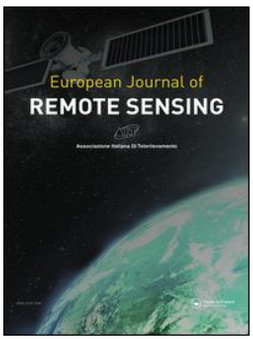

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Semi-automatic derivation of channel network from a high-resolution DTM: the example of an Italian alpine region

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Abstract

High-resolution digital terrain models (HR-DTMs) of regional coverage open interesting scenarios for the analysis of landscape, including derivation and analysis of channel network. In this study, we present the derivation of the channel network from a HR-DTM for the Autonomous Province of Trento. A preliminary automatic extraction of the raw channel network was conducted using a curvature-based algorithm applied to a 4 m resolution DTM derived from an airborne LiDAR survey carried out in 2006. The raw channel network automatically extracted from the HR-DTM underwent a supervised control to check the spatial pattern of the hydrographic network. The supervised control was carried out by means of different informative layers (i.e. geomorphometric indexes, orthophoto imagery and technical cartography) resulting in an accurate and fine-scale channel network.

Keywords: Channel network, high-resolution DTM, geomorphometry.

Introduction

The detailed cartographic delineation of the channel network plays a fundamental role in manifold landscape management issues, such as water resources management, geo-hydrological risk analysis, buildup of technical cartography, and legal matters related to land use.

In mountain regions the patterns and density of hydrographic network are generally highly complex and heterogenous mainly in response to the wide variety of geo-structural and geomorphological settings, as well as to the high spatial variability of local climate regimes. Moreover, human activities in mountain regions result in a wide variety of environmental impacts. In some cases, channel network has been modified for drainage and irrigation purposes, in other the alteration of drainage patterns is due to the presence of man-made

features, such as roads and urbanized areas. The last 40 years have seen relevant changes in land use in mountain regions, with an important increase of urbanized areas and road network, and consequent modifications of the hydrographic network. Human activities that influence runoff generation and drainage pattern have reflections in the context of hydro-geological hazard and water resources management. Accordingly, an up-to-date detailed recognition of the channel network is needed for landscape management purposes.

The hydrographic network is made up of channels that run through the watershed surface, converging to its outlet. The definition of channel, referring to the common perception of stream and river, does not present any particular problem of interpretation. The characteristic elements of a channel are the presence of flowing water with a velocity proportional to the energy gradient in the direction of motion and a transversely confined geometry that defines a wetted section [Dalla Fontana, 2005]. The interpretation of the hydrographic network becomes more complicated when the presence of water is linked to different phases of the hydrological cycle. The absence of a permanent drainage is typical of watercourses in dry climate regions whereas in humid climates it is characteristic, especially but not exclusively, of headwater channels [Marchi et al., 2008; Brardinoni et al., 2009].

The study of the processes that underlie the formation of channel heads, i.e. the starting points of the hydrographic network, their recognition in the field and the extraction of synthetic network starting from Digital Terrain Model (DTM) have been the subject of numerous researches [Tarboton et al., 1991; Montgomery and Dietrich, 1992; Dietrich et al., 1993; Montgomery and Foufoula-Georgiou, 1993; Dalla Fontana and Marchi, 2003; Hancock and Evans, 2006; Molloy and Stepinski, 2007; Tarolli and Dalla Fontana, 2009; Orlandini et al., 2011; Sofia et al., 2011].

Nowadays the availability of high-resolution digital terrain models (HR-DTMs), especially those derived from airborne LiDAR (Light Detection and Ranging), has permitted significant advances in different fields of earth science, including landslide analysis and mapping [McKean and Roering, 2004; Van Den Eeckhaut et al., 2005; Ardizzone et al., 2007, Booth et al., 2009; Tarolli et al., 2012] and recognition of surface morphology in different contexts [Staley et al., 2006; Frankel and Dolan, 2007; Cavalli and Marchi, 2008; Cavalli et al., 2008; Trevisani et al., 2009; Trevisani et al., 2010; Pirotti et al., 2012]. These terrain models offer an unprecedented capability to interpret surface morphology and the related geomorphic and hydrological processes [Tarolli et al., 2009; Cavalli et al., 2012; Trevisani et al., 2012]. Accordingly, also research in channel network analysis greatly benefits from the availability of HR-DTMs [Notebaert et al., 2009; Vianello et al., 2009; Cavalli and Tarolli, 2011] which favor the application and development of several techniques for the identification of channel heads and the extraction of channel networks, e.g. the use of wavelets [Lashermes et al., 2007], nonlinear filters [Passalacqua et al., 2010], and the statistical processing of curvature [Tarolli and Dalla Fontana, 2009], different geomorphometric indices [Thommeret et al., 2010; Cazorzi et al., 2012] and openness maps [Sofia et al., 2011]. Moreover, the availability of HR-DTMs of regional coverage is increasing, thanks to technological developments and decreasing costs of data acquisition and processing, opening interesting prospects for the analysis and the definition of the channel network.

In this study, we present our experience in the derivation of channel network from a HR-DTM for an alpine region (Autonomous Province of Trento, Northern Italy), covering an area of 6210 km^2. The derivation of the channel network is conducted via a geomorphometric

approach. The digitally derived channel network is then verified and refined manually with an extensive comparison with ground truth. The refining process of channel network was particularly useful for the precise definition of channel heads as well as for the correction of channel reaches in complex morphological and difficult to be interpreted areas. In particular, an important part of the refining process was corroborated by extensive field surveys in area morphologically affected by anthropic activities, such as urban areas and road infrastructures. Moreover, we analyze the interaction between human activities and the channel network by comparing the channel network derived from the HR-DTM with field evidences collected during extensive field surveys.

Study area and LiDAR data

The Autonomous Province of Trento (northern Italy) is an alpine region covering an area of 6210 km^2 (Fig. 1). The landscape of the region presents an heterogeneous surface morphology with about 70% of the total area lying above 1000 m a.s.l. and a mean elevation of 1400 m a.s.l.. Land use is typical of mountain landscape: forests (especially conifer stands) cover around 70% of the total area, while rocky outcrops and bare ground occupy 11.5% of the territory. Urbanized and agricultural areas are mostly located in valley floors covering around the 19% of the Province. The region is characterized by a complex geo-structural setting, marked by important structural lineaments and relevant deformation structures [Castellarin et al., 2005].

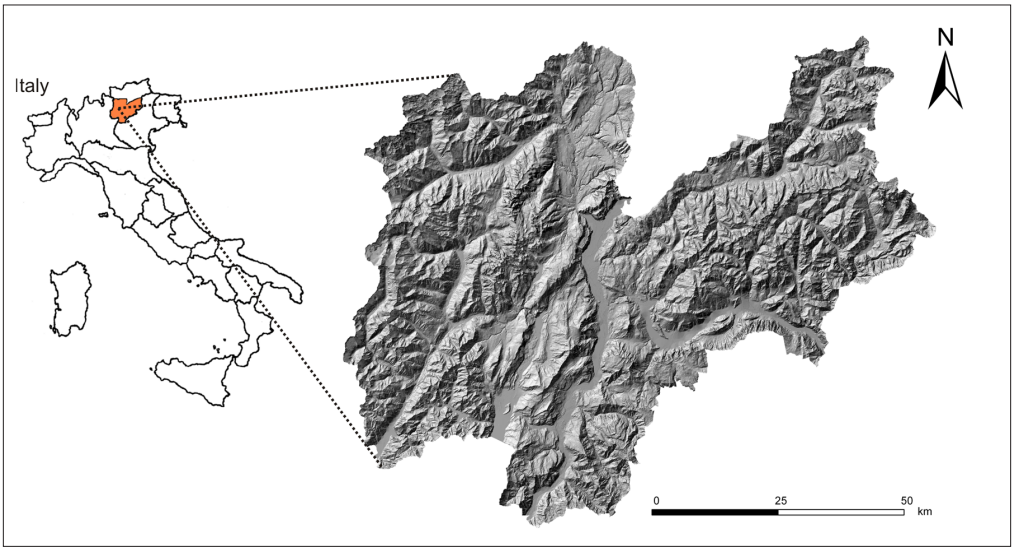

Figure 1 - Location map for the Province of Trento study site (Trentino, Italy).

The bedrock of the area is constituted by a mosaic of different lithologies, ranging from Permian to Tertiary age. Almost all the area is part the Southern Alpine Units composed by intrusive and effusive magmatic rocks, metamorphic rocks and a variety of sedimentary rocks (mainly calcareous and dolomitic). Only a small portion of the area, on the northwest, is part

of Australpine system, characterized by the presence of basement rocks (lower Paleozoic) like phyllites, micaschists, paragneisses with some associated marbles and amphibolites. The transition between Austroalpine system and the Southern Alpine Units is marked by the relevant tectonic lineament "Periadriatic Lineament" located in correspondence of Val di Sole. Quaternary deposits are widespread in the area, mainly consisting in glacial deposits and talus slope at the highest elevations and colluvial and alluvial deposits in the valley floors.

The whole territory of the Autonomous Province of Trento is covered by an HR-DTM derived from airborne LiDAR data, which is freely available for download (http://www.territorio.provincia.tn.it/S.I.A.T.). The entire Province was covered by different flights between autumn 2006 and winter 2007. The surveyed area was divided into two sections with different point density and accuracy standards in order to provide a DTM resolution of 1 m (0.15 m vertical accuracy) for main valley and urbanized area, and 2 m (0.3 m vertical accuracy) for the remaining areas. The HR-DTM was provided in 1410 and 345 blocks with 2 km side with the 1 m and 2 m resolution, respectively.

Methodology

DTMs are a mandatory topographic informative layer useful for the automatic definition of the drainage paths and, consequently, of the digital channel network of a given basin. Different algorithms have been implemented in both commercial and open source GIS software, which allow generating a drainage network from DTM [Montgomery and Foufoula-Georgiou, 1993; Desmet et al., 1999; Tarboton and Ames, 2001]. The developed methodology, which will be described in detail in subsequent sections, mainly requires two analysis steps: (i) the automatic derivation from the HR-DTM of a preliminary channel network, and (ii) supervised control aimed at the refinement of the preliminary channel network and at the classification of the reaches according to their main characteristics.

Raw channel network derivation

A preliminary analysis was conducted in order to test different algorithms for extracting a preliminary ('raw') channel network from the HR-DTM. In order to carry out in a consistent manner the elaborations required for the automatic derivation of the raw channel network, it was necessary to create a unique DTM with a homogeneous resolution for the whole Province of Trento. A resolution of 4 m of the LiDAR DTM has been chosen to achieve the optimal trade-off between the high detail required and the large extent of the area to be analyzed. The resolution reduction by 1 to 2 m and, subsequently, from 2 to 4 m was achieved by using the Aggregate tool of ArcGIS 9.3 Spatial Analyst computing the mean of the cell values of the input DTM into a moving window of size equal to the new resolution. Due to the difficulties to manage a unique 4-m DTM of the Province, the study area has been divided into 5 sub-regions (North-East, North-West, South, South-East, South-West) in which the basic hydrologic layers, i.e. hydrologically correct DTM (with an algorithm based on sink filling approach), flow direction (with classic D8 algorithm), and upslope area, have been derived. A further subdivision into 47 hydrologic drainage basins was necessary in order to define, for homogeneous areas, the appropriate thresholds for channel extraction (Fig. 2).

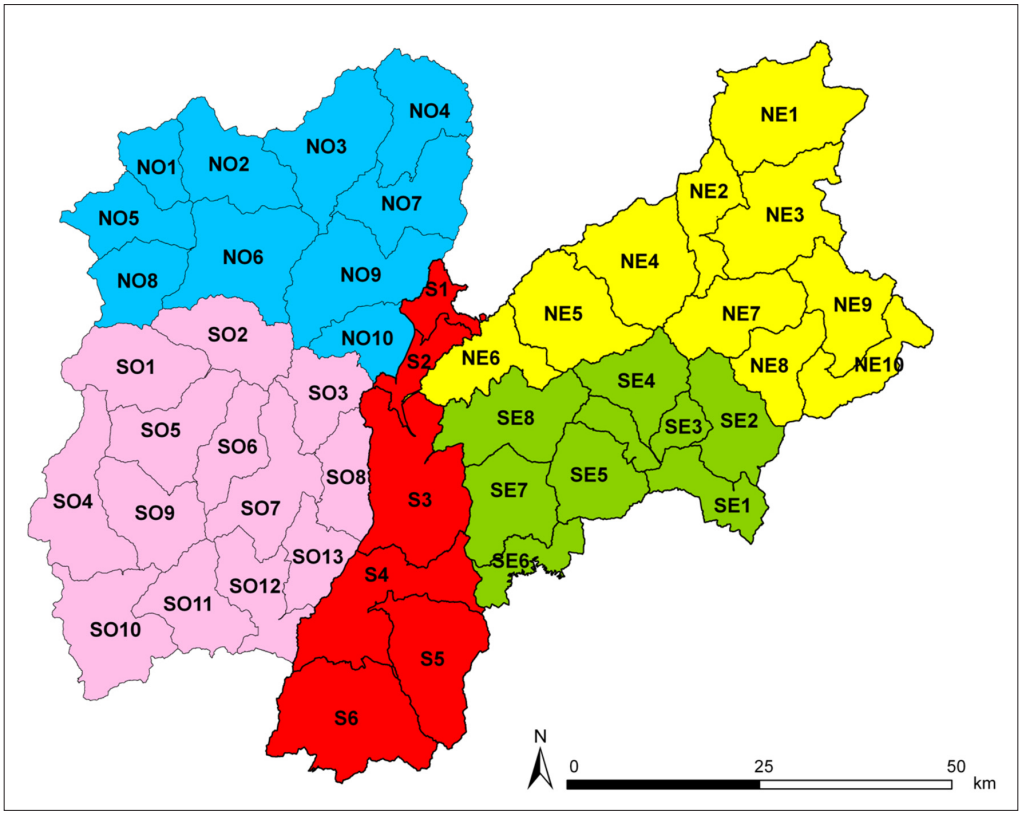

Figure 2 - Subdivision of the study area into 5 sub-regions named NE, NO, SE, S, SO, and their respective sub-basins.

Initially, two different morphological algorithms for extracting the channel network from the HR-DTM were tested: a curvature-based and a modified slope-dependent threshold area approach. A numerical/statistical approach for the definition of the thresholds was avoided in relation to two main reasons: (i) an extensive quality control and manual refinement of the derived channel network was a commitment of the planned procedure. Accordingly, this reduced the need to invest many resources in the definition of the thresholds given the possibility to refine manually the channel heads; (ii) the definition of a numerical/statistical procedure for the optimization of thresholds would have required the availability of a high resolution digital channel network for a wide set of test areas (considering the morphological heterogeneity of the area). This process is time consuming and the derivation of the test channel network would be operated via the same thematic layers used for the control and refinement of the raw channel network, leading to a kind of circularity.

The tests aimed at the comparison between the mentioned algorithms were conducted on the Alto Avisio basin (NE1 basin in Fig. 2), covering an area of approximately 210 km^2. This area was chosen because of its wide variety of morphological settings and the representativeness of the hydrologic network. Moreover, the Alto Avisio basin was particularly well suited for conducting intensive field surveys aimed at the validation of the derived raw channel networks.

Curvature-based method

The first algorithm we tested was the Curvature-based method [Tarboton and Ames, 2001] implemented in the TauDEM (Terrain Analysis Using Digital Elevation Models, http://hydrology.usu.edu/taudem/taudem4.0/index.html).

The algorithm first identifies upwards curved grid cells using the approach of Peuker and Douglas [1975] reported by Band [1986]: initially the pixels of highest elevation in a 4-cell moving window are flagged and then, after one sweep of the matrix, the unflagged cells are identified as drainage courses (Fig. 3). Before identifying upwardly curving grid cells, the DTM is first smoothed by a kernel with weights at the center, sides, and diagonals. The patterns of upward curved cells lack connectivity and are not readily amenable to delineate channel network. The connection of upwards curved cells is achieved by computing a weighted contributing area using only the identified upward curved cells as a weighting field. A threshold in this weighted drainage area is finally applied to delineate channel network. This means that the threshold in the Curvature-based algorithm is expressed in number of upward curved grid cells in contrast to contributing area based algorithms where the threshold is commonly expressed in terms of surface facilitating a comparison with other environments.

As in the case of the Slope-dependent threshold area method, threshold was defined following a trial and error approach based on a visual evaluation of the density and channel heads location of the derived channel network.

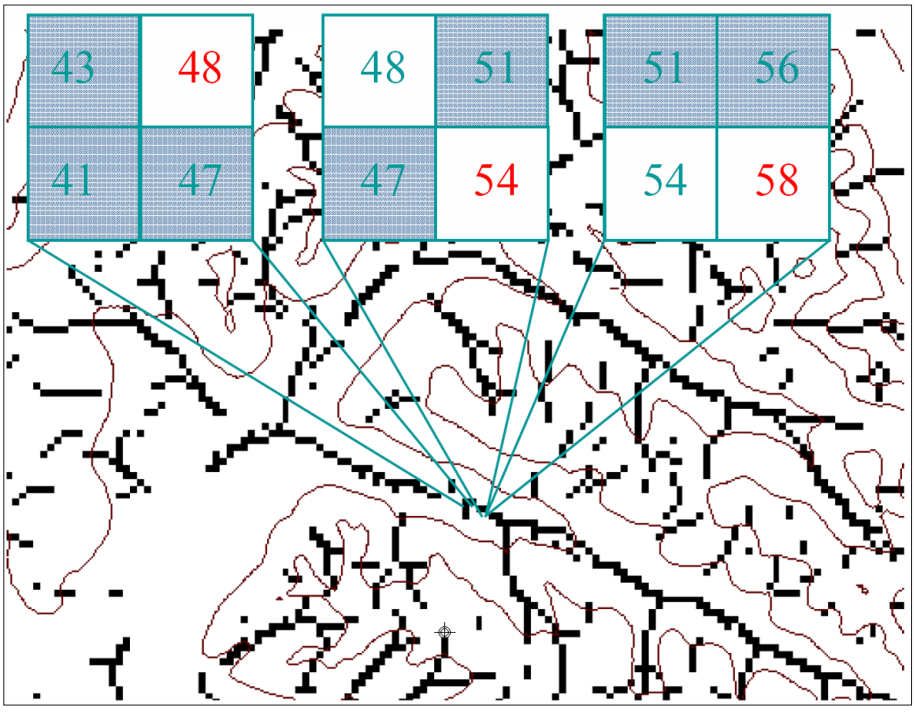

Figure 3 - Method of Peuker and Douglas [1975] for the identification of the upwards grid cells. The highest grid cell in each set of four is selected (white). The remaining unflagged (blue) grid cells represent drainage courses (from Tarboton and Ames [2001]).

Modified Slope-dependent threshold area method

The other algorithm we tested was the Slope-dependent threshold area method [Montgomery and Dietrich, 1992; Tarboton et al., 1992; Tarboton, 1997] as implemented in the TauDEM software. With this method the channel derivation is based on a slope- area relationship:

$$T = a^n S^m \quad [1]$$

Where a is the specific drainage area, i.e. upslope contributing area per unit contour width, S is the slope expressed as tangent of the slope angle, n and m are the exponents of a and S, respectively. When T is above a defined threshold a channel head is defined. Even in this case, the determination of the threshold relies on an heuristic procedure based on field evidences and visual control of drainage network density.

In this work, in order to reduce the degrees of freedom of eq. [1], we set up n=1 and m=2, as in the first application of the method by Montgomery and Dietrich [1992]. Consequently the equation becomes:

$$T = aS^2 \quad [2]$$

This formulation is a strong simplification of eq. [1], and it is deemed important to remark as the original formulation [1] opens interesting prospects for the modeling of a wide range of runoff generation processes. Unfortunately, the definition of exponents n and m require more complex and possibly physically based procedures of calibration. In equation [1], the factor S^2 can be interpreted as a multiplicative factor of the specific drainage area a, which amplifies or reduces a, depending on slope values. According to this formulation, at 45° (slope=1) we have no effect on drainage area, with higher slopes we have amplification and lower slopes attenuation.

When applied directly to HR-DTMs this method tends to produce side effects such as a very dense channel network on steep slopes and a too much coarse network in plain areas. However, we observed that with some ad-hoc modifications of the original algorithm, required and suggested by the available high resolution, the Slope-dependent threshold area method could be proficiently applied with HR-DTMs. The performed modifications are summarized briefly in the following lines:

i) In the equation [2] we used for S not the single pixel local slope but an upslope average slope: i.e. for a given pixel, corresponding to a potential channel head, the slope used corresponds to the average local slope of the related drainage basin;

ii) We defined, because of purely algebraic considerations, an upper and lower threshold on slope corresponding respectively to $\sqrt{2}$ (around 55°) and 0.577 (corresponding to 30°) limiting the multiplicative factor S^2 respectively to 2 and 1/3. The upper threshold, together with the use of an average slope, prevents the derivation of a too dense drainage network on steep slopes. The lower threshold was set to reduce the side effect of a too coarse drainage network on flat areas.

Choice of the method

Both approaches, applied to the Alto Avisio pilot area (NE1 basin in Figure 2), generate

suitable results in terms of drainage density and channel heads location, with a slight better performance of the Curvature-based algorithm in low-slope areas (Fig. 4).

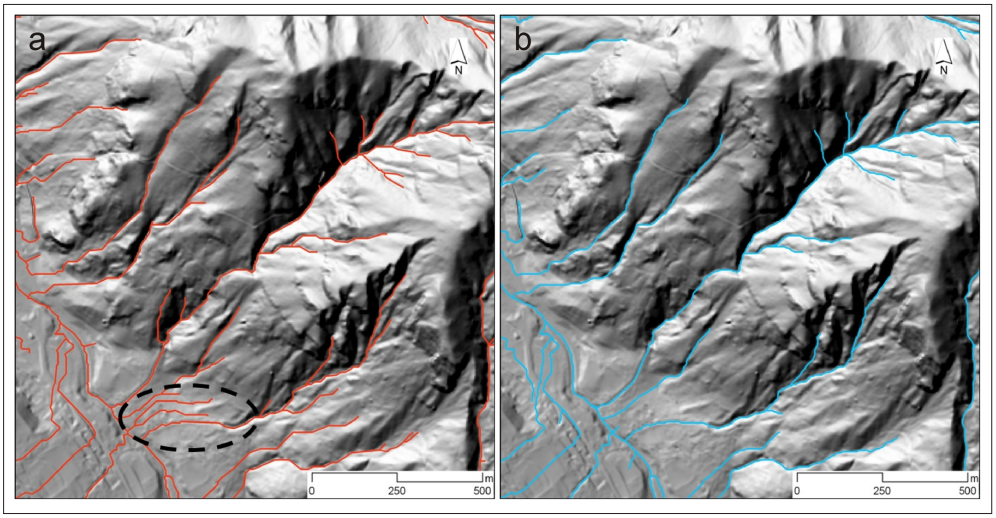

Figure 4 - Comparison between the two methods described in this paper in a sample area. (a) Slope-dependent threshold area method; (b) Curvature-based method. The dotted line outlines a higher drainage density in the flat area for the slope-dependent threshold area method.

For the final derivation of the raw channel network we decided to use the Curvature-based algorithm. This choice is only marginally based on its slight better performance in low-slope areas. The main reason is that this algorithm, differently from the slope/area based one, does not require ad-hoc modifications which increase the complexity of the procedure and which could require a more in deep analysis in regard to the involved physical processes in order to justify the calculation parameters. Moreover, another reason that argues in favor of the Curvature-based approach when applied on HR-DTMs relies on the definition of channel head. Montgomery and Dietrich [1988] defined a channel head as "the farthest upslope location of a channel with well-defined banks", definition then rephrased by Dietrich and Dunne [1993] as "the upstream boundary of concentrated water flow and sediment transport between definable banks". According to these definitions of channel heads, it is evident that the geometric and morphologic element plays a key role in determining the channel network. HR-DTMs can effectively represent the morphologic signature of channels; thus the choice of a Curvature-based algorithm, enhancing the importance of the geometric element in the channel network derivation, seems the most appropriate.

Supervised quality control and network classification

The automatically derived channel network represents a 'raw' hydrographic network that needs a supervised quality control and, in some cases, manual refinements. This is related to different factors among which the inherent limitations of a exclusively morphological approach in the definition of channel heads, possible errors and artifacts in the HR-DTM,

and, mostly, anthropic influences (e.g. culverts, bridges, secondary roads).
Before performing the supervised quality analysis, the raster of the 'raw' hydrographic network has been converted into vector format taking into account the flow path direction of the channel network and dividing it into separate reaches (a reach originates from a channel head or from the junction of two upstream reaches). To remove artifacts generated in this phase, namely the sudden changes in direction of the segments that compose the polyline, the Polynomial Approximation with Exponential Kernel smoothing algorithm [Bodansky et al., 2002] has been applied to the vector 'raw' channel network.
The quality control and refinement procedures were carried out by means of visual interpretation of different informative layers in a GIS environment and via field surveys mainly tailored on urbanized areas and channel head locations. The geographic informative layers used for the refinement of channel network can be grouped into two classes: (i) technical and thematic cartography and high resolution orthophoto imagery (Fig. 5), and (ii) geomorphometric indexes derived from the HR-DTM.

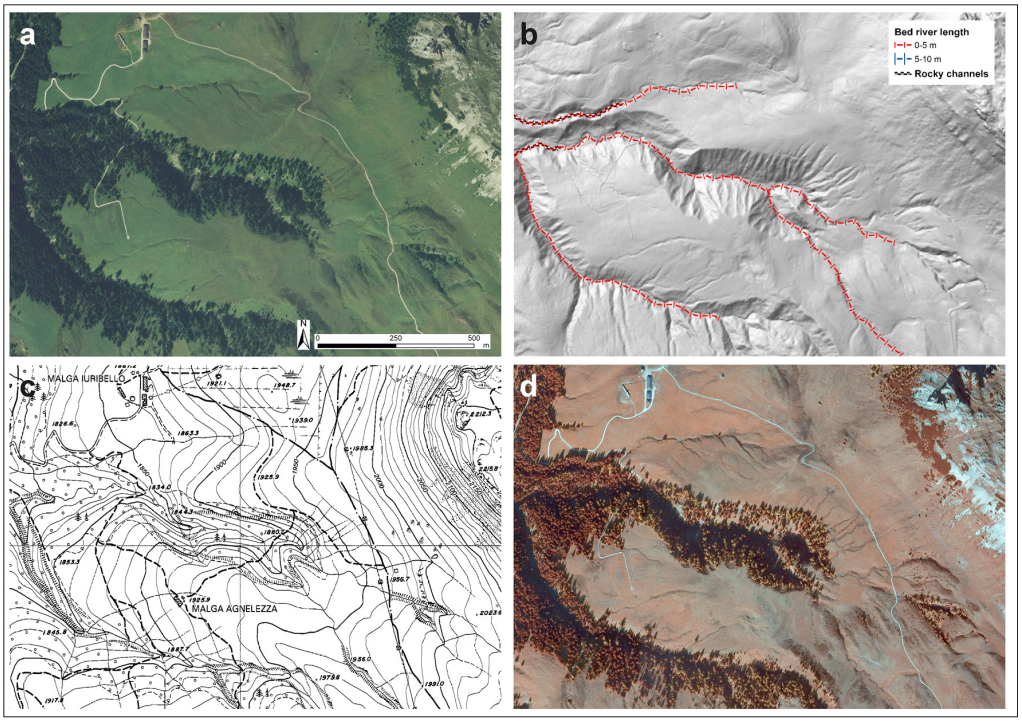

Figure 5 - Illustration of some of the thematic layers used for the revision of the raw channel network: (a) panchromatic orthophoto; (b) morphological and sedimentological map; (c) technical cartography (1:10000); (d) near-infrared orthophoto.

With regard to the first class, various layers have proven useful in this phase of the analysis. Traditional technical cartography (1:10000 and 1:25000 scale) furnished valuable information about the channel network pattern of the study area (Fig. 5c), especially

the one at 1:25000 scale that was compiled by Italian Military Geographical Institute (IGMI) also via field surveys. Nevertheless, it has to be taken into account that technical cartography is dating back to 80s (1:10000) and 50s (1:25000). Several thematic layers (i.e. geomorphologic, geologic, and land use maps, hydraulic regulation works and roads layers) help interpret and, if necessary, correct the channel network pattern (Fig. 5b). Orthophoto images acquired in the recent years (2006 and 2008) are probably the most important layers in the supervised analysis since they provide updated information about the actual pattern of the channel network that is consistent with LiDAR HR-DTM with the only limitation of shadows in few limited areas (Fig. 5a). Particularly valuable information has been provided by using the near infrared band to create a false-color image of 2008. This kind of image greatly enhances the presence of water (Fig. 5d).
Geomorphometric indexes will be discussed in detail in the following sub-section.

The quality control and refinement procedures included the need to perform a channel network classification aimed to differentiate channel reaches according to their main characteristics. In particular, every reach of the hydrographic network has been classified into one of the following three classes (Fig. 6):

- Real: existing channels;
- Virtual: drainage paths in unchanneled areas, connecting real channels;
- Covered channels: in correspondence of culverts and bridges.

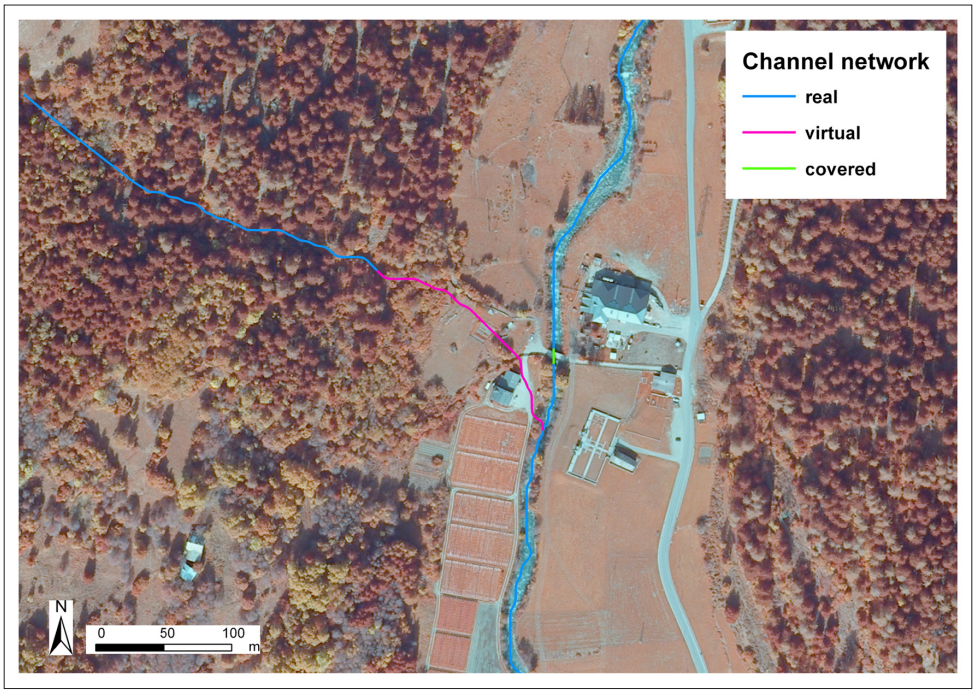

Figure 6 - Example of the classified channel network showing the different class types.

Geomorphometric layers

The second group of geographic informative layers used for the refinement of channel network includes various geomorphometric indexes that can be derived directly from the HR-DTM. The high resolution and good quality of the LiDAR DTM have allowed the generation of geomorphometric parameters [Hengl and Reuter, 2009] useful to undertake the analysis of interpretation even in forested areas where the first group layers have problems of interpretability (e.g. orthophoto) or of accuracy (e.g. technical cartography). Four parameters were derived from the HR-DTM: (i) shaded relief, (ii) Openness [Yokoyama et al., 2002], (iii) local anomalies, and (iv) plan curvature (Fig. 7).

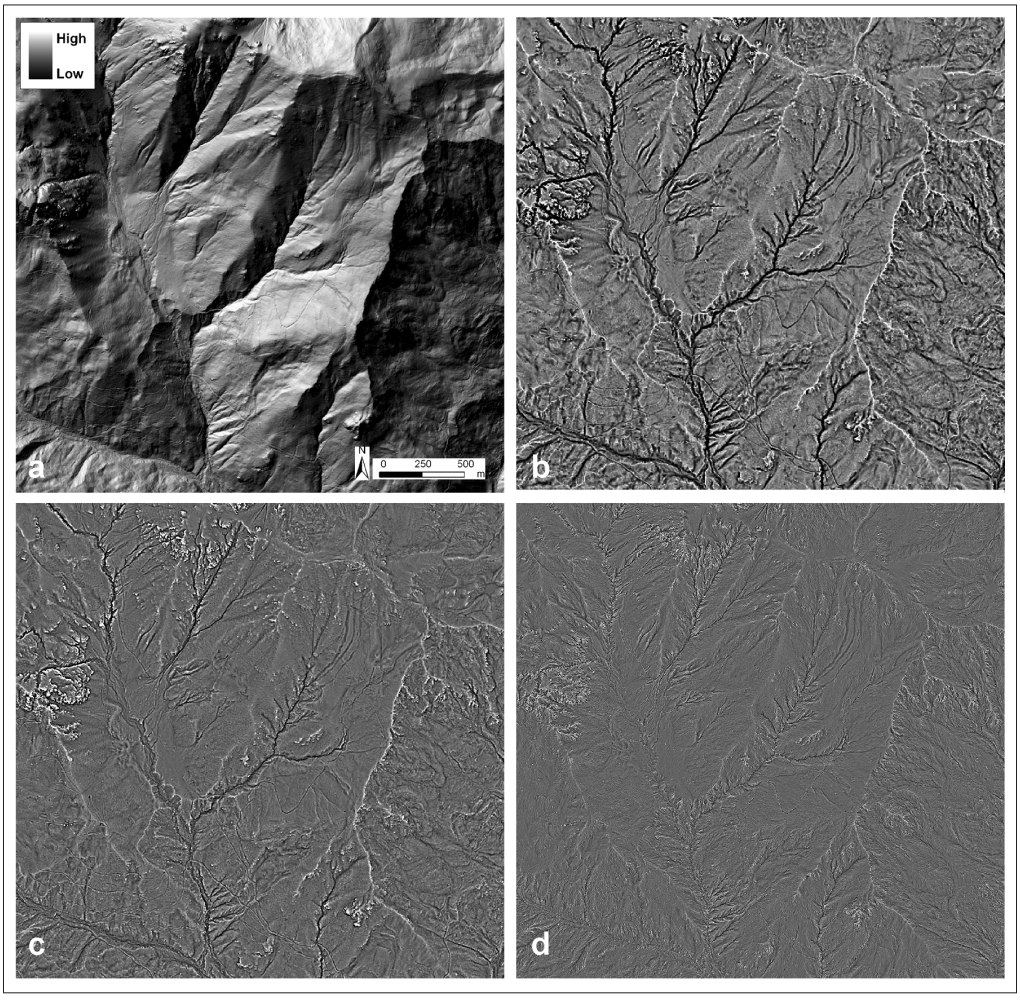

Figure 7 - Geomorphometric parameters derived from HR-DTM for a sample area. (a) Shaded relief; (b) Openness; (c) Local anomalies; (d) Plan curvature.

The shaded relief map of the study area was created from the HR-DTM with 2 m cell size to take advantage of the highest resolution available (Fig. 7a). The shaded relief map, representing the hypothetical illumination of the surface, is a classic geomorphometric parameter useful for visualization purpose. It can be produced by setting a position for a hypothetical light source and determining the illumination values of each cell in relation to neighboring cells. The shaded relief maps of the five macro-areas were created using a hypothetical light source from the North-West direction with a zenith of 45° and an azimuth of 315° (i.e. the default for many GIS software). The input values of zenith and azimuth angles are then processed along with slope and aspect computations to obtain the final shade relief value for each cell in the output raster, according to the following algorithm [Burrough and McDonnell, 1998]:

$$Shade = 255 \cdot \{[cos(z) \cdot cos(S)] + [sen(z) \cdot sen(S) \cdot cos(az - A)]\} \quad [3]$$

where z is the zenith angle, az the azimuth angle (both expressed in radians), S and A are slope and aspect, respectively.

The calculation of local anomalies is a typical sharpening technique [Campbell, 2008] useful to enhance high frequency morphological features such as structural lineaments, channel incisions, small scarps, local roughness, etc (e.g., [Carturan et al., 2009; Trevisani et al., 2009; Cazorzi et al., 2012]). The local anomalies are derived via a simple sharpening technique i.e. making the difference between the original DTM (2 m resolution) and a smoothed one; an example of the resulting map is showed in (Fig. 7c), where the smoothed DTM was derived via moving averages with a window size of 8 m.

The Openness index [Yokoyama et al., 2002] is a surface representation which requires no light source, thus removing one limitation of relief shading (i.e. the presence of shadowed areas) and it is less affected by the DTM noise afflicting most other geomorphometric parameters. Openness expresses the degree of dominance or enclosure of a location on an irregular surface. It is an angular measure of the relation between surface relief and horizontal distance. Topographic openness is calculated as the average of either zenith (Φ) or nadir (Ψ) angles along eight azimuths D (0, 45, 90, 135, 180, 225, 270 and 315) within a radial distance L [Yokoyama et al., 2002]. Openness thus provides two visual perspectives: it is designated "positive" and "negative" in the same sense as has been used to express terrain-slope curvature. Positive openness Φ_L is convex-upward and refers to the calculation with zenith angles; negative openness Ψ_L is concave-upward and refers to evaluation with nadir angles [Sofia et al., 2011].

Along the azimuth direction (D), the zenith angle ${}_D\Phi_L$ at a cell within radial distance L is:

$${}_D\Phi_L = 90 - {}_D\beta_L \quad [4]$$

where ${}_D\beta_L$ is the minimum elevation angle for which the line-of sight is unobstructed along L. Nadir angle ${}_D\Psi_L$ is expressed as follow:

$$ {}_{D}\Psi_L = 90 + {}_{D}\delta_L \quad [5] $$

where ${}_{D}\delta_L$ is the minimum angle of depression for which the line-of sight is unobstructed along L.
The positive Openness Φ_L of a DTM cell is defined as follow:

$$ \Phi_L = \frac{({}_{0}\Phi_L + {}_{45}\Phi_L + \cdots + {}_{315}\Phi_L)}{8} \quad [6] $$

and the negative Openness Ψ_L:

$$ \Psi_L = \frac{({}_{0}\Psi_L + {}_{45}\Psi_L + \cdots + {}_{315}\Phi\Psi_L)}{8} \quad [7] $$

by varying L, landforms at different scales can be represented.
The resulting map resembles shaded relief or slope maps, but emphasizes dominant surface concavity and convexity (Fig. 7b).
Curvature is defined as the rate of change of the slope and is usually determined as the second derivative of the surface. The two most frequently calculated forms are: (i) profile curvature, calculated along the direction of maximum slope, and (ii) plan curvature, calculated orthogonally to the direction of maximum slope. The latter provides a measure of convergence and divergence of flow and is often used for the identification of ridges and channels on DTM [Cavalli and Marchi, 2008]. Therefore, a plan curvature map is particularly appropriate for interpretative purpose in the quality control and refinement phase of the 'raw' channel network (Fig. 7d).

Results and discussion

The raw channel network was derived using the curvature-based algorithm and setting different thresholds ranging from 80 to 120 in the 47 catchments reported in Figure 2. Figure 8 shows the result of the application of the proposed methodology to the Alto Avisio test area. The overall development of the derived channel network, including both real channels and reaches classified as virtual and covered, is approximately 27600 km. Virtual and covered reaches constitute 19.5% (about 5400 km) of the total channel network length. In particular, the procedure was able to detect a large number of covered reaches (5870, the 4.2% of the total number of hydrographic network reaches) for a total length of 84 km.
The classification into real, virtual and covered reaches is of considerable importance since it allows adapting the channel network for various purposes. For example, virtual reaches, i.e. drainage paths connecting a channel ending without a connection to a receiving watercourse, should not be reported in topographic maps. Heavy rainfall events can cause floods typically resulting in runoff conveying also along unchanneled surfaces or roads. Being virtual reaches derived from the 'raw' channel network, thus, following the computed flow directions, they can represent the preferential flow paths in case of intense storm (Fig. 9). Therefore, when the channel network has to be used for geo-hydrological risk analysis or modeling purpose, the virtual reaches deserve to be preserved.

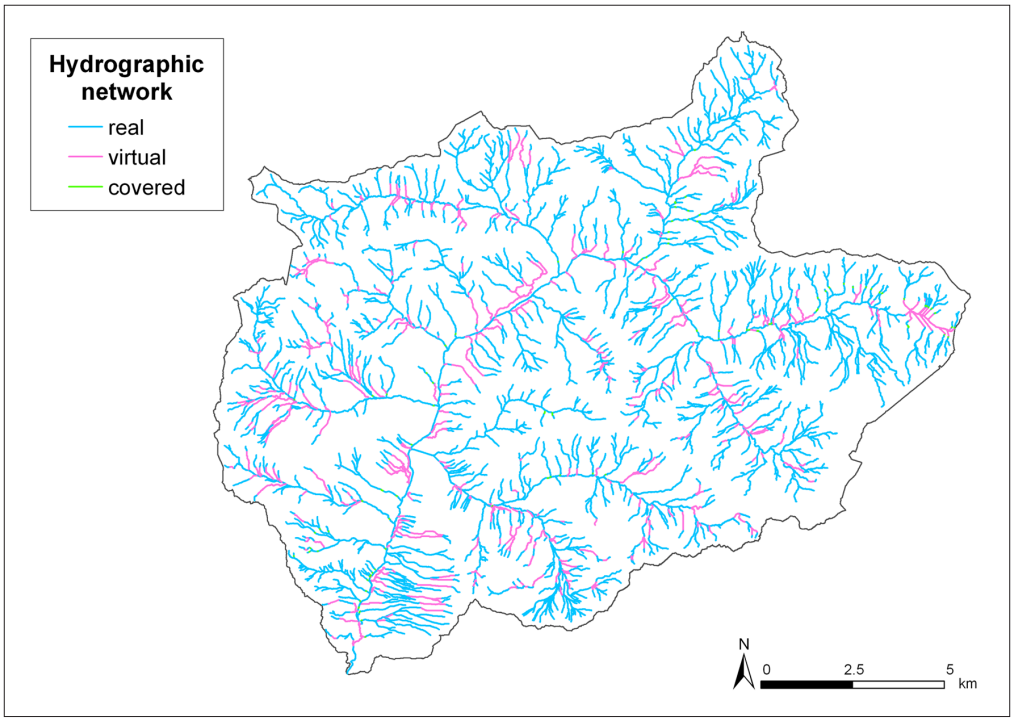

Figure 8 - The map illustrates the new classified channel network for the Alto Avisio basin (NE1 in Fig. 2) resulting from the semi-automatic procedure proposed.

Figure 9 - A forest road classified as virtual reach affected by runoff triggered by an intense storm.

The benefits of the applied methodology emerge from Figure 10 presenting a rather flat and urbanized area of the Province. The LiDAR-based channel network is clearly more detailed, more accurate and with a higher completeness if compared with the technical cartography channel network (red line in Figure 10).

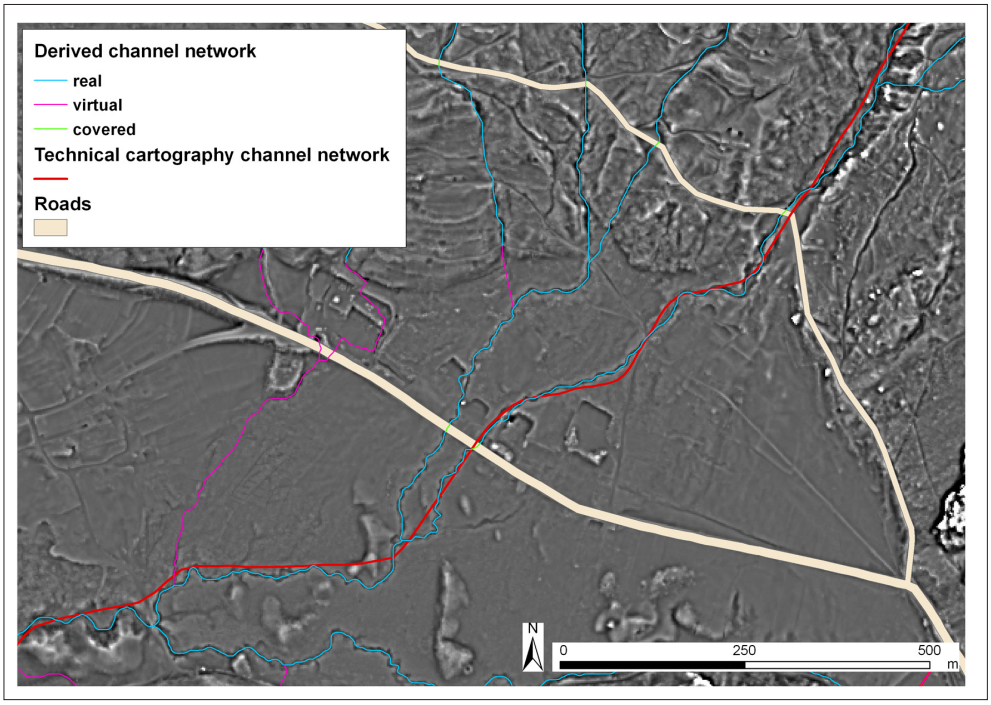

Figure 10 - Comparison between the technical cartography channel network and the derived one.

The high degree of extensiveness is also proved by the high values of drainage density. The drainage density (D_d) represents an important morphometric parameter closely related to significant environmental factors as climate, vegetation, and soil and rock properties and is defined as follows:

$$D_d = \frac{L_T}{A} \quad [8]$$

Where L_T is the total length of the channel network (km) within area A (km^2).
Table 1 shows drainage density values for the 47 basins in which the Province of Trento has been subdivided (Fig. 2). It's important to highlight that not all these areas are headwater catchments. Some of them are actually interbasins, defined as the area directly drained by a reach of the main stem lying between two tributaries [Verdin and Verdin, 1999]. The derived channel network reaches were classified according to the Horton-Strahler ordering and maximum values within the above mentioned areas are also shown in Table 1. The

maximum Horton-Strahler order of areas relating to the Adige river has not been reported since Adige receives the discharge from a large basin of about 7500 km^2 external to the Province of Trento.

Table 1 – Main morphometric parameters of the channel network of Trento Province computed for the 47 basins reported in Figure 2 (Typology: B=Basin; IB=Interbasin).

Catchment	Area (km^2)	Length (km)	Maximum order (-)	Drainage density (km^{-1})	Typology
S1	45.49	240.66	-	4.55	IB
S5	175.37	607.10	-	3.01	B
S2	53.95	201.02	-	3.36	IB
S3	234.53	708.84	-	2.32	IB
S4	201.45	511.56	-	1.94	IB
S6	231.94	928.37	-	3.46	IB
NO1	68.32	209.38	5	2.55	B
SE2	129.24	481.56	5	2.76	B
SE6	70.77	221.37	5	2.75	B
NE1	209.17	758.99	6	2.96	B
NE3	186.00	764.13	6	3.33	B
NE7	137.45	684.95	6	4.56	B
NO2	142.44	603.49	6	3.49	B
NO4	135.41	386.68	6	2.44	B
NO5	105.24	418.50	6	3.04	B
NO8	104.29	460.23	6	3.62	B
SE4	112.32	365.62	6	2.83	B
SE5	119.16	539.03	6	3.82	IB
SE7	132.75	473.38	6	2.94	B
SE8	158.48	510.36	6	2.73	B
SO2	131.11	850.83	6	5.08	B
SO3	97.59	708.84	6	2.75	B
SO4	176.11	1024.54	6	4.64	B
SO8	93.94	275.73	6	2.00	IB
SO9	132.64	820.00	6	5.02	B
SO11	123.76	672.77	6	4.48	B
NE2	95.02	505.91	7	4.55	B
NE4	182.78	687.41	7	3.04	IB
NE5	167.62	652.00	7	3.42	IB
NE6	111.89	393.14	7	3.08	IB
NE8	99.65	530.68	7	4.88	IB
NE9	127.77	910.43	7	6.10	B
NE10	99.96	729.53	7	6.39	B
NO3	178.52	862.62	7	4.11	B
NO6	195.05	895.34	7	3.86	IB
NO7	149.88	366.20	7	1.96	IB
NO9	197.32	794.11	7	2.88	B
NO10	83.36	314.07	7	3.08	IB
SE1	88.50	440.23	7	4.06	IB
SE3	81.45	273.09	7	2.70	B
SO1	149.64	783.34	7	3.83	B
SO5	140.51	822.26	7	4.35	IB
SO6	92.61	605.98	7	5.43	B
SO7	153.92	504.83	7	2.52	B
SO10	176.92	1282.71	7	6.24	B
SO12	115.14	468.78	7	2.92	B
SO13	85.64	308.26	7	2.59	IB

The drainage density of channel network considering only real and covered reaches, has a mean value of 3.54 km^{-1}, ranging from 1.94 to 6.39 km^{-1}, for S4 (subcatchment of the Adige river between the Calliano and Chizzola localities) and NE 10 (lower Torrente Cismon basin including Torrente Noana tributary) catchment, respectively.
Some considerations relating to drainage density can be formulated looking at the histogram of Figure 11 and to the spatial distribution of the drainage density of the basins (Fig. 12). The analysis of drainage density conducted should be viewed as a preliminary analysis because of the statistics and the spatial patterns of drainage density are affected by the area and shape of defined basins. Consequently, this analysis is focused only on the more relevant characteristics of drainage density.

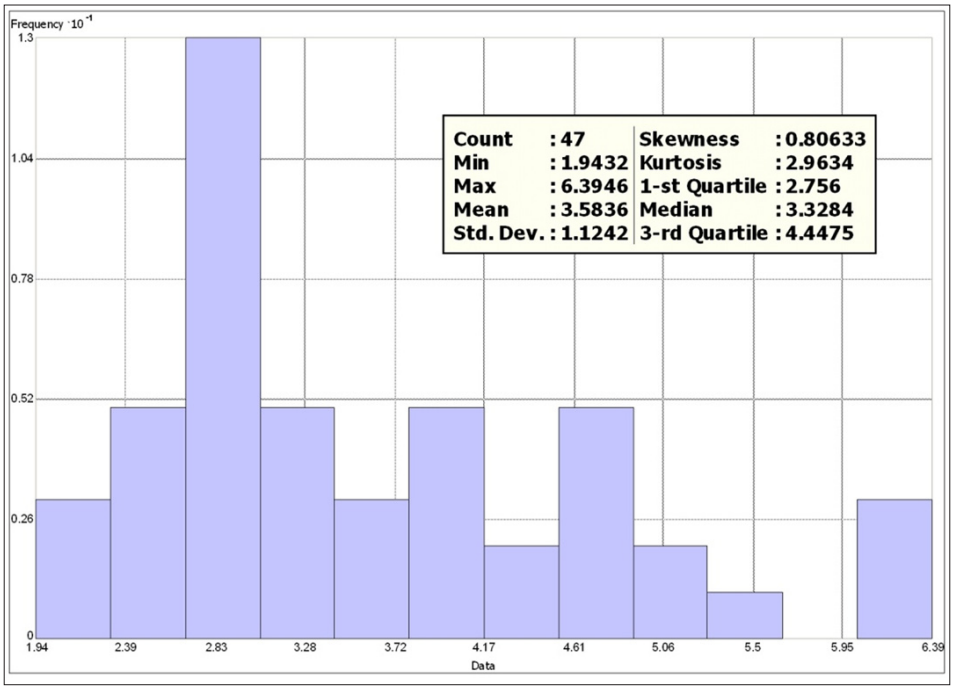

Figure 11 - Histogram of drainage density computed for the 47 basins with reported main summaries statistics.

The histogram (Fig. 11) of drainage density has a slight positive distortion, characterized by a higher dispersion toward high values of drainage density. This positive distortion is also outlined by the summary statistics of drainage density (Fig. 11) which show a difference between mean density (3.52 km^{-1}) and the median density (3.32 km^{-1}) and a skewness of 0.80. The basins with higher density (Fig. 12) are located on the west and east margins of the Trento Province coverage. The basins with higher density appear to be located in correspondence of areas characterized by relevant tectonic lineaments (faults and overthrusts), strong deformation of geological bodies and high contrast of competence between lithologies [Castellarin et al., 2005]. From this perspective an ad-hoc study is

necessary to decipher the possible connections between channel network density and geometry and the geo-structural local setting at the different spatial scales.

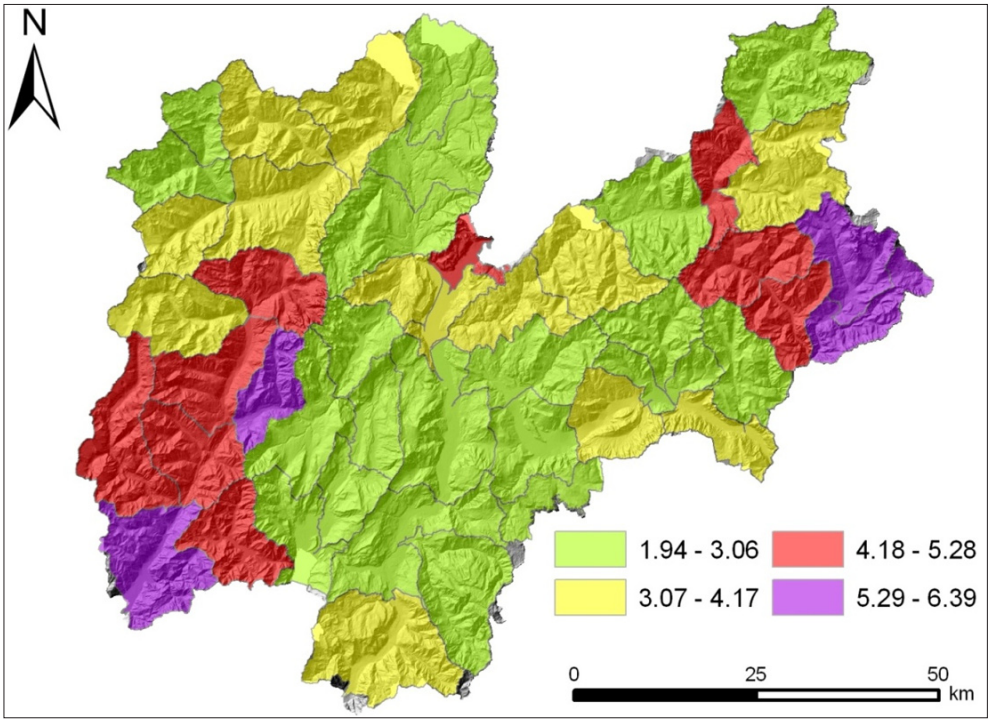

Figure 12 - Subdivision of the defined basins into 4 classes of drainage density (equal interval width).

The overall high values of drainage density reveal the great detail of the results of the proposed methodology. It is worth noting that the definition of the channel network of the Province of Trento and, consequently, the reported drainage density can be considered scale independent when a HR-DTM is used as basis for the analysis. A major advantage of the proposed approach is that it permits overcoming the dependency of channel network representation on the map scale. Many first-order channels are not visible on coarse-scale aerial photographs especially when the topographic signature of the channel is fine. Traditional methods, such as stereophotogrammetry, produce channel network patterns deeply linked to the scale of the used photographs. In cartography the concept of scale is related to the level of detail of a map whereas the same concept when dealing with gridded DTM is closely related to cell size or grid resolution [Hengl and Reuter, 2009]. A HR-DTM, as the one used in this study, can be considered a representation of topography at a scale approaching reality. For the same reason, the channel network derived from HR-DTMs can be considered not related to a given scale, thus resulting in more realistic values of drainage density.

Nevertheless, where man-made features (roads, culverts etc.) and urbanized areas are present, this method is not capable of deriving the effective channel network. In these areas,

where the aerial photo and geomorphometric indexes interpretation is also difficult, field surveys are needed in order to revise the flow paths defined by the automatic derivation procedure. The supervised control analysis revealed the presence of 1930 areas in which the definition of the channels was uncertain. In these areas an intense campaign of field survey was conducted, allowing to obtain a significant database (approximately 20,000 GPS points and 30,000 photographs) describing the characteristics of the urbanized channel network. This database has been made available to technical offices of the Province of Trento responsible for the management of critical reaches of the channel network.

Concluding remarks

In this paper a semi-automatic methodology has been developed for the derivation of the channel network from a High-Resolution Digital Terrain Model at regional scale for the Autonomous Province of Trento (Italy). The main advantage of this two-steps procedure (automatic extraction and supervised control) relies on the fact that the manual editing task is limited due to the high quality, in terms of channel heads location, spatial pattern and drainage density, of the automatic extracted preliminary channel network. The preliminary channel network greatly benefits of the high resolution and quality of the available regional LiDAR DTM, where the morphological signature of channel network is greatly highlighted. Furthermore, the choice of a curvature-based algorithm for deriving the preliminary channel network, that for its morphological nature fully exploits HR-DTM characteristics and enhances the importance of the geometric element, seems the most appropriate.

The procedure provides satisfactory results in areas less affected by human activities, also in presence of dense vegetation cover and complex morphology. In urban areas, and in other zones with a strong anthropic influence, the GIS-derived channel network has to be complemented and corrected by means of field surveys.

This approach is a cost/time efficient methodology that fits well with the needs of a dynamic and constantly up-to-date cartography resulting in an accurate and highly detailed definition of a countrywide channel network.

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