Flow routing algorithms and landslide modelling

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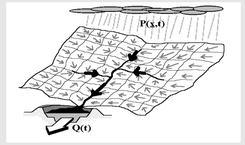
Abstract

The physical processes governing shallow landslide triggering can be ascribed to hydrological and geomechanic forcings. Modelling shallow landslide triggering via hydrogeomorphic spatially distributed model requires to extract for any location in the river basin the geomorphic and hydrologic attributes. The Digital Elevation Models allow an easy quantification of several morphologic and hydrologic landscape properties e.g. primary attributes such as slope, aspect, plan and profile curvature, flow path lengths and secondary attributes such as topographic index and drainage area per unit contour length. Although all of these attributes are used when assessing the hydrological forcings to shallow landslide triggering, it has to be stressed that the flow direction and accumulation algorithm plays a significant role in the accurate physical representation of those water-driven slope instability phenomena. In this study three flow direction algorithm (D8, D8-LTD and D∞) are applied in conjunction with two DEM correction techniques for the treatment of pits and flat areas (ArcInfo standard approach and PEM4PIT), in order to determine the terrain attributes needed as input for the hydrogeomorphic model Shalstab. Quantitative results corresponding to the implementation of the different hydrogeomorphic terrain analysis algorithms on different case studies provide an objective framework for testing the accuracy and performance of the different schemes in relation to the DEM-based hydrogeomorphic prediction of shallow landslides.

Methodology: flow routing



How to determine flow routing and contributing area?

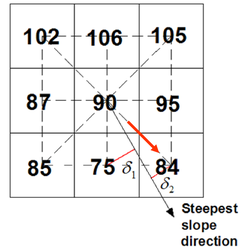
1 D8

Deterministic eight node - D8 (O'Callaghan and Mark, 1984): among the eight neighbours chooses the one toward which the slope is strongest. The D8 algorithm works well to delineate the network of streams and basin boundaries, and flow convergence in valleys. However, it limits the flow to one grid cell, and as a result, is unable to simulate divergent flows over hillslopes. Moreover, using only eight discrete flow angles, most often it shows parallel flow paths in either the cardinal or diagonal directions.

102	106	105
87	90	95
85	75	84

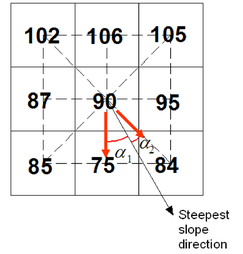
2 D8-LTD

Least Transversal Deviation - LTD (Orlandini et al., 2003): after using the D8 method for steepest (downward) slope calculation, an unique discrete flow direction is chosen according to least linear distance (δ1 or δ2 in the figure) between the center of the receiving cell and the path along the steepest direction that originates at the center of the drained cell. A further parameter (dampening factor) allows to retain full memory of upstream Transversal Deviation. It highlights deviations at the end of elemental drainage paths. This method is developed to mitigate the effects of grid artifacts affecting the D8.



3 D∞

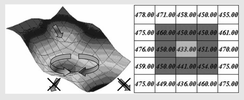
D-Infinity (D∞ or Dinf) [Tarboton, 1997] is a Multi Flow method that selects direction for the central cell according to the steepest descent of the eight triangular facets formed in the 3 by 3 grid cell window, but with a quantity varying continuously between 0 and 2p. The flow is partitioned between one or two neighbour pixels whose center forms the steepest triangle based on the resulting downslope vector. The proportion of flow along each triangle edge is inversely proportional to the angle between the steepest downward direction and the edge.



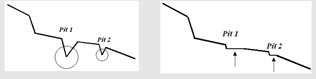
Methodology: DEM correction methods for removing pits

1: Standard ArcInfo Approach

The Standard ArcInfo approach for removing pits consists in the application of FILL routine, that arises pit elevation up to the lower elevation between the 8 surroindings cells.



478.00	471.00	458.00	458.00	455.00
475.00	460.00	458.00	458.00	461.00
476.00	458.00	433.00	451.00	478.00
459.00	458.00	441.00	454.00	475.00
475.00	449.00	436.00	468.00	475.00



2: PEM4PIT

PEM4PIT [Grimaldi et al, 2007] removes flat areas and pits implementing the same governing physical processes that give shape to the characteristic river basin landforms, and in particular fluvial erosion and diffusive processes. In fact, PEM4PIT stands for Physical Erosion Model for Pit Removal, but the pit concept is extended to include not only artificial depressions, but also flat areas, and any other basin cell for which a steepest downward slope cannot be defined. The elevation of DEM pit and flat area cells are modified using a simple landscape equilibrium model represented by the following continuity of mass equation for steady-state topography:

$$0 = U - \beta A^{\theta} S + D\nabla^2 z$$

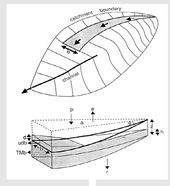
where U is the tectonic uplift rate, $\beta A^{\theta} S$ is the fluvial incision term, and $D\nabla^2 z$ gives erosion or deposition rate by diffusive hillslope processes depending on landscape shape (i.e., divergent, planar, convergent). S is the steepest downstream slope, A is the contributing area at the location, θ is the scaling slope–area coefficient and β is the surface erodibility, $\nabla^2 z$ is the hillslope curvature and D is the hillslope diffusivity, derived from the divergence of slope dependent linear sediment transport equation of hillslope diffusion.

Methodology: Shalstab Model

Shalstab [Montgomery & Dietrich, 1998] is a Landslide Triggering Model based on an infinite slope form of Mohr-Coulomb failure law and on a steady state shallow subsurface flow:

Stability Equation

$$\frac{h}{z} = \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\phi}\right)$$



Hydrologic Model

$$\frac{h}{z} = \frac{q}{T}\frac{a}{b\sin\theta}$$

$$\frac{q}{T} = \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\phi}\right)\frac{b}{a}\sin\theta$$

Conclusions

Shalstab model is commonly used for landslide modelling, though its sensitivity to flow routing algorithms and DEM correction methods (for removing pits and flat areas) has never been widely investigated.

In this work we show how the model results can be affected by the choice of the flow direction method (here 3 methods are applied: D8, D8-LTD, D∞) and the choice of DEM correction method (here 2 methods are used: Standard ArcInfo approach – FILL routine -, and PEM4PIT, a new method for removing pits and flat areas that is physically based).

References

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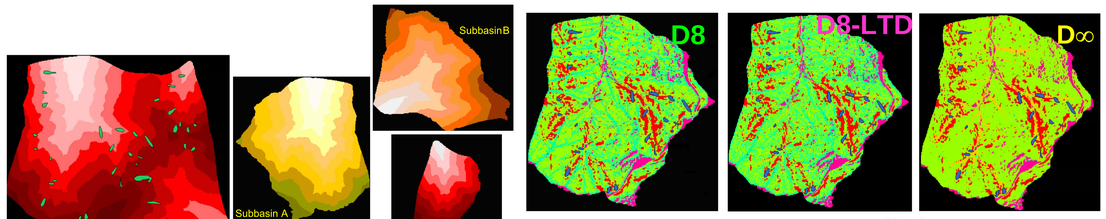
Orlandini S., Moretti G., Franchini M., Aldighieri B. and Testa B., 2003, Path-based methods for the determination of non-dispersive drainage directions in grid-based digital elevation models, Water Resources Research 39(6), 1144, DOI: 10.1029/2002WR001639.
Tarborton D.G., 1997, A new method for the determination of flow directions and upslope areas in grid digital elevation model, Water Resources Research 33: 309-319.

Case Study 1

The study site consists of a 0.3 km² drainage basin along Mettman ridge in the Coast Range, north of Coos Bay, Oregon. The area is highly dissected and characterized by narrow ridge tops and steep slopes. Many shallow landslides and debris flows were observed occurred in this area from 1987 to 1992.

Shalstab has been applied investigating its sensitivity to Flow routing methods; the DEM correction method here applied is the Standard ArcInfo approach for all of the three Flow routing algorithms.



sub-basin A	q/T<-2.5		
	d8	d8-ltd	DINF
I1	42.5%	90.6%	41.1%
I2	5.3%	3.5%	5.1%
I3	89.2%	64.6%	89.1%
I4	99.1%	99.8%	99.1%
Itot	59.0%	64.6%	58.6%

sub-basin B	q/T<-2.5		
	d8	d8-ltd	DINF
I1	31.6%	78.2%	1.3%
I2	8.0%	19.8%	0.1%
I3	92.8%	93.7%	76.1%
I4	98.6%	99.5%	97.5%
Itot	57.8%	72.8%	43.8%

sub-basin C	q/T<-2.5		
	d8	d8-ltd	DINF
I1	34.3%	33.7%	29.9%
I2	11.5%	9.9%	8.9%
I3	88.5%	86.8%	86.7%
I4	96.9%	96.8%	96.6%
Itot	57.8%	56.8%	55.5%

I1= UR/UO
I2= UR/UC
I3= SR/SO
I4= SR/SC
Itot = I1+I2+I3+I4
where
UO = Observed Unstable Cells
SO = Observed Stable Cells
UC = Simulated Unstable Cells
UR = Rightly Simulated Unstable Cells
UW = Wrongly Simulated Unstable Cells
SC = Simulated Stable Cells
SR = Rightly Simulated Stable Cells
SW = Wrongly Simulated Stable Cells

Chronic Instability
< - 3.1
-3.1 - -2.8
-2.8 - -2.5
-2.5 - - 2
> -2.0
Stable
No Data

Case Study 2

Norcia basin is located in the centre of Italy, it has an area of 100 km², the elevation ranges from 696 to 2428 m a.s.l. and the average slope is 23% ranging from 0% to 115%.

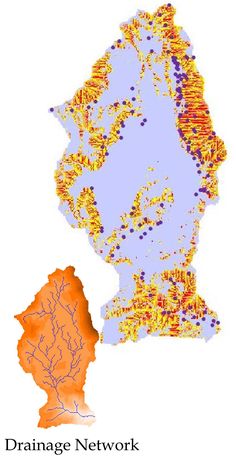
Shalstab has been applied investigating its sensitivity to DEM correction method and Flow routing method.

	CellValue	CellCount	Percent	CumPercent	Instability
PEM4PIT - D8	1	33	0.05	0.05	Cronic Instability
	2	4605	7.56	7.62	< -3.1
	3	2892	4.75	12.37	-3.1 - -2.8
	4	3916	6.43	18.80	-2.8 - -2.5
	5	11142	18.30	37.10	-2.5 - -2
	6	0	0.00	37.10	> -2.0
	7	38296	62.90	100.00	Stable

	CellValue	CellCount	Percent	CumPercent	Instability
PEM4PIT - D8_LTD	1	33	0.05	0.05	Cronic Instability
	2	4494	7.38	7.44	< -3.1
	3	2760	4.53	11.97	-3.1 - -2.8
	4	3903	6.41	18.38	-2.8 - -2.5
	5	11398	18.72	37.10	-2.5 - -2
	6	0	0.00	37.10	> -2.0
	7	38296	62.90	100.00	Stable

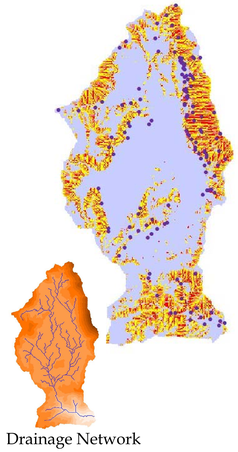
	CellValue	CellCount	Percent	CumPercent	Instability
SHALSTAB	1	33	0.05	0.05	Cronic Instability
	2	6735	11.06	11.12	< -3.1
	3	6475	10.63	21.75	-3.1 - -2.8
	4	6619	10.87	32.62	-2.8 - -2.5
	5	2726	4.48	37.10	-2.5 - -2
	6	0	0.00	37.10	> -2.0
	7	38296	62.90	100.00	Stable

PEM4PIT + D8



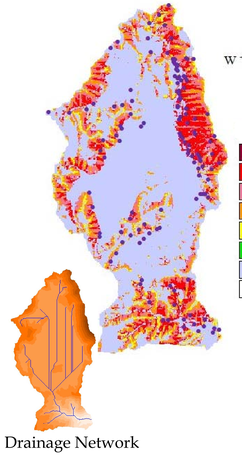
Drainage Network

PEM4PIT + LTD



Drainage Network

Standard Shalstab = ArcInfo Approach (Fill + D8)



Drainage Network

N
W E
S

Norcia Shallow Landslides

Chronic Instability
< - 3.1
-3.1 - -2.8
-2.8 - -2.5
-2.5 - - 2
> -2.0
Stable
No Data