case, the network of flow directions is a set of cell-based data for which the module defines a unique flow direction for each cell. Because the published algorithms are topography-based only, we believe that large discrepancies between the computed flow networks and the real network would be found wherever agricultural features have an effect on the flow directions.

In most existing networks of flow directions, the flow directions are defined based on the DEM only. Thereafter, a flow direction network computed from the DEM only is named 'topographic flow network.' The novelty of the 'flow network' module is its ability to account for the effects of human-induced features on the water flow directions in the agricultural watersheds. The improved flow network better mimics the actual flow network and thus enhances the prediction of the water flow locations and fluxes. Because of this improvement, the watershed manager will make more accurate decisions for the implementation of soil and conservation practices. Accounting for agricultural features implies some specific processing, as detailed below.

2.1. Data

Three types of geographic and semantic data are required by the 'flow network' module.

2.1.1. Roughness

The first mandatory layer represents the agricultural fields as polygons. This vector-type layer must cover the entire area to be modeled. Each polygon is associated with attributes describing the soil surface characteristics, such as the soil surface roughness. Following Souchère et al. (1998), the roughness is defined as the height difference (in cm) between the high points and low points of the soil surface microtopography. The roughness is defined at the scale of a square meter *along* the tillage direction (first roughness index) and *across* the tillage direction (second roughness index). These indices were specifically designed for the overland flow studies. They can be noted by visual inspection during field mapping. Each of the two roughness indices is tagged using a six-level scale (Table 1). Thus, two roughness attributes are recorded for each polygon. The polygons must also have an attribute describing the tillage direction in degrees (from 0 to 179°).

2.1.2. Topography

The second mandatory layer is raster-type and represents the topography of the studied area. It is a DEM. The common area between the DEM and the agricultural field polygons defines the largest area that can be modeled by the 'flow network' module. To account for the edge effects caused by some numerical treatments, a 5-cell buffer is added around the area defined by the agricultural field polygons.

2.1.3. Preferential flow paths

The third layer is optional. It accounts for the preferential flow paths caused by objects such as the headlands (i.e., the unplowed land at both ends of a field after the primary plowing: headlands are usually plowed subsequently, across the primary plowing direction), open furrows (i.e., a long shallow trench in the ground left in the middle of the field or between two fields after plowing), and roads. This layer is vector-type with a line topology. Each line has attributes describing its hydrologic behavior. Depending on these attributes, changes in the flow directions of the underlying cells will be made, thereby modifying the flow network.

2.2. Computation of the flow network

The successive stages of the algorithm are illustrated in Fig. 1.

2.2.1. Stage 1 — building the topographic flow model of flow directions

In a Geographical Information System (GIS) software using square cell raster grids, one of eight possible flow directions is assigned to each grid cell. Each of these eight possible directions leads to one of the eight neighboring cells. The flow direction for the cell under inspection is computed from a raster DEM representing the topography by selecting the neighboring cell with the steepest descent. This generates a strictly convergent flow network (i.e., the flow of one cell is never routed to more than one other cell). When applied to a DEM free of sinks, starting from any cell and following the flow direction from cell to cell always leads to the edges of the studied area (the edges can be identified by cells with a special value called 'NODATA').

The first stage consists of computing the topographic flow network. It is called the topographic flow network because it is built by accounting for the topography only. This network is then used as a reference to

Table 1
Roughness heights and corresponding levels.

Roughness height	Level
From 0 to 1 cm	0
From 1 to 2 cm	1
From 2 to 5 cm	2
From 5 to 10 cm	3
From 10 to 15 cm	4
More than 15 cm	5