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A physically-based method for removing pits in digital elevation models

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Abstract

Spurious pits in digital elevation models (DEMs) are traditionally removed by filling depressions, often creating flat regions that lead to inaccurate estimation of landscape flow directions. In this study, a physical approach based on a simple landscape evolution model is proposed for DEM pit removal. This method, an alternative to traditional geometrical procedures, enforces more realistic slopes and flow directions on topography. The procedure is compared with the method most commonly used in the literature and distributed with commercial GIS software where, generally, elevations of a depression are increased up to the lowest value among neighbouring cells. Several tests are performed and parameters sensitivity is carried out in order to demonstrate the performance of the proposed model as compared to traditional methods.

Keywords: Geographical Information Systems; GIS; Digital elevation models; DEM; Pit filling; Depressions in DEMs; Sinks in DEMs; Errors in DEMs; Landscape evolution models; Drainage networks

1. Introduction

The extraction and analysis of hydrogeomorphic features from digital elevation models (DEMs) is a topic of increasing interest in various earth science disciplines [e.g.] [3,20,25,27,40]. In hydrology DEMs have been widely used in the last couple of decades [e.g.] [2,6,30,45]. Recent spatially distributed hydrology models utilize DEM-based automated procedures to characterize overland flow patterns. Unfortunately all DEMs have incorrect, spurious, errors commonly referred to as sinks [7,29], depressions [19,23,31] and pits [33].

Pits are closed artificial depressions, often formed when a cell is surrounded by cells with higher elevations [21]. DEMs usually show a large number of pits, up to 5% or more of the total number of cells in a given domain [35,36]. Processing the DEM of Italy produced by the Italian Geographic Military Institute (IGMI) at a resolution of 75 m we identified pits covering approximately 1% of the total surface. Table 1 also shows the number of pits found in the USGS NED DEM [11], and the SRTM DEM [8,41] for the Rio Salado watershed (3635 km^2) in New Mexico (USA). Pits are usually concentrated in flat areas, in floodplain regions, and in the proximity of certain types of landforms, such as multiple

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Table 1
Summary table for the Italian and the Rio Salado DEM including the DEM pixel dimension (resolution), the total number of cells composing the digital elevation matrix, the total number of pits considering adjacent pits as a single unit, and the total number of cells identified as pits

Area	DEM	Resolution (m)	Total # of cells	Pits	Tot pit cells
Italy	IGMI	75	44,735,003	53,781	459,227
Italy	IGMI	60*	69,898,403	65,486	735,939
Italy	IGMI	150*	11,183,684	27,427	137,276
Italy	IGMI	250*	4,026,174	13,564	56,121
Salado	USGS	~30	5,038,290	7403	16,979
Salado	SRTM	~30	5,028,246	7436	16,871
Salado	SRTM	~90	558,670	1375	2979

* Sample data.

channels, dunes, or sediment deposits that are usually not well represented by largely available DEMs. Urbanized and vegetated areas are also potential locations of errors during DEM processing. Despite the fact that they only occupy limited areas in DEMS, pits create discontinuities in drainage patterns dramatically influencing hydrological response of drainage basins. Thus, DEMs need to be preprocessed to remove such anomalies. The common practice is to automatically detect artificial depressions, always present in DEMs [45], and to fill them up to the elevation of surrounding pixels.

It has been reported that the number of depressions is inversely proportional to the DEM resolution [18]. Pits can also be generated while interpolating DEMs for changing grid spacing. In fact, resampling a DEM to increase the resolution (downscaling) leads to more pits while decreasing the resolution (upscaling) reduces the total number of pits but the total percentage area covered by pits increases. For example, resampling the IGMI DEM of Italy from 75 m to 60 m we found that the total number of pits increases 21%. In contrast, upscaling to 150 m the total number of pits decreases 49% but the total area covered by sinks increases 20% (see Table 1).

It should be noted that pits in the above discussion are composed of those cells or groups of adjacent cells that are surrounded by cells at higher elevation [16], while in the developing of the proposed approach we also define a pit as a cell surrounded by cells at the same elevation.

Commercial geographic information system (GIS) packages are traditionally equipped with a pit removal tool. The most widely used correction method simply increases the elevation of the pit until it reaches the elevation of the downstream cell. The procedure is iteratively repeated until all pits are corrected or more appropriately when all cells can be hydrologically assigned a downstream flow direction. This method, commonly referred to as pit filling [16], is implemented in most common GIS softwares, including ESRI ArcInfo [7], and the open source Unix-based GRASS. The pit filling method, widely used for its simplicity, does have some drawbacks and limitations. The method tends to create large flat regions. Consequently flow paths are misinterpreted forming unrealistic parallel channels and other artificial features. Moreover, the pit filling method is also computationally intense and tends to dramatically impact the original surface, especially for complex situations like adjacent pits and nested catchments [19]. To overcome these problems several alternative methods have been proposed. With the exception of procedures which consider flat areas and depressions as natural features and try to determine flow directions without modifying elevations [4,5,10,22], the majority of methods try to adjust elevations to create hydrologically sound DEMs [23]. For example, Martz and Garbrecht [23,24], and Rieger [32] propose to "breach" the depression favouring the flow downstream through the bounding outlet. Tianqi et al. [36] propose to tune elevation adjustments in relation to the location of the depression in the basin with the aim of reproducing a more natural channel profile. Soille et al. [34] propose to "carve" the terrain to enforce convergent flow patterns. Several other methods can be found in the literature; some of them couple existing methods [e.g.] [19,33] and others have the goal of decreasing the computational burden [e.g.] [31,39]. It is worth noting that even though the interaction between hydrogeomorphic physical processes and resulting topography is commonly acknowledged [e.g.] [1,15], the majority of existing pit filling methods do not try to represent physical processes but are based on geometrical, morphological and stochastic approaches. An exception may be the pseudo-physical method of Tianqi et al. [36].

In this paper, a new physically-based approach for pit removal based on an existing interpolation model [12,13,28] is introduced. The model employs a simple long-term mass balance concept in geomorphology, suggesting balance between erosion and uplift (or base-level fall). Compared to other approaches the proposed method predicts more realistic drainage patterns and slopes. More accurate values of local slope could lead to improved prediction in spatially distributed models of hydrology, and to improved mapping of geomorphologic indices that describe similarities in the landscape hydrologic and geomorphic response (i.e. TOPMODEL topographic index [16]). We first describe the new pit-filling approach in Section 2, followed by a sensitivity analysis of parameters in Section 3. In Section 4, a case study highlights the differences with the proposed and an existing pit filling approaches.

2. The physically-based pit removing method

Pit elevations are adjusted using a simple landscape equilibrium model represented by the following continuity of mass equation for steady-state topography [28]

$$0 = U - \beta A^{\theta} S + D\nabla^2 z \tag{1}$$

where U is the tectonic uplift rate [L/T], $\beta A^{\theta} S$ is the fluvial incision term [L/T], and $D\nabla^2 z$ gives erosion or deposition rate [L/T] by diffusive hillslope processes depending on landscape shape (i.e., divergent, planar, convergent). S is the steepest downstream slope [L/L], A is the contributing area at the location [L^2], θ is the scaling slope–area coefficient and β is the surface erodibility [$L^{1-2\theta}/T$], which is related to lithology, climate and channel geometry [14,42]; $\nabla^2 z$ is the hillslope curvature [L^{-1}] and D is the hillslope diffusivity [L^2/T], derived from the divergence of slope dependent linear sediment transport equation of hillslope diffusion [9]. Tarboton et al. [35] used Eq. (1) to derive a slope–area scaling relationship for fluvial topography, and used it for the extraction of channel networks from DEMs. The validity of Eq. (1) has been widely explored [26,37,43,44] in numerical models of long-term landscape evolution.

Recently, a new physically based interpolation has been developed implementing Eq. (1) to obtain a regularized grid at desired resolution either from a set of observed points, or from an existing grid [12,13,28]. The approach we use here is a logical extension of this interpolation method, used to correct elevation of depressions in DEMs. The acronym PEM4PIT (Physical Erosion Model for PIT filling) is used to refer to the method.

The implementation of Eq. (1) within the pit removal algorithm is characterized by two loops: the outer and the inner loop are described in the flowchart of Fig. 1.

The inner loop is composed of the following steps:

(1) Calculation of flow direction, and contributing area for every cell of the DEM based on the D8 approach [16] for which each grid cell flows to only one of the eight neighbouring grid cells, chosen with the steepest descent-slope criterion.

(2) Identification of depressions and integration of Eq. (1) in the discrete form. The equation is normalized by uplift, U, resulting in:

$$0 = 1 - \beta A^{\theta}\left(\frac{z - z_{\mathrm{d}}}{\Delta l}\right) + \frac{4D}{\Delta x^2}(\breve{z} - z) \tag{2}$$

where z_{d} is the elevation of the downstream node (see the following schematic example to understand how the downstream node is defined), Δl is the distance between cells, Δx is the grid resolution, $\breve{z}$ is the mean elevation estimated on the nearest four points of the pit. The uplift is subsumed in the coefficients of the equation, so from now on U is treated as if had a value of 1 [28].

The outer loop checks for the hydrologic consistency of the surface, and computes flow accumulations, and where necessary calls the inner loop if needed (Fig. 1).

As described in the flow chart (Fig. 1), the procedure ends when all DEM cells are hydrologically connected to the domain boundaries or more simply when all pits are removed.

The following schematic example shows the implementation of PEM4PIT as compared to the classic pit filling method applied to a grid of 24 cells, obtained by resampling the DEM of a real basin that contains a single pit (Fig. 2a). The routine increases the elevation of the pit up to the elevation of the deepest downstream point. Once the depression is filled and both points, the original pit and the deepest downstream point, have the same elevation (Fig. 2b: i.e. 1801) PEM4PIT, follows the algorithm schematized in Fig. 1:

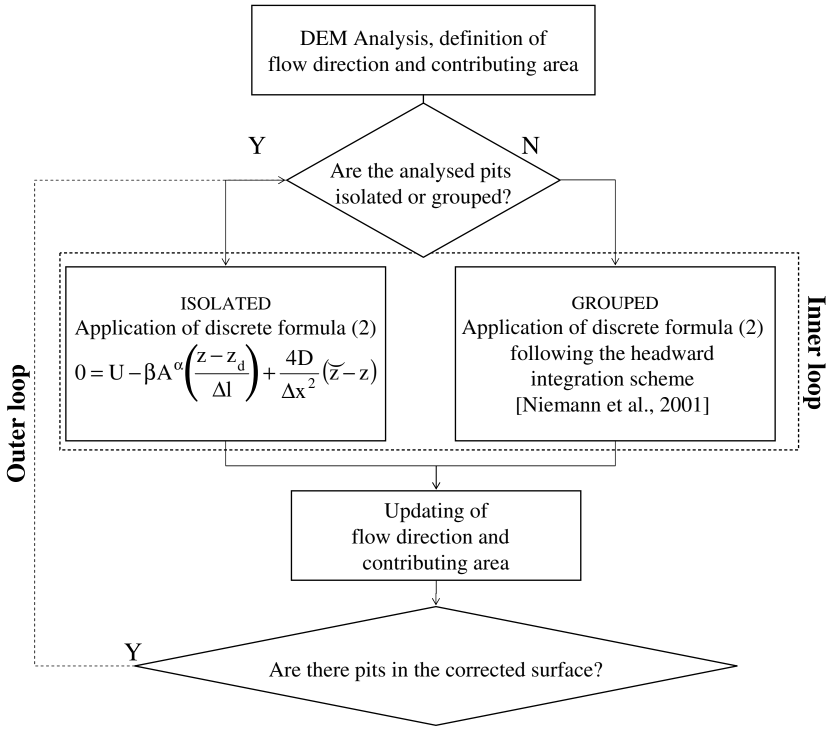
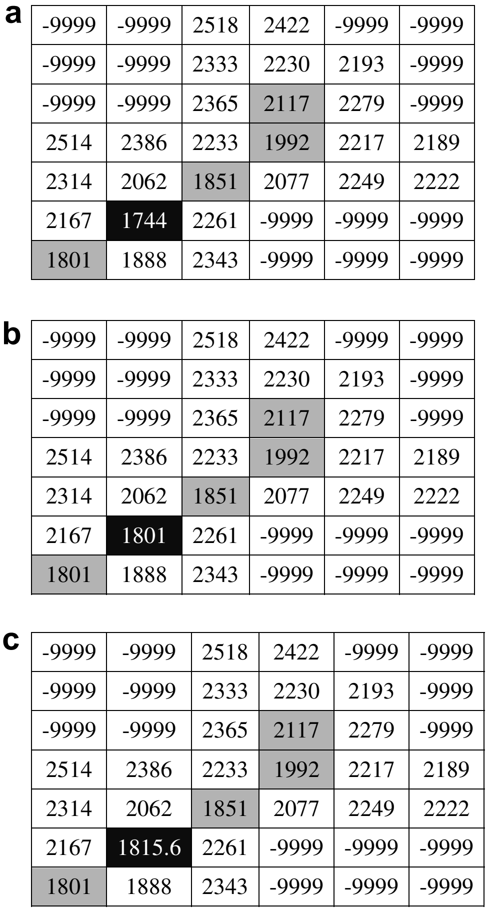


Fig. 1. Flowchart of the method isolated refers to a depression composed of a single cell while grouped refers to a multi-cell depressions.



a

-9999	-9999	2518	2422	-9999	-9999
-9999	-9999	2333	2230	2193	-9999
-9999	-9999	2365	2117	2279	-9999
2514	2386	2233	1992	2217	2189
2314	2062	1851	2077	2249	2222
2167	1744	2261	-9999	-9999	-9999
1801	1888	2343	-9999	-9999	-9999

b

-9999	-9999	2518	2422	-9999	-9999
-9999	-9999	2333	2230	2193	-9999
-9999	-9999	2365	2117	2279	-9999
2514	2386	2233	1992	2217	2189
2314	2062	1851	2077	2249	2222
2167	1801	2261	-9999	-9999	-9999
1801	1888	2343	-9999	-9999	-9999

c

-9999	-9999	2518	2422	-9999	-9999
-9999	-9999	2333	2230	2193	-9999
-9999	-9999	2365	2117	2279	-9999
2514	2386	2233	1992	2217	2189
2314	2062	1851	2077	2249	2222
2167	1815.6	2261	-9999	-9999	-9999
1801	1888	2343	-9999	-9999	-9999

Fig. 2. Numerical schematic example; original DEM (a), DEM corrected with ArcInfo (b), and with the PEM4PIT method (c). In evidence, blueline cells (shaded gray) and pits (shaded black).

(1) During the first iteration, discrete Eq. (2) is used without the fluvial erosion term, because there is not downward slope in a depression. The pit node new elevation is 9907.0 m ($\Delta x = 5000$, $D = 800$).
(2) In the second iteration, after updating the flow direction, slope and contributing areas, Eq. (2) is applied this time using the fluvial erosion parameters. The pit node final elevation is 1815.6 m ($\beta = 0.1$; $\theta = 0.5$).

In the above example the outer loop is not necessary since other pits are not generated after the first inner loop. While the classic pit filling method fills the depression creating a flat surface, PEM4PIT assigns a slope accordingly to the physical processes governing the phenomenon and the physical properties of the terrain represented by Eq. (1) and its parameters β, θ and D.

3. Parameter sensitivity analysis

As described in the previous section the physically-based approach needs three input parameters: β, θ and D. These parameters have been subject of investigations, model applications and field campaigns [37,38]. As stated earlier here the parameters are normalized by tectonic uplift. In this section, the sensitivity of PEM4PIT to parameters is investigated and model performance is compared to the standard ArcInfo method. The study area is the WE38 experimental watershed, located approximately 40 km north of Harrisburg, in a predominantly agricultural area belonging to the East Mahantango Creek catchment in Pennsylvania. It has a drainage area of 7.29 km^2. The DEM of the WE38 watershed is extracted from the USGS NED at 30 m of resolution.

The PEM4PIT approach is used to process the WE38 DEM using the following set of parameters:

- β: 0.01, 0.05, 0.1, 0.2, 0.5, 0.7, and 0.9 with $D = 300$, $\theta = 0.5$;
- D: 100, 300, 500, 700, and 900 with $\beta = 0.1$, $\theta = 0.5$;
- θ: 0.3, 0.4, 0.5, 0.6, and 0.7 with $\beta = 0.1$, $D = 300$.

The impact of varying parameters on PEM4PIT performance is quantified using the elevation and mean slope of modified cells, and the properties of the stream network, as compared to the traditional ArcInfo method. The

Table 2
Summary table of results for experiments conducted with varying parameters β, D, θ using the PEM4PIT method on the WE38 DEM as compared to the ArcInfo method (last row of the table)

β	D	θ	nmc	memc	msmc	nbc	ncbc
0.01	300	0.5	641	244.22	0.042	284	183
0.05	300	0.5	500	242.53	0.040	294	175
0.1	300	0.5	463	242.31	0.038	286	175
0.2	300	0.5	357	236.93	0.031	280	200
0.5	300	0.5	245	233.06	0.020	287	217
0.7	300	0.5	150	232.25	0.015	279	241
0.9	300	0.5	123	231.43	0.012	280	253
0.1	100	0.5	2257	262.71	0.060	282	54
0.1	200	0.5	633	243.20	0.043	289	155
0.1	400	0.5	408	238.52	0.034	281	204
0.1	500	0.5	357	239.58	0.033	283	199
0.1	700	0.5	289	237.91	0.029	286	222
0.1	900	0.5	263	237.06	0.026	281	223
0.1	300	0.3	629	244.16	0.0417	280	149
0.1	300	0.4	511	243.20	0.041	282	160
0.1	300	0.45	497	240.33	0.038	286	193
0.1	300	0.5	463	242.31	0.038	286	175
0.1	300	0.55	431	241.95	0.034	287	184
0.1	300	0.6	346	237.38	0.030	280	206
0.1	300	0.7	188	237.38	0.030	279	226
0.9	100	0.5	198	234.04	0.020	276	234
0.9	300	0.3	408	238.22	0.033	286	187
0.01	900	0.5	306	238.01	0.031	281	207
0.1	900	0.3	301	237.91	0.030	280	208
0.01	300	0.7	497	242.69	0.040	285	182
0.1	100	0.7	469	240.32	0.036	282	164
	ArcInfo		63	230.88	0.000	278	–

nmc, number of totally modified cells; memc, mean elevation of modified cells; msmc, mean slope of modified cells; nbc, number of cells composing the blueline; ncbc, number of coincident blueline cells.

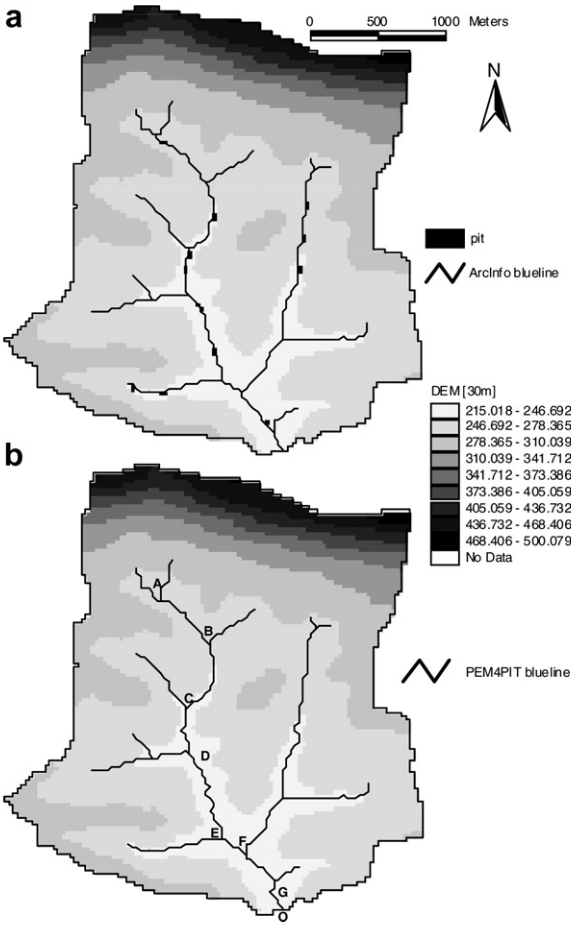


Fig. 3. Planimetric comparison of automatically extracted bluelines using the standard pit filling method (a) and the PEM4PIT method on the WE38 using $\beta = 0.7$, $D = 300$ and, $\theta = 0.5$ (b).

stream network (or blue line) is defined here from the contributing area grid using a user-defined threshold value [16], 0.2 km^2 in this case. From results (Table 2) it is noted that:

- As β, D, and θ values increase, the PEM4PIT results in statistics similar to the ArcInfo method;
- for $\beta \to \infty$ PEM4PIT behaves exactly like ArcInfo, filling depressions with flat surfaces. This result was expected. For high values of β, the diffusive term in Eq. (2) becomes negligible, and the new value of z is: $z = \frac{U\times\Delta l}{\beta A^{\theta}} + z_{\mathrm{d}}$. As a result, the elevation of the pit will be approximately equal to the elevation of the downstream cell (z–z_{d}) creating a flat surface.
- The planimetric location of the bluelines (estimates of river locations) can be significantly different from the ArcInfo method when using low values of β, D and θ (note the number of coincident blueline cells in Table 2). For these parameters the pit elevation will be consistently increased, probably becoming higher than the elevation of adjacent nodes. This adjustment usually produces new depressions or in any case modifies the original location of blueline cells.
- Visualizing the planimetric location of bluelines corresponding to a wide range of all input parameters PEM4-PIT produces realistic stream networks.
- For this specific case study the only set of parameters that leads to unrealistic results is $\beta = 0.1$, $D = 100$, and $\theta = 0.5$. The low diffusivity coefficient in this case creates saddles or similar landscape features that relocate channels and produce artificial outlets.

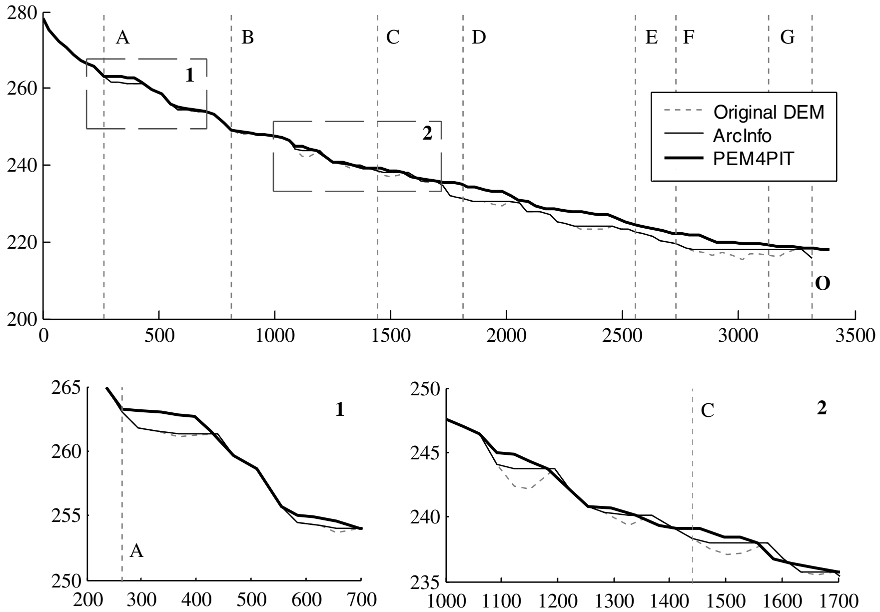


Fig. 4. Altimetric profile of bluelines extracted with ArcInfo and PEM4PIT before and after correcting for pits on the WE38 using $\beta = 0.7$, $D = 300$ and, $\theta = 0.5$. Notations of the A–O link refer to the plan view of the profile shown in Fig. 3. (note: units are in m).

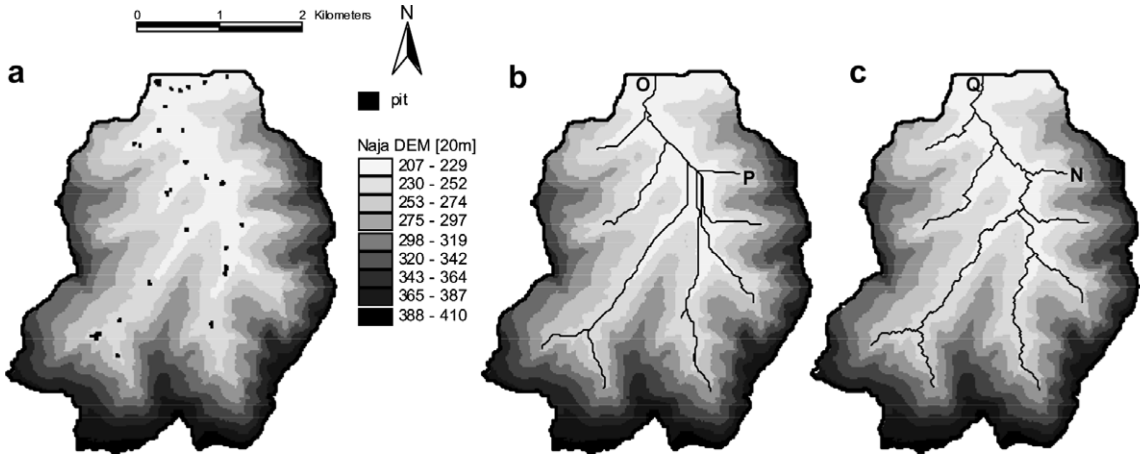


Fig. 5. Representation of a nested subcatchment of the Naja basin with pits (a); automatically extracted blueline with ArcInfo (b) and PEM4PIT (c) on the hillshaded DEM.

- The mean slope of the entire DEM, processed by the new method (not shown here for brevity), is always lower than that of the filled (ArcInfo) DEM since adjusting the pit node elevation to accommodate a positive downstream slope in PEM4PIT will decrease the slope of neighbouring nodes. This behaviour is also evident in Fig. 2b and c: the new value (1815.6) gives to the selected node a positive slope ($\Delta h = +14.6$ m) but at the same time the slope of the five neighbouring nodes ($z_1 = 2314$, $z_2 = 2062$, $z_3 = 1851$, $z_4 = 2261$, $z_5 = 2343$) decreases.
- The model seems to be more sensitive to the fluvial incision terms β and θ as respect to the diffusivity D (see last section of Table 2), as expected since pits are usually located in fluvially-eroded regions of the basin.

It is interesting to note that, for a wide range of input parameters the planimetric position of the stream network does not differ significantly from Arcinfo; nevertheless, while ArcInfo elevation adjustments produce flat areas PEM4PIT results in draining profiles. This can be seen in Figs. 3 and 4 representing PEM4PIT performance with $\beta = 0.7$, $D = 300$ and, $\theta = 0.5$ in contrast to the performance of the Arcinfo algorithm.

4. Case study application

PEM4PIT is used in a subcatchment of the Naja river. The Naja, a tributary of the Tiber river, is located in the central part of the Appenine mountains in Italy (42.76°N, 12.41°E). The DEM is extracted from an IGMI DEM at 20 m of resolution and integer elevation values. The

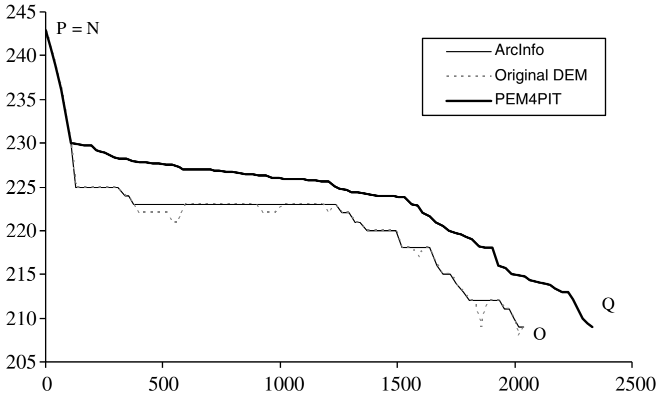


Fig. 6. Comparison of altimetric profiles of channels derived with ArcInfo for the link P–O (planimetry in Fig. 5b) and PEM4PIT (b) for the link N–Q (planimetry in Fig. 5c) as compared to the profile extracted from the original DEM (note: units are in meters).

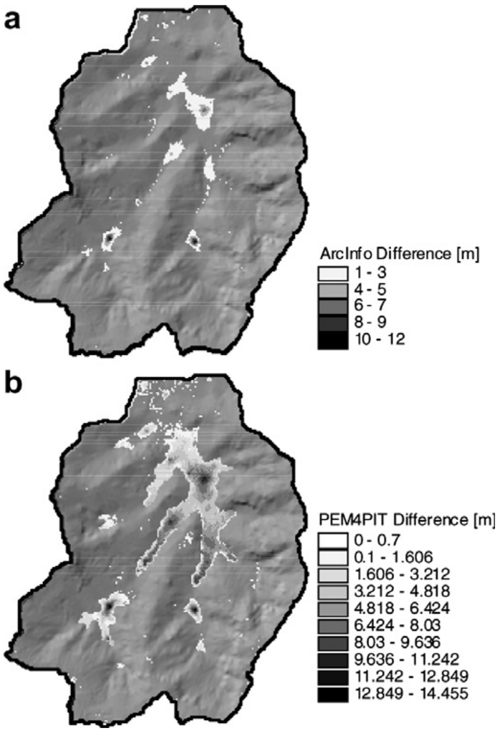


Fig. 7. Elevations difference between original DEM and corrected DEM with the standard pit filling method (a), and the PEM4PIT method (b) superimposed on the shaded relief DEM.

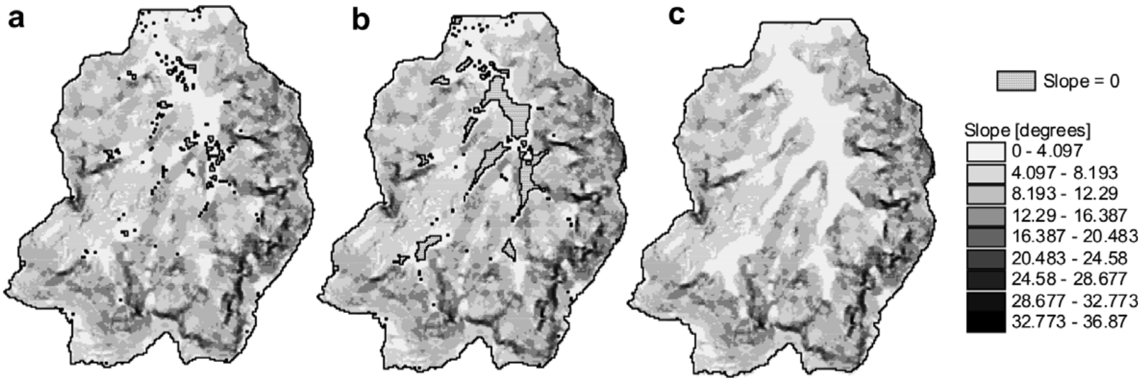


Fig. 8. Comparison of slope grid of the original DEM (a), filled DEM (b), and DEM corrected with PEM4PIT (c). Shaded zones have slope equal to zero.

selected subcatchment drains an area of approximately 12.5 km^2 while the entire Naja basin covers 167 km^2.

The DEM is first processed with the standard pit filling method and the stream network extracted identifying cells with an upslope area of 0.3 km^2. The original DEM contains 34 depressions mainly distributed in the large floodplain. Figs. 5a and b show the planar hillslopes and parallel channels resulting from the extraction of the network and pit filling using the standard ArcInfo approach.

The PEM4PIT method is then applied using $\beta = 0.4$, $D = 300$, and $\theta = 0.5$. Figs. 5b and c contrast the ArcInfo procedure and the physically-based method. The planimetric comparison shows the more natural network obtained with PEM4PIT which creates sinuous channels and more realistic junctions in the large flat floodplain. The altimetric profiles, represented in Fig. 6, illustrate how the standard method creates large flat areas filling depressions, while PEM4PIT results in a more natural channel profile. PEM4-PIT, in adjusting elevations to remove pits, produces a longer drainage path as respect to the filling procedure. Note the planimetric differences between Fig. 5b (filling method) and Fig. 5c (PEM4PIT) and the corresponding altimetric profiles PO and NQ represented in Fig. 6.

Fig. 7 shows the altimetric differences between original DEM and corrected DEM with the ArcInfo method (Fig. 7a) and the PEM4PIT method (Fig. 7b) superimposed on the shaded relief DEM. The ArcInfo method modifies 982 cells, while PEM4PIT adjusts the elevation of a much larger number of cells; but only 3910 cells suffer an adjustment of more than 1 m. A large number of nodes need to be corrected in order to enforce hydrologically sound slopes in artificially flat areas.

The improvements of the proposed approach are also evident in Fig. 8 which shows the grid slopes before (Fig. 8a) and after prepocessing with the standard pit filling method (Fig. 8b) and PEM4PIT (Fig. 8c). In the original DEM only few locations in the basin have a slope equal to zero and they are probably artificial and not representative of the terrain. The standard pit filling method creates a large flat region of 0.558 km^2, 5 times larger of the initial 0.141 km^2, as clearly shown comparing Fig. 8a and b. Fig. 8c shows the distribution of slopes after implementing the PEM4PIT preprocessing method. There are no zones at zero slope but a large number of cells are adjusted to drain at slopes slightly greater than zero.

Several experiments conducted on the study area by adjusting the erodibility coefficient β, the diffusivity D and the slope–area coefficient θ show that the method, although sensitive to all input parameters, produces realistic results using a wide range for all three input parameters.

5. Conclusion

In this paper, a physically-based pit removal method is introduced. A simplified erosion model, characterized by the fluvial and diffusivity terms, is integrated on DEM pit nodes. The aim is to assign new elevation values that are compatible with the physical processes potentially acting on the terrain. As a result, the method enforces positive downstream slopes, in contrast to the standard approach that fills depressions creating flat artificial surfaces.

The differences shown in Figs. 6, 8b and 8c highlight the significant impact of the proposed approach. The standard pit filling method provides unrealistic draining profiles that could influence the estimation of geomorphologic indiceses related to local slope values.

The approach is more sensitive to the erodibility parameter β and to the slope–area coefficient θ, while the diffusivity D has a minor influence on results.

A case study of an Italian watershed shows that the new method yields slopes and directions of drainage that are more hydrologically-correct than those resulting from traditional pit filling approaches.

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