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Multi temporal LiDAR-DTMs as a tool for modelling a complex landslide: a case study in the Rotolon catchment (Eastern Italian Alps)

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Abstract

The geomorphological change detection through the comparison of repeated topographic surveys is a recent approach that benefits greatly from the latest developments in topographical data acquisition techniques. Among them, airborne LiDAR makes the monitoring of geomorphological changes a more reliable and accurate approach for natural hazard and risk management. In this study, two LiDAR-DTMs (2 m resolution) were acquired just before and after a complex 340 000 m^3 landslide event (4 November 2010) that generated a debris flow in the channel of the Rotolon catchment (Eastern Italian Alps). The analysis of these data was used to set up the initial condition for the application of a dynamic model.

The comparison between the pre- and post-event DTMs allowed to identify erosion and depositional areas and the volume of the landslide. The knowledge of the phenomenon dynamics was the base of a sound back-analysis of the event with the 3-D numerical model DAN3D. This particular code was selected for its capability to modify the rheology and the parameters of the moving mass during run-out, as actually observed along the path of the 2010 debris flow.

Nowadays some portions of Mt. Rotolon flank are still moving and show signs of detachment. The same soil parameters used in the back-analysis model could be used to simulate the run-out for possible future landslides allowing to generate reliable risk scenarios useful for awareness of civil defense and strategy on emergency plans.

1 Introduction

Recent improvements in topographical data acquisition techniques and software allow to derive high-resolution Digital Terrain Models (DTMs) and to develop new methodologies for analyzing earth surface processes (e.g., McKean and Roering, 2004; Lane et al., 2004; Lashermes et al., 2007; Iwahashi et al., 2012; Cavalli et al., 2013; Tarolli, 2014). Among these techniques, Light Detection And Ranging (LiDAR) is probably the

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most important technological innovation for geomorphic research (Roering et al., 2013) and, in the last years, its applications in geomorphology and natural hazard fields have significantly increased (Notebaert et al., 2009; Jaboyedoff et al., 2012; Roering et al., 2013). In particular, comparison between LiDAR-derived DTMs obtained from successive surveys gives the possibility to produce DEM of Differences (DoD) maps, which represent a valuable tool to interpret the evolution of geomorphological processes and to quantitatively assess morphological changes due to erosion and deposition on rivers (Lane et al., 2003; Wheaton et al., 2010; Picco et al., 2013;), in case of debris flows (Scheidl et al., 2008; Theule et al., 2012; Blasone et al., 2014) and landslides (Burns et al., 2010; DeLong et al., 2012).

Another tool broadly used to investigate the dynamics of geomorphological process is numerical modelling (Hungr et al., 2005; Rickenmann, 2005). Dynamic run-out models can forecast the propagation of material after initial failure and delineate the zones where elements at risk will suffer an impact with a certain level of intensity (Quan Luna et al., 2011). The results of these models are an appropriate input for vulnerability and risk assessments (van Westen et al., 2006). An important feature of run-out models is the possibility to perform forward analyses (Bossi et al., 2013) and forecast changes in hazards (Crosta et al., 2006). Dynamic computer models have the potential to simulate geomorphological processes with an acceptable degree of accuracy. Once this is achieved, a range of potential hazard scenarios can be analyzed and the results can be used to inform local authorities and the population in order to respond to these hazards and plan to reduce associated risks (Quan Luna et al., 2014). To model properly the run-out pattern of the flow material during its downslope movement, detailed topographic information from the sliding track and the source zone is needed. Formerly, DTMs for landslide investigation were realized through GPS surveys (Marcato et al., 2006) or derived from contour lines and photogrammetry (Sosio et al., 2008). Nowadays, an improvement in the precision of the DTMs can be expected by using laser scanning techniques, such as LiDAR. This will avoid the problem of the lack of accuracy of the DTMs and the stochastic changes in topography during the run-out process (van Asch et al., 2007). In this paper we report the use of DoD maps as a base to calibrate a 3-D model, using the numerical code DAN3D (McDougall and Hungr, 2004), of a large debris flow event that occurred on 4 November 2010 in the Eastern Italian Alps.

2 Study area

The Rotolon catchment is located in north eastern Italy (Veneto Region, Italy) and it covers an area of 5 km^2 (Fig. 1). The valley stretches along an S-shape from 1930 to 590 m where the touristic village of Recoaro Terme is located. The basin is bordered by mountains made of sedimentary rocks Triassic in age (from Scitian to Retian) such as dolomite, limestone, sandstones, marls and gypsum. These lithotypes show evident signs of weathering and are affected by joints and fractures. Rarely igneous rocks appear, mainly rhyolite but also breccia and tuff.

Thick alluvial deposits cover the upper part of the basin, some originating from rock falls detached from the dolomitic and calcareous formation located above, some deriving from the alteration of the underneath strata of clayey marls. Steep slopes characterize these deposits, thus predisposing the sediments to mass movement events (Altieri et al., 1994).

The instability phenomena occurring in the Rotolon catchment are linked with the presence of a large DGSD (Deep-seated Gravitational Slope Deformation) with a volume of some million m^3. The type of movements in the upper part are various: falls, topples, rotational slides that sometimes evolve in debris-flow along the Rotolon stream. The vulnerable elements in the catchment are two villages set beside the channel (namely Turcati and Parlati), two bridges and some road sections along with the city of Recoaro Terme that is located more downstream (Fig. 1).

Several important debris flow events have been documented in the Rotolon catchment since 1798. In 1985 a large reactivation led to a renewed interest in the phenomenon mainly aimed at the definition of possible mitigation measures. More recently, in 2009, a debris flow threatened the village of Turcati, depositing in the channel a volume of 30 000 m^3 of debris. In the last event occurred in 4 November 2010, a mass of 340 000 m^3 detached as a rotational slide from the flanks of mount Carega and partially evolved in a debris flow along the main channel. This event produced a channel aggradation of about 3 m nearby Turcati and Parlati villages, causing alarm among the population.

To mitigate the hazard and protect the exposed population an automatic monitoring network (Frigerio et al., 2014) and an early-warning system (Bossi et al., 2015) have been implemented. At the same time it was crucial to obtain a reliable model of the event in order to select the more appropriate material properties to use for defining risk scenarios and design mitigation measures.

3 Methods

3.1 DoD

Two LiDAR surveys have been conducted in the Rotolon catchment by the Soil Defence Department of the Veneto Region. The first was carried out in 21 October 2010 by the Regional Authority just 13 days before the event, and the second with the same characteristics (i.e. sensors, flight parameters, average point density) was carried out on 23 November. The average point density for both surveys was about 8 pts m^{-2} while the vertical accuracy (Root Mean Square Error – RMSE) of laser data was 0.072 and 0.044 m for the October and November surveys, respectively. The available data consisted in 11 ASCII files already interpolated with a triangulation algorithm and then resampled with linear interpolation on a 2 m × 2 m grid. The 11 files were then converted in ESRI raster format and merged into a single DTM with particular attention to the spatial coherence of the two surveys.

A first comparison between the pre- and post-event DTMs was carried out with the Change Vector Analyses (CVA) tool implemented in the open source GIS Whitebox 2.0.2 (http://www.uoguelph.ca/~hydrogeo/Whitebox/). The tool calculates the magnitude (Fig. 2) and the direction of variation (erosion or deposit) by simply subtracting the two topographic surfaces. The resulting rasters show clearly the pattern of the event but are also affected by noise mainly related to the vertical and horizontal accuracy of the LiDAR data (Cavalli and Tarolli, 2011) and to the different results of the filtering process applied to remove LiDAR points belonging to vegetation and buildings in the two raw datasets. Therefore error propagation was taken into account before quantitative comparisons of sequential DTMs. Both magnitude and direction of variation maps were used to draw a boundary of the area affected by the event in order to focus the DoD analysis where the most evident morphologic variations occurred.

For the DoD analysis, the software GCD 5 (Geomorphic Change Detection, plugin version for ArcGIS) was used (Wheaton et al., 2010). In the code several methods to calibrate the DoD calculation are presented. In order to adopt an approach based on the spatially variable assessment of the error it is necessary to have information about spatially variable DTM quality that is strictly related to the quality of the survey data (Wheaton et al., 2010). Since original LiDAR point clouds were not available, the evaluation of spatial uncertainty in each individual DTM was not possible and a simple minimum level of detection ($_{\mathrm{min}}$LoD) (Brasinghton et al., 2000; Fuller et al., 2003) approach, considering a uniform error, was used. Predicted elevation changes that occur beneath $_{\mathrm{min}}$LoD are discarded whereas elevation changes above this limit are treated as real. Brasington et al. (2003) showed the individual errors in the DEMs can be propagated into the DoD as:

$$\delta u_{\mathrm{DoD}} = \sqrt{(\delta z_{\mathrm{new}})^2 - (\delta z_{\mathrm{old}})^2} \tag{1}$$

where δu_{DoD} is the propagated error in the DoD and δz_{new} and δz_{old} are the individual errors of the post- and pre-event DTM respectively. For the analysis the error in both DTMs was set at 0.2 m, usual error of airborne LiDAR DTM (Cavalli and Tarolli, 2011) and considered as uniformly distributed.

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3.2 Numerical method

The 3-D simulation was performed with DAN3D software (Hungr and McDougall, 2009) which uses an adapted Smoothed Particle Hydrodynamics (SPH) approach. The rock mass is discretized in numerous particles that flow forced by topography based on a selected rheology.

A 3-D modelling code was necessary for modelling the Rotolon landslide as the peculiar course of the river alters the dynamic of the flow, with marked effects of path curvature in the erosion/deposition pattern. Among 3-D codes, DAN3D was chosen because it allows to modify the rheology of the landslide along the path. The DTM on which the process is simulated could be divided in different zones in which the properties of the flowing mass and of the substrate are assigned. This was crucial because the dynamic of the Rotolon landslide was complex and it was necessary, for example, to recreate the fluidification mechanism caused by the inlet of the Agno di Campogrosso (hereafter called Agno), a secondary stream. In fact the Agno inlet was considered a separation zone between the upper and lower part of the landslide track. Moreover, DAN3D allows to consider entrainment of material during the process and permits to select the maximum erosion depth for each zone of the track. The mechanism of entrainment follows an empirical approach based on the parameter E (erosion rate [m^{-1}]) which represents the increase of the volume of the flowing mass per unit of distance travelled (McDougall and Hungr, 2005).

The modelling of the Rotolon landslide followed a back analysis procedure. The soil parameters are selected through trial-and-error on the basis of the DoD data analysis. In DAN3D the input files are a source area file, which represents the initial geometry of the sliding mass, and the topography file. The availability of pre and post-DTM files allowed to greatly reduce the uncertainties connected with these data as the source file was clearly highlighted in the DoD map and the pre-event DTM was an almost no-error topography file. However in order to reduce the computational time of the simulation the cell were resampled in a 5 m × 5 m grid.

4 Results

4.1 DoD analysis

The resulting differential DTM (Fig. 3) was analyzed in order to identify erosion and depositional areas related to the event and to quantify them in terms of volume. Main results are listed in Table 1.

Results show a sort of balance between deposition and erosion within the catchment with a total erosion of 400 000 m^3. The 2010 event detached a mass of 340 000 m^3 from the main source area in the upper part of the catchment. This mass partially evolved in a debris flow that stretched for 4.5 km threatening some villages. The total net volume difference of 15 000 m^3 can be considered as bed load transport at the catchment outlet.

4.2 The event, as described by the DoD

The dynamic of the 2010 event was quite complex due to the morphology of the valley, the type of sediment involved and the amount of detached material (about 340 000 m^3).

Just after the detachment, part of the material (20 000 m^2) stopped against the upper left flank, filling a small depression and not contributing to the flow along the Rotolon stream. The other 320 000 m^3 fell down in a track characterized by a 27° slope, thus acquiring further energy. Moreover, the presence of a bend along the channel caused erosion on the external part of the river bed due to the effect of transversal velocities. This caused two small lateral failure on the left bank. Later on, in a 900 m long and 15° inclined track located upstream Agno di inlet, 186 000 m^3 of material settled. Since here the total erosion was 21 000 m^3, leaving 155 000 m^3 of sediment entering the flatter part of the valley.

The DoD analysis shows that from the Agno inlet the material flowed for another 3 km in a 7° inclined channel depositing 149 000 m^3 of material. This suggests that there was a modification of the rheology of the flowing mass due to the increasing

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of water content. Data show that the large Giorgetti check dam (Fig. 1), located just upstream of the city of Recoaro Terme, represents the last section along the Rotolon stream in which a significant deposition occurred.

4.3 Modelling

The coupling of frictional and turbulent behavior allows to describe better the complex dynamic of the landslide, its long travel distance coupled with more than 10 % of entrainment. Therefore during the calibration process a Voellmy rheology (Voellmy, 1955) was selected for the model:

$$\tau_{zx} = -\left(f\sigma_z + \frac{\rho g v_x^2}{\xi}\right) \tag{2}$$

where f is the friction coefficient ($f = \tan\varphi_b$ with φ_b bulk basal friction angle) and ξ the turbulence parameter. For the upper part a friction coefficient of $f = 0.18$ and a turbulence parameter of $\xi = 200\,\mathrm{m\,s^{-2}}$ have been selected whereas $f = 0.05$ and $\xi = 200\,\mathrm{m\,s^{-2}}$ were used for the lower part. These are typical parameters for the modeling of a debris flow in alpine environment (Quan Luna et al., 2013). Moreover an erosion rate of 0.0001 has been imposed, with a maximum erosion depth of 5 m in the upper part of the track.

As the kinematics of the phenomenon in the detachment area was complex, with the left bank movement difficult to simulate with the same code, our model focused on reconstructing the dynamic and deposition pattern along the channel track and the results show a good correspondence with the DoD data (Fig. 5). Actually the volume deposited in the upper section was 196 000 $\mathrm{m^3}$ while in the lower tract was 152 000 $\mathrm{m^3}$. The errors are therefore 10 000 $\mathrm{m^3}$ upstream the Agno di inlet and just 3000 $\mathrm{m^3}$ downstream, that is an acceptable accuracy for the modelling of a large landslide. Nevertheless the deposition pattern is not perfectly reconstructed; the biggest discrepancy is located just after the Agno inlet. In the real event the fluidification process took some space and time to develop with a marked transversal dynamic of deposition in the external part of the curve and erosion in the intern, where the clear water would have likely flown. In the model, on the contrary, the modification of the rheology is immediate and this kind of phenomenon is not recreated properly. Therefore in the map of the deposits derived from the DAN3D simulation the levee of the deposit after the Agno inlet is not present. Another smaller difference is located in the channel upstream the Agno inlet: even though the deposition is coherent with the DoD for thickness and shape of the deposit, a smearing effect at the border is present with a 20 m buffer outside the DoD deposit contour. Eventually, the material did not reach the Giorgetti dam. This discrepancy may be explained by the time lag (19 days) between the actual event and the post-event LiDAR survey: it is presumable that some sediment transport occurred after the event and that the deposition front advanced along the channel.

5 Discussion and conclusions

In 2013 Worni et al. stated that the future challenges in numerical modelling of flows are linked to the capability of understanding precisely the dynamic of the phenomena and to the availability of high-resolution DTMs. In this paper we present the use of multitemporal LiDAR DTMs as a tool to analyze mass movement events in each zone of its track in terms of erosion and deposition obtaining a clear description of the whole process.

The availability of pre- and post-event DTMs allowed to enhance the consistency of the numerical model reconstructing the event of 4 November 2010 in the Rotolon catchment. In Table 2 the main results of the simulation are presented: in the track zone the erosion values are almost equal and the 13 000 m^3 discrepancy in deposited volume is less than 4 % the total volume of the event.

The DoD approach could thus be used to improve the reliability of back-analysis-based numerical model as the reconstruction of the phenomena usually depends on the definition of a distinct source area, a highly defined pre-event topographic file and

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a spatial distributed source of information about the erosion/deposition pattern. However the use of DoD for the analysis of fast moving does not provide the velocities data which are usually obtained through a monitoring system (Arattano and Marchi, 2005). The lack of velocity data is highly compensated by the information provided by the DoD, nevertheless for future, similar studies is advisable to consider also the set up of some geotechnical instrumentation.

The availability of a pre-event LiDAR survey acquired 13 days before the reactivation was a lucky coincidence and represents the best possible condition. It was possible to simulate the flow over a topographical surface that was not altered by sediment transport processes occurring naturally in the catchment, smaller landslides or human interference. In usual practice though, while requesting a post-event LiDAR survey is relatively easy, the possibility to obtain a pre-event DTM depends on the capability to sustain the economical effort of periodic flights, although their cost has dramatically decrease (Reutebuch et al., 2005). Thus a rational approach could be to investigate the whole territory as measure zero and then concentrate flights for postevent assessment or in periodic surveys on event prone areas, where a consistent model is necessary to design countermeasure work. The capability to provide a good description of the phenomenon and a reliable numerical model, both describing consistently the whole event from source area to deposition lobes, will also help in evaluating the best options for structural mitigation measures at basin scale. In this perspective the integration of DoD analysis with numerical modelling represents a valuable tool for hazard assessment and risk mitigation.

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Table 1. Main results of the DoD analysis; the thresholded net volume difference and related error are highlighted in bold.

Attribute	Raw	Thresholded DoD Estimate:		
AREAL:				
Total Area of Erosion (m^2)	114 900	91 732		
Total Area of Deposition (m^2)	180 276	156 656		
VOLUMETRIC:			± Error Volume	% Error
Total Volume of Erosion (m^3)	404 048	400 890	±25 946	6 %
Total Volume of Deposition (m^3)	387 705	384 551	±44 309	12 %
Total Volume of Difference (m^3)	791 752	785 441	±70 255	9 %
Total Net Volume Difference (m^3)	−16 343	**−16 339**	**±51 347**	314 %
PERCENTAGES (BY VOLUME)				
Percent Erosion	51 %	51 %		
Percent Deposition	49 %	49 %		
Percent Imbalance (departure from equilibrium)	−1 %	−1 %		

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Table 2. Comparison, in terms of volume, of the main results of the DoD analysis and the DAN3D simulation.

Volume [m^3]	DoD Erosion	DoD Deposit	DoD Balance	DAN3D Erosion	DAN3D Deposit	DAN3D Balance	Difference between Dod and DAN3D Deposit
Detachment Area							
Main detachment	342 263	1915		332 123*	17 761		
Lateral zone	5227	25 553			1025		
Mass leaving the detachment area			320 022			313 337	6685
Debris-flow track above the Agno inlet	21 746	186 523			196 317		−9794
Debris-flow track below the Agno inlet	14 275	149 274			152 747		−3473
Whole debris-flow track	36 021	335 797		35 727	349 064		13 267

* Source area in DAN3D.

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Multi temporal LiDAR-DTMs as a tool for modelling a complex landslide
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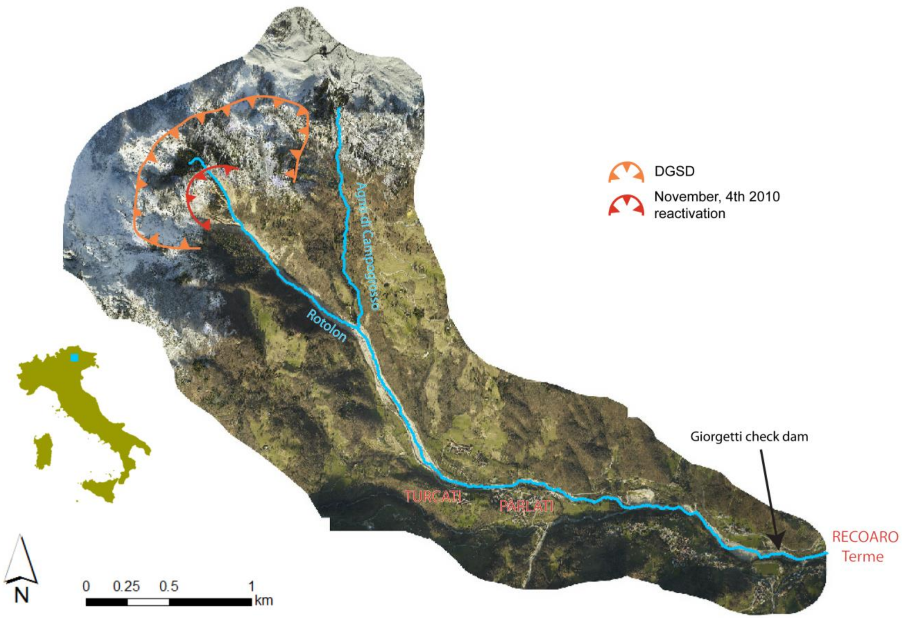

Figure 1. Study area, post-event orthophoto with highlighted the main hydrographic network and the landslides crowns.

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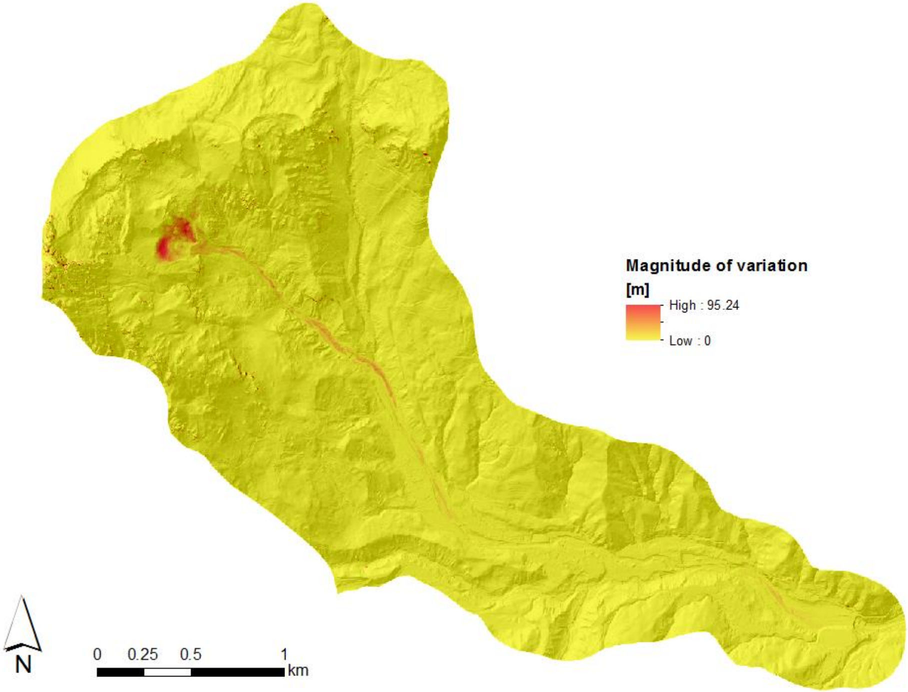

Figure 2. Magnitude of geomorphic change in the Rotolon catchment.

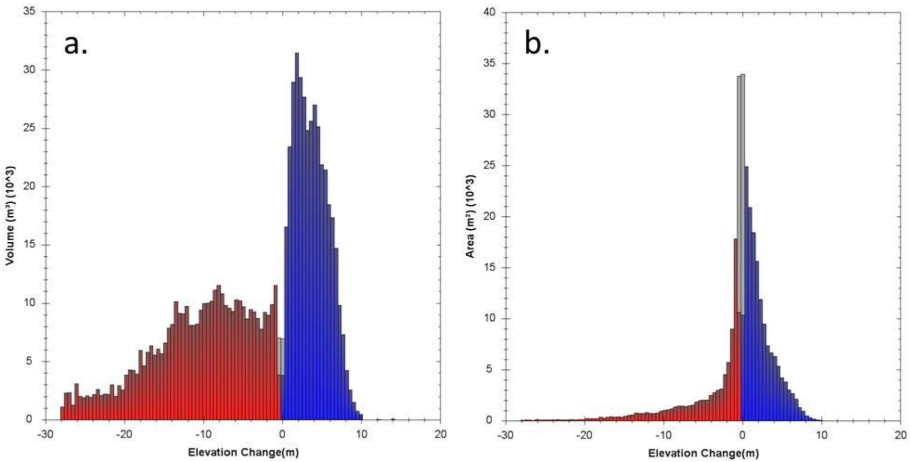

Figure 3. Volumetric **(a)** and areal **(b)** distribution **(a)** of the morphologic variations occurred between October and November 2010. In blue deposition, in red erosion, in grey the values discarded for the volumetric assessment.

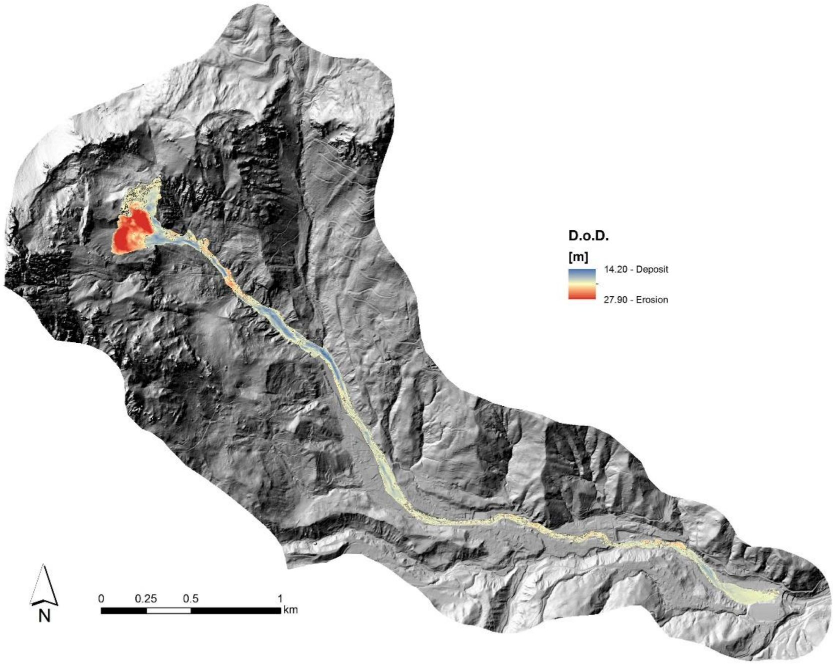

Figure 4. DoD map over shaded relief of the Rotolon catchment.

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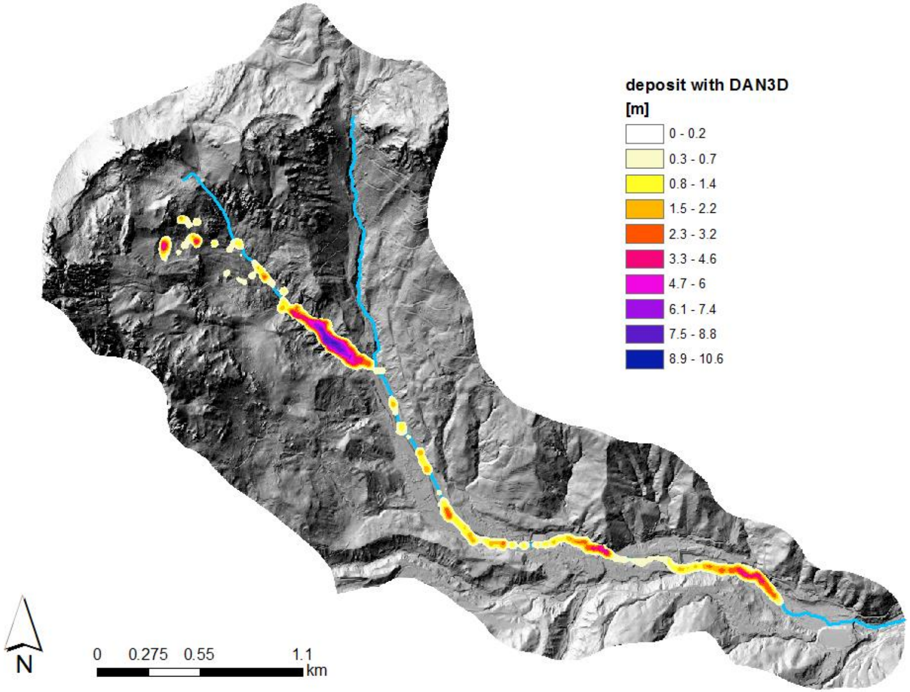

Figure 5. Results of the back analysis simulation with DAN3D, distribution of the deposits.