



Recognition of surface flow processes influenced by roads and trails in mountain areas using high-resolution topography

Paolo Tarolli^{1*}, Simone Calligaro², Federico Cazorzi³ and Giancarlo Dalla Fontana¹

¹Department of Land, Environment, Agriculture and Forestry, University of Padova, Agripolis viale dell'Università 16, 35020 Legnaro (PD), Italy

²Interdepartmental Research Center for Cartography, Photogrammetry, Remote Sensing and GIS (CIRGEO), University of Padova, Agripolis viale dell'Università 16, 35020 Legnaro (PD), Italy

³Department of Agriculture and Environmental Science, University of Udine, via delle Scienze 208, 33100 Udine (UD), Italy

*Corresponding author, e-mail address: paolo.tarolli@unipd.it

Abstract

Road networks in mountainous forest landscapes have the potential to increase the susceptibility to erosion and shallow landsliding. The same issue is observed also for minor trail networks, with evidences of surface erosion due to surface flow redistribution. This could be a problem in regions such as the Italian Alps where forestry and tourist activities are a relevant part of the local economy. This is just one among the several effects of modern anthropogenic forcing: it is now well accepted by the scientific community that we are living in a new era where human activities may leave a significant signature on the Earth, by altering its morphology, and significantly affecting the related surface processes. In this work, we proposed a methodology for the automatic recognition of roads and trails induced flow direction changes. The algorithm is based on the calculation of the drainage area variation in the presence, or in the absence of anthropic features such as roads and trails on hillslopes. To simulate the absence of alteration, the surface was smoothed considering moving windows of varying size. In the analysis, we used a 1 and 0.5 m Airborne Laser Swath Mapping technology (ALSM), using LiDAR (Light Detection And Ranging), and 0.2 m Terrestrial Laser Scanner (TLS) derived Digital Terrain Models (DTMs). The aim of the work is to underline the effectiveness of the proposed method based on high resolution topography in the detailed recognition of surface flow direction alteration due to roads, but also trail networks. We propose an automatic method to map at a large scale such alterations, also in areas where it is difficult to recognize them without a trail network surveyed in the field. This methodology could be considered as a support for modeling (i.e., terrain stability and erosion models), and it can be used to interactively assist the design of new infrastructure to reduce their effects on surface instabilities. The reported methodology

could also have a role in risk management and environmental planning for mountain areas where tourism and the related economic activities are critical, and where also trails deserve attention due to induced slope instabilities.

Keywords: LiDAR, TLS, DTM, road and trail networks, erosion, landslides.

Introduction

In the last few years, the topic related to the new geological epoch affected by the human activities has been the focus of a progressive intense discussion in the scientific community [Zalasiewicz et al., 2011]. The scientific community is debating the fact that we are living in a new era, the Anthropocene [Crutzen, 2002; Zalasiewicz et al., 2011], due to the heavy fingerprint that the man is leaving on the planet. One clear example is the relevance for human society of dense road networks, that actually affect a great part of the landscape. A well-designed road network allows fast communications, an efficient performance of every aspect of productive activities and a good environmental management. However, road networks and their related drainage system may change the surface flow directions, affecting the surface morphology with new hollows or erosion in areas that were stable before the road constructions (Figure 1, example of forest road induced landslide on the Eastern Italian Alps), thus increasing the risk for exposed infrastructures and socioeconomic activities. This is a critical issue not only for densely populated floodplains or urban environments, but also for mountain regions where forestry and tourist activities are a relevant part of the local economy. Human activities changed significantly the landscape of these regions, so the question is: how such alterations may affect the Earth surface processes, and as a consequence, the related surface morphology? An answer to this question would be an advance in understating the landscape evolution in the Anthropocene. Several years ago few researchers started to discuss about the influence of forest roads on the surface hydrology with related effect on surface erosion and sediment production [Reid and Dunne, 1984].



Figure 1 - Example of road induced landslide on the Eastern Italian Alps [picture courtesy of Cazorzi F.].

The construction of a road network determines three main effects on water flow: I) the overland flow and subsurface flow interception by the road surface and the road cutslopes respectively [Reid and Dunne, 1984; Luce and Cundy, 1994; Montgomery, 1994; Ziegler and Giambelluca, 1997; Luce and Black, 1999; Wemple et al., 2001; Borga et al., 2004]; II) flow concentration, both on the road surface and along man-made cross ditches; III) alteration of natural flow directions, with the extension of the drainage network to portions of land not previously channeled [Gucinski et al., 2001]. In general, several experimental studies have been carried out in mountain catchments, considering the water flow distribution and sediment budget variations caused by forest road networks, e.g. Jones and Grant [1996], Thomas and Megahan [1998], Croke et al. [2005]. It is therefore clear that it is relevant to analyze in detail and with high accuracy the location where the alteration of surface flow due to roads is observed, and to derive a map of such alterations, eventually proposing solutions to mitigate or prevent the problem. In order to make this analysis feasible on a large scale, thus avoiding to go on field surveys over the investigated road network, these solutions can be obtained thanks to the detailed information about local topography derived from Digital Terrain Models (DTMs). The greater the detail of this information, the greater the accuracy of information on surface flow directions, and the related alteration due to roads or any other anthropogenic factors. In the last decade, a range of new remote-sensing techniques has led to a dramatic increase in terrain information. Both Terrestrial Laser Scanner (TLS) and Airborne Laser Swath Mapping technology (ALSM), using LiDAR (Light Detection And Ranging) technology, now provide high resolution topographic data with notable advantages over traditional survey techniques [Slatton et al., 2007; Tarolli et al., 2009; Cavalli and Tarolli, 2011]. A valuable characteristic of these technologies is their capability to produce sub-meter resolution DTMs and DSMs (Digital Surface Models) [Corona et al., 2012; Pirotti et al., 2012a,b] over large areas. The capability to describe with high resolution and accuracy the surface morphology at hillslope scale [Tarolli and Dalla Fontana, 2009], for example, represents an important advance in the analysis of the earth surface processes of the alpine headwater catchment, since the morphology of such regions is strongly influenced by erosion processes [Montgomery and Dietrich, 1994; Stock and Dietrich, 2003; Cavalli et al., 2012; Trevisani et al., 2012]. Nowadays, it is possible to recognize divergent-convex landforms, associated with the dominance of hillslope processes, and convergent-concave landforms, associated with fluvial-dominated erosion [Tarolli and Dalla Fontana, 2009; Passalacqua et al., 2010; Pirotti and Tarolli, 2010; Sofia et al., 2011]. In addition to this, thanks to high resolution topography it is possible to represent in detail hillslope flow directions, thus, through the analysis of their complexity, it is possible to characterize and differentiate areas with different morphology and geology [Orlandini et al., 2011]. All the ongoing researches using LiDAR indicate the effectiveness of high-resolution elevation data for the analysis of land surface morphology, especially for the recognition of channelized processes and channel bed morphology [Trevisani et al., 2010]. In such context, this work presents a methodology based on high resolution LiDAR derived topography for the automatic recognition of roads and trails induced flow direction changes. The advance of such approach, in respect to other analyses conducted in the last decade on forest roads [Borga et al., 2004, 2005], is to underline the effectiveness of LiDAR data (both airborne and TLS derived) for the automatic recognition of flow path changes, due also to smaller road networks such as trails. We propose an automatic method to map at a large scale these

alterations, as a first useful stage for more complex modeling applications. The methodology was applied in the North-Eastern part of Italy. We considered three case studies where forest roads and trail networks, and the related instabilities or flow direction redistribution have been accurately surveyed in the field. For the study areas, detailed airborne LiDAR, and TLS elevation data are available. The methodology can be useful to define criteria for risk management and suitable environmental planning in those mountain areas where forest roads and trails are relevant for tourism (eg. trekking), and related economic activities.

Study Areas

The study domain consists of two selected areas (Fig. 2b) near the village of Paularo, in Carnia, a region of Eastern Italian Alps, and two headwater basins of the Dolomites (Eastern Italian Alps): the Upper Cordevole (Fig. 2c), and Rio Cordon catchment (Fig. 2d).

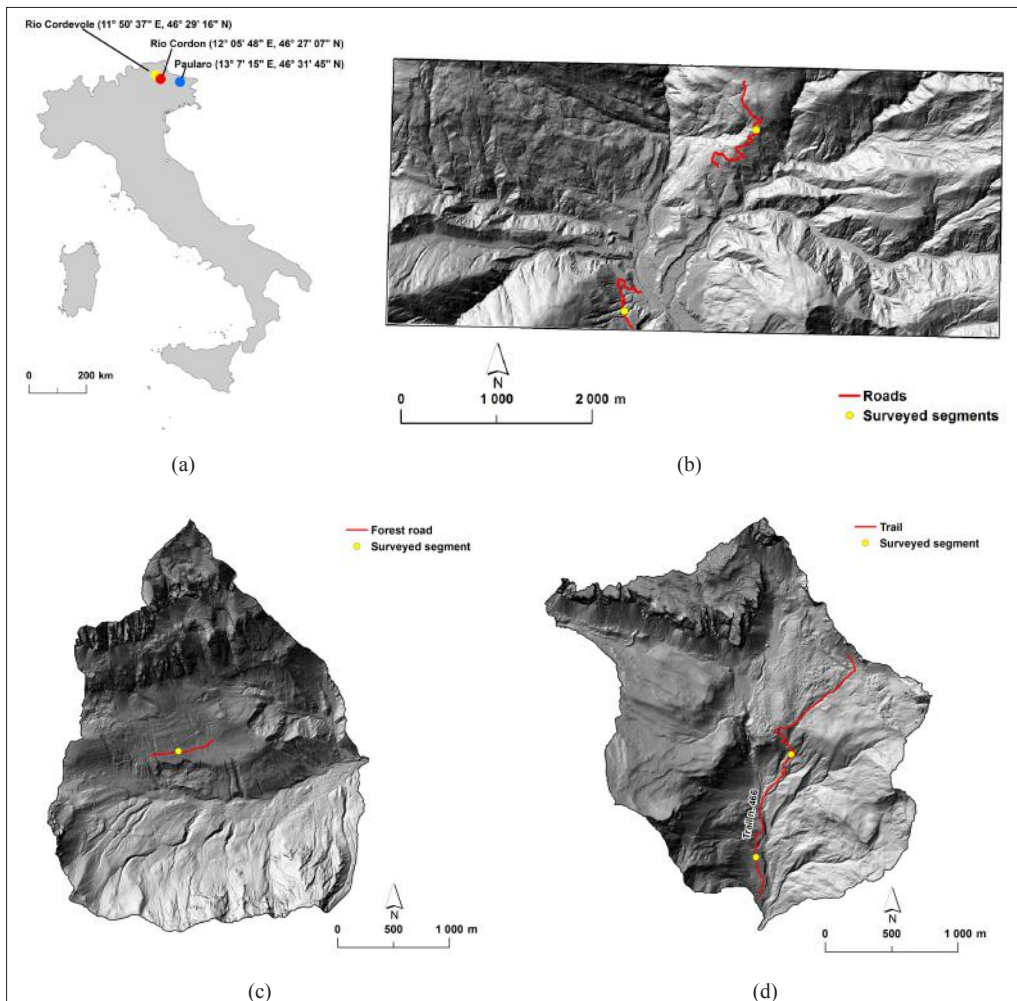


Figure 2 - The figure shows the location of the study areas (a), and detail of the Paularo field site (b), Upper Cordevole (c) and Rio Cordon basin (d); surveyed segments are shown.

Paularo area

The Paularo area spans on 18 km² and presents elevations ranging between 614 and 1537 m a.s.l. with an average elevation of 1011 m a.s.l.. The average slope is 29.5°, with a maximum value of 89.8°. The area is characterized by the presence of several villages, road networks and activities such as forestry, pasture, and high-altitude farms. The area has a typical climate of the easternmost sector of the Italian Alps with short dry periods and a mean annual precipitation of about 1600 mm. The recorded annual precipitation ranges from 1200 up to 2400 mm (mean, minimum and maximum values of annual precipitation at Paularo meteorological station reported in “Atlante climatologico del Friuli Venezia Giulia – Climatic Atlas”, published online by the ARPA-OSMER [Cicogna, 2008]). Precipitation occurs mainly as snowfall from December to March; runoff is usually dominated by snowmelt from March to May. During summer, flash floods with heavy solid transport are quite common.

Upper Cordevole catchment

The upper Cordevole catchment has a surface of 7.08 km², and its elevation ranges between 1853 and 3152 m a.s.l., with a mean elevation of 2274 m. The catchment mean slope is about 31°, but it reaches a maximum value of 88°. The Upper Cordevole river in the last decade has been the subject of several analyses of channel bed morphologies and landslide activities [Borga et al., 2002; Vianello and D’Agostino, 2007; Vianello et al., 2009]. The basin is mainly characterized by high-altitude grassland and bedrock outcrops. The area is interested by a dense road and trail network connected to the presence of Pass Pordoi, a popular tourist overlook point over the Dolomites, and of several ski resorts.

Rio Cordon catchment

The Rio Cordon catchment, thanks to the evident earth surface geomorphic processes such as landslides, was deeply surveyed in the past [Dalla Fontana and Marchi, 2003; Tarolli et al., 2008; Passalacqua et al., 2010; Tarolli et al., 2012]. The catchment has a surface of 5 km²; the elevation ranges between 1814 and 2760 m a.s.l., with an average value of 2257 m a.s.l. The catchment slope has an average value of 25.8°, and a maximum value of 84°. The area is frequently considered for tourist recreation activities during summer (trekking), and winter (mountain ski), and it is characterized by a dense trail network (eg. CAI, Italian Alpine Club, trail n. 466). Pasture activities are also present. Both the Upper Cordevole and the Rio Cordon catchment are characterized by a mean annual rainfall of about 1100 mm. Precipitation occurs mainly in the form of snowfall from November to April. Runoff is dominated by snowmelt in May and June, but summer and early autumn floods represent an important contribution to the flow regime.

Data

Airborne LiDAR survey

The LiDAR data and high-resolution aerial photographs were acquired from a helicopter using an ALTM Optech instrument, and a Rollei H20 Digital camera. The survey design point density was greater than 2 pts/m², recording up to four returns, including the first and the last. The absolute vertical accuracy, evaluated by a direct comparison between LiDAR and ground differential DGPS elevation points, was estimated to be less than 0.3 m in flat areas, an acceptable value for LiDAR analyses in the field of geomorphology [Mckean and Roering, 2004; Glenn et al., 2006; Frankel and Dolan, 2007; Tarolli and Dalla Fontana, 2009]. The

LiDAR bare ground dataset was used to generate DTMs at 1 m (Paularo area), and 0.5 m (Upper Cordevole and Rio Cordon catchment) resolution with the natural neighbor method [Sibson, 1981], already proved to be useful for geomorphic analysis in previous works [i.e. Pirotti and Tarolli, 2010; Orlandini et al., 2011; Lin et al., 2013].

TLS survey

For part of the Rio Cordon catchment, a TLS survey was also performed using a Riegl LMS-Z620 laser scanner. The instrument offers a maximum range up to 2 km in combination with high accuracy (10 mm), and high-speed data acquisition (from 11,000 pts/sec at low scanning rate to 8,000 pts/sec at high scanning rate). For each measured point, the scanner records the range, horizontal alignment angle, vertical alignment angle and backscattered signal amplitude. The Riegl LMS-Z620 is integrated with a high-resolution (12.9 megapixel) Nikon D90 digital camera equipped with a 20 mm lens, that provides an RGB value to the sampled point cloud. We decide to arrange such detailed TLS survey in order to derive very high resolution (less than 0.5 m of grid cell size) DTMs, to improve the automatic recognition of trail effects on surface water flow. The survey was carried out in October 2011, and consisted in four scan positions (three days survey, and one night survey), from which 66,023,721 elevation points were collected. Average points density was 126 pts/m². The raw TLS elevation points, then were filtered to remove the vegetation. After the vegetation filtering process about 31,711,034 points remained, with an average point density of 82 pts/m². The absolute vertical accuracy, evaluated by a ground differential DGPS, was estimated to be less than 0.1 m. The TLS dataset was used to generate a DTM at 0.2 m, considering the natural neighbor method [Sibson, 1981], as in the previous instance.

Field survey

Several field surveys were carried out, during spring 2009, summer 2010, and 2011. Flow direction changes due to roads or trails, and related hillslope instabilities were mapped with DGPS. We selected a few clear examples as a test area of our method.



Figure 3 - Case study P1 of Paularo showing a section of a forest road where there is a clear evidence of water flow interception. In the figure also a simple drainage system is shown.

Two case studies, P1 and P2 (Figs. 2b, 3 and 4) were identified in the Paularo region where a surface water path alteration and redistribution due to roads were observed with the post-event evidence of sediment deposition and other water flow signs. The roads have an average width of 2.5 m. The two examples are shown in the Figure 3, and 4 respectively. In Figure 3 the P1 case study with an evidence of the interception of water by a forest road is shown. Such area is critical since the upper hillslope is totally wet. There is also some sort of drainage system, but it does not seem to work properly because of the water surveyed on the road. Figure 4 shows the case study P2 where there is an evidence of erosion (Fig. 4b), and also of a recent sediment deposition on the road surface (Fig. 4c). Interviews with the local community underlined that the road generally suffers from heavy erosion during significant rainfall events.

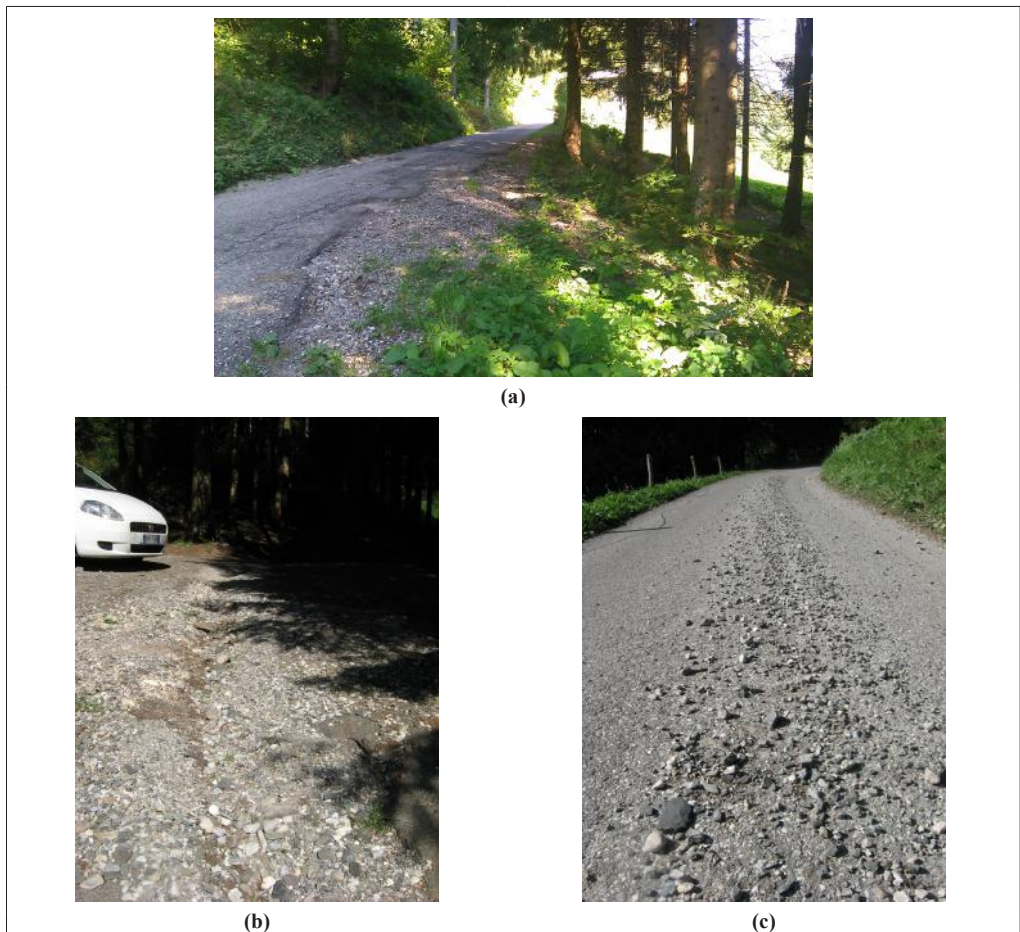


Figure 4 - Case study P2 of Paularo showing: (a) the road section subject to flow direction alteration, (b) erosion outside the road, and (c) sediment deposition along the road.

We identified a third case study in the Upper Cordevole basin (Fig. 5), where there is an evidence of erosion along the forest road, because of its interception of the upslope flow

path. It is possible to have a clear evidence of this issue looking at the Figure 10a, where a small stream is totally shifted few meters on the right, due to road interception. The road has an average width of about 2.5 m.



Figure 5 - Case study of the Upper Cordevole basin, where it is evident the erosion along the forest road.

In the Rio Cordon basin, we identified two sections, C1 and C2 respectively, of the CAI trail 466, with evidence of erosion due to surface water interception (Figures 6a and b respectively). The trail has a width of 1.5 m.

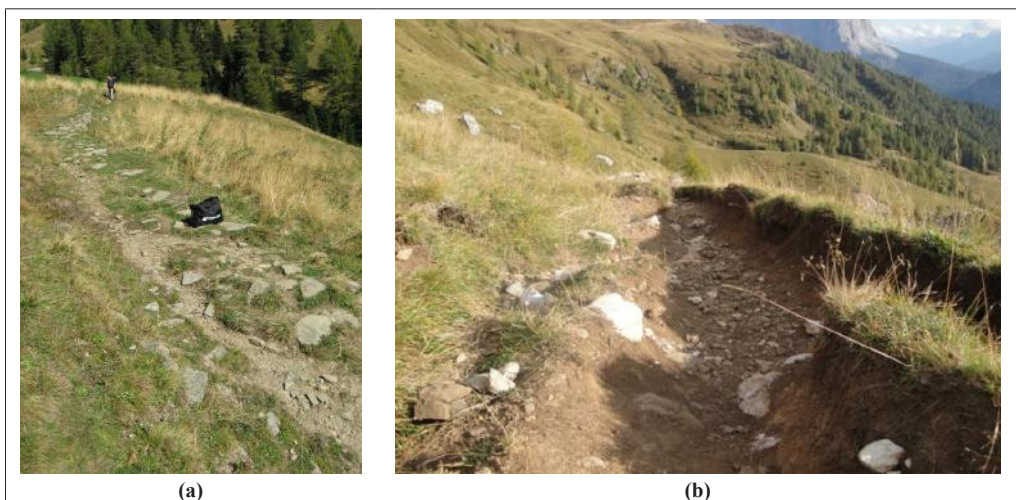


Figure 6 - Case study (a) C1, and (b) C2 of the Rio Cordon basin with evidence of surface erosion.

Methods

A morphometric index is proposed, to quantify the effect of roads and trail networks on contributing area distributions (and therefore, on flow paths) within catchments. The index is called RPII (Relative Path Impact Index) and is calculated as follows:

$$\text{RPII} = \ln\left(\frac{A_r - A_{sm}}{A_{sm}}\right) \quad [1]$$

where A_r is contributing area evaluated in the presence of forest roads and trails on hillslopes, while A_{sm} is the contributing area in the absence of morphological alterations on hillslopes. The logarithmic form is given to emphasize and map only such areas where an increase of the drainage area is observed due to road alteration. The higher the is RPII index, the stronger is the alteration. In Figure 7, a non-logarithmic RPII index map is shown in order to underline the usefulness of the logarithmic form that assures a clear output in the color scale. Surface flow direction changes can have stabilizing effects too (decrease in drainage areas, which results in a negative value of the ratio $\frac{A_r - A_{sm}}{A_{sm}}$).

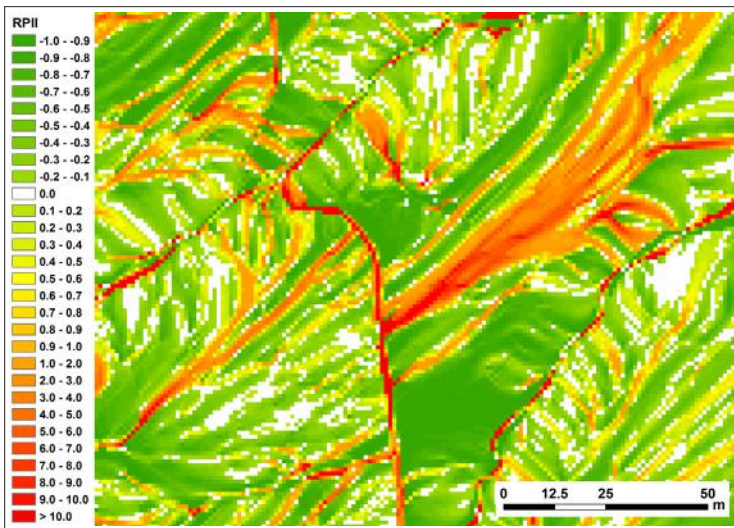


Figure 7 - Example of non-logarithmic RPII map for the P1 case study of Paularo obtained from 1 m DTM and a smoothing kernel of 11x11 (~ 4 L).

Nevertheless, because the \ln of a negative number is undefined, only the worst situations in term of likely surface instability were considered, where an increase in drainage area is observed. The assumption is that technical measures are not necessary in the area where the stability improves (decrease in drainage area). For the calculation of the drainage area we used the D_∞ flow direction algorithm [Tarboton, 1997], because of its advantages over the methods that restrict the flow to eight possible directions (D8, introducing grid

bias) [O’Callaghan and Mark, 1984], or proportioned flow according to slope (introducing unrealistic dispersion) [Quinn et al., 1991]. To simulate the absence of roads and trail, we considered a smoothed DTM based on the quadratic approximation of the original surface solved within a local moving window. The smoothing was carried out extensively on the whole DTM. With this approach, some morphological features not related to roads and trails are obviously removed and simplified. Nevertheless, as we said before, our goal is to suggest a simple, fast and fully automatic method able to process an entire landscape without a-priori knowledge about anthropogenic features. In order to smooth the DTM, we decided to use the bivariate quadratic function introduced by Evans [1979] that is expressed as:

$$Z = ax^2 + by^2 + cxy + dx + ey + f \quad [2]$$

where x , y , and Z are local coordinates, and a to f are quadratic coefficients. This function was found to perform well in the presence of elevation errors [Albani et al., 2004; Florinsky, 1998]. The same quadratic approach has been successfully applied also in several other analyses on earth surface morphology and feature extraction [Pirotti and Tarolli, 2010; Sofia et al., 2011; Tarolli et al., 2012]. In this work, the function has been tested with a progressively increasing moving window (Tab. 1): we have considered n times the feature width (L) – where L is the road or trail width – since it was demonstrated in recent works [Pirotti and Tarolli, 2010; Tarolli et al., 2012], that the moving window size to process the surface has to be related to the feature width to be investigated. This analysis has been introduced to test the best solution for the detection of surface flow alteration throughout RPII. The analysis was then performed to test different grid cell sizes and investigated feature widths.

Table 1 - Summary of the kernel sizes used for the smoothing DTM procedure, for the different case studies considered in the work.

DTM	feature width	2L	3L	4L	5L	6L	7L
1 m	road (2.5 m)	5x5	7x7	11x11	13x13	15x15	17x17
0.5 m	trail (1.5 m)	7x7	9x9	13x13	15x15	19x19	21x21
0.2 m	trail (1.5 m)	15x15	23x23	31x31	37x37	45x45	53x53

Results

Paularo area

Figure 8 shows the case study P1 of Paularo area, the RPII maps obtained from the 1 m DTM, with a progressive increasing of the kernel (from 2 to 7 L) used for the smoothing procedure. Looking at such figures, the better RPII emphasizing the sections of the road subject to flow direction changes is the one calculated using a kernel size of 4 L (~ 11 m). Actually, 4 L should determine a kernel size of 10 m, but the bivariate quadratic function works with odd pixels [Wood, 1996], therefore this measure has to be rounded to an odd number (in this case 11 m). The same procedure has also been carried out for the other case studies. The RPII recognizes a clear area of a likely water flow alteration due to the road, and this process was actually surveyed in the field exactly at the same location (Fig. 3). This is a useful example of the effectiveness of high resolution topography in understanding flow direction alterations. In general, kernels greater than 2 L seem to present similar performance, with less differences among them. We decided to stop the analysis at 7 L since no clear evidence of changes is observed in RPII performances.

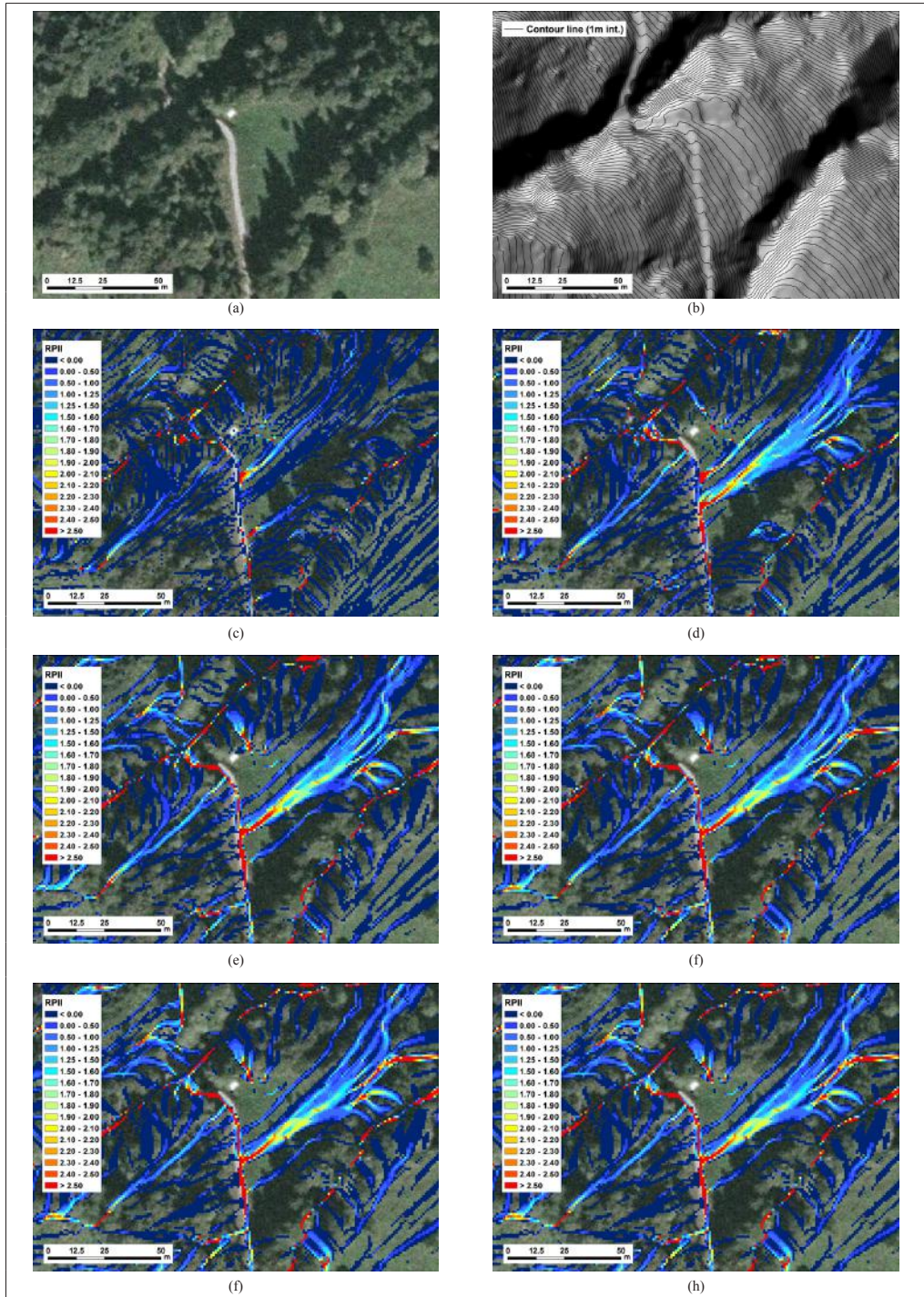


Figure 8 - Aerial photograph (a), hillshade (b), and RPII maps for the P1 case study of Paularo obtained from 1 m DTM and with a progressive increasing of the kernel used for the smoothing procedure (c) 5x5, (d) 7x7, (e) 11x11, (f), 13x13, (g) 15x15, and (h) 17x17.

Figure 9 shows the P2 case study of Paularo, where we considered 4 L kernel, the same for the first case study since the feature width is the same.

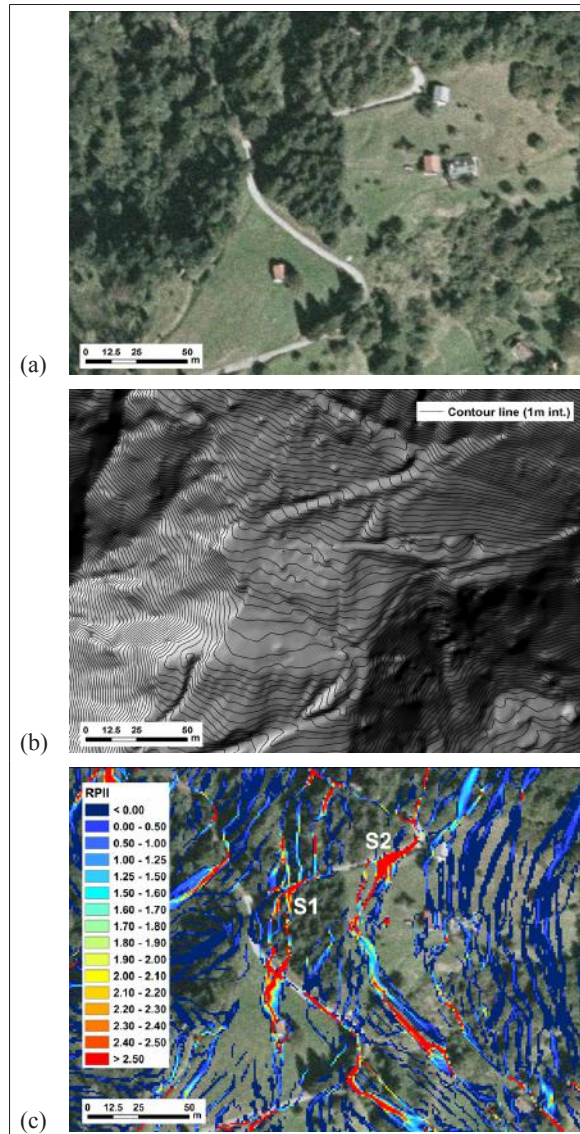


Figure 9 - Aerial photograph (a), hillshade (b), and (c) RPII map for the P2 case study of Paularo obtained from 1 m DTM, and a smoothing kernel of 11x11 (~ 4 L).

The RPII map indicates two critical points: one (S1) is exactly the point surveyed in the field, the other (S2) is an upslope flow direction alteration, but without an actual evidence of erosion. Having said that, in this place there is a hollow covered by a pasture as a likely sign of past erosion due to water flow redirection on the road.

Upper Cordevole catchment

Figure 10 shows the case study of the Upper Cordevole catchment. This is a very clear example of the road induced erosion, where a forest road (2.5 m width) induces an 8.5 m deviation of a channel.

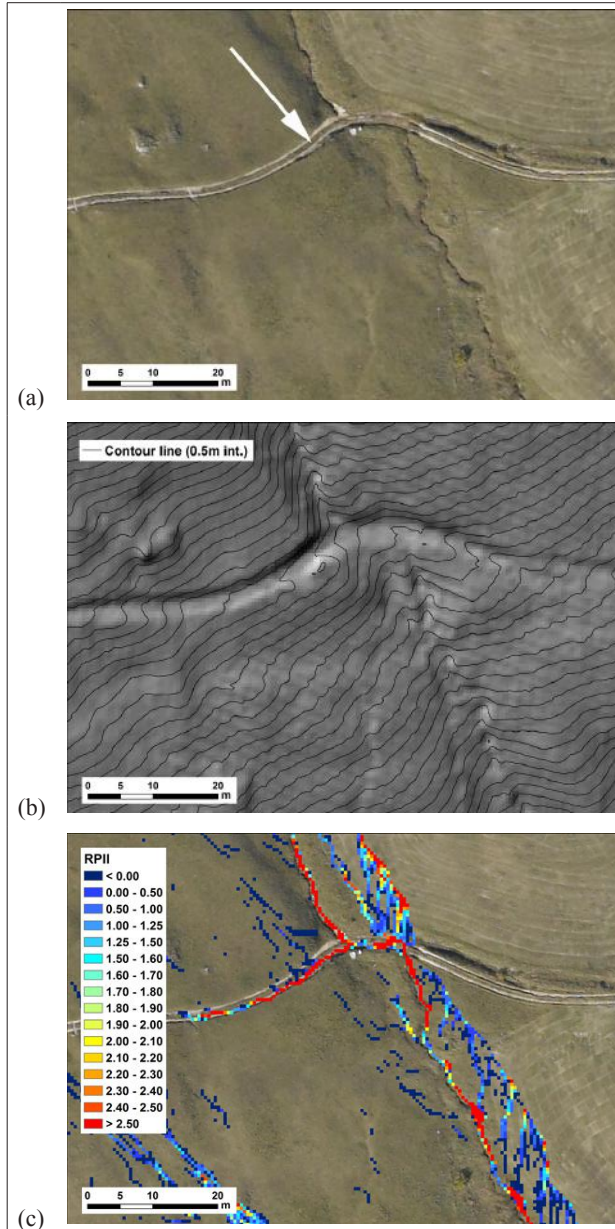


Figure 10 - Aerial photograph (a), hillshade (b), and (c) RPII map for the case study of Upper Cordevole obtained from 0.5 m DTM, and a smoothing kernel of 21x21 (~ 4 L).

In Figure 10a, the white arrow marks the section of the road affected by erosion. This section is rightly signed with high values of RPII (Fig. 10c). The RPII map showed in Figure 10c is derived from a 0.5 m DTM smoothed with a kernel of four times the road width. The map clearly reports the drainage area alterations below and along the road for deviation and interceptions of surface flow. Pixels with high values of RPII index reported above the road depends on flow deviation induced by another road.

Rio Cordon catchment

Figure 11 shows the RPII maps of the case study C1 of the Rio Cordon, derived from the 1 and 0.5 m DTM respectively, where a trail (CAI 466) was considered instead of the road. The moving window size used to smooth the DTM was about four times the trail width (Tab. 1) of the investigated feature.

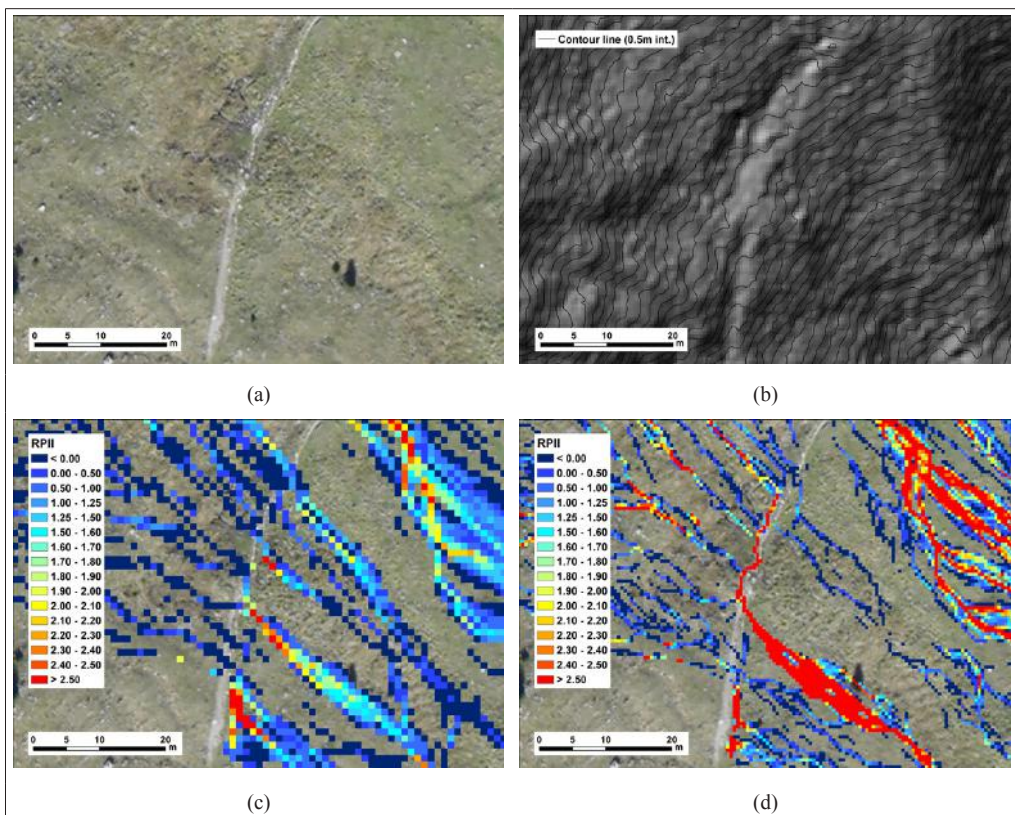


Figure 11 - Aerial photograph (a), hillshade (b), and RPII maps for the C1 case study of Rio Cordon with (c) 1 m, and (d) 0.5 m DTM with smoothing kernel of 7x7, and 13x13 (~ 4 L).

For this case study and window size the RPII performs better using 0.5 m DTM. In the case of trail, smaller than a road, a 1 m grid cell size is not small enough to recognize in detail the flow direction alteration. This result is interesting and it underlines how, when a good LiDAR ground point density database is available, it is recommended to use a 0.5 m instead

of a 1 m DTM for a better understanding of the earth surface morphology, and the related processes. Using 0.5 m grid cell size it is possible to better intercept the flow directions within the trail (Fig. 11b), thus recognizing the section subject to surface erosion (Fig. 6a). Figure 12 shows the RPII maps for the case study C1, obtained from the 0.5 m DTM, with a progressively increase of the kernel (from 2 to 7 L) used for the smoothing procedure. In this case as well the better RPII that emphasized the section of the trail subject to flow direction changes is the one calculated with a kernel size greater than 2 or 3 L (4.5 m).

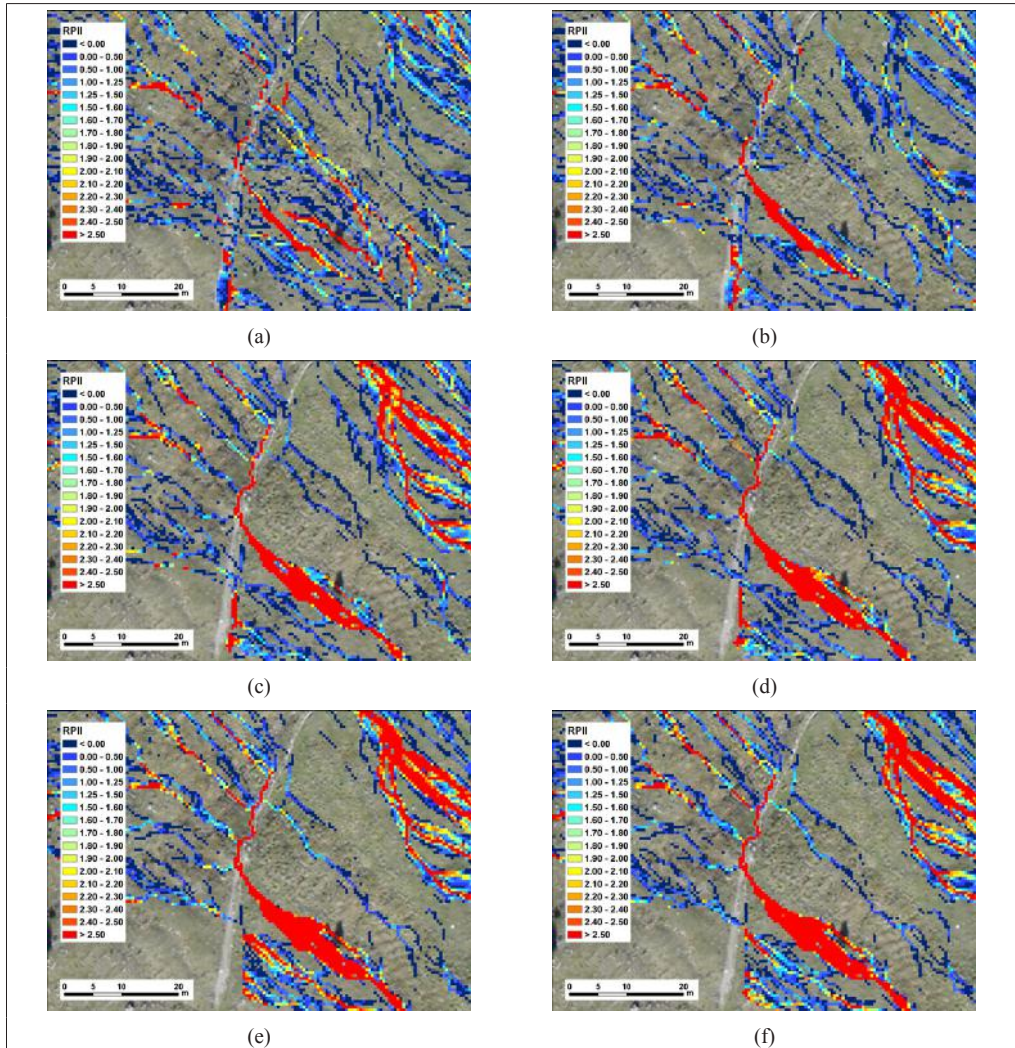


Figure 12 - RPII maps for the C1 case study of Rio Cordon with a 0.5 m DTM and smoothing kernel of (a) 7x7, (b) 9x9, (c) 13x13, (d), 15x15, (e) 19x19, and (f) 21x21.

Another suitable performance of the RPII is that related to the case study C2, showed in Figure 13. In this case, the section of the trail affected by evident erosion (see Figure 6b,

in the study area description) was correctly recognized with higher values of the RPII, but only with a DTM with a resolution higher than 0.5 m (0.2 m TLS-derived DTM, Figure 13b). There are some areas where a 0.5 m DTM still is not detailed enough. The used kernel is about 4 times the trail width. The RPII calculated using a 0.2 m DTM derived from TLS survey can recognize micromorphology and the minor flow direction changes that affect the hillslope.

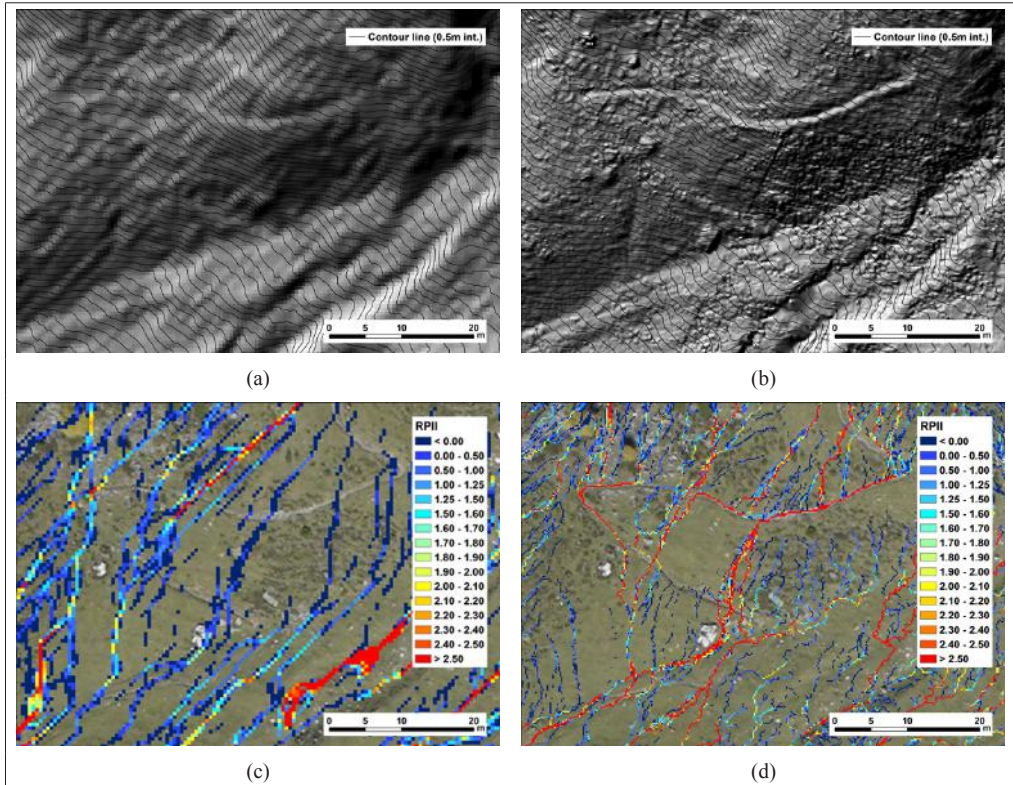


Figure 13 - Hillshade and RPII maps for the C2 case study of Rio Cordon with (a) (c) 0.5 m, and (b) (d) 0.2 m DTM respectively, with smoothing kernel of 13x13 and 31x31 (~ 4 L).

Figure 14 shows the RPII maps related to the case study C2, obtained from the 0.2 m DTM, with a progressively increase of the kernel size (same sizes adopted for the other DTM resolution) used for the smoothing procedure. In this case, it seems that even when using a 2 L window size it is possible to have an RPII index suitable for the recognition of flow direction alteration. While the application of the RPII using centimetric DTM in this environment may not be useful since the erosion does not represent a critical issue such as that observed for the road networks, it could be an interesting application in other landscapes with different land uses. If we consider, for example, agricultural hilly landscapes the fact that thanks to centimetric TLS derived DTMs it is possible to recognize the surface erosion or malfunctioning drainage system really represents an advance for a better agricultural planning.

Looking at all the presented case studies, the RPII appears to be a useful, fast, automatic and objective instrument, even if in some situations it recognizes also flow direction changes due to natural features smoothed by the kernel and not related to road or trail networks. This methodology could be considered as a first and relatively fast approach to map water surface paths alteration due to roads or trail network presence, as an important factor triggering surface instabilities.

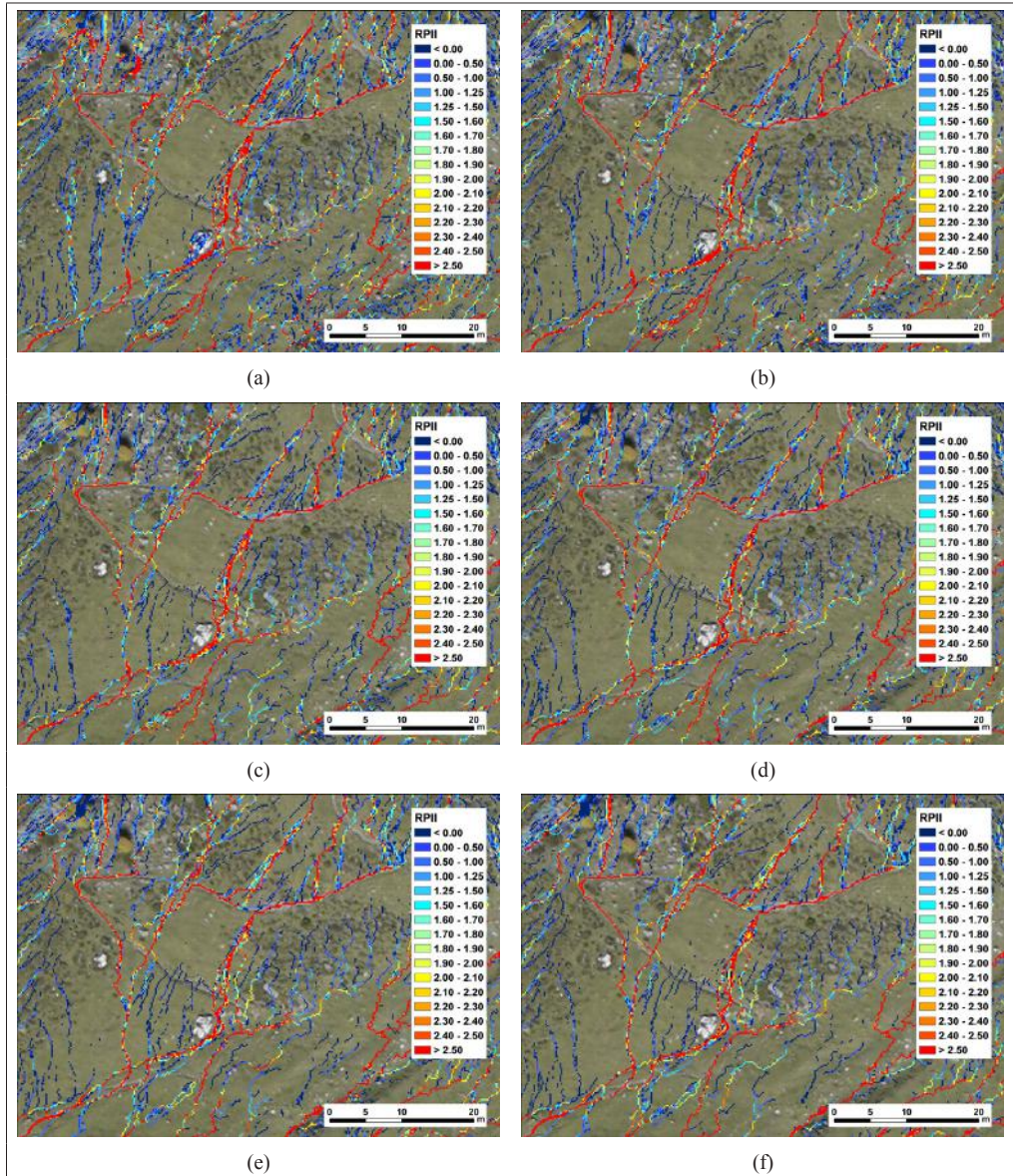


Figure 14 - RPII maps for the C2 case study of Rio Cordon with a 0.2 m DTM, and smoothing kernel of (a) 15x15, (b) 23x23, (c) 31x31, (d), 37x37, (e) 45x45, and (f) 53x53.

Conclusions

In this paper, an objective methodology is presented, able to identify alterations of surface flow direction due to roads and trail networks. The method is based on the calculation of a morphometric index called Relative Path Impact Index (RPII). The RPII evaluates the difference in drainage area in the presence, and in the absence of anthropic features such as roads and trails on hillslopes. To simulate the absence of such feature, the surface is smoothed approximating a quadratic function considering moving windows of varying size. In the analysis, different DTM grid cell sizes were considered and derived from airborne LiDAR (0.5 and 1 m), and Terrestrial Laser Scanner (0.2 m). The RPII showed a good performance in all the presented case studies. In the case of the road network, it was possible to recognize flow direction alterations exactly where an active erosion or evidence of surface water flow were actually surveyed in the field. The results show also that the RPII, where the topographic information is very detailed ($DTM \leq 0.5$ m), is useful for the recognition of local surface flow direction alteration due to minor networks such as trails. In all the examined case studies, the proposed methodology has proven to be a valuable tool for the identification of sections subject to alteration of runoff, and therefore related to potential instability. However, in some case the RPII does not refer to any erosion in the field, and some alterations are not derived by roads or trails, but simply by other morphological forms. Despite these limitations, a map showing the likely sections of a road subject to potential alteration of flow direction, in any condition of forest cover (thanks to LiDAR technology), is effective for identifying erosional risk area. Indeed, the RPII is a preliminary, fast and objective analysis of a landscape, while more detailed assessments require the use of more sophisticated modeling techniques, and field verification. This tool can be used to interactively assist the final user on the task of surface instability analysis, erosion and landslide risk management for a suitable environmental planning. Such information may be useful for the design of structural (drainage cross ditches), or non-structural measures (different urban development) for the risk mitigation.

The new remotely sensed technologies such airborne or terrestrial laser scanners (in addition to others, such SAR - Synthetic Aperture Radar), and the derived high resolution topography will surely play a key role in the recognition and analysis of the anthropogenic fingerprints on the Earth Surface, for a better understanding of the related Earth Surface Processes and Landscape Evolution, especially in the epoch we are living, where the Earth is more and most significantly affected by the human activities.

Acknowledgements

This study was partly supported by the Italian Ministry of University and Research - GRANT PRIN 2005 "National network of experimental basins for monitoring and modelling of hydrogeological hazard", and by Interreg IV A MassMove project. The Riegl LMS-620 data were elaborated by the Interdepartmental Research Center for Cartography, Photogrammetry, Remote Sensing and GIS at University of Padova (CIRGEO). The authors thank the two anonymous reviewers for valuable suggestions that significantly improved the manuscript.

References

Albani M., Klinkenberg B., Andison D.W., Kimmins J.P. (2004) - *The choice of window size in approximating topographic surfaces from digital elevation models*. International

- Journal of Geographical Information Science, 18 (6): 577-593. doi: <http://dx.doi.org/10.1080/13658810410001701987>.
- Borga M., Dalla Fontana G., Gregoretto C., Marchi L. (2002) - *Assessment of shallow landsliding by using a physically based model of hillslope stability*. Hydrological Processes, 16: 2833-2851. doi: <http://dx.doi.org/10.1002/hyp.1074>.
- Borga M., Tonelli F., Selleroni J. (2004) - *A physically-based model of the effects of forest roads on slope stability*. Water Resources Research, 40 (12): W12202. doi: <http://dx.doi.org/10.1029/2004WR003238>.
- Borga M., Tonelli F., Dalla Fontana G., Cazorzi F. (2005) - *Evaluating the influence of forest roads on shallow landsliding*. Ecological Modelling, 187: 85-98. doi: <http://dx.doi.org/10.1016/j.ecolmodel.2005.01.055>.
- Cavalli M., Tarolli P. (2011) - *Application of LiDAR technology for rivers analysis*. Italian Journal of Engineering Geology and Environment, Special Issue, 1: 33-44. doi: <http://dx.doi.org/10.4408/IJEGE.2011-01.S-03>.
- Cavalli M., Trevisani S., Comiti F., Marchi L. (2012) - *Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments*. Geomorphology. doi: <http://dx.doi.org/10.1016/j.geomorph.2012.05.007>.
- Cicogna A. (2008) - *Atlante climatico del Friuli Venezia Giulia. 1-Precipitazioni*. Agenzia Regionale per la Protezione dell'Ambiente del Friuli Venezia Giulia, Osservatorio Meteorologico Regionale.
- Corona P., Cartisano R., Salvati R., Chirici G., Floris A., Di Martino P., Marchetti M., Scrinzi G., Clementel F., Travaglini D., Torresan C. (2012) - *Airborne Laser Scanning to support forest resource management under alpine, temperate and Mediterranean environments in Italy*. European Journal of Remote Sensing, 45: 27-37. doi: <http://dx.doi.org/10.5721/EuJRS20124503>.
- Croke J., Mockler S., Fogarty P., Takken I. (2005) - *Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity*. Geomorphology, 68: 257-268. doi: <http://dx.doi.org/10.1016/j.geomorph.2004.11.020>.
- Crutzen P. J. (2002) - *Geology of mankind*. Nature, 415: 23. doi: <http://dx.doi.org/10.1038/415023a>.
- Dalla Fontana G., Marchi L. (2003) - *Slope-area relationships and sediment dynamics in two alpine streams*. Hydrological Processes, 17 (1): 73-87. doi: <http://dx.doi.org/10.1002/hyp.1115>.
- Evans I.S. (1979) - *An integrated system of terrain analysis and slope mapping*. Final report on grant DA-ERO-591-73-G0040. University of Durham, England.
- Florinsky I.V. (1998) - *Accuracy of local topographic variables derived from digital elevation models*. International Journal of Geographical Information Science, 12 (1): 47-61. doi: <http://dx.doi.org/10.1080/136588198242003>.
- Frankel K.L., Dolan J.F. (2007) - *Characterizing arid-region alluvial fan surface roughness with airborne laser swath mapping digital topographic data*. Journal of Geophysical Research, 112: F02025. doi: <http://dx.doi.org/10.1029/2006JF000644>.
- Glenn N.F., Streutker D.R., Chadwick D.J., Thackray G.D., Dorsch S.J. (2006) - *Analysis of LiDAR-derived topographic information for characterizing and differentiating landslide morphology and activity*. Geomorphology, 73: 131-148. doi: <http://dx.doi.org/10.1016/j.geomorph.2006.03.007>.

- org/10.1016/j.geomorph.2005.07.006.
- Gucinski H., Furniss M.J., Ziemer R.R., Brookes M.H. (2001) - *Forest roads: a synthesis of scientific information*. Gen. Tech. Rep. PNW-GTR-509. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 103 pp.
- Jones J.A., Grant G.E. (1996) - *Peak flow response to clear-cutting and roads in small and large basins, western Cascades, Oregon*. Water Resources Research, 32 (4): 959-974. doi: <http://dx.doi.org/10.1029/95WR03493>.
- Lin C.W., Tseng C.-M., Tseng Y.-H., Fei L.-Y., Hsieh Y.-C., Tarolli P. (2013) - *Recognition of large scale deep-seated landslides in forest areas of Taiwan using high resolution topography*. Journal of Asian Earth Sciences, 62: 389-400. doi: <http://dx.doi.org/10.1016/j.jseaes.2012.10.022>.
- Luce C.H., Cundy T.W. (1994) - *Parameter identification for a runoff model for forest roads*. Water Resources Research, 30 (4): 1057-1069. doi: <http://dx.doi.org/10.1029/93WR03348>.
- Luce C.H., Black T.A. (1999) - *Sediment production from forest roads in western Oregon*. Water Resources Research, 35 (8): 2561-2570. doi: <http://dx.doi.org/10.1029/1999WR900135>.
- Mckean J., Roering J. (2004) - *Objective landslide detection and surface morphology mapping using highresolution airborne laser altimetry*. Geomorphology, 57: 331-351. doi: [http://dx.doi.org/10.1016/S0169-555X\(03\)00164-8](http://dx.doi.org/10.1016/S0169-555X(03)00164-8).
- Montgomery D.R. (1994) - *Road surface drainage, channel initiation, and slope instability*. Water Resources Research, 30 (6): 1925-1932. doi: <http://dx.doi.org/10.1029/94WR00538>.
- Montgomery D.R., Dietrich W.E. (1994) - *A physically based model for the topographic control on shallow landsliding*. Water Resources Research, 30: 1153-1171. doi: <http://dx.doi.org/10.1029/93WR02979>.
- O'Callaghan J.F., Mark D.M. (1984) - *The extraction of drainage networks from digital elevation data*. Comput. Vision Graphics Image Process, 28: 328-344. doi: [http://dx.doi.org/10.1016/S0734-189X\(84\)80011-0](http://dx.doi.org/10.1016/S0734-189X(84)80011-0).
- Orlandini S., Tarolli P., Moretti G., Dalla Fontana G. (2011) - *On the prediction of channel heads in a complex alpine terrain using gridded elevation data*. Water Resources Research, 47: W02538.
- Passalacqua P., Tarolli P., Fuofoula-Georgiou E. (2010) - *Testing space-scale methodologies for automatic geomorphic feature extraction from LiDAR in a complex mountainous landscape*. Water Resources Research, 46: W11535. doi: <http://dx.doi.org/10.1029/2009WR008812>.
- Pirotti F., Tarolli P. (2010) - *Suitability of LiDAR point density and derived landform curvature maps for channel network extraction*. Hydrological Processes, 24: 1187-1197. doi: <http://dx.doi.org/10.1002/hyp.7582>.
- Pirotti F., Grigolato S., Lingua E., Sitzia T., Tarolli P. (2012a) - *Laser Scanner Applications in Forest and Environmental Sciences*. Italian Journal of Remote Sensing, 44 (1): 109-123. doi: <http://dx.doi.org/10.5721/ItJRS20124419>.
- Pirotti F., Guarnieri A., Vettore A. (2012b) - *Ground filtering and vegetation mapping using multi-return terrestrial laser scanning*. ISPRS Journal of Photogrammetry and Remote Sensing. doi: <http://dx.doi.org/10.1016/j.isprsjprs.2012.08.003>

- Quinn P., Beven K., Chevallier P., Planchon O. (1991) - *The prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models*. *Hydrol. Proc.*, 5: 59-80. doi: <http://dx.doi.org/10.1002/hyp.3360050106>.
- Reid L.M., Dunne T. (1984) - *Sediment production from forest road surfaces*. *Water Resources Research*, 20: 1753-1761. doi: <http://dx.doi.org/10.1029/WR020i011p01753>.
- Sibson R. (1981) - *A brief description of natural neighbor interpolation* (Chapter 2). In: Barnett, V. *Interpreting Multivariate Data*. John Wiley, Chichester, 21-36.
- Slatton K.C., Carter W.E., Shrestha R.L., Dietrich W.E. (2007) - *Airborne laser swath mapping: achieving the resolution and accuracy required for geosurficial research*. *Geophysical Research Letters*, 34: L23S10. doi: <http://dx.doi.org/10.1029/2007GL031939>.
- Sofia G., Tarolli P., Cazorzi F., Dalla Fontana G. (2011) - *An objective approach for feature extraction: distribution analysis and statistical descriptors for scale choice and channel network identification*. *Hydrology and Earth System Science*, 15: 1387-1402. doi: <http://dx.doi.org/10.5194/hess-15-1387-2011>.
- Stock J., Dietrich W.E. (2003) - *Valley incision by debris flows: evidence of a topographic signature*. *Water Resources Research*, 39: 1089. doi: <http://dx.doi.org/10.1029/2001WR001057>.
- Tarboton D.G. (1997) - *A new method for the determination of flow directions and upslope areas in grid digital elevation models*. *Water Resources Research*, 33: 309-319. doi: <http://dx.doi.org/10.1029/96WR03137>.
- Tarolli P., Borga M., Dalla Fontana G. (2008) - *Analyzing the influence of upslope bedrock outcrops on shallow landsliding*. *Geomorphology*, 93: 186-200. doi: <http://dx.doi.org/10.1016/j.geomorph.2007.02.017>.
- Tarolli P., Arrowsmith J.R., Vivoni E.R. (2009) - *Understanding earth surface processes from remotely sensed digital terrain models*. *Geomorphology*, 113: 1-3. doi: <http://dx.doi.org/10.1016/j.geomorph.2009.07.005>.
- Tarolli P., Dalla Fontana G. (2009) - *Hillslope to valley transition morphology: new opportunities from high resolution DTMs*. *Geomorphology*, 113: 47-56. doi: <http://dx.doi.org/10.1016/j.geomorph.2009.02.006>.
- Tarolli P., Sofia G., Dalla Fontana G. (2012) - *Geomorphic features extraction from high resolution topography: landslide crowns and bank erosion*. *Natural Hazards*, 61: 65-83. doi: <http://dx.doi.org/10.1007/s11069-010-9695-2>.
- Thomas R.B., Megahan W.F. (1998) - *Peak flow response to clear-cutting and roads in small and large basins, western Cascades, Oregon: a second opinion*. *Water Resources Research*, 34 (12): 3393-3403. doi: <http://dx.doi.org/10.1029/98WR02500>.
- Trevisani S., Cavalli M., Marchi L. (2010) - *Reading the bed morphology of a mountain stream: a geomorphometric study on high-resolution topographic data*. *Hydrology and Earth System Science*, 14: 393-405. doi: <http://dx.doi.org/10.5194/hess-14-393-2010>.
- Trevisani S., Cavalli M., Marchi L. (2012) - *Surface texture analysis of a high-resolution DTM: Interpreting an alpine basin*. *Geomorphology*, 161-162: 26-39. doi: <http://dx.doi.org/10.1016/j.geomorph.2012.03.031>.
- Vianello A., D'Agostino V. (2007) - *Bankfull width and morphological units in an alpine stream of the dolomites (Northern Italy)*. *Geomorphology*, 83: 266-281. doi: <http://dx.doi.org/10.1016/j.geomorph.2006.02.023>.
- Vianello A., Cavalli M., Tarolli P. (2009) - *LiDAR-derived slopes for headwater channel network analysis*. *Catena*, 76: 97-106. doi: <http://dx.doi.org/10.1016/j.catena.2008.09.012>.

- Wemple B.C., Swanson F.J., Jones J.A. (2001) - *Forest roads and geomorphic process interactions, Cascade Range, Oregon*. Earth Surface Processes Landforms, 26: 191-204. doi: [http://dx.doi.org/10.1002/1096-9837\(200102\)26:2<191::AID-ESP175>3.0.CO;2-U](http://dx.doi.org/10.1002/1096-9837(200102)26:2<191::AID-ESP175>3.0.CO;2-U).
- Wood J. (1996) - *The geomorphological characterisation of digital elevation models*. Ph.D. Thesis, University of Leicester.
- Zalasiewicz J., Williams M., Haywood A., Ellis M. (2011) - *The Anthropocene: a new epoch of geological time?* Philosophical Transactions of the Royal Society A, 369: 835-841. doi: <http://dx.doi.org/10.1098/rsta.2010.0339>.
- Ziegler A.D., Giambelluca T.W. (1997) - *Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand*. Journal of Hydrology, 196: 204-229. doi: [http://dx.doi.org/10.1016/S0022-1694\(96\)03288-X](http://dx.doi.org/10.1016/S0022-1694(96)03288-X).

Received 05/07/2012, accepted 20/10/2012