

1. Introduction

Depressions (Fig. 1a) and flat areas in Digital Elevation Models (DEMs) are considered spurious features that, for hydrological applications, have to be removed from the raw data in order to define the direction of water flow on the surface. Such artifacts can derive by: i) interpolation methods used to produce the DEM starting from point data; ii) the truncation of elevation values to switch from real to integer precision; iii) issues related to indirect methodologies (e.g. air- and spaceborne sensors) adopted to acquire elevation data; iv) the application of the traditional and most diffuses procedures (i.e. *flooding*) able to remove pits but not flat areas: this consists in filling depressions until reaching the elevation of their lowest surrounding, obtaining a flat surface (Fig. 1b). After correcting the DEM the stream network can be extracted using different techniques (Nardi et al., 2008).

The main drawback of the common correction procedure is that it simulates an unrealistic channel network composed by straight and parallel stream links (Fig. 1c).

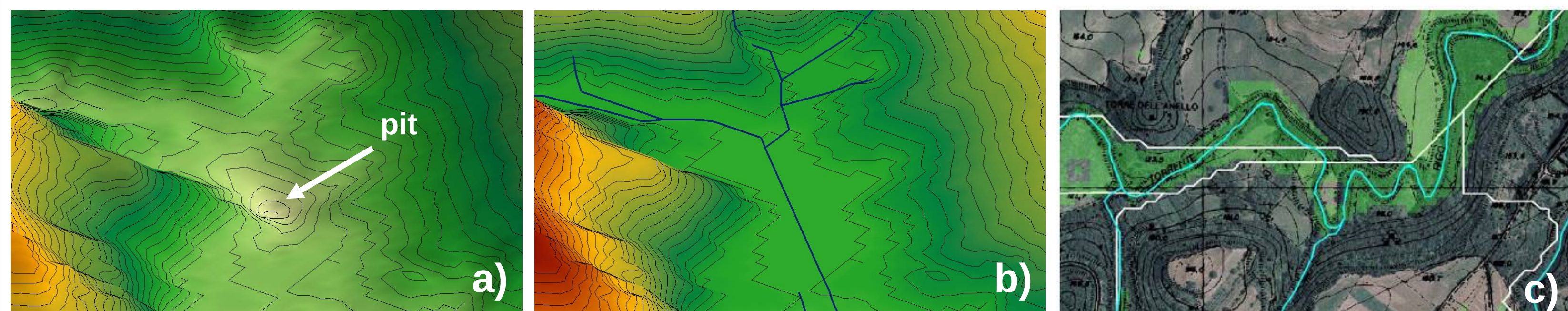


Fig. 1 – a) Example of pit; b) Correction of the pit in a) by the standard flooding procedure and extraction of the stream network; c) Comparison between the simulated stream network by flooding (white line) and the true one (blue line) (Nardi et al., 2008).

Despite *flooding* procedures resolve and eliminate pits, allowing the flow direction delineation according to the Jenson and Domingue's algorithm (1988), nevertheless a lot of uncertainties arise in selecting the flow direction inside flat spots because of their strong increase after *flooding*.

Basin (m)	Source	Resolution (m)	Precision	Area (km ²)	Pit (%)	(%) flat areas before <i>flooding</i>	(%) flat areas after <i>flooding</i>
Montana	NED	30	Float	83.62	2.86	0.48	12.15
Naja	IGMI	20	Integer	12.01	0.16	5.97	10.49
Ortacesus	IGMI	25	Float	210.53	0.17	7.09	9.66
Padru	IGMI	25	Float	78	0.14	2	3.88
Pastena	IGMI	40	Integer	40.91	0.12	3.42	20.54
Terranova	IGMI	30	Integer	37.61	0.07	0.91	3.42
Torres	IGMI	25	Float	44.22	0.12	13.84	16.73
Tuscania	IGMI	20	Integer	24.14	0.15	36.93	40.42
Vernon	NED	30	Float	264.95	1.09	6.32	

Tab. 1 - Basins analyzed by Nardi et al. (2008) and their occurring of spurious features.

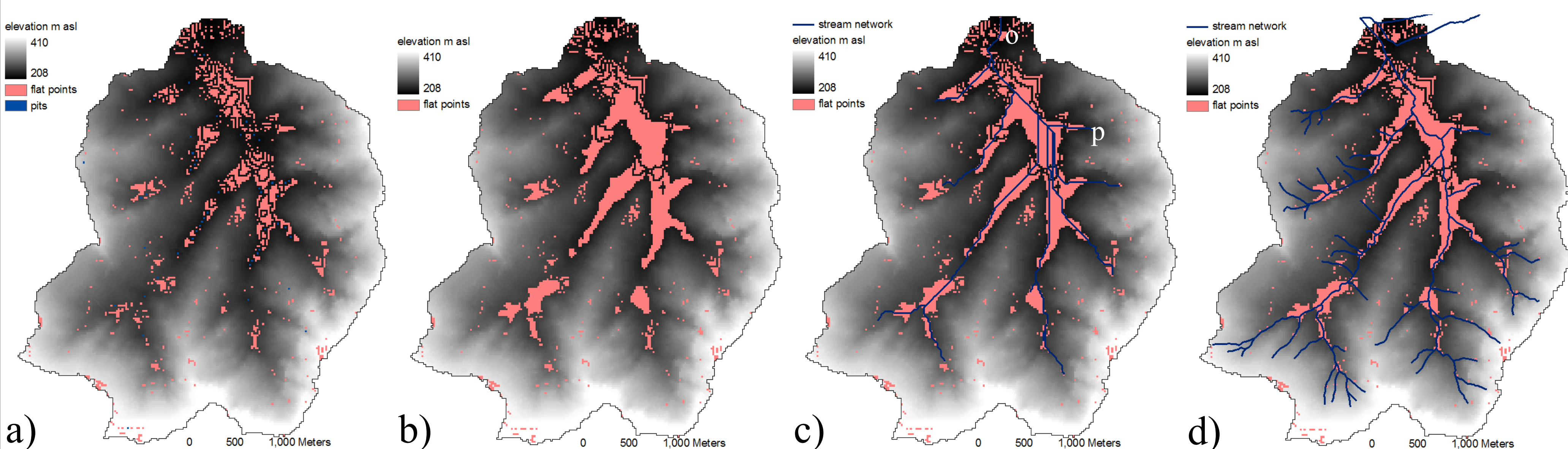


Fig. 2 - a) Distribution of pits (0.16%) and flat areas (5.97%) for the raw DEM of Naja basin (Italy); b) distribution of flat areas (10.49%) over the same DEM after applying the flooding procedure; c) stream network extracted after delineating flow direction by Jenson & Domingue's (1988) approach; d) true stream network obtained by digitizing topographic map at scale 1:25000.

2. The PEM4PIT

The PEM4PIT (Physical Erosion Model for PIT and flat areas correction, Grimaldi et al., 2007) was recently introduced to resolve the pit/flat area issue. It simulates the topographic surface evolution assuming the equilibrium between the tectonic uplift and the sediment flows produced by fluvial erosion and overland diffusion, using the following equation:

$$0 = U - k_e A^{\theta} \left(\frac{z - z_d}{\Delta l} \right) + \frac{4k_d}{\Delta x^2} (\bar{z} - z) \quad (1)$$

U [LT⁻¹] is the tectonic uplift
 k_e [L^{1-2θ}/T] is the soil erodibility
 A [L²] is the contributing area of the considered DEM cell
 z [L] is the elevation of the considered DEM cell
 z_d [L] is the elevation of the downstream cell
 Δl [L] is the horizontal distance between z and z_d cells
 θ is the exponent of the slope-area relationship (0.2-0.7)
 k_d [L²T] is the diffusivity coefficient
 $\bar{z}$ [L] is the average among the elevations of its four adjacent cardinal cells
 Δx is the cell resolution

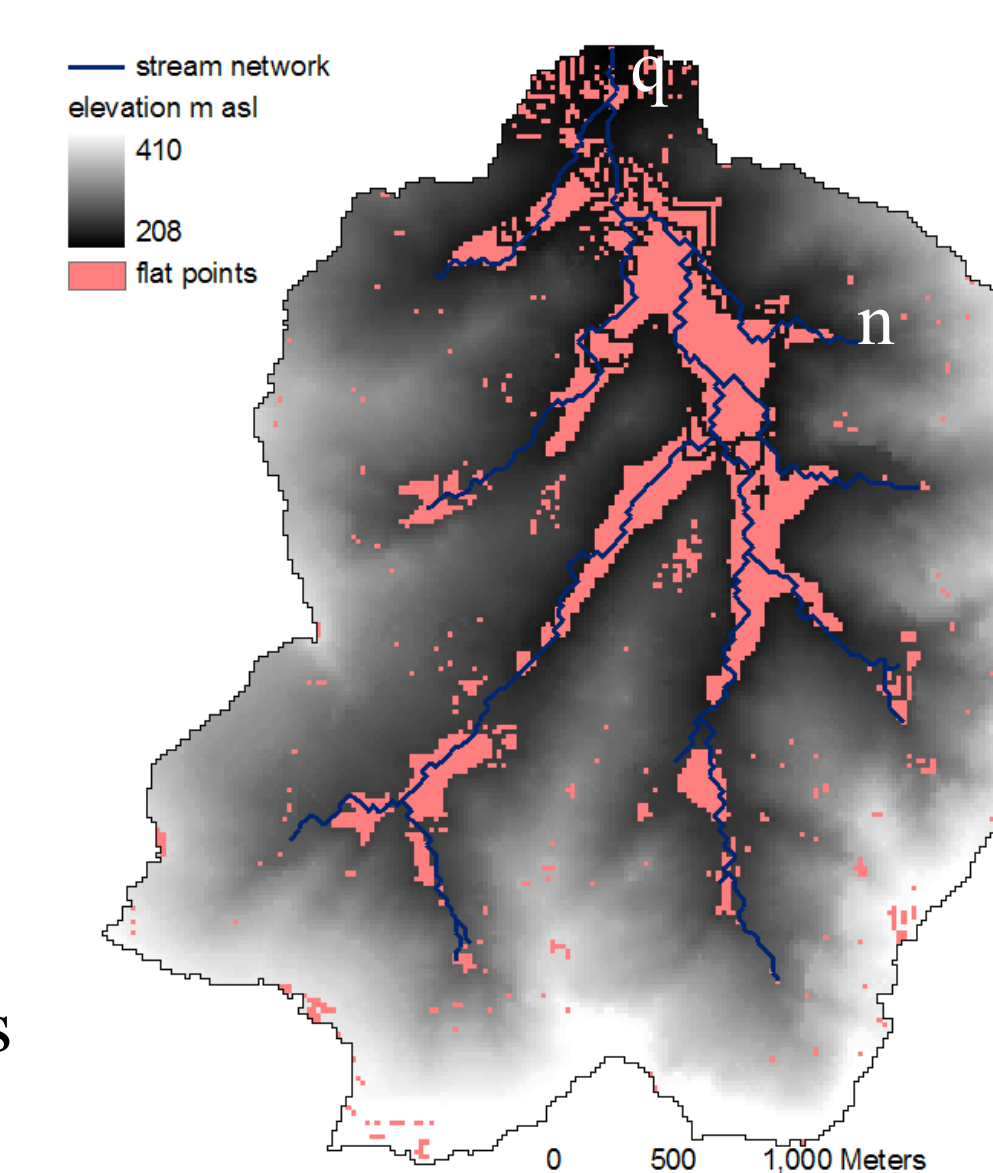


Fig. 3 - Stream network extracted after applying PEM4PIT and delineating flow direction by D8 scheme from the O'Callaghan & Mark's (1988) approach over the same DEM than in Fig. 2.

PEM4PIT starts from Eq.(1), normalizing it by U (tectonic uplift is considered spatially invariant at the basin scale), to correct iteratively all the points with null or negative slope. Eq.(1) becomes:

$$z = \frac{1 + \frac{\beta A^{\theta}}{\Delta l} z_d + \frac{4D}{\Delta x^2} \bar{z}}{\frac{\beta A^{\theta}}{\Delta l} + \frac{4D}{\Delta x^2}} \quad (2) \quad \begin{matrix} \beta = k_e / U \\ D = k_d / U \end{matrix}$$

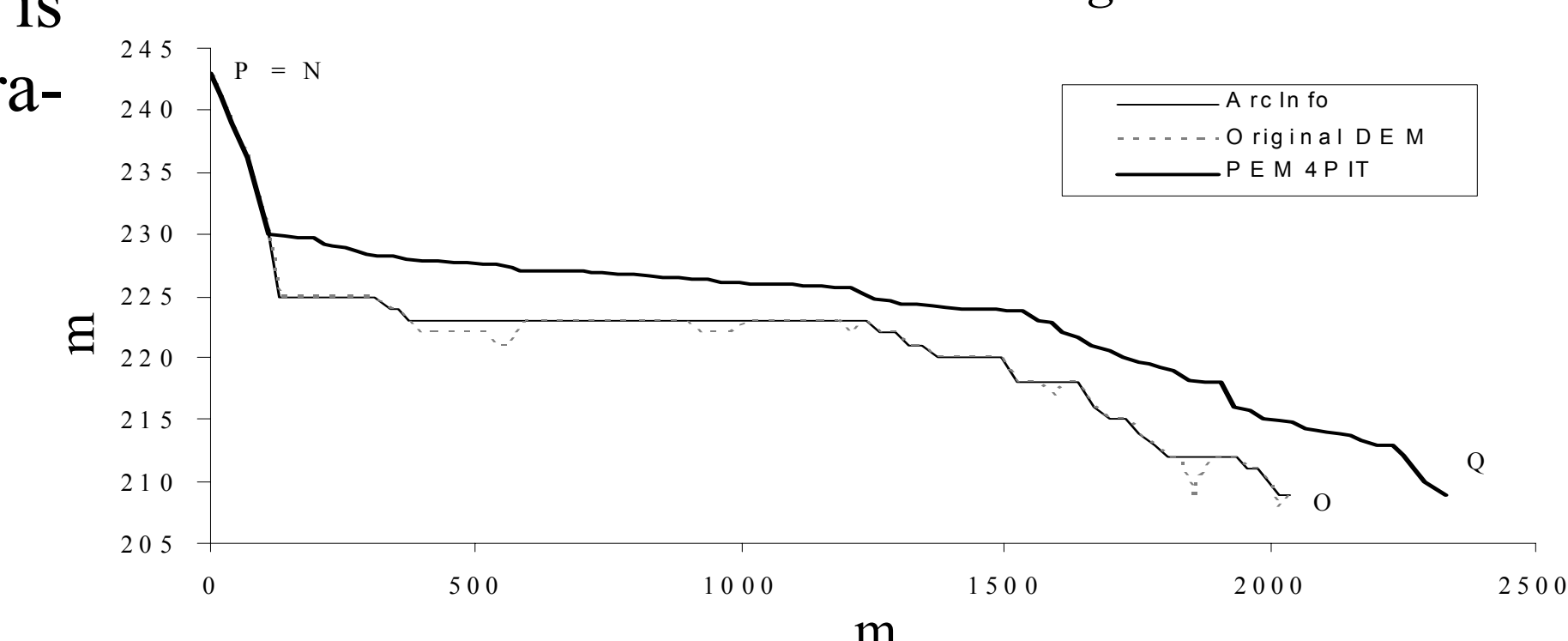


Fig. 4 - Altimetric profiles of the links P-O (Fig. 2c) and N-Q (Fig. 3) as compared to the profile extracted from the original DEM.

3. The flat area issue

In order to assess the terrain analysis procedure which performs better in correcting DEM and representing the stream network in terms of metrics and geometry, Nardi et al. (2008) carried out a deep study focused on flat spots. Different combinations of DEM correction techniques (DEMC) and single flow direction (SFD) delineation methods were considered.

	DEMC	J&D	O&M-D8	Orl	Rho8	O&M-D8	G&M	Rho8	O&M-D8	PEM4PIT	Digitized
	SFD	D8	D8-LTD	D8	D8	D8-LTD	D8-LTD	D8	D8-LTD	D8-LTD	D8
MONTANA	Count	43	66	68	67	64	67	59	98	100	100
	Dd	2.24	1.97	1.97	1.97	1.95	1.98	1.93	2.2	2.2	2.42
	Max	840	424.3	424.3	424.3	212.1	212.1	212.1	212.1	212.1	240
	Mean	131.9	75.3	73.3	74.4	77	74.8	82.7	86.8	85.6	61.7
	SD	166.3	77.1	73	75.2	49.9	47.6	46.5	40.7	38.8	40.7
NAJA	Count	37	54	53	53	52	49	49	118	121	118
	Dd	5.21	4.71	5.02	4.94	4.2	4.15	4.15	6.26	6.18	6.26
	Max	520	300	300	300	1203	1203	1203	240.4	226.3	240.4
	Mean	109.1	67.5	73.4	72.2	62.6	65.6	65.6	41.1	39.4	41.1
	SD	126.6	68.1	69.9	69.1	51.8	50.8	51.8	35.7	31.1	42.3
ORTACESUS	Count	62	175	194	179	155	157	147	372	379	363
	Dd	1.19	1.29	1.32	1.31	1.19	1.17	1.15	2.34	2.33	2.32
	Max	1675	548	530.3	654.1	742.5	742.5	742.5	335.9	335.9	335.9
	Mean	178.7	68.9	63.5	68.6	71.2	69.6	73	58.7	57.5	59.8
	SD	351.3	73.1	68.3	76.6	83.3	84.1	86.5	49.3	47.4	49.4
PADRU	Count	58	128	132	128	58	55	58	142	145	144
	Dd	3.03	2.84	2.86	2.78	2.35	2.33	2.35	3.86	3.87	3.91
	Max	1225	247.5	176.8	176.8	530.3	530.3	530.3	247.5	247.5	212.1
	Mean	186.6	47.9	48.8	47.6	87.4	91.3	87.5	58.7	56.6	58.7
	SD	285.8	32.7	28.6	27.1	100.3	109.3	95.6	42.1	40.9	42.5
PASTENA	Count	13	10	10	10	28	28	24	107	111	122
	Dd	1.27	1.28	1.28	1.28	1.24	1.25	1.2	2.38	2.36	2.45
	Max	1527.3	1563.9	1563.9	1563.9	1244.5	1244.5	1244.5	339.4	339.4	440
	Mean	418.8	547.4	547.4	547.4	547.4	547.4	547.4	81.2	81.2	88.1
	SD	478.2	510.1	510.1	510.1	276.7	276.8	293.4	73.4	69.3	66.3
TERRANOVA	Count	103	101	94	102	122	118	125	178	182	176
	Dd	4.39	4.35	4.13	4.09	4.62	4.51	4.58	5.43	5.34	5.21
	Max	670	870	870	870	381.8	381.8	480	297	300	300
	Mean	89	90	91.9	83.9	79.1	80	76.6	63.8	61.3	61.8
	SD	113.9	115.5	121	114.5	68.4	74	72.7	47.6	49	49.4
TORRES	Count	98	140	146	141	128	129	125	280	286	275
	Dd	4.45	4.25	4.25	4.22	4.08	3.88	3.89	5.71	5.53	5.61
	Max	1300	575	575	575	353.6	353.6	353.6	282.8	282.8	282.8
	Mean	114.4	76.5	73.4	75.4	81.8	71.9	78.5	51	48.7	51
	SD	165.6	86.6	86.4	87.1	71.2	65.3	69.1	36.2	34.3	35.2
TUSCANIA	Count	53	64	64	60	121	125	119	192	194	193
	Dd	1	1.21	1.2	1.2	1.62	1.62	1.54	1.94	1.98	1.93
	Max	580	367.7	367.7	600	254.6	254.6	254.6	367.7	367.7	367.7
	Mean	87.6	87.3	87	92.9	62.2	60.1	59.8	46.9	46.9	47.4
	SD	106.1	75.5	75.2	99.3	53.2	52.4	50.2	41.2	41.7	41.2
VERNON	Count	53	128	126	125	83	86	84	163	168	163
	Dd	0.9	0.6	0.6	0.6	0.6	0.61	0.6	0.61	0.61	0.61
	Max	2475	1187.9	1187.9	1187.9	721.2	721.2	721.2	361.3	339.4	361.3
	Mean	280.4	77.6	78.7	79.3	119.8	116	118.4	61.6	59.7	61.6
	SD	456.8	114.5	115.5	115.2	142.5	130.8	142	47.2	45.2	47.2

Tab. 2 - Quantitative analysis of stream network extracted on flat areas summarizing results in number of links (Count), drainage density (Dd, km/km²) and statistics (maximum, mean and standard deviation) of link length for the nine study basins.

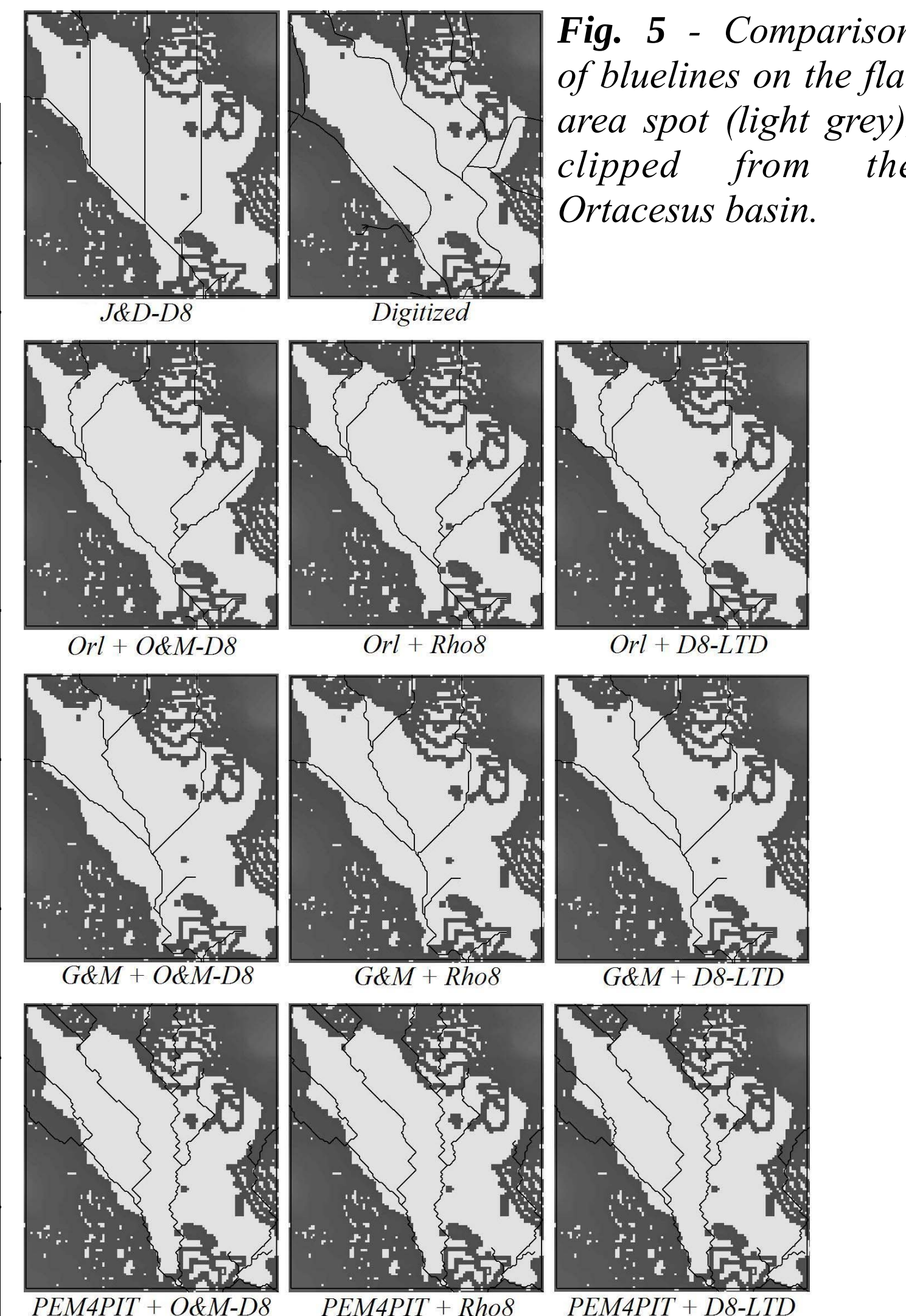


Fig. 5 - Comparison of blue lines on the flat area spot (light grey), clipped from the Ortacesus basin.
J&D-D8: D8 by Jenson and Domingue (1988)
Orl: DEM correction by Orlandini et al. (2003)
G&M: DEM correction by Garbrecht & Martz (1997)
PEM4PIT: DEM correction by Grimaldi et al. (2007)
O&M-D8: D8 by O'Callaghan & Mark (1984)
Rho8: Random D8 by Fairfield & Leimarie (1991)
D8-LTD: D8 by Orlandini et al. (2003)
Digitized: digitized blueline

4. The estimate of β and D

Despite PEM4PIT proved to be more suitable than commonly used geometric methods to reconstruct hydrologically connected topography and reliable stream network metrics, fundamental in rainfall/runoff modeling, the best choice of the three model parameters (D , β , θ) remained an open issue to be investigated. An effort was made by Santini et al. (in review) on several ASTER DEMs to supply the PEM4PIT of a parameter estimation procedure based on following assumptions: the diffusive component of surface evolution dominates on hillslopes; the fluvial one in accumulation areas; in transitional areas the two components may combine.

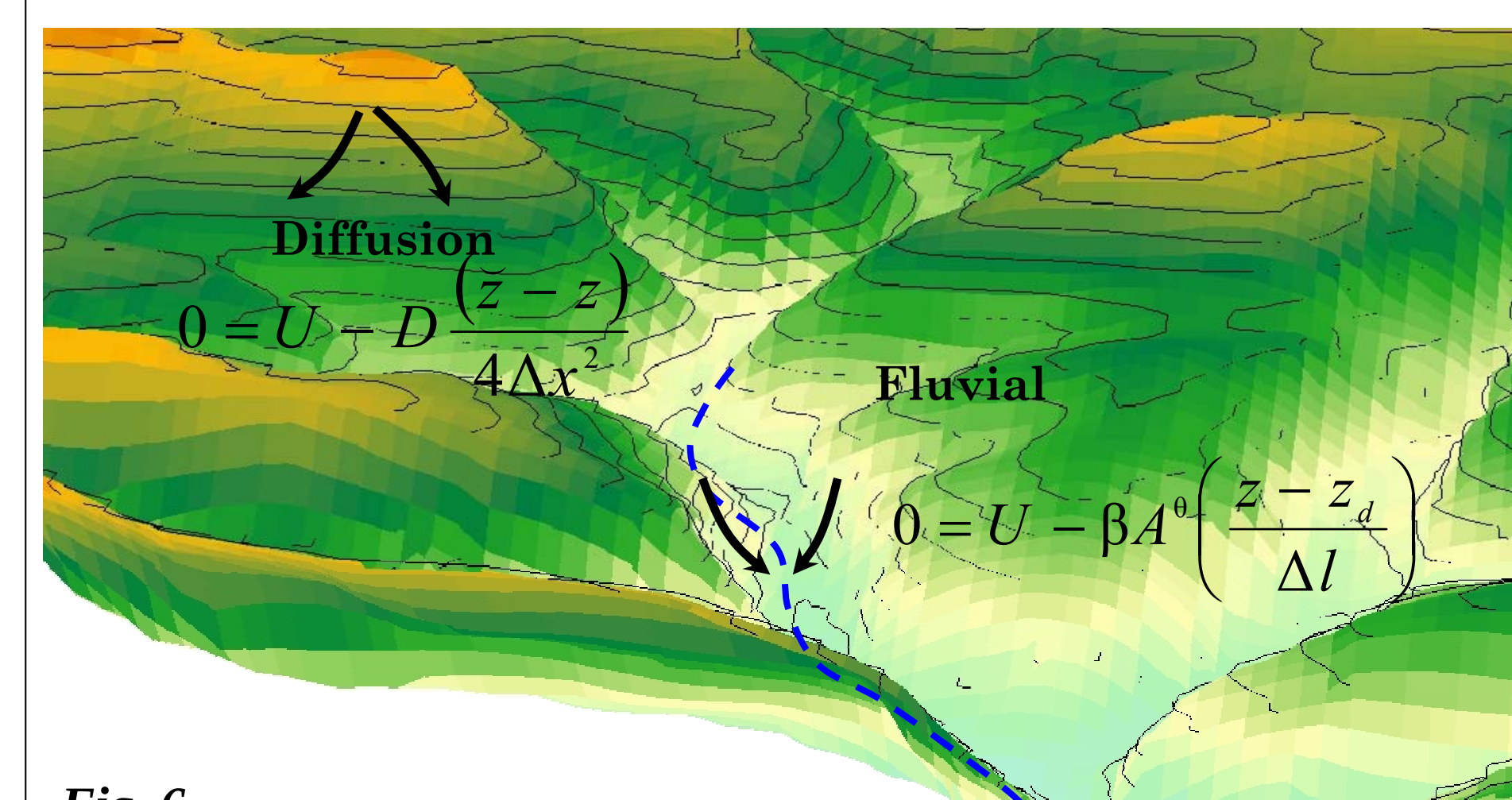


Fig. 6

basin	total n. of cells	mean D	n. cells for D estimation	$\theta = 0.3$ mean β	$\theta = 0.4$ mean β	$\theta = 0.5$ mean β	n. cells for β estimation
ast03	114.21	257	27.39	0.20	0.06	0.02	3.04
ast07	22.59	246	31.07	0.43	0.13	0.04	3.37
ast10	35.67	275	30.54	0.54	0.17	0.05	4.15
sangi	50.92	251	30.24	0.27	0.08	0.02	4.06
terra	37.61	173	31.12	0.17	0.05	0.01	4.62
as1	131.16	296	25.98	0.27	0.08	0.02	2.86
as2	53.97	277	25.34	0.17	0.04	0.01	2.25
as3	35.15	271	31.13	0.19	0.05	0.01	2.06
as4	63.61	311	24.75	0.33	0.10	0.03	3.45
as5	49.48	275	30.07	0.21	0.05	0.01	1.62

Tab. 3 - Summary of D and β values (with $\theta=0.3$, 0.4 and 0.5) and number of DEM cells considered for their respective estimation.

basin	$\theta=0.3$			$\theta=0.4$			$\theta=0.5$		
	modified cells %	mean (m)	st dev (m)	modified cells %	mean (m)	st dev (m)	modified cells %	mean (m)	st dev (m)
ast03	5.82	0.28	1.33	5.98	0.30	1.42	6.01	0.31	1.45
ast07	23.43	2.48	8.02	24.65	2.79	8.46	23.96	2.61	8.18
ast10	25.76	1.84	3.91	29.46	2.57	4.93	29.71	2.57	4.86
sangi	8.56	0.61	3.02	8.79	0.63	3.01	9.10	0.69	3.22
terra	5.10	1.29	7.90	5.24	1.33	8.00	5.22	1.33	7.99
as1	16.57	1.50	4.65	16.73	1.54	4.74	17.74	1.76	5.14
as2	9.51	0.66	3.01	9.91	0.72	3.15	10.12	0.75	3.26
as3	7.43	0.55	2.46	7.71	0.58	2.55	7.64	0.57	2.46
as4	14.17	0.71	2.28	14.53	0.74	2.36	15.00	0.79	2.43
as5	9.17	0.92	3.77	9.44	0.95	3.80	9.53	1.00	3.99

Tab. 4 - Impact of PEM4PIT over raw DEMs with the three different sets of estimated parameters by changing θ .

5. The estimate of θ

After a preliminary stream network extraction by standard procedures (*flooding* + SFD), two methods are tested for θ estimation. ASTER DEMs for four study basins in Basilicata region (Italy) are used as input dataset: AST07, AST10, AST11 and AST12.

Method 1

Horton parameters R_a (area ratio) and R_s (slope ratio) are calculated and used to estimate θ (Flint, 1974).

$$\theta = \frac{\ln R_s}{\ln R_a}$$

	AST07	AST10	AST11
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