GEOMORPHOMETRY 2020 PERUGIA, ITALY JUNE 22 - 26 2020

Geomorphic systems, sediment connectivity and geomorphodiversity: relations within a small mountain catchment in the Lepontine Alps

Irene Maria Bollati[1,§], Marco Cavalli[2]
[1]Earth Science Department "Ardito Desio", Università degli Studi di Milano, Milano, Italy
[2]Research Institute for Geo-Hydrological Protection, Padova, Italy
[§] irene.bollati@unimi.it

Abstract—**Mountain regions are characterized by a spatial geomorphic heterogeneity that confers to the environment a significant geomorphodiversity, functioning as a substrate for biodiversity. It is hence important to understand the geomorphic dynamics and its evolution in space and time. A different spatial scale approach was developed to evaluate the relationship existing among geomorphological processes, sediment connectivity and geomorphodiversity. The study areas are the Veglia-Devero Natural Park (Lepontine Alps) and a small mountain catchment (Buscagna catchment) where the analysis was carried out at a highest detail. At the natural park scale, a preliminary geomorphological map was realized and then the index of Geomorphodiversity was computed highlighting the differentiation between the two sides of the Buscagna glacial valley. In the Buscagna catchment where also the index of Connectivity was calculated, the integrated analysis of the two indices allowed to identifying different *geomorpho-connectivity sectors*, testifying the role of geomorphic processes in regulating sediment fluxes and, consequently, controlling landscape units.**

I. INTRODUCTION

Geomorphic systems may present an extremely variable behavior in narrow spaces, especially in mountain environments. This variability can be regarded as *geomorphodiversity* intended as "geodiversity with respect to geomorphology" [1] so that the geomorphological richness of territories could be compared "taking into account the scale of investigation, the purpose of the research and the level of scientific quality" [2]. Geomorphodiversity is usually quantified counting different geomorphic elements included within cells of a certain size (*direct methods*; e.g. [3]) or inferring it indirectly from relief morphometric features (*indirect methods*; e.g. [4; 5]). Geomorphodiversity, hence, mirrors the variability of geomorphic systems dynamic behavior in relation to topographic features. At the core of this dynamic, there are the erosion-transport-sedimentation patterns along channel networks and on the hillslopes, linking sources-to-sinks. In some cases, especially in mountain areas, the continuity of sediment fluxes is regulated by intrinsic (geology, morphometric features of slopes) and extrinsic factors (meteorological events, human interventions). All these aspects are related to the *sediment connectivity*, i.e. the degree of linkage (lateral, longitudinal and vertical) that controls sediment fluxes throughout landscape [6]. Sediment connectivity is an emerging property of a geomorphic system (i.e. coupling relationship between elementary units: landforms, slope units, subcatchments) and reflects the potential of water/sediment to move through the system [7]. According to [8; 9; 10], it is possible also to distinguish between i) *structural connectivity* that describes the spatial contiguity of landscape units and ii) *functional connectivity* that is process based. In this last case, considering geomorphic systems and the related sediment connectivity [11] as a functional component of ecosystems, the influence on soil development, and consequently on vegetation, could be highly relevant [12]. Vegetation could interfere with geomorphic dynamics, being a regulating agent, but also suffering from the impact of geomorphic processes [13]. The main aim of this work is the assessment, through specific indices, of the relationship among geomorphological systems, sediment connectivity and geomorphodiversity in a small mountain catchment. At this scope, the geomorphodiversity assessment was primarily focused, at a wider scale, on the Veglia Devero Natural Park (VDNP, Lepontine Alps). According to the obtained results, the Buscagna stream catchment (12 km^2), was selected to perform a sediment connectivity evaluation. The outcomes of this analysis will be hence discussed in the perspectives of a holistic approach including other components of the landscape.

II. STUDY AREA & PRELIMINARY CONSIDERATIONS

The Buscagna stream catchment is SW-NE elongated and ranges in altitude from 1650 m a.s.l. (Devero plain) to 3237 m a.s.l. (Boccareccio Peak). In the catchment the following lithologies, belonging to the upper and lower Pennidic Nappes,

Irene Maria Bollati and Marco Cavalli (2020) Geomorphic systems, sediment connectivity and geomorphodiversity: relations within a small mountain catchment in the Lepontine Alps:
in Massimiliano Alvioli, Ivan Marchesini, Laura Melelli & Peter Guth, eds., Proceedings of the Geomorphometry 2020 Conference, doi:10.30437/GEOMORPHOMETRY2020_14.

outcrop (e.g. [14; 15]): i) orthogneisses with locally intercalated amphibolites, micaschists and paragneiss (Monte Leone Unit); ii) ultramafites rocks, mainly serpentinites (Ultramafic Cervandone-Geisspfad Complex) iii) calcschists and marbles. The i) and ii) type of rocks outcrop on the northwestern side of the Buscagna Stream catchment, while the iii) rocks outcrop on the southeastern side of the catchment.

Concerning geomorphological features, the Buscagna valley is a glacio-structural valley set along the contact between gneisses and calcschists and intensely shaped by glaciers. The landscape reflects the geological and geomorphological dichotomy between the slopes. The northwestern slope, constituted mainly by gneisses, is characterized by a high relief energy, and it is affected by cryoclastism and gravity-related processes like rockfalls and debris-flows. Composite cones (sensu [16]), fed by different processes (water-related, mass wasting and snow avalanches) are recurrent. Calcschists and marbles cropping out along the southeastern slope and at the valley head are more suitable to erosion, soluble and affected by hypogean and epygean karst processes. Pleistocene glacial landforms and deposits are very widespread and are constituted by abundant glacial debris (moraines and erratics), transversal and lateral glacial steps, hanging glacial valley and basins. In the NW-lateral hanging basins Holocenic glaciers, nowadays almost extinct, were present. At higher altitudes, the more recent glacial deposits have been undergoing reworking by paraglacial-type dynamics (sensu [17]). Snow avalanches are also important modeling agent.

III. METHODS

A. Geomorphodiversity Index Calculation

The geomorphological map of the VDNP (Fig, 1a) represented the input data for the calculation of the *Geomorphodiversity Index* (*GmI*). The map was elaborated reorganizing the available data concerning geology and geomorphology, along with an orthophotos interpretation. The methodology proposed by the ISPRA-AIGeo Commission on Geomorphological Mapping was adopted [18]. Hence, lithologies were grouped according to the behavior towards geomorphic processes and landforms were classified according to the genetic processes.

To produce a thematic map on geomorphodiversity of the VDNP, a direct method based on the geomorphological map was selected [19] and using *ArcGIS* functionalities. The area was divided into cells of 500 x 500 m. This size was decided after comparative tests on a random portion of the study area, varying the cells and comparing it with the average size of the landforms represented in the geomorphological map (0.08 km^2). The *GmI* was then calculated for each cell by summing the number of different landforms within each cell and dissolving them according to the landform type (a partial mirror of the genetic process). This was intended to consider landforms only once inside each cell. The final result includes polygons, lines and points for which *sub-GmIs* were created during the procedure. The *Union* tool allowed obtaining the final value for the *GmI* for each cell. The values were finally classified according to the quantile method.

B. Connectivity Index Calculation

Sediment connectivity Index (*IC*), proposed by [6] (https://github.com/HydrogeomorphologyTool), is a topographic based approach and it is mainly addressed to assess the lateral connectivity. The *IC* calculation (1) considers the: i) *Upslope Component* (D_{up}), i.e. the potential for downward routing of the sediment produced upslope (2); ii) *Downslope Component* (D_{dn}), that takes into account the flow path length that a particle has to travel to arrive to the nearest target or sink (3).

$$\textit{Index of Connectivity } (IC) = log10\left(\frac{Dup}{Ddn}\right) \quad (1)$$

$$\textit{Upslope Component } (Dup) = \overline{\text{WS}}\ \sqrt{A} \quad (2)$$

$$\textit{Downslope Component } (Ddn) = \sum_i \frac{di}{WiSi} \quad (3)$$

In the formulas: i) W is the average weighting factor, i.e. *Surface Roughness* calculated according to [20]; ii) S is the *Average Slope Gradient*; iii) A is the *Upslope Contributing Area*; iv) d is the length of the flow path according to the steepest downslope direction. In the *Ddn*, the calculation is performed for each *i*-th cell. To perform this analysis, a high-resolution DTM is required [7; 20]. The DTM used for this research is a LiDAR-based DTM with a 5 m resolution (source Geoportale Regione Piemonte; http://www.geoportale.piemonte.it/cms/). Considering DTM resolution, the moving window size for roughness calculation was set at 3x3. The input DTM was hydrologically corrected using the *Pit remove* tool of the *TauDEM 5.3.7* (http://www.engineering.usu.edu/dtarb/taudem) whereas the catchment and the channel network were defined using the *Watershed delineator* of *ArcSwat 2012.10_2_19* (https://swat.tamu.edu/software/arcswat/).

IV. RESULTS AND DISCUSSIONS

Geomorphodiversity Index map

The VDNP is characterized by a variable geomorphodiversity, with local hot spots (red), and other areas more characterized by diffuse low geodiversity (green) (Fig. 1b). Considering the Buscagna Stream catchment, the glacio-structural valley is, in fact, evidently asymmetric due to the different susceptibility of gneisses and calcschists to geomorphic processes, also due to the regional dipping of the surfaces (Fig. 1a).

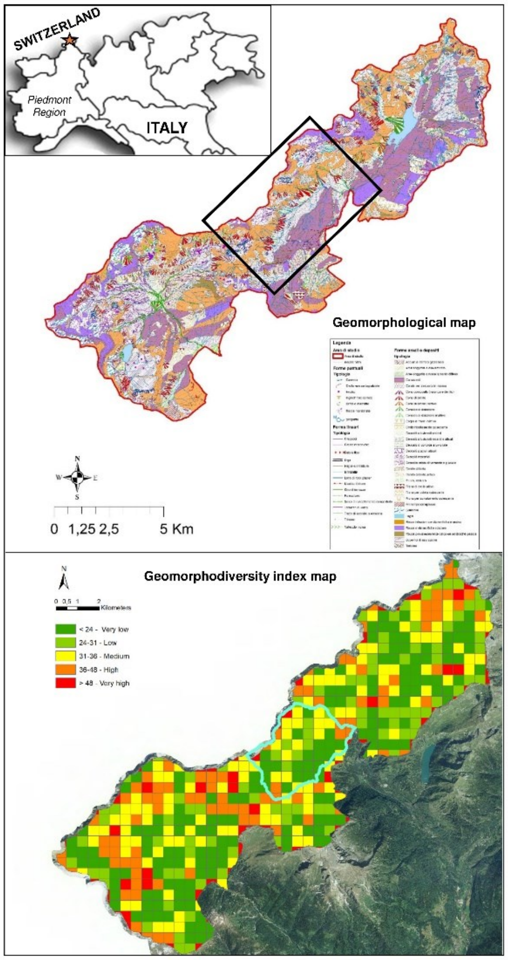

Figure 1. Geomorphological map (a) and Geomorphodiversity Index map (b).

This asymmetry is mirrored in the *GmI* map where:

i) the prevalence of green on the southeastern side of the valley, where calcschists outcrop continuously, could be attributed to the low diversification of landforms and to the large width of landforms due to water-related processes (V-shaped valleys, karst features), glacier action undergoing a structural control;

ii) the medium to high geomorphodiversity values are associated to the highest elevation areas of the northwestern slope (Cervandone, Cornera and Boccareccio Peak slopes) and the related hanging glacial basin (glacial, crionival, gravity- and water-related landforms, more heterogeneous lithology, and local structural influence).

In this method of *GmI* calculation, the role of geomorphological mapping at multi-catchment scale (Fig. 1a) is crucial. According to the results, the Buscagna stream catchment was then selected to perform a more in-detail analysis, applying the *IC*.

Connectivity Index maps

The *IC* maps result different if the outlet (Fig. 2a) or the main streams (Fig. 2b) and the channels (Fig. 2c) were selected as a target of the analysis [11]. Using the outlet as a target (Fig. 2a), a relationship between connectivity patterns and geomorphodiversity can be highlighted. In the Buscagna catchment, in fact, it is possible to appreciate quite clearly the differentiation among the two sides of the valley:

i) low *IC* values (green colour) characterize the calcschists slope. A structural controlled hydrographic pattern mainly constituted by V-shaped valleys, trenches and fractures that interrupt a wide rocky surface shaped by ancient glaciers (C; Fig. 2a);

ii) high *IC* values (red colour) characterize the high relief gneiss slope, especially in correspondence to debris flow and snow avalanche channels re-elaborating glacial and slope debris (B). These higher IC conditions are interrupted by glacial hollows (A1 and A2; Fig. 2a) and steps, acting as sinks (A1) or as a sudden change in longitudinal connectivity (A2) [7; 11].

Considering the main streams (Fig. 2b) and the channels as target (Fig. 2c), the hydrographic pattern role is even more delineated. It is well evident in Fig. 2a how the glacial tributary basins progressively lose the differentiation, well evident in Fig. 2a, between slopes characterized by high connectivity and bottom of the basins (A) where the debris effectively accumulates, correctly characterized by low *IC* values.

Summarizing, as already shown by other Authors in other study cases [7; 11], at least 5 typologies of *geomorpho-connectivity sectors* could be identified:

A1, A2 – Hanging glacial basins: the glacial originated hollows act as temporary sediment traps, and are characterized by a great quantity of debris of glacial and gravity origin, and are surrounded by talus slope deposits. The frontal moraine, in the Cornera basin (A1) in particular, remains hanging on the glacial step that separates the Cornera basin from the valley bottom. The moraine is undergoing dismantling, releasing slowly debris along a high connectivity area and feeding the B1 composite cone.

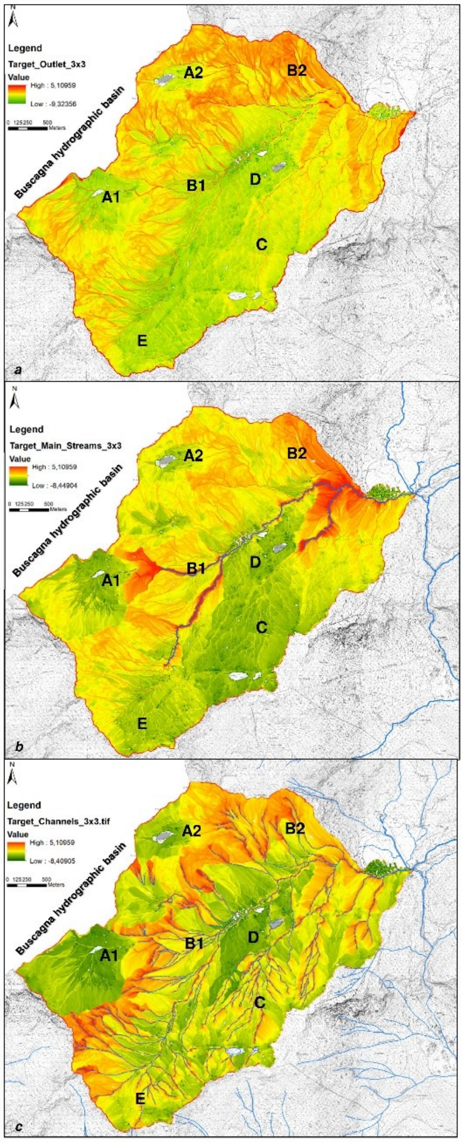

Figure 2. Connectivity Index maps: targeting outlet (a) and targeting channel network (b, c). Capital letters indicates the geomorpho-connectivity sectors discussed along the text.

B1, B2 – Polygenic cones and relative feeding areas: they are generated by the combination of different processes related to water-gravity-snow. Debris flow channels represent an effective way for debris transport. In some cases, snow avalanches can play a role in connectivity since on the one hand, they contribute to the transport of rocky and woody debris, and on the other hand, they can also partially damming the channels as occurred close to the Buscagna outlet during the 2018 (B2). They are especially highlighted considering as a target the main streams (Fig. 2b) or, even more, channels (Fig. 2c).

C – Karst-suitable rocky surfaces shaped by glaciers: the drainage of the debris occurs along small V-shaped valleys, often controlled by the structural pattern. More relevant in this case could be the assessment of the vertical connectivity.

D – Pleistocene glacial deposits: these areas are characterized by widespread, coarse and thick glacial debris. This debris is stocked as relatively high moraines to which the hydrographic network has to adapt.

E - Karst-suitable block fields: in the head of the valley, marble outcrops have been quite completely dissected by gelifraction in coarse blocks, between which fine matrix is often absent. The rocks are karst-susceptible and in this case, the connectivity features described for C and D may combine.

According to the presented results, the comparison with a geomorphological map revealed to be fundamental both in geomorphodiversity and sediment connectivity analyses, as already shown, for the second case, by [7].

V. Conclusions

In the present research, the *GmI* was expected to provide information at VDNP scale (500 X 500 m cell size) and, according to the results of the *GmI*, the *IC* (5 X 5 m cell size) was derived in small mountain catchment where the relationship between sediment connectivity, geomorphology and geomorphodiversity was investigated.

IC confirms to be very suitable for small mountain catchments characterized by a local diversification of geomorphic processes and a complex topography. Using as a target the outlet or the main streams or, even more, the channel network, provide a different detail on processes. Moreover, for this reason, the coupling with a geomorphological map is essential.

Considering the fallouts of geomorphic processes and sediment connectivity on the other components of the ecosystem, a holistic approach is the focus of the in progress investigations. In particular, as already suggested by [21; 9], further elaborations are aimed at comparing these results with geopedological and dendrogeomorphological outcomes.

References

[1] Panizza, M., 2009. "The geomorphodiversity of the Dolomites (Italy): a key of geoheritage assessment" Geoheritage 1, 33-42.

[2] Zwoliński, Z., A., Najwer, M., Giardino, 2018. “Methods for assessing geodiversity”. In: Geoheritage, pp. 27-52.

[3] Pereira, D.I., P., Pereira, J., Brilha, L. Santos, 2013. "Geodiversity assessment of Paraná State (Brazil): an innovative approach". Env. Manage. 52(3), 541-552.

[4] Zwoliński, Z., 2009. "The routine of landform geodiversity map design for the Polish Carpathian Mts." Land. Anal. 11, 77-85.

[5] Melelli, L., F., Vergari, L., Liucci, M., Del Monte, 2017. "Geomorphodiversity index: Quantifying the diversity of landforms and physical landscape" Sci. Tot. Env. 584, 701-714.

[6] Cavalli, M., S., Trevisani, F., Comiti, L., Marchi, 2013. "Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments" Geomorphology 188, 31-41.

[7] Cavalli, M., T., Heckmann, L., Marchi, 2019. "Sediment connectivity in proglacial areas" In Geomorphology of Proglacial Systems (pp. 271-287). Springer, Cham.

[8] Heckmann, T., Cavalli, M., Cerdan, O., Foerster, S., Javaux, M., Lode, E., Smetanova, A., Vericat, D, Brardinoni, F., 2018. "Indices of sediment connectivity: opportunities, challenges and limitations". Earth Sci. Rev. 187, 77-108.

[9] Cavalli, M., Vericat, D., Pereira, P., 2019. "Mapping water and sediment connectivity". Sci. Tot. Env. 660, 899-912.

[10] Zingaro, M., A., Refice, E., Giachetta, A., D'Addabbo, F., Lovergine, V., De Pasquale, G., Pepe, P., Brandolini, A. Cevasco, D., Capolongo, 2019. "Sediment mobility and connectivity in a catchment: A new mapping approach" Sci. Tot. Env. 672, 763-775.

[11] Messenzehl, K., T., Hoffmann, R., Dikau, 2014. "Sediment connectivity in the high-alpine valley of Val Müschauns, Swiss National Park—linking geomorphic field mapping with geomorphometric modelling" Geomorphology 221, 215-229.

[12] Seijmonsbergen, A.C., J.A.M., Van den Ancker, P.D., Jungerius, S.J., Norder, 2019. "Can geodiversity help to save the soil archives?" In: Van Mourik, J.J. and Van Der Meer, J.M. (Eds). Reading the soil archives – unravelling the geoecological code of paleosols and sediment cores. Developments in Quaternary Science 18, pp. 275–298.

[13] Bollati, I., B.C., Lenz, A., Golzio, A. Masseroli, 2018. "Tree rings as ecological indicator of geomorphic activity in geoheritage studies" Ecol Ind, 93, 899-916.

[14] Bigioggero, B., A., Colombo, A., Cavallo, B., Aldighieri, A., Tunesi, 2007. "Geological-structural sketch-map of the Ossola-Simplon area". Snam Rete Gas Ed. (1 map; 1: 50.000 scale)"

[15] Steck, A., 2008. "Tectonics of the Simplon massif and Lepontine gneiss dome: deformation structures due to collision between the underthrusting European plate and the Adriatic indenter". Swiss J. Geosc. 101(2), 515-546.

[16] Baroni, C., R., Gentili, S., Armiraglio, 2013. "Vegetation analysis on composite debris cones". In Dating Torrential Processes on Fans and Cones pp. 187-201.

[17] Ballantyne, C.K., 2002. "Paraglacial geomorphology". Quat. Sci. Rev. 21(18-19), 1935-2017.

[18] ISPRA, 2018. "Carta Geomorfologica d'Italia alla scala 1:50.000 - Aggiornamento ed integrazioni delle linee guida della Carta Geomorfologica d'Italia alla scala 1:50.000", Fascicolo I, Quaderni, serie III, Volume 13, pp. 93.

[19] Bollati I., M., Paleari, E., Zanoletti, M., Pelfini, 2017. "Indexing Geomorphodiversity in the Veglia-Devero Natural Park (Western Italian Alps)", In "Innovative technologies for monitoring past and present geomorpholigical processes", VIIth Young Geomorphologists' Day, Napoli, 15-16 giugno, 2017

[20] Cavalli, M., L. Marchi, 2008. "Characterisation of the surface morphology of an alpine alluvial fan using airborne LiDAR" Nat. Haz. Earth Sys. Sci. 8(2), 323-333.

[21] Savi, S., M., Schneuwly‐Bollschweiler, B., Bommer‐Denns, M., Stoffel, F., Schlunegger, 2013. "Geomorphic coupling between hillslopes and channels in the Swiss Alps". Earth Surf. Process. Landform 38(9), 959-969.