Computers & Geosciences 60 (2013) 81–87

Contents lists available at SciVerse ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

An anisotropic flow-routing algorithm for digital elevation models

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ARTICLE INFO

Article history:
Received 12 April 2013
Received in revised form
10 July 2013
Accepted 15 July 2013
Available online 23 July 2013

Keywords:
Flow routing
Digital elevation model
Tillage direction
Erosion
USLE

ABSTRACT

Tillage operations produce systematic small-scale surface roughness which is generally not visible in digital elevation models, but which nonetheless may significantly modify the runoff patterns in cultivated areas. Commonly used flow-routing algorithms which direct the flow towards the steepest slope are not able to describe the effect of tillage-induced roughness. We introduce a flow-routing algorithm which accounts for anisotropic roughness resulting from tillage and then use it as a part of a USLE-type erosion model in order to study the effect of tillage direction on soil loss. The model is first calibrated against the results from a long-term field experiment. Results from a test case are then used to demonstrate the utilization of the model with a complicated land surface topography.

1. Introduction

Landscape topography affects many hydrological and geomorphological processes, including overland flow of water and soil erosion (Hengl and Reuter, 2009). When computational techniques are used in the analysis of these processes, topography is represented by digital elevation models (DEMs) which typically give a square-grid representation of the land surface such that each grid cell contains information about the elevation of the area represented by the cell. Improved accuracy of DEMs and increased available computational power has enabled extensive use of DEMs in many applications. Especially developments in laser scanning techniques have provided effective and reliable methods for DEM generation (Petrie and Toth, 2009).

Flow routing is an important part of hydrological algorithms as the terrain shape greatly affects the movement of water and suspended and dissolved materials carried by it. Flow-routing algorithms can be roughly categorized into two groups: from a given grid cell, flow is either routed to a single neighbouring cell or divided to multiple directions. Flow routing algorithms were recently reviewed by Wilson et al. (2008).

Multiple flow direction flow-routing algorithms divide the flow to several neighbouring grid cells on the basis of local terrain conditions. Such an approach inevitably leads to flow dispersion, i.e., flow spreads from a given grid cell to several downslope cells. On larger spatial scales dispersion occurs on convex landforms and such a dispersion is captured by DEMs well if multiple flow directions are allowed. On sub-grid scale dispersion can be understood either as a numerical artefact arising from the discrete DEM grid or as a physical effect due to sub-grid-scale features, such as microtopography or vegetation, that are not resolved by DEM. According to Tarboton (1997), flow-routing algorithms should avoid or minimize dispersion, and physical dispersion could be modelled separately, if necessary. On the other hand, single flow direction algorithms are not able to describe bifurcant flow patterns.

One important effect of microtopography is observed when flow is directed along some systematic features such as plough furrows or other tillage-induced agricultural patterns. Typically flow-routing algorithms aim to direct the flow towards the steepest slope. However, field observations indicate, especially on gentle slopes, that tillage-induced surface roughness may greatly affect the flow directions and thus the flow patterns as water follows tillage direction rather than slope direction (Ludwig et al., 1995; Souchere et al., 1998; Takken et al., 2001a,b,c; Svoray and Markovitch, 2009).

Specific applications where flow-routing algorithms are utilized are DEM-based erosion models such as the USLE family of models (Wischmeier and Smith, 1978; Renard et al., 1991; Kinnell, 2010). In USLE, the average annual soil loss per unit area is obtained from an equation in which six component factors are multiplied together. Surface topography affects two of them, i.e. the L and S factors, which account for the slope length and steepness, respectively. When utilizing DEMs in USLE modelling, L factor is commonly replaced by the upslope area which is the area of the cells contributing flow to a given grid cell. Thus, estimation of L factor in USLE relies heavily on the used flow-routing algorithm.

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0098-3004/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cageo.2013.07.012

In this paper we present an anisotropic flow-routing algorithm operating on square grids. The proposed algorithm is based on a specific multiple flow direction flow-routing method generalized such that, in addition to the slope, the discrete flow directions are anisotropically weighted to account for the tillage-induced flow patterns. We show that the method is able to produce compatible results to relevant experimental observations reported earlier in literature. The proposed algorithm is used as a part of USLE-type erosion model and calibrated by using data from a long-term field experiment, in which the effect of plough direction on soil erosion was studied. Finally the use of the model is demonstrated on a field plot with complicated surface topography.

2. Methods

2.1. Digital elevation model

The numerical representation of the land surfaces considered in this work was retrieved from National Land Survey of Finland. The square-grid DEMs were based on airborne LIDAR (Light Detection and Ranging) scanning. The horizontal resolution of the DEMs describing the two areas considered, Aurajoki and Mustiala (see below), were 1 m and 2 m, respectively.

2.2. Aurajoki field

For model calibration, we use data from the Aurajoki experimental field in South–West Finland (60°48′N, 22°37′E). The field consisted of 12 plots and experiments with several cultivation methods which were carried out in between 1989 and 2002 (Puustinen et al., 2005).

All plots have almost uniform slope of 8–9%. We utilize data from the mouldboard ploughing experiment carried out as a part of the study: the effect of plough direction on soil erosion was studied by performing ploughing in the slope direction on one of the plots (plot 6) and ploughing along the contour lines on another one (plot 1). Since the majority of the soil loss under Finnish climatic conditions occur outside the growing season when the surfaces of fields used for annual crops are left bare after the autumn ploughing, this experiment provides suitable calibration data for our purposes. A detailed description of the experiments can be found in Puustinen et al. (2005).

2.3. USLE-type erosion models

The Universal Soil Loss Equation (USLE) and its variants are widely used empirical models for erosional soil loss estimation (Wischmeier and Smith, 1978; Renard et al., 1991; Kinnell, 2010). The estimate is given as follows:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P, \tag{1}$$

where A is the average annual soil loss per unit area, R the rainfall-runoff erosivity factor, K the soil erodibility factor, L the slope length factor, S the slope steepness factor, C the soil cover factor, and P the support practice factor. The L and S factors are commonly combined to LS factor which contains the effect of surface topography on the soil loss. Since the focus of this paper is on introducing the effect of tillage-induced roughness into LS factor, hereinafter we only consider changes in the LS factor and neglect the other ones. This exclusion is reasonable since we use the model on field scale, on which we can assume other factors to remain as constants.

In a given grid cell, we calculate the dimensionless LS factor as

$$LS = (U/22.13\ \text{m})^{0.4} \times (\sin\theta/0.0896)^{1.3}, \tag{2}$$

where U is the upslope area per unit width and θ the slope angle (Moore and Burch, 1986). Both of these quantities are directly derived from DEM. The values of LS factor are relative and describe erosion from a particular grid cell relative to a 22.13 m long unit plot with a slope of 9%. We calculate the slope angle θ (and later surface gradients) by using standard 3×3 Sobel gradient masks.

2.4. Flow routing

Various algorithms have been proposed for flow direction analysis. Usually these methods are based on the assumption that flow direction can be approximated by the steepest slope direction of the terrain. Most flow-routing algorithms operate on square-grid-based DEMs and they direct flow from a grid cell to one or several of the eight nearest neighbouring grid cells. To make notations concise, we define a set of unit vectors pointing to the eight neighbouring cells: $\hat{\mathbf{e}}_i = (\cos((i-1)\pi/4), \sin((i-1)\pi/4))$, $i = 1\ldots8$. Below we briefly describe only those flow-routing algorithms that are relevant for the present work, while a comprehensive review can be found elsewhere (Wilson et al., 2008).

The simplest approach for flow routing is the D8 single-flow-direction algorithm (O'Callaghan and Mark, 1984). In D8 approach, flow is directed to a single neighbouring grid cell which is selected on the basis of steepest downward slope. Second widely used method is the multiple flow direction algorithm (MD8) which allocates flow from a given grid cell to all adjacent downslope cells (Quinn et al., 1991). The relative amount of the flow to each downslope direction is in proportion to the slope towards that direction. The MD8 algorithm has been modified by introducing a power law to the flow apportioning (Freeman, 1991; Holmgren, 1994), i.e., the proportion of flow that is directed towards the direction $\hat{\mathbf{e}}_i$ is

$$f_i = \begin{cases} \dfrac{s_i^M}{\sum_{j=1}^{8}(\max\{0, s_j\})^M} & \text{if } s_i > 0 \\ 0 & \text{if } s_i < 0 \end{cases} \tag{3}$$

where s_i is the slope gradient towards direction i defined such that $s_i > 0$ for downward slopes. This flow apportioning is more general and reduces to standard MD8 algorithm when exponent $M=1$ and to D8 when $M \to \infty$. The dimensionless parameter M thus determines how converging or diverging flow pattern is obtained. In the multiple flow direction methods, a 'contour length' is sometimes used to give different weights for cardinal and diagonal directions (Quinn et al., 1991). Here we do not use the contour length but it can be straightforwardly included if necessary.

2.5. Anisotropic flow routing

In standard flow-routing algorithms, flow direction depends only on the slope. In real situation, the systematic features not resolved by DEM can cause some directions to be more prone for the flow than others. On agricultural land, tillage patterns can greatly alter the flow direction in a way that water follows tillage-induced small-scale features such as, e.g., plough furrows. However, with the currently available and computationally feasible DEM resolutions these features are not visible and therefore standard flow-routing algorithms do not take their effect into the account. In erosion modelling, also the slope angle can be significantly reduced if water follows the microtopographic features rather than the direction of the steepest slope.

To account for the systematic sub-grid-scale roughness in flow routing, we generalize the power-law-form flow-routing algorithm in the case where flow is more probable in some predetermined direction. To this end, we introduce a unit vector $\hat{\mathbf{u}}$ which points along the tillage direction. The direction of this