Geomorphometry for studying the evolution of small basins: an example in the Italian Adriatic foredeep

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Abstract—**The present work focused on the influence of pre-erosion slope morphometry on the arrangement and evolution of small basins in the Periadriatic belt of central Italy. *MSI* (Morphometric Slope Index) was considered as general index for slope morphometry and tested as geomorphometric driver of fluvial erosion processes. Using two DEMs with different resolution (30 m cell-size ASTER Global DEM and 10 m cell-size Italian TINITALY DEM) and *TauDEM* toolbox within ArcGIS, we automatically extracted watersheds and stream networks. We firstly proved their validity through visual investigation and statistics, and analyzed the effect of the different resolution on the morphometric parameters. Subsequently, we analyzed the influence of *MSI* on both drainage network and eroded volume through Regression Analysis and t-Student Statistics using the DEM which was proved to be the most correct. We reached the following main outcomes: (i) the slope morphometric features combined in *MSI* strongly influenced the amount of eroded material since the inception of fluvial erosion process, (ii) the drainage density was linked to *MSI* by a logarithmic trend, and (iii) this relation directly depended on lithological features of the basins due to different lithotechnical behavior of clay and conglomerate on which they were set. We proposed a further advancement of this research focused on geomorphological hazards, considering *MSI* as predictor, e.g., of landslides, and developing a model for landslides susceptibility.**

I. INTRODUCTION

Classical methods for analyzing hydrographical basins include the morphometric analysis of drainage networks and catchments through numerical indexes which consider basin area and stream length, following in the Horton’s footsteps since 1945 [1]. The most used parameter for drainage networks is drainage density (*D*, as the ratio between total drainage length and basin area), which describes their evolutionary stage: a basin with high *D* is well organized therefore is at an advanced evolutionary stage in which the drainage network is fully developed, and vice versa.

As demonstrated in numerous studies, the development and setting of drainage systems are strongly influenced by the initial slope topography. Laboratory experiments demonstrated that the final arrangement of a basin is considerably different not only by varying the slope gradient [2] [3], but also its form [4]. The studies on natural basins revealed the complex relation between drainage and slope parameters. In fact, *D* can vary positively or negatively with slope gradient depending on the dominant erosion process in the watersheds (fluvial incision or landslide, respectively) [5] [6] [7] [8]. Moreover, the greater the source area, the more complex is the drainage network [9]. These studies, however, considered the slope parameters individually, resulting in partial relations with morphogenetic processes and losing the overall effect of their interactions.

In our studies [10] [11] [12] [13], we focused on the role of general slope morphometry on the erosion processes. We introduced a unique reference index for basin morphometry, named *MSI* (Morphometric Slope Index), which includes both areal and linear features, such as size, shape, inclination, length and width. It was applied on the entire drainage basin considering the initial topography prior to erosion, which was reconstructed using the heights of watershed divide by filling the fluvial incision. Its formula is:

$$MSI = R_c \cdot L \cdot A_{3D} / A_{2D} \qquad (1)$$

where R_c is circularity ratio, L is slope length, A_{2D} and A_{3D} are plane and surface area, respectively. We tested *MSI* on *calanchi* (Italian badlands) because they represent miniature models of catchments but have lithological and climate homogeneity that allows isolating morphometric factors. We demonstrated its effectiveness in determining the arrangement of stream network, the type of erosion processes and the amount of erosion.

The present work introduced the first application of *MSI* to small basins, and was aimed at revealing the influence of slope morphometry on their evolution. We chose small basins set on clayey slopes in the Adriatic foredeep of Central Italy, because they are more sensitive to the transformations of physical environment, in particular their drainage networks, but have

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quite homogenous geological and climatic characteristics. Combining GIS technologies and advanced statistics, we analyzed the role of general slope morphometry summarized in *MSI* on the current arrangement of drainage network and the eroded volume since the basin inception, comparing two different DEMs.

II. GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The Periadriatic belt of central Italy lies in the Plio-Pleistocene foredeep succession composed of clays in which are interposed clastic deposits with lenticular geometry and is closed on the Adriatic coast by a powerful deposit of sands, gravels and conglomerates of fluvial-deltaic or coastal environment [14]. These deposits are arranged in a NE vergence monocline as consequence of the compressive phase and the subsequent uplift started since the Pleistocene and still active [15]. This created an extensive coastal morphostructure cut from W to E by the main (cataclinal) watercourses whose corresponding valley floors are often filled by fluvial deposits [16]. Climatically, this area belongs to a temperate sub-littoral regime with scarce annual rainfall, mainly autumnal, dry summer and medium temperatures [17] that favor intense erosion processes.

III. MATERIALS AND METHODS

We chose 37 small basins directly flowing in the Adriatic sea, 18 in the Abruzzo Region and 19 in the Marche Region (Tab. I). All of them were handled within ArcGIS 9.3 using two DEMs with different resolution: ASTER Global DEM (GDEM) [18] and the Italian DEM from National Institute of Geophysics and Volcanology (TINITALY) [19] [20]. The former was 30 m cell-size, while the latter was 10 m. The data were successively compared in order to analyze the effect of the different resolution on the morphometric parameters and their relations.

We extracted the drainage features of each basin for both GDEM and TINITALY using *TauDEM* (Terrain Analysis Using Digital Elevation Models) tools developed by Prof. Tarboton and freely downloadable from his website [21] [22]. We used the *Single Watershed Model* which automatically delineates stream network and watershed following a sequence of tools starting from the DEM and the outlet point shapefile. The final products were the hydrological correct stream network and watershed shapefiles, of which we calculated *D*.

For each watershed we built the pre-erosion DTM inserting the heights of current divide as Point Values in the *Topo-to-Raster* interpolation tool (Fig. 1) [11] and, on it, we calculated the pre-erosion 3D area (A_{3D}). After measuring A_{2D}, L and R_c, we calculated *MSI* using (1). Subtracting, through *Cut/Fill* tool, the current DEMs from the pre-erosion ones, we estimated the volume of eroded material (V) in each basin and computed its average value by dividing it by A_{2D} (V/A_{2D}).

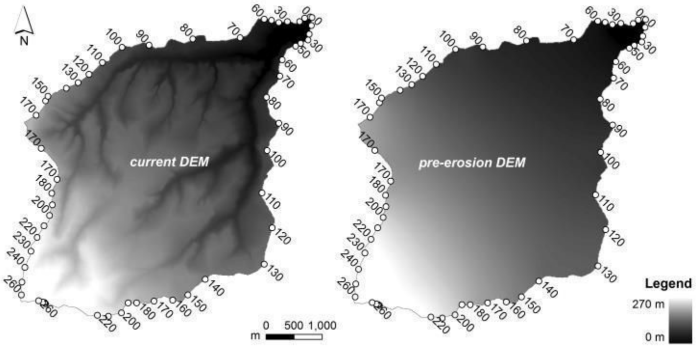

Figure 1. Example of current and pre-erosion DEMs of Acquachiara basin from TINITALY. White dots indicate some of the heights of the drainage divide used for the pre-erosion surface reconstruction through *Topo-to-Raster* tool.

Using SPSS Statistics Desktop V22.0 – trial packages, we firstly compared the two DEMs in order to test their validity and analyze the effect of different resolution on the morphometric parameters. Successively, we investigated the relations among the parameters using the DEM which was proved to be the most correct.

IV. RESULTS

For testing the validity of the features obtained from *TauDEM* tools, we used two approaches: visual investigation and statistics. The former consisted in comparing the *TauDEM* stream networks and divides with Regional Topographic Maps (CTR). TINITALY derived features were almost perfectly coincident with CTR ones and the main nodes could be superimposed, but also GDEM gave satisfactory results although not perfectly superimposing and being reduced (i.e. shorter streams). The latter approach consisted in comparing the values of *D*, *MSI* and V/A_{2D} for the two DEMs using t-Student Statistics that showed the differences between the mean values of the variables. The one variable that showed significant differences between GDEM and TINITALY derived data was *D* ($t = 5.11$, $p < 0.05$), while *MSI* and V/A_{2D} did not show any significant differences (respectively, $t = 0.96$ and $t = 0.48$, $p > 0.05$).

In order to analyze the influence of slope morphometry on both the drainage network and the eroded volume, we performed the Regression Analysis between the morphometric variables. The interpolation functions and relative statistical quality index (R^2) were reported in Tab. II. They revealed a significant relation between V/A_{2D} and *MSI* for both GDEM ($R^2 = 0.54$) and TINITALY ($R^2 = 0.40$) derived data, as expected from the validation procedure.

TABLE I. DATABASE. THE ASTERISK (*) INDICATES BASINS WITH MAINLY CONGLOMERATE LITHOLOGY, WHILE THE OTHERS WERE MAINLY CLAYEY.

BASINS	***TINITALY***			***GDEM***		
	***MSI* (m)**	***D* (m^{-1})**	***V/A$_{2D}$* (m)**	***MSI* (m)**	***D* (m^{-1})**	***V/A$_{2D}$* (m)**
ABRUZZO						
Acquachiara *	3098	0.0017	12.39	2654	0.0020	11.57
Arielli *	3244	0.0012	20.89	2204	0.0017	21.43
Borsacchio	1730	0.0053	42.80	1573	0.0012	37.64
Buonanotte *	2337	0.0009	42.28	2026	0.0013	36.44
Calvano	3771	0.0021	88.42	3788	0.0011	82.61
Cerrano *	2272	0.0032	81.11	2139	0.0009	82.10
Feltrino *	5200	0.0013	43.19	3797	0.0015	43.47
Giardino *	1541	0.0069	27.92	1107	0.0012	27.31
Grande *	3863	0.0013	16.35	2718	0.0019	17.88
Lebba *	2765	0.0022	15.83	1905	0.0019	16.21
Mazzocco *	1487	0.0044	33.53	1274	0.0011	30.81
Moro	4744	0.0024	74.50	3500	0.0012	68.67
Osento	4833	0.0016	59.85	4260	0.0013	60.23
Piomba	4742	0.0026	106.55	3975	0.0010	95.85
Riccio *	2572	0.0022	13.81	2034	0.0020	13.05
Salinello	6209	0.0021	104.20	5161	0.0013	101.22
Vallelunga *	1552	0.0024	36.60	1418	0.0013	33.24
Vibrata	5087	0.0014	37.44	4755	0.0017	41.84
MARCHE						
Albula *	3240	0.0021	96.48	2858	0.0009	87.73
Arzilla	5362	0.0029	80.11	5374	0.0012	73.58
Asola	3285	0.0053	73.76	3022	0.0012	73.92
Bellaluce	1690	0.0069	31.47	1842	0.0014	25.22
Canale *	1460	0.0084	47.93	1487	0.0016	42.37
Caronte *	1744	0.0077	39.81	1549	0.0013	36.58
Molinetto *	1071	0.0051	44.78	1091	0.0015	40.36
Tavole *	574	0.0081	14.53	444	0.0031	11.79
San Biagio *	1542	0.0040	43.21	1474	0.0017	42.44
Sant'Egidio *	2519	0.0022	35.00	2513	0.0018	32.04
Ete Vivo	6807	0.0019	109.03	6272	0.0013	95.13
Genica	2249	0.0048	57.52	2061	0.0014	47.52
Menocchia	5387	0.0019	101.96	5155	0.0012	106.54
Petronilla	1179	0.0092	34.05	983	0.0017	28.88
Ragnola *	1726	0.0033	54.76	1870	0.0011	46.90
Rubiano	2475	0.0077	26.30	2076	0.0016	29.52
no-name *	1578	0.0065	31.74	1325	0.0013	30.53
Tesino	4666	0.0027	107.37	4478	0.0012	104.73
Valloscura	1629	0.0023	46.29	1434	0.0011	46.38

The relation between *D* and *MSI* was significant for only TINITALY derived data ($R^2 = 0.48$). Considering TINITALY, in the regression plot chart (Fig. 2) we individuated two main logarithmic trends, both with higher statistical significance, that corresponded to different lithological conditions: basins whose surface mainly lied on clays belonged to the upper interpolator ($R^2 = 0.81$; black in Fig. 2), while basins whose surface mainly lied on conglomerates belonged to the lower interpolator ($R^2 = 0.60$; grey in Fig. 2). The clayey basins had higher *MSI* mean value (M = 4013 m) while conglomeratic basins had lower *MSI* mean value (M = 2269 m) that were statistically different ($t = 3.71$, $p < 0.05$), but *D* was not statistically different ($t = 0.04$, $p > 0.05$). There was only one outlier (Valloscura basin) that could be included in the conglomerates series but was mainly clayey.

TABLE II. REGRESSION BETWEEN *D* AND *MSI* AND *V/A$_{2D}$* AND *MSI* FOR GDEM AND TINITALY DATA.

	INTERPOLATION FUNCTION	***R^2***
GDEM	$D = -0.0003 \ln(MSI) + 0.0038$	0.18
	$V/A_{2D} = 0.01\, MSI + 11.42$	0.54
TINITALY	$D = -0.003 \ln(MSI) + 0.0266$	0.48
	$V/A_{2D} = 0.01\, MSI + 17.05$	0.40

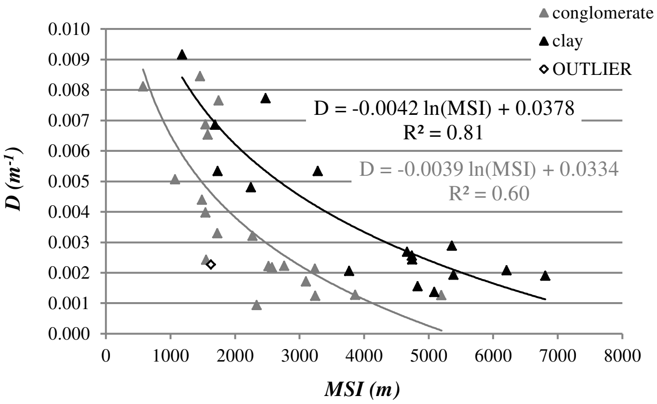

Figure 2. Regression between *D* and *MSI* of TINITALY data with distinction of basins' lithology (manly conglomerate in grey, mainly clay in back).

V. DISCUSSION AND CONCLUSION

The first application of *MSI* to small basins introduced in the present work aimed at investigating the influence of slope morphometry on their arrangement and evolution.

We used *TauDEM* toolbox, implemented for ArcGIS, to automatically derive stream networks and divides, and tested their validity. The validation procedure strengthened the effectiveness of this method for streams and divides automatic delineation, on the one hands, and the greater correctness of TINITALY for deriving stream network, on the other hands. This was mostly due to the TINITALY DEM building methods since it was built from Regional Topographic Maps that made it more precise and detailed [20]. The difference between GDEM and TINITALY derived *D* was expected considering the different DEMs' cell size in accordance with the observation made just above, while the lack of difference for *MSI* and *V/A$_{2D}$* highlighted the validity of both DEMs for deriving slope morphometric data.

The Regression Analysis between *V/A$_{2D}$* and *MSI* pointed out the influence of general slope morphometry on the amount of eroded material since the inception of fluvial erosion process. Moreover, assuming that slope morphometry influenced the erosion processes and that their efficacy with respect to the amount of eroded material was a function of their duration, this positive relation might indicate that the basins activated approximately in the same time [12]. This issue, however, needs to be further investigated.

Furthermore, the Regression Analysis between *D* and *MSI* allowed many considerations. Firstly, although *D* was generally influenced by *MSI* regardless the lithology, the lithological characteristics had a great effect on this relation, in particular depending on the different lithotechnical behavior of clay and conglomerate. Basins set on clayey slopes had more developed drainage networks (higher drainage length) but also wider surface (higher A_{2D}) not resulting in higher *D*; moreover, they had more gentle morphology (higher *L* and lower inclination) [10] and wider surface (higher *A* and R_c) resulting in higher *MSI*. Otherwise, basins set on conglomeratic slopes had less developed drainage network (lower drainage length) but also smaller surface (lower A_{2D}) not resulting in higher *D*; moreover, they had steeper morphology (lower *L* and higher inclination) and smallest surface (lower *A* and R_c) resulting in lower *MSI*. Secondly, the Regression Analysis showed that *D* and *MSI* were linked each other by a logarithmic trend directly dependent on the lithological features of the basins, indicating that small increasing (decreasing) of *MSI* produced high decreasing (increasing) of *D*.

In conclusion, we can stress the effectiveness of *MSI* not only as general index for slope morphometry, but also as morphometric driver of fluvial processes as it represented and summarized the main slope morphometric features. It determined both the arrangement of drainage networks and the amount of soil erosion, and allowed to reconstruct the geomorphological evolution of small basins. Further advancement of this research could focus on geomorphological hazards, studying the effect of *MSI* as predictor, e.g., of landslides. At present, we are trying to develop a model for landslides susceptibility taking into account the outcomes of our present and previous researches.

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