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Analysis of the behavior of three digital elevation model correction methods on critical natural scenarios

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ABSTRACT

Study region: The methods explored in this study were tested in two study areas: Italy and Cuba.
Study focus: Virtually all Digital Elevation Models (DEM) contain flat areas or depression pixels that may be artifacts or actual landscape representations. These features must be removed before any further hydrological application can proceed. Diverse algorithms have been developed for the purpose of correcting these aspects, differing in how they handle the nature of the depressions, as well as the adopted mathematical procedures. In the present work, the behavior of a standard (*Fill*) and two advanced (*TOPAZ and PEM4PIT*) DEM correction methods on three critical natural scenarios is analyzed. Extensive flat areas, abrupt slope changes and large depressions – expressed in terms of: (1) geomorphological changes (elevation, affected area and slope); (2) flow velocity; (3) river network and width functions (WF) – are affected.
New hydrological insights for the region: Results confirm improved performance of the advanced methods over the standard method for each case study in Italy and Cuba. The analyzed parameters also show that correction processes are strongly influenced by the relief, the size of the predominating depressions and the neighbouring depressions. There is no one method among those compared which works optimally for every type of correction, and given that the majority of basins have diverse topographical conditions, a different approach to the corrections process and its computational procedures is likely needed.

1. Introduction

Natural sciences, from geomorphology to vegetation sciences, show increasing interest in applications based on the accurate representation of topography, as provided by the most recent digital elevation models (DEMs) (Muñoz and Kravchenko, 2012; Elshehaby et al., 2013; Petroselli et al., 2013, 2014; Fan et al., 2014; Nourani and Zanardo, 2014). Hydrology is one discipline that has directly benefited from available terrain models. Virtually all watershed representations, however, contain flat areas or depression pixels that may be artifacts or actual landscape representations (Fisher and Tate, 2006; Pan et al., 2012). These features cause interruptions while calculating downstream flow through a DEM (Grimaldi et al., 2007; Arnold,

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2010; Petroselli and Alvarez, 2012), which is the basis for every posterior hydrological modeling step. It has been found that even applications of more recent hydrological models can provide incorrect results when performed with the most detailed DEMs if depressions and flat areas are not properly addressed (Petroselli, 2012).

Depressions can be corrected by applying diverse algorithms. Known by the acronym of *Fill* or *Filling* (hereafter Fill) (Jenson and Domingue, 1988), this method considers all depressions in DEMs to be errors caused by the underestimation of elevation at a certain point. The correction fills the sinks to permit overflow continuity. The procedure has been implemented in widely used commercial geographic information system (GIS) software packages such as ArcGIS, and the open source, Unix-based GRASS. As a result of its large diffusion and availability, Fill has become a reference for comparison with newly developed approaches and a standard for scientific and practical applications.

The Topographic Parametrization (TOPAZ) (Martz and Garbrecht, 1999) method also assumes all depressions as artifacts, however it considers the possibility of both underestimation and overestimation of the elevation of some cells. Based on these two possibilities of the sources of depressions, the procedure consists of breaching a potential wall and/or filling depressions. In addition, the flat areas generated by flooding are corrected, recalculating the elevation, iteratively adding an infinitesimal number to the pixel elevation, and in doing so, forcing the flow algorithms toward lower terrain (Garbrecht and Martz, 1997).

In an attempt at modeling natural processes, the physically based erosion model for pit and flat areas removal (PEM4PIT) was developed. This method, regardless of the nature of the depressions, performs the correction by applying a simplified physically based landscape evolution equation (Grimaldi et al., 2007). Moreover, the correction process is addressed based on local surface interpolation (e.g. Pan et al., 2012). Another potential solution is the combination of several of the previously mentioned processes (Kenny et al., 2008) – with the condition of starting from a particular kind of DEM – interpolated with the ANUDEM method (Australian National University DEM), using the river network as a boundary condition.

A different proposition consists of redirecting the flow within depressions until continuity is obtained and the basin outlet is reached (e.g. Wang et al., 2009). This method has the ability to achieve flow continuity, but does so at the cost of misinterpreting the river network. Other methods of achieving the desired results may be used (e.g. Planchon and Darboux, 2001; Temme et al., 2006; Wang and Liu, 2007; Zhu et al., 2013; Barnes et al., 2014; Jojene and Meriam, 2014), but the majority of existing methods dealing with pit filling and flat-areas are based on geometric, morphological and stochastic approaches, introducing uncertainty and/or not considering physical topographic phenomena (Petroselli, 2012).

According to different considerations regarding the nature of depressions and the adopted mathematical procedures, each method may impose particular landscapes after correction and flat area treatment. In the first instance, it is the consideration of all depressions as errors. Here the correction is addressed by one of two methodologies: flooding the depression, adopted by the standard Fill method, or by the combination of flooding the depression and/or breaching the depression edges with the imposition of an artificial gradient through the flooded region, by applying mathematical procedures (i.e. interpolation, looping addition of arbitrary infinitesimal values to the cells elevation, etc.). Alternatively, there is the physically based method, which carries the implicit consideration of all depressions as real features, and the correction consists of the simulation of natural processes over the terrain.

It is important to note that hydrological modeling, following DEM preprocessing, is influenced by the propagation of inputs and errors. Since the correction constitutes the first step in hydrological modeling, a better understanding of this process can contribute to improved accuracy. Besides the large availability of correction methods, it is common in the literature to find new methods being proposed, rather than additional detailed descriptions of the potential and limitations of those methods already developed. The majority of methodological comparisons in the literature involve assessing the application of a newly developed method and the standard Fill method to particular basins or artificial DEMs. There is a lack of comparisons between some of the more advanced methods and their efficacy in correcting critical natural scenarios that can be found in real watersheds.

The aim of the present work is to analyze the behavior of the standard (*Fill*) and two advanced (*TOPAZ and PEM4PIT*) DEM correction methods on three critical natural scenarios affected by extensive flat areas, abrupt slope changes and large depressions, expressed in terms of: (1) geomorphological changes (affected area, elevation changes and slope changes); (2) flow velocity; and (3) width function (WF).

The standard Fill method adopts the simplest solution to the correction issue. Here all depressions are considered artifacts and are flooded to permit flow continuity. However, the treatment of flat areas is not included. The TOPAZ correction, on the other hand, performs a more complex function, although still geometric, also considering all depressions as false, as well as rendering the depression edge breached; in this case, the remaining sink is flooded and the generated flat area is treated by the looped addition of infinitesimal values. The selection of this method is based on the tendency to reduce the area of the depressions with the breaching technique, and it results in a DEM without flat areas after correction (Garbrecht and Martz, 1997). The PEM4PIT was selected for this study because it is the only method that adopts a physically based method to address the correction. The three methodologies are compared simultaneously for the first time.

Three basins were selected as representative of critical geomorphological conditions; one Cuban and two Italian. The Cuban basin is characterized by irregular relief, including: peculiar isolated hills having rounded and tower-like forms, known as Mogotes; large natural depressions; and an extensive interior valley. The two Italian basins have more regular landscapes; one hilly zone of around 20% slope along the basin extension, including a large natural depression; and an almost flat plain (majority of slope values less than 6%, with a predominance of 1% slope). The selected parameters, the affected area, as well as the changes in elevation and slope are expressions of the influences of each method over the terrain; the flow

Table 1
Selected study areas.

	Area (Km^2)	Location	Outlet Coordinates (E;N)	Reference System	Cell size (m)	Source
V_aniversario	131.2	Pinar del Rio, Cuba	199457; 294335	NAD 27 Cuba North	25 × 25	Interpolated DEM
Terranova	37.6	Basilicata, Italy	610906; 4425457	UTM 32	30 × 30	IGMI
Tuscania	24.1	Lazio, Italy	239483; 4690267	UTM 32	20 × 20	IGMI

velocity distribution and values represent the effect of those changes on the hydro-geomorphological basin characteristic, and the width function, i.e. the residency time distribution, represents the effect on the hydrological modeling results.

2. Materials and methods

2.1. Study areas

One Cuban and two Italian basins were selected (See Table 1) as natural representations of critical relief conditions. The Cuban basin, V Aniversario, is a location of agricultural and economic interest with an area of 131.2 km^2. The region contains some of the most peculiar geographic formations in Cuba, the "Mogotes", a term used for Karst hills, typically rounded, tower-like forms surrounded by nearly flat alluvial plains. This basin has a typically tropical climate with an average temperature of 25.1 °C and a yearly cumulative precipitation of 1770 mm.

The other two basins are located in Italy: the first, Terranova, is located in Basilicata, in southern Italy, and has an area of 37.6 km^2; it is characterized by an almost constant slope, descending around 1300 m from the upper divide to the outlet. Another characteristic of interest is a large natural depression in the center of the basin. The second basin, Tuscania, is located near Rome in central Italy and has an area of 24.1 km^2; it is characterized by a very low relief, with a large number of cells of slope less than 0.09%, equivalent to 41.2% of the basin area. The Italian basins have a typically Mediterranean climate with hot dry summers and mild wet winters.

The V Aniversario DEM was obtained by interpolation of digitized data from a 1:10000-elevation map, resulting in a 25 × 25 m resolution digital elevation model. The Italian Geographic Military Institute (IGMI, 2003) provided the two Italian DEMs. Terranova is characterized by cells of 30 × 30 m resolution, and Tuscania by cells of 20 × 20 m resolution. Our interest resides with the morphological characteristics of these basins. V Aniversario combines large plane areas, hills and Mogotes. Such conditions constitute a challenge for preprocessing techniques, testing the possibilities of the methods to deal, for example, with slope changes, especially around the Mogotes' edges, which tend to be nearly vertical. Tuscania is a flat region, largely affected by pits and nearly zero slope areas. Conversely, there are large natural closed depressions in both V Aniversario and Terranova, whose treatment could represent a source of error.

2.2. Methodologies: DEM correction methods

Three methods have been selected for comparison, representing the three main methodologies to address the correction process: Fill (Jenson and Domingue, 1988); TOPAZ (Martz and Garbrecht, 1999); and PEM4PIT (Grimaldi et al., 2007). A brief background is presented below.

In the Fill method, as mentioned before, pits and depressions are considered false as a result of underestimating the elevation at certain points. Therefore, depressions are filled, raising the elevation until it reaches the lower neighbour (Fig. 2). The result is a flat area, whose treatment is not included in the procedure. When the correction occurs in single cells, the effect does not affect the flow direction algorithm; however, the larger the number of continuous affected cells, the more the result of flow direction assignment will be affected.

For the TOPAZ method (Martz and Garbrecht, 1999), all depressions are regarded as spurious points, resulting from underestimation or overestimation of the elevation. This involves two possibilities: the occurrence of sinks by underestimation of elevation at certain points, or the presence of closed depressions, generated by a false wall for overestimation of height in some cell(s). The proposed solution consists of three steps.

First, the points where the flow direction assignment is not possible and at least one neighbouring cell has higher elevation are flagged. This step permits the separation of inflow sinks and flat areas, avoiding the treatment and consequent breaching of plane areas. The corresponding contributing area at each inflow sink is determined. If some edge cells of the inflow-sink contributing area have lower elevation neighbours on both sides, this area will be considered a closed depression to be breached.

The breaching algorithm is the second step. The edge points adjacent to a lower elevation cell outside the contributing area are selected as potential outlets. If more than one potential outlet is identified, then the one with the lowest elevation is selected. If the lowest elevation is shared, the one with the steepest slope out of the contributing area will be selected. Following these criteria, breaching is permitted only through an area of higher elevation that separates two areas of lower elevation. Additionally, the breaching length is limited to a maximum value of two cells in order to avoid breaching of any possible topographical feature. If all conditions are fulfilled, breaching takes place. Otherwise, the depression is simply filled.

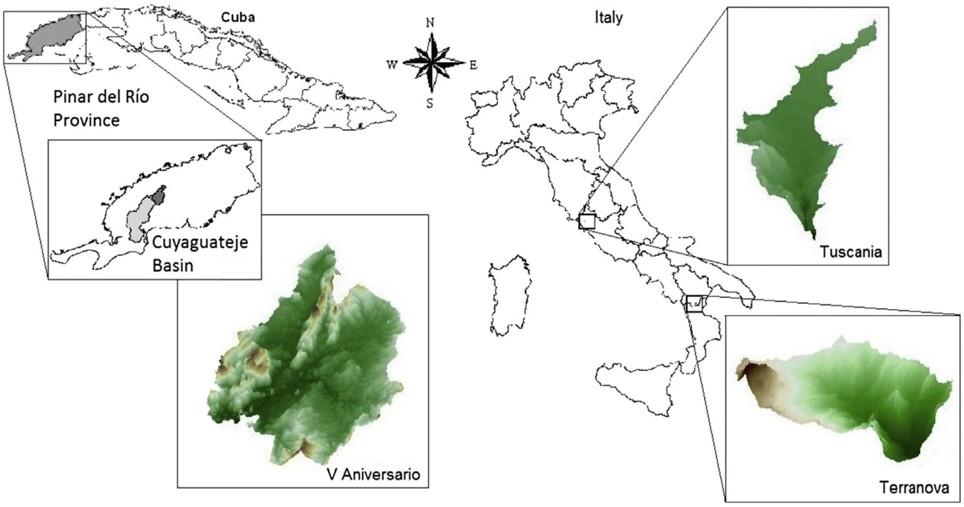


Fig. 1. Basin locations.

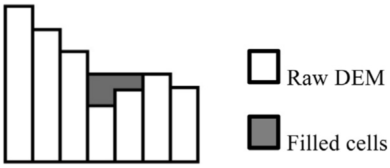


Fig. 2. Lateral profile of *Fill* application.

After the breaching process, some closed depressions might only be reduced, remaining partially unchanged. To complete the correction process, the remaining depressions, as well as depressions where breaching was not possible, are filled.

The TOPAZ procedure raises the elevation of cells inside the depression to the selected outlet elevation value. After that, the flat areas are treated by adding infinitesimally small values to the elevation at some cells; enough to allow the computer algorithms to assign the flow direction (Garbrecht and Martz, 1997). Adding values of 10^{-5} order, the elevations are incremented to generate into the filled area gradients toward lower terrain and forward higher terrain. The result is a DEM free of zero slope areas, where the flow direction can be defined at every cell. For further details see Garbrecht and Martz (1997) and Martz and Garbrecht (1999).

The PEM4PIT proposes a different solution, implementing the simplified physically based landscape evolution equation:

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

where U is the tectonic uplift rate, $\beta A^{\theta} S$ is the fluvial incision term, $D\nabla^2 z$ represents the erosion or deposition rate by diffusive processes depending on landscape shape, A is the contributing area at the site, θ is the scaling slope–area coefficient, β is the surface erodibility, and D is the hillslope diffusivity (Grimaldi et al., 2007). This method simulates the topographic surface evolution, assuming equilibrium between tectonic uplift and the sediment flows produced by fluvial erosion and overland diffusion. The model is able to provide a DEM free of pits and flat areas, without zero slope cells (Grimaldi et al., 2007).

2.3. Considerations in hydrological modeling

Hydrological modeling is an important component of integrated, collaborative, and adaptive water resources management (Rathinasamy et al., 2013; Straith et al., 2014; Butler and Adamowski, 2015; Inam et al., 2015), and is strongly related to the estimation of surface runoff behavior, expressed mainly by flow velocity values and their spatial distribution. In this respect, slope plays a major role in the more commonly used equations (e.g. Darcy-Weisbach, Manning, Soil Conservation Service (SCS), Maidment et al., 1996), being the only necessary parameter in some cases.

Slope is largely affected by DEM correction (Srivastava, 2000) because the change in elevation of just one cell as a consequence of the correction process can affect the slope at the chosen point as well as in some of the adjacent cells (often the eight neighbouring cells).

In this research, slope was calculated using the standard method implemented in many GIS software programs, both proprietary and open source. The method consists of assigning to every cell the average slope in eight possible directions.

Table 2
Slope Classes.

Class	Slope interval (%)	Class name
I	S < 1	Flat
II	1 ≥ S < 5	Slightly sloping
III	5 ≥ S < 10	Highly sloping
IV	10 ≥ S < 20	Steep
V	S > 20	Very steep

For a better understanding of correction effects, five classes of slope, presented in Table 2 (Sprenger, 1978), have been established.

The slope map after corrections is a determinant for the values of hillslope flow velocity, i.e. the velocity of the water flowing above the ground, and the WF structure. The hillslope velocity is defined as in Grimaldi et al. (2010), adopting the NRCS scheme and using the equation:

$$V_h = a\sqrt{S} \tag{2}$$

where V_h (m/s) is the flow velocity in the single hillslope cell, S is the cell slope (−), and a (m/s) is a coefficient related to soil use (McCuen, 1998). To reduce potential overestimation for $S > 0.04$, Eq. (2) is applied with (UDFCD, 1990):

$$S' = 0.05247 + 0.06363*S - 0.182e^{-62.38S} \tag{3}$$

To avoid unrealistic values, a further reasonable condition is applied, limiting the resulting velocity values to within an acceptable range of $0.05 \le V_h \le 2$ m/s (Piscopia et al., 2015).

The adopted methodology for river network extraction is described in this section. The flow routing was performed based on the previously calculated slope map using an optimized single flow direction algorithm (Nardi et al., 2008). This algorithm consists of a conservative D8-based model in the channel cells, but avoiding the grid-bias and the inability of the original D8 approach to represent actual hillslope processes. In particular, the estimation of flow direction (FD), contributing area (CA), and flow length (FL) were performed using the D8 model for stream network cells and the D∞ dispersive flow path model for hillslope areas (Petroselli and Fernández Alvarez, 2012).

River network cells were determined using the curvature-based scheme in conjunction with the automated constant drop analysis algorithm for the identification of the channel initiation threshold (Tarboton et al., 1991). The Width Function (WF), which represents the travel-time probability density function, is defined here according to (Grimaldi and Petroselli, 2014):

$$WF(t)\frac{L_c(x)}{V_c(x)} + \frac{L_h(x)}{V_h(x)} \tag{4}$$

Where L_h and L_c are the hillslope and channel flow path function of the DEM cell x, respectively, and V_h and V_c are the hillslope and channel flow velocities, respectively. In the previous equation V_h is estimated using [2] while V_c, which represents the only calibration parameter (Grimaldi et al., 2012a), is calculated assuming that the center of the mass of the WF is equal to the basin lag time. It is noteworthy that it is also possible to calibrate WF so that its base time is equal to the basin concentration time, but we prefer to consider the lag time because of the high variability of the concentration time (Grimaldi et al., 2012b). From a practical standpoint, the WFs have been calculated using the recently published software EBA4SUB – Event Based Approach for Small and Ungauged Basins (Piscopia et al., 2015).

2.4. Elements of comparison

To investigate the effect of the correction methods, the results were analyzed in terms of affected area, elevation changes, slope changes and the distribution of velocity values. These elements permit an evaluation of the geomorphological transformations as direct consequences of the correction process without the application of hydrological modeling.

The direct impact over the DEM is presented as affected area (Fig. 3) and the transformed volume corresponding to those areas, together with some statistical description (minimum, maximum, average and standard deviation) and the correlation coefficient for affected areas between raw DEMs and corrected DEMs (Table 3).

The percentages of pits and flat areas after correction, and the statistical description of slope, are presented in combination with the slope class distribution, which represents the proportion of every single slope class over the DEM before and after corrections (Table 4). Velocity values across the basin are described through statistical summary (Table 5), frequency distribution of velocities (Graph 1) and spatial distribution maps (Fig. 4). Results regarding the river network extraction and the WF are presented as expressions of the influence of correction methods on hydrological modeling. The extracted river networks are visually compared with the digitized ones, and the WFs are compared between each other, incorporating the residence time distribution, and the position and intensity of peaks.

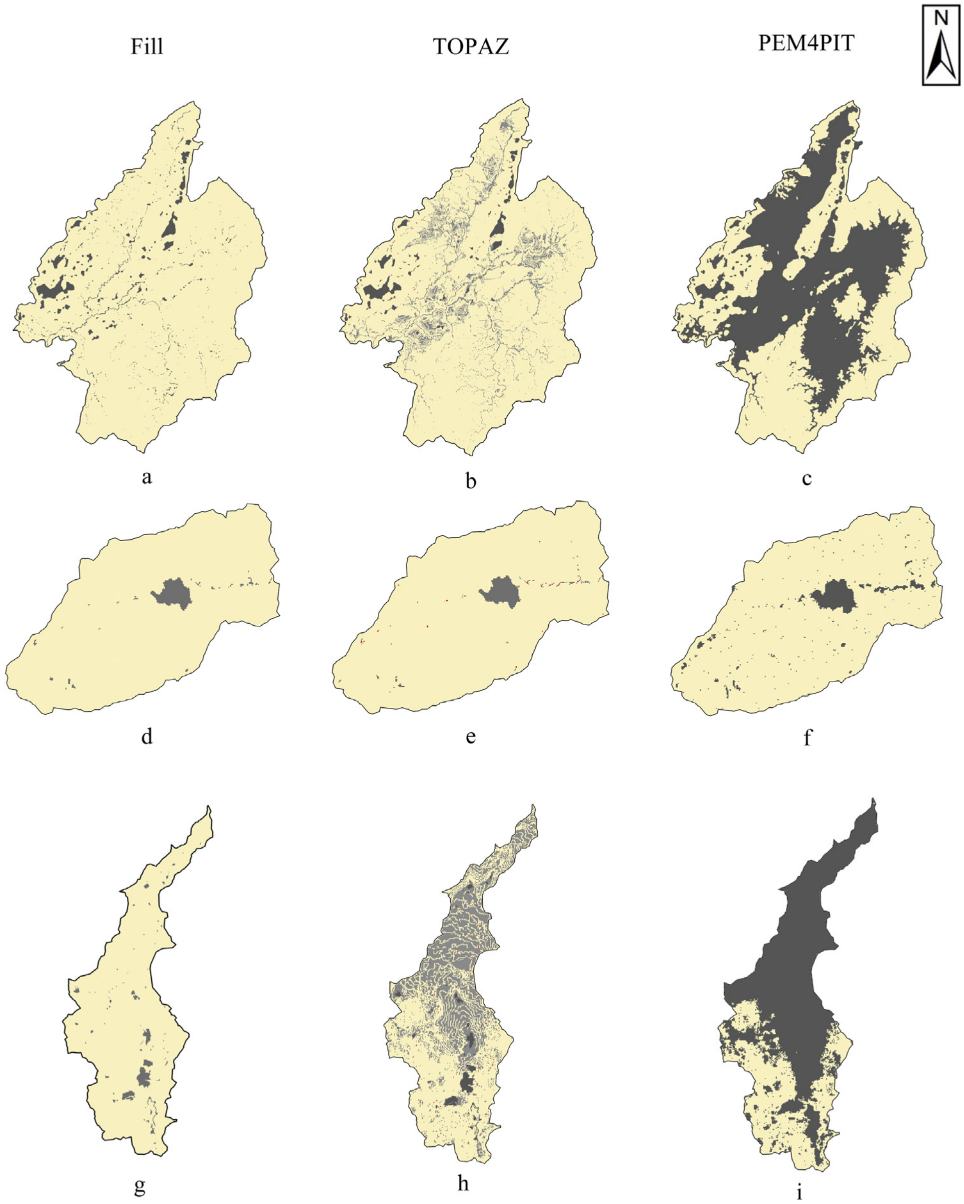
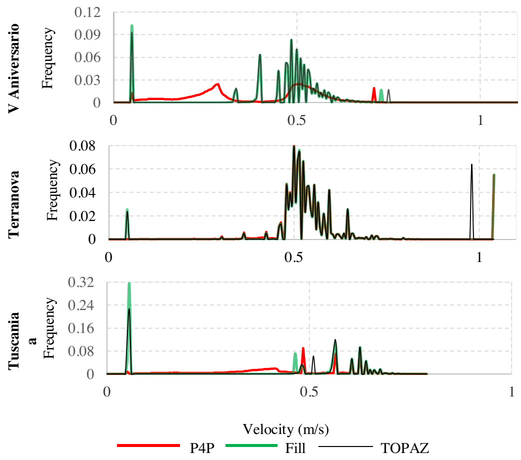


Fig. 3. Maps of transformed areas resulting from the correction process (a–c) V Aniversario; (d–f) Terranova; (g–i) Tuscania. (Beige: area not transformed; Gray: areas of elevation increased (Light gray: areas of elevation increased by less than 0.001m); Red: areas of decreased elevation).

3. Results and discussion

3.1. Transformations of area and volume

Regarding the affected area and the volume associated with the transformation, it is possible to see from Table 3 that the largest spatial influences were produced by PEM4PIT in each case study. Fig. 3 shows the spatial distribution of these changes. From Fig. 3(b, e, h), the results of the two components of the TOPAZ method can be observed: the correction of depressions and the treatment of flat areas. Regarding the correction process, in all three cases of the TOPAZ application (Fig. 3b, e, h), it can be seen that there is an increase in the elevation inside the depression, as well as a reduction in the elevation in one or two cells on the edge of the depression. Through the combination of these techniques, in several cases, TOPAZ performs the correction, locally affecting the smallest area possible. This effect can be seen, comparing the correction of isolated depressions, through visual inspection of the three cases studies (e.g. independents depression in the west region of Tuscania Basin Fig. 3d–f). Regarding the treatment of flat areas, Fig. 3(b, h) shows extensive areas of V Aniversario and Tuscania, where the elevation was increased less than 0.001 m by TOPAZ. The technique of cyclic increments of 10^{-5} order



Graph 1. Frequency distribution of velocities.

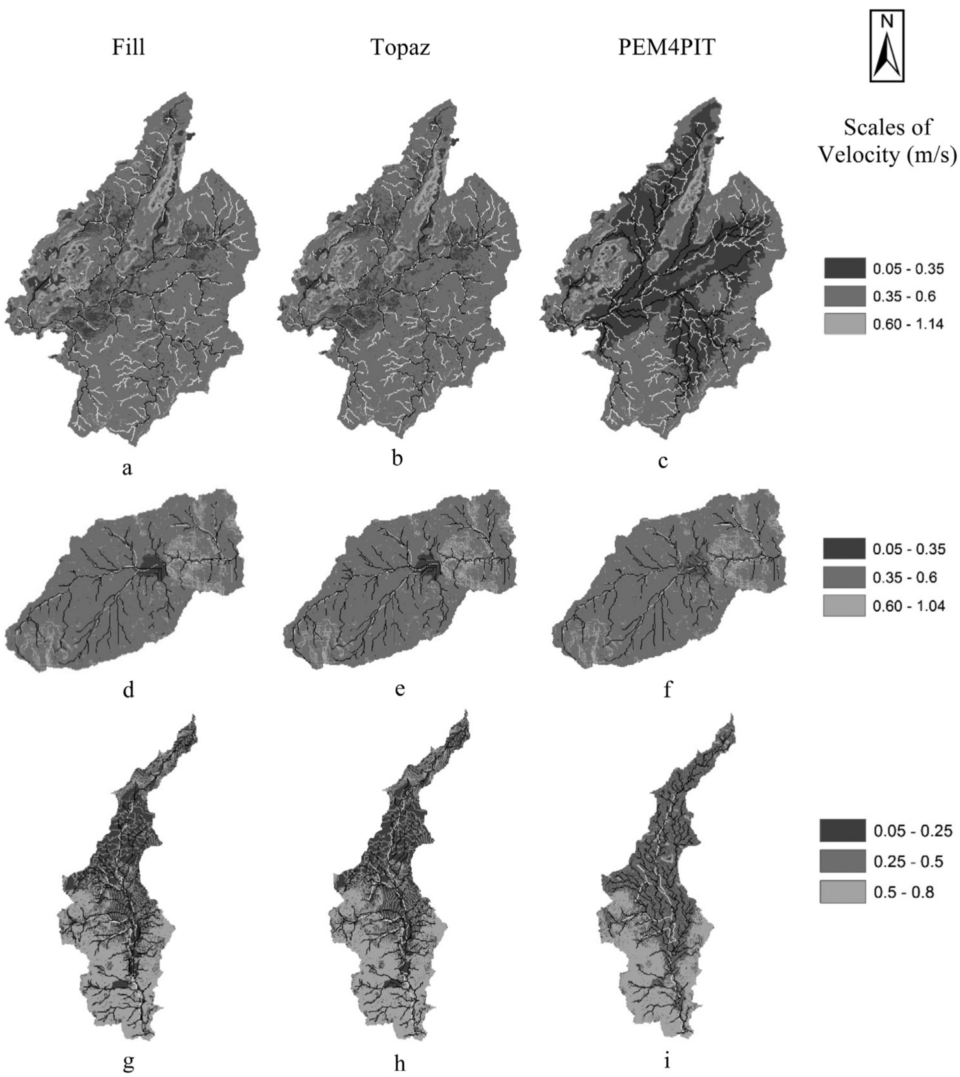


Fig. 4. Spatial velocities distribution (a–c) V Aniversario; (d–f) Terranova; (g–i) Tuscania (solid white: Digitized Network; solid black: Extracted Network).

Table 3
Statistical description of elevations and correlation coefficients for the transformed areas.

		Statistical description of elevation				Transformations		R^2 Coeff.
		Min.	Max.	Aver.	Stdrd. Dev.	Area (%)	Volume (10^6 m^3)	Transf. Area
V Aniversario	Raw DEM	86.5	453	170.5	63.43	–	–	–
	Fill	86.5	453	170.9	63.45	4.18	62.72	0.959
	TOPAZ	86	453	170.4	63.40	6.72	48.55	0.967
							−0.625 47.92	
	PEM4PIT	86.5	453	179.3	57.26	47.88	1147.18	0.895
Terranova	Raw DEM	725	2050	1295	256.46	–	–	–
	Fill	725	2050	1295.8	255.62	2.53	29.15	0.989
	TOPAZ	725	2050	1295.8	255.64	2.56	28.09	0.986
							−0.15 27.94	
	PEM4PIT	725	2050	1296.2	255.27	4.82	44.08	0.995
Tuscania	Raw DEM	75	227	147.38	20.57	–	–	–
	Fill	75	227	147.47	20.44	2.87	2.30	0.963
	TOPAZ	75	227	147.47	20.45	30.02	2.15	0.994
							−0.06 2.09	
	PEM4PIT	75	227	152.43	19.31	67.63	121.84	0.969

Table 4
Qualitative description of the slope transformation.

		Statistical description of slope				Pit (%)	Slope Zero (%)					
		Min	Max	Mean	Stand.Dev.			I	II	III	IV	V
VAniversario	Raw DEM	0.6^*10^{-3}	249.4	20.3	20.2	0.59	0	3.1	19.8	16.1	23.3	37.7
	Fill	0	249.9	19.6	19.9	0	3.4	4.9	19.7	16.1	23.3	36.4
	TOPAZ	0	249.9	19.7	19.9	0	4^*10^{-2}	4.8	19.1	16	23.3	36.8
	PEM4PIT	0.1	249.4	15.9	20.7	0	0	29.8	17.7	6.3	14.5	31.7
Terranova	Raw DEM	0	158.2	29.1	17.3	0.19	4^*10^{-3}	0.05	1	3.3	29.7	65.9
	Fill	0	158.2	28.5	17.6	0	1.8	1.9	1.2	3.4	29.1	64.5
	TOPAZ	0	158.2	28.6	17.6	0	0.9	1.8	1.1	3.4	29.1	64.6
	PEM4PIT	0.14	158.2	28.2	17.5	0	0	0.6	2.9	3.8	29	63.6
Tuscania	Raw DEM	0	62.5	4.8	5.5	0.6	18	25.2	41.8	18.4	12	2.5
	Fill	0	62.5	4.6	5.4	0	21.4	28.3	40	17.9	11.5	2.4
	TOPAZ	0	62.5	4.6	5.4	0	0.19	27.7	40.9	17.5	11.5	2.4
	PEM4PIT	0.04	44.6	4	5.0	0	0	31.1	42.4	15.1	9.7	1.8

Table 5
Velocity (m/s) map statistics.

		Velocity Channel	Velocity Hillslope		Mean	Stand. Dev.
			Min	Max		
V Aniversario	Fill	0.73	0.05	1.14	0.46	0.15
	TOPAZ	0.75	0.05	1.14	0.45	0.15
	PEM4PIT	0.71	0.05	1.14	0.4	0.17
Terranova	Fill	1.04	0.05	1.04	0.55	0.15
	TOPAZ	0.98	0.05	0.98	0.55	0.14
	PEM4PIT	1.04	0.05	1.04	0.56	0.13
Tuscania	Fill	0.47	0.05	0.79	0.38	0.25
	TOPAZ	0.49	0.05	0.79	0.39	0.26
	PEM4PIT	0.49	0.05	0.79	0.43	0.16

of magnitude permits the TOPAZ method to address flow in flat areas, with a minimum of changes to the original DEM. Conversely, for the same flat areas of V Aniversario and Tuscania, the PEM4PIT method increased the elevation throughout the region, to create an extensive and continuous downward slope (Fig. 3c, i), while the use of the Fill method did not result in any changes to the elevation (Fig. 3a, g).

From the statistical description, the largest changes occur in the average elevation values in V Aniversario and Tuscania performed by PEM4PIT, which increased by 9 and 5 m, respectively. Similarly, higher changes in volume correspond to PEM4PIT. In V Aniversario, for example, while Fill and TOPAZ transform volumes of 62.72×10^6 m^3 and 48.55×10^6 m^3 respectively, PEM4PIT transforms a volume of 1147.18×10^6 m^3. These results are consistent with the physics of the method. While the mathematical methods correct a limited area defined by the extension of the depressions, PEM4PIT works to adjust the correction to the outskirts in an effort to simulate erosive processes, increasing the number of affected elements. This behavior leads to the misinterpretation of both the steepest regions surrounding the Mogotes in V Aniversario, where the PEM4PIT corrected the whole interior valley equivalent to 47.88% of the basin area and the large flat regions where erosion is not a predominant phenomenon, shown in the correction of 67.63% of the Tuscania basin extension.

The R^2 coefficient pertaining to the affected cells was higher for TOPAZ on V Aniversario and Tuscania (0.967 and 0.994, respectively), and for PEM4PIT on Terranova (0.995). The best correlations of TOPAZ on V Aniversario and Tuscania, are consistent with the treatment of the extensive flat areas in both basins (Fig. 3b, h), and show the capability of the method to deal with this critical condition. The result of just 4.82% of the affected area, and the high correlation coefficient for PEM4PIT for Terranova, indicates the suitability of simulated erosive processes instead of mathematical procedures to correct depressions within the steepest region. It is noteworthy that the Fill method affects the minor areas in all cases, however, in no cases does it produce the highest correlation coefficient.

3.2. Slope

From the quantitative description of slope (Table 4), it can be observed that the three correction methods are able to remove all pits in each case study. There are, however, some differences regarding the flat area treatment and the redistribution percentage of cells within the established classes of slope.

Observing the statistical description, it is evident that the principal differences correspond with PEM4PIT on V Aniversario and Tuscania. The mean slope of V Aniversario changes from 20.28 to 15.94%. In the case of Tuscania, the maximum slope decreases from 62.5 to 44.6%. These results are consistent in both basins, with the large affected area and the landscape smoothness produced by the physically based method PEM4PIT.

Comparing slope class distribution after correction, it is possible to see that the mathematical methods, Fill and TOPAZ, produce very similar results in each case, both between one another and with respect to the raw DEM. It is noteworthy, however, that the Fill method generates new flat areas after correction. By direct observation, the flat areas when using the Fill method are grouped in continuous regions, representing a source of error for the flow direction assignment. In the case of TOPAZ correction, the zero slope areas generally correspond with individual cells.

The new distributions of slope produced by PEM4PIT on V Aniversario and Terranova basins describe the large transformations along those regions. In the case of V Aniversario, the increase in the first class from 3.1 to 29.8%, and the reduction of the other four classes, at around 10% differences for classes III and IV, reflect the leveling of the large affected area. In the Terranova basin, the first class is augmented from 25.2 to 31.1%, and the second from 41.8 to 42.4%, which together make up a landscape with 73.4% of the total extension with slope less than 5%.

3.3. Velocity and river network

With the imposition of the minimum hillslope velocity of 0.05 m/s, it is possible to obtain similar velocity statistics between corrections for each case study. From Table 5, some differences of mean and standard deviation can be noted. However, the frequency distribution (Graph 1), the maps of spatial distribution of velocities and the river network structure (Fig. 4) show some dissimilarity between the three study cases.

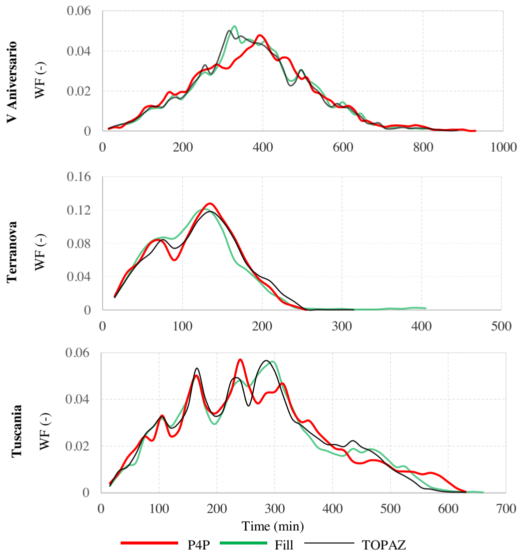
The statistical description of the Tuscania basin (Table 5) shows that PEM4PIT generates a mean of 0.43, versus 0.38 and 0.39 from Fill and TOPAZ, respectively. The standard deviation of this basin is affected as well by PEM4PIT, diminished by 0.10 with respect to Fill and TOPAZ. The large transformations by PEM4PIT on V Aniversario are not clearly expressed by the statistical description of velocity, rendering the maps of spatial velocities distribution and the frequency distribution graphs more interesting.

The frequency distribution of V Aniversario (Graph 1) shows the curves of the numerical methods Fill and TOPAZ characterized by multiple peaks, while the physically based method PEM4PIT presents a smooth curve with only two peaks. Fig. 4c shows the interior valley of V Aniversario grouping together the lowest velocities after PEM4PIT correction, which explains the shape in the frequency distribution and the river network incongruities. The river networks extracted in V Aniversario with Fill and TOPAZ corrections have better visual matching than the digitized versions. In hills, however, all three river networks have similar shapes.

Regarding the velocity of the Terranova basin, it is possible to assess the general similarities between the three correction results on both the frequency curves and spatial distributions. It should be noted, however, that peaks of low velocities in the Fill and TOPAZ frequency curves – associated with null slope and very low slope (in the order of 10^{-5}) areas, respectively – are generated after the correction of the central natural depression that characterizes the Terranova basin. The PEM4PIT does not show this kind of result because of the natural gradient imposed on the large depression.

The river network structure throughout the central depression of the Terranova is influenced by the aforementioned differences in slope values between correction results. This can be observed in the unrealistic parallel stream lines over the flat surfaces generated by Fill. The stream extracted with TOPAZ correction shows a winding line from higher elevation to the center, and parallel patterns from the center to the depression outlet. The result of PEM4PIT shows a more winding network structure and better visual matching with the digitized network according to the natural gradient imposed during correction.

For the Tuscania basin, the three curves of velocity frequency correspond well for values greater than 0.6 m/s, and mismatch in the interval from 0 to 0.6 m/s, showing different results in flat area treatment between methods. The Fill method creates extensive zero slope surfaces, influencing the frequency curve with peaks of minimal values of velocity. The TOPAZ method creates very low slope areas, which, after the application of the velocity equation, are indistinguishable, resulting in



Graph 2. Width function.

a peak of minimal velocity in the frequency curve. PEM4PIT simulates erosive processes along the large flat extension, from where it is possible to assume the velocity distribution from 0 to 0.6 m/s and the river network through the valley as not representative of Tuscania basin hydro-geomorphology. Similar behavior can also be observed regarding the velocity spatial distribution and river network structure in the steepest area, located at the south end of the basin (See 3D in Fig. 1). The results from this area may justify the similarities between the three methods for values greater than 0.6 m/s in the frequency curve.

3.4. Width function

In the case of the V Aniversario watershed, the three WFs (Graph 2) appear similar but display variations in their peaks in terms of position and intensity, which could affect hydrological modeling in terms of peak discharge.

In the Terranova river basin, the three WFs are quite similar; the major difference is a long tail for the DEM corrected with Fill, translating to a small area characterized by long residence times. This circumstance is due to the points representing small or null slopes and the consequent assignment of lower thresholds for hillslope velocity. It is noteworthy that the calibration of the WF based on the lag time results in a similar base time that is positive for hydrological modeling subjected to any selected DEM correction method. The adoption of a specified and constant channel velocity for all three DEMs would have increased the differences in the three WFs since the base times would have differed as well.

For the Tuscania basin, the three WFs again appear quite similar with some variation between them. However, the general shape of the basin is preserved and expressed by the residence time distribution. This result appears sound since the WF is a lumped characteristic of the basin, and able to overcome local topographic differences.

The results confirm the frequently discussed behavior of the Fill method (e.g. Grimaldi et al., 2007; Arnold, 2010), showing how it concentrates changes into depression areas, introducing zero slope surfaces after correction and some regions of minimum velocity and unrealistic patterns when the river network is extracted. These situations can affect hydrological modeling results proportional to the extension of the depressions. From a computational point of view, however, since the flow direction algorithms are not affected by a single cell with zero slope, the Fill correction is the simplest and most practical solution to correct depressions the size of one cell; especially considering the increase in availability of higher resolution DEMs, where each cell represents a smaller area.

TOPAZ seems to be a very adaptable method, able to correct depressions in all relief conditions, and performing smaller changes in elevation than the other two methods, even when large areas are affected in the process. It must be considered, however, that in the case of large depressions, it can produce similar results to the Fill method regarding velocity values and network patterns. This is due to the addition of infinitesimal values to permit flow through the depressions. This characteristic could represent an advantage in correcting depressions, whether real or not, if they are located in a low slope region. When depressions are located on hills, however, an unnatural and contrasting gradient with respect to the environment will be imposed, in which case this would not be the most suitable result.

Considering all case studies, the physically based PEM4PIT method generates unrealistic relief patterns when correcting both interior valleys and large flat extensions, where the imposition of a gradient by the simulation of erosive processes is not coherent with the landscape. Although, when the PEM4PIT performs the correction on regions of regular slope from medium to high, it shows spatial distribution of velocity values and river network patterns more coherent with the landscape, particularly for large depressions located on hills.

4. Conclusions

In an effort to gain a better understanding of depression treatment techniques in DEM preprocessing, the behavior of the standard (*Fill*) and two advanced (*TOPAZ and PEM4PIT*) DEM correction methods was analyzed on three critical natural scenarios affected by extensive flat areas, abrupt slope changes and large depressions. The disadvantages of Fill correction have been confirmed, the application of one of the advanced methods being more suitable (TOPAZ or PEM4PIT) for the natural scenarios analyzed in this paper.

After having compared the two selected advanced methods for the first time, highlighting advantages and drawbacks of both methods, we can conclude that the suitability of each correction method depends on the predominating basin relief, as well as the size of the depressions. Considering that the majority of basins combine diverse topographic conditions in different proportions, one preferred method among those compared cannot be chosen which can be applied to each basin. However, the TOPAZ method seems to be preferable for correcting depressions in areas of irregular relief as well as flat regions, while PEM4PIT is preferable for correcting depressions located in regions of medium slope.

These results can lead to understanding the correction process as a classification problem, since for particular combinations of relief and depression characteristics, mathematical methods can constitute more versatile and simple solutions. For others, physically based correction methods may be more suitable from a hydrological point of view. It would be interesting to consider the development of an algorithm capable of grouping depressions, to be corrected using the most suitable method for each group. This kind of tool could provide researchers and analysts with a more versatile tool, particularly in hydrological applications.

Conflict of interests

There is no conflict of interest with this paper.

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