



Reduce mapping errors in the production of landslide inventory maps

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An approach to reduce mapping errors in the production of landslide inventory maps

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Abstract

Landslide inventory maps (LIMs) show where landslides have occurred in an area, and provide information useful to different types of landslide studies, including susceptibility and hazard modelling and validation, risk assessment, erosion analyses, and to evaluate relationships between landslides and geological settings. Despite recent technological advancements, visual interpretation of aerial photographs (API) remains the most common method to prepare LIMs. In this work, we present a new semi-automatic procedure that exploits GIS technology for the digitalization of landslide data obtained through API. To test the procedure, and to compare it to a consolidated landslide mapping method, we prepared two LIMs starting from the same set of landslide API data, which were digitalized (a) manually adopting a consolidated visual transfer method, and (b) adopting our new semi-automatic procedure. Results indicate that the new semi-automatic procedure is more efficient and results in a more accurate LIM. With the new procedure, the landslide positional error decreases with increasing landslide size following a power-law. We expect that our work will help adopt standards for transferring landslide information from the aerial photographs to a digital landslide map, contributing to the production of accurate landslide maps.

1 Introduction

Landslide inventory maps (LIMs) document the type and extent of mass movements in areas ranging from single slopes, or groups of slopes (Cardinali et al., 2001), to regions (e.g. Brabb and Pampeyan, 1972; Antonini et al., 1993; Duman et al., 2005), and even entire States or Nations (Delaunay, 1981; Radbruch-Hall et al., 1982; Brabb et al., 1989; Cardinali et al., 1990; Reichenbach et al., 1998; Trigila et al., 2010). LIMs are prepared using a variety of techniques and methods (Guzzetti et al., 2012), including: (i) analysis of archive and historical information (Reichenbach et al., 1998; Salvati et al., 2003), (ii) visual interpretation of stereoscopic aerial photographs (aerial photo

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interpretation, API) (Guzzetti and Cardinali, 1989, 1990; Cardinali et al., 1990; Brun-
den, 1993; Antonini et al., 2002a, b; Guzzetti et al., 2002, 2012; Galli et al., 2008;
Santangelo et al., 2010, 2013), (iii) visual analysis of LiDAR-derived images (Ardiz-
zone et al., 2007; Van den Eeckhaut et al., 2007; Haneberg et al., 2009; Guzzetti et al.,
2012; Razak et al., 2011, 2013), (iv) visual inspection of monoscopic (Marcelino et al.,
2009; Gao and Maroa, 2010; Fiorucci et al., 2011; Giordan et al., 2013) and stereo-
scopic (Fiorucci et al., 2011; Ardizzone et al., 2013) satellite images, and (v) image
processing techniques (Guzzetti et al., 2012) applied to LiDAR elevation data (Martha
et al., 2010; Lu et al., 2011; Stumpf and Kerle, 2011; Van den Eeckhaut et al., 2012)
and satellite imagery (Rosin and Hervás, 2005; Borghuis et al., 2007; Yang and Chen,
2010; Mondini et al., 2011a, 2013, 2014; Mondini and Chang, 2014).

Despite modern technological advancements, and the availability of new imagery, the
visual interpretation of aerial photography (aerial photo interpretation, API) remains the
most common method to obtain information on landslides (Brunsdon, 1993; Guzzetti
et al., 2012). In many areas, aerial photographs (APs) are the only source of landslide
information in the period between 1920s and 1973, when the images captured by the
first Landsat satellite became available (McDonald and Grubbs, 1975; Sauchyn and
Trench, 1978).

Production of LIMs through API is known to be a subjective and error prone operation
(Guzzetti et al., 2012). The quality of the final map depends on multiple factors, includ-
ing the experience and skills of the photo-interpreter(s), the scale of the APs and of
the base map used to prepare the inventory, and the complexity of the terrain (Carrara
et al., 1992; Ardizzone et al., 2002; Galli et al., 2008). A crucial – and underestimated
– source of error that influences the quality of a LIM lays in the transfer of information
from the original APs used to recognize the landslides, to the base map used to pro-
duce the LIM (Marchesini et al., 2013; Santangelo et al., 2015b). Most commonly, the
transfer of information from the APs to the (digital or paper) map is performed visually.
To the best of our knowledge, no attempt has been made to quantify the error intro-
duced by the visual transfer of the landslide information from the APs to the base map,

and to investigate technological alternatives to the visual transfer that may reduce the mapping errors, contributing to improve the quality of LIMs.

We present a new semi-automatic GIS procedure for the digitalization of landslides and other geomorphological information obtained through API. We test the new procedure in a 93 km² area near Taormina, Sicily, where landslides are abundant. In our test area, we compare two LIMs obtained using a consolidated manual procedure for preparing the inventory and the new semi-automatic procedure, and we discuss advantages and drawbacks of the new method compared to the traditional approach.

2 Study area and materials

For our experiment, we selected a 93 km² area along the E coast of Sicily, near Taormina (Fig. 1). In the area, elevation ranges from sea level to 1187 m, with a mean elevation of 410 m, computed from a 2 m × 2 m Digital Elevation Model (DEM). Terrain slope is the range between 0 and 88°, with an average of 41°, and most of the slopes facing towards SSW. Most of the area is drained by the Alcantara River that flows into the Ionian Sea and is characterised by a deep canyon cut into lava flows of the Etna Volcano. A W–E trending antiformal ridge shapes the morphology of the area (APAT, 2008). Conglomerate, sandstone, and clay pertaining to the Capo D’Orlando Flysch crop out along the SE limb of the ridge. Metamorphic rocks, mainly phyllites and massive and layered carbonate rocks, crop out on the ridge top, and lavas are present in the canyon carved by the Alcantara River. The composite lithological assemblage and the complex structural setting control the morphology of the slopes, and the location, type, abundance, and pattern of the landslides. Large, deep-seated landslides and “sackung-type” features (Di Maggio et al., 2014) are most common where metamorphic rocks crop out. Slides, earthflows, complex and composite landslides, and large debris flows are abundant where flysch rocks crop out. In places, hard rocks (carbonate, lava flow) form steep, locally overhanging walls that represent the source areas of rock falls, topples, and minor rockslides.

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For the study area, the following materials were available to us: (i) a topographic base map at 1 : 10 000 scale, (ii) a 2 m × 2 m resolution DEM obtained from a Lidar survey, (iii) a colour orthophoto map with a ground sampling distance, GSD = 0.25 m, and (iv) twelve black and white aerial photographs (APs) flown on 7 July 2005 at a nominal scale of 1 : 28 000. The APs were 23 cm × 23 cm in size, each covering an area of approximately 34 km², and were taken using a “WILD” camera with a focal length of 153.64 mm. The side overlap between two adjacent APs is about 70 %, and the strip overlap about 20 %.

3 Production of a landslide inventory map

Production of a landslide inventory map (LIM) is the result of a complex process that consists of multiple steps, from the visual analysis of the stereoscopic APs using a stereoscope, to the storage of the landslide information in a GIS. Based on our experience, and the production of LIMs for more than 4×10^5 km² in different physiological and climatic settings in Italy (Antonini et al., 1993, 2002b; Ardizzone et al., 2012; Cardinali et al., 2001; Guzzetti and Cardinali, 1989; Santangelo et al., 2015a), and elsewhere in the World (e.g. Cardinali et al., 1990), we identify three main steps for the production of a LIM (Fig. 2).

First, (step A in Fig. 2) all the topographic, morphological, geological, and environmental data and information useful for the recognition of the landslides are collected and organized. Next, (step B in Fig. 2) the available stereoscopic APs are interpreted visually (aerial photograph interpretation, API) by an interpreter – or by two interpreters when “discussion” stereoscopes are used to improve the quality of the landslide mapping (Guzzetti and Cardinali, 1990; Galli et al., 2008). In this step, the interpreter decides whether or not a feature observed in the APs is (or is not) a landslide, and determines the type (Cruden and Varnes, 1996), relative age (Santangelo et al., 2013), and estimated depth of the landslide. An expected degree of confidence in the recognition can also be attributed to each landslide, or other recognized geomorphological feature

(Razak et al., 2013). The interpreter draws the landslide and the additional thematic information detected on the APs on a transparent plastic sheet (template) placed over the AP using fine-scale (0.3 mm, or smaller) colour felt pens. Next, (step C in Fig. 2) the information shown on the transparent plastic sheet is transferred to the base map, and stored in a GIS. This can be performed using a consolidated manual procedure, or the new semi-automatic procedure proposed in this work (Fig. 2).

3.1 Manual procedure

The manual procedure consists in the following four sub-steps (Santangelo et al., 2012; Marchesini et al., 2013). First, the information drawn on the plastic sheets placed over the APs (Fig. 3a) is transferred visually (re-drawn) to a second undeformable plastic sheet placed over the topographic base map (Fig. 3b). In this sub-step, all the topographic distortions present in the AP – the result of the conical view of the AP – are adjusted visually to match the undistorted (projected) topographic map. Second, the undistorted plastic sheet is scanned – typically using a large-scale (A0 format) scanner, imported as a raster file in a GIS, and geo-referenced. Third, the landslide and the thematic information is transformed from raster to vector format (vectorization) using automatic, semi-automatic, or manual methods. Fourth, the single vector elements, each representing a landslide or a portion of a landslide (e.g. a landslide escarpment, a landslide boundary), or a morphological or geological feature (e.g. fault traces, trenches) are assembled in single or in multiple vector features. Lastly, each landslide feature is coded (labelled) with the appropriate landslide information, and stored in a GIS in single or multiple layers (Fig. 3c). When multiple layers are used, the different layers can show landslides of different types, or of different ages or periods (Santangelo et al., 2013, 2015a).

Transfer of the landslide and thematic information from the AP to the base map using the manual procedure inevitably introduces errors in the LIM, including errors in the position, size, and shape of the individual landslides (Ardizzone et al., 2002; Marchesini et al., 2013). The mapping errors have different causes, including: (i) the different

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projections of the AP (perspective or central projection) and the topographic base map (orthographic projection), (ii) the different scales of the APs and the topographic map, (iii) a smaller number of reference points on the topographic map compared to the AP, (iv) the quality of the topographic map, and (v) the complexity of the terrain. The manual method is time consuming (Galli et al., 2008), and the quality of the LIM depends largely on the ability of the operator to transfer correctly the mapped landslide and thematic information from the AP to the base map.

3.2 Semi-automatic procedure

We propose a new, semi-automatic procedure to transfer the landslide and the thematic information recognized in the APs to the topographic base map. The procedure consists of the following four sub-steps (Fig. 1). First, the single AP and the associated plastic sheets showing the landslide and thematic information are scanned. Three separate scans are prepared, including: (i) a grey tones (8 bit) image of the AP with the plastic sheet (Fig. 4a), (ii) a black and white (1 bit) image of the plastic sheet without the AP (Fig. 4b), and (iii) a colour (24 bit) of the plastic sheet, also without the AP (Fig. 4c). The three scanned images are stored in the GRASS GIS as an imagery group in a project with Cartesian coordinates (i.e. a generic (x, y) mapset). Second, the imagery group is ortho-rectified. For the purpose, the grey tones (8 bit) scanned image of the AP and the associated plastic sheet is used for the interior and the exterior orientations of the AP, and of the landslide and thematic information. Third, the landslide and the thematic information shown in the scanned plastic sheet is transformed from raster to vector format, automatically. Fourth, the individual vector elements are assembled in single or in multiple vector features, each representing e.g. a landslide or a portion of a landslide, or thematic information. Lastly, the landslide/thematic features are manually labelled with the appropriate information, and stored in the GIS in single or multiple layers (Fig. 3c). To code the individual vector features we exploit the 24 bit colour image, using the colours shown in the original (colour) plastic sheet (Fig. 4c).

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For our experiment, to scan the AP and the associated plastic sheets showing the landslide and the thematic information, we used an A3-format (42.0 cm × 29.7 cm) Epson Expression™ 10 000 XL scanner, and the SilverFast® Ai IT8 v.6.6 scanning software. The APs were scanned at a resolution of 1200 dpi, corresponding to a ground resolution of ~ 0.6 m at the scale of the APs (1 : 28 000). Considering the scales of the AP and of the topographic base map (1 : 10 000), and the general accuracy with which landslides are detected from API, the scanning resolution was considered adequate.

For the ortho-rectification of the scanned images we used the *i.ortho.photo* module of GRASS GIS (GRASS development team, 2012) (Fig. 5a and b). The module requires as input data: (i) the scanned images of the AP (Fig. 4), (ii) a DEM, (iii) a georeferenced orthophoto or a detailed topographic map of the study area, and (iv) the parameters of the camera used to take the aerial photograph (Rocchini et al., 2011). For the interior orientation, the coordinates of the eight fiducial marks were associated using the centre of symmetry of the AP as the origin. For the exterior orientation (Fig. 5b), the *i.ortho.photo* module requires that a sufficient number of ground control points (GCPs) are placed on the AP. In the literature, 16 GCPs are considered sufficient if each GCP is placed with an accuracy of 1/3 of the pixel size (Bernstein, 1983; Rocchini et al., 2011), and if the GCPs cover the entire AP avoiding clustering effects. For our experiment, 16 to 20 GCPs were selected in each AP. Lastly, *i.ortho.photo* requires a number of output parameters, including the resolution (usually meters per cell/pixel width or length) of the ortho-rectified image and the interpolation method (e.g. nearest neighbour, bilinear, bicubic, etc.) used to resample the pixels of the scanned images to the target grid of a given coordinate reference system. The ortho-rectified images are exported as GeoTIFF files, for subsequent vectorization and coding of the landslide and thematic information.

For the automatic vectorization of the single ortho-rectified images we used the ArcScan extension of ArcMap™ (ArcGIS® 10). The software uses as input a raster layer (1 bit) of the interpreted template (i.e. an ortho-rectified image showing the thematic information only, Fig. 5c). The individual vector features (points, lines, polygons) are



cleaned topologically, and then stored in shape files. The attribute table is then compiled with the appropriate landslide/thematic information using a pre-defined legend.

3.3 Accuracy of the ortho-rectification

For the rectification of APs, Rocchini et al. (2011) have shown that a robust ortho-rectification algorithm provides better results than rectifications techniques that do not use digital terrain information (i.e. a DEM). We exploited the algorithm described by Rocchini et al. (2011) and implemented in the *i.ortho.photo* module of GRASS GIS (GRASS development team, 2012). Figure 6a shows measures of the co-registration accuracy of the APs and the ortho-photograph used for the exterior orientation. For 63 GCPs (different from the GCPs used for the exterior orientation), we obtained a total RMSE of 5 m, and a 3σ data concentration ellipse < 10 m along the x axis and the y axis. Considering that the graphical error for an AP at 1 : 28 000 scale is 5.6 m (where the graphical error is $0.2\text{ mm} \times 28\,000$), and the (nominal) width of the felt pen used to draw the landslide information on the plastic sheets was 0.3 mm, corresponding to 8.4 m at the scale of the APs, we conclude that the semi-automatic ortho-rectification method is suitable for the production of a LIM, at 1 : 10 000 scale.

In Fig. 6b, we show 40 data points, out of the 63 GCPs of Fig. 6a, for which it was possible to find corresponding points on the 1 : 10 000 scale topographic map. Those points were used to evaluate the co-registration accuracy between the topographic base map used for the visual transfer using the manual procedure, and the orthophoto used for the exterior orientation in the semi-automatic procedure. We measured a total RMSE of 2.7 m, and a maximum RMSE of 6.2 m, which reveal a good co-registration between the ortho-photograph used for the exterior orientation of the APs, and the topographic base map used as reference for the manual procedure. The good co-registration accuracy allows for the comparison between the LIMs produced using the manual and the semi-automatic procedures.

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4 Results

From the visual interpretation of the twelve APs (five complete stereograms) covering our study area (Fig. 7), and using the same topographic base map, we produced two LIMs. The first landslide map (Map A, Fig. 7a) was prepared adopting the traditional (consolidated) manual method to transfer the information from the APs to the base map, and in the GIS. The second landslide map (Map B, Fig. 7b) was prepared adopting the new semi-automatic method to transfer the information from the APs to the base map, and in the GIS. Availability of two maps covering the same area and showing the same landslides allows for qualitative and quantitative comparisons of the maps. Since the differences in the two maps lay in the method used to transfer the information from the APs to the GIS, analysis of the differences allows us to evaluate the performances of the two methods, outlining advantages and limitations.

We performed an analysis of the mismatch between the inventories resulting from the manual and the semi-automatic methods. Figure 8 shows a qualitative comparison of the two LIMs in four areas (black boxes in Fig. 7) that we consider representative of different, typical mapping conditions. Visual inspection of Fig. 8a reveals an overall agreement between the two maps, with local variations dependent on the size of the landslides. In Fig. 8b, there is a good agreement in the geographical location of the single landslides, but the size of some of the landslides differs, locally significantly. Some of the mapped landslides (a' , c' to g' in Fig. 8b) are larger in Map A and smaller in Map B, indicating a systematic overestimation of the size of the landslides when transferring the landslide information visually. Conversely, landslide b' (Map A) is smaller than the corresponding landslide b (Map B), mapped using the semi-automatic procedure. Inspection of Fig. 8c reveals that, with a few exceptions, the size (area) of the landslides shown in the two maps are very similar, but the geographical position of some of the landslides varies significantly. In particular, the corresponding landslides a and a' and d and d' do not overlap. Landslides c and c' and b and b' , overlap partially but their position does not correspond, entirely. Finally, Fig. 8d shows an area where the

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agreement between the two maps is very poor. In this area, both the size (extent) and the geographical location of some of the landslides are affected by very large errors (e.g. landslides b and b' , c and c' , and d and d'). In addition, Fig. 8d shows that one landslide shown in Map A (i.e. e') is not present in Map B and, vice versa, landslide a in Map B is not shown in Map A. Should we consider Map B (prepared through the semi-automatic procedure) as the reference (“true”) map, polygon e' would be considered a commission error and polygon a an omission error. The differences between the two maps are the result of modifications introduced by the interpreter when transferring the information manually from the AP to the base map. The operator introduces the (rare) changes locally, in the attempt to adjust the landslide mapping to the local topographic setting shown by the base map.

Table 1 summarizes statistics of landslide area (size) for the two LIMs. The smallest landslide in Map A is a slide with $A_L = 4.37 \times 10^2 \text{ m}^2$. The same landslide in Map B has $A_L = 3.77 \times 10^2 \text{ m}^2$ (a difference of 60 m^2). The smallest landslide in Map B is a slide with $A_L = 1.66 \times 10^2 \text{ m}^2$. The corresponding landslide in Map A has $A_L = 7.07 \times 10^2 \text{ m}^2$ (a difference of 95 m^2). The largest landslide in Map B is a slide with $A_L = 1.84 \times 10^6 \text{ m}^2$. In Map A, the same slide has $A_L = 1.80 \times 10^6 \text{ m}^2$, revealing a difference of $4 \times 10^4 \text{ m}^2$ (2%) in size. In Map A, obtained using the manual procedure, the average landslide area is $\bar{A}_L = 7.48 \times 10^4 \text{ m}^2$, and in Map B, obtained exploiting the semi-automatic procedure, the average landslide area is $\bar{A}_L = 7.40 \times 10^4 \text{ m}^2$. This is a reduction of 1.1% of the average landslide area. The total landslide area is $A_{LT} = 3.74 \times 10^7 \text{ m}^2$ for Map A, and $A_{LT} = 3.57 \times 10^7 \text{ m}^2$ for Map B. The reduction in the total landslide area, $1.7 \times 10^6 \text{ m}^2$, is not small (4.5%) and conditions the percentage of landslide area (landslide density), which is 39.1% for Map A (manual procedure) and 38.4% for Map B (semi-automatic procedure).

The probability (or frequency) of landslide area A_L is known to obey a typical probability distribution (Stark and Hovius, 2001; Guzzetti et al., 2002; Malamud et al., 2004). For small landslides, the probability of landslide area $p(A_L)$ increases with landslide

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area A_L up to a maximum value (the “rollover”) after which $\rho(A_L)$ decreases rapidly following a power-law. The empirical $\rho(A_L)$ are reasonably well approximated by the double-Pareto (Stark and Hovius, 2001) or the inverse Gamma (Malamud et al., 2004) functions. Using specific software (Rossi et al., 2012) we determined the $\rho(A_L)$ for the two inventories. Results are shown in Fig. 9a–d that portray the inverse Gamma approximation to the $\rho(A_L)$ for Map A (manual method) and Map B (semi-automatic method), respectively. Comparison of Fig. 9a–d reveals that, despite a slight difference in the slope of the power-law scaling ($\alpha = 2.06$ for Map A and $\alpha = 2.02$ for Map B, Table 2), the two distributions are in good agreement for $A_L > 1 \times 10^3 \text{ m}^2$, and are somewhat different only for smaller landslides ($A_L < 1 \times 10^3 \text{ m}^2$). Furthermore, Table 2 shows that the rollover for Map A ($A_L = 6.40 \times 10^3 \text{ m}^2$) is slightly larger than for Map B ($A_L = 5.33 \times 10^3 \text{ m}^2$).

We obtained an additional quantitative analysis of the differences between the two inventories modifying the mapping error index E proposed by Carrara et al. (1992), and used e.g. by Ardizzone et al. (2002) and by Galli et al. (2008). The innovation of our work was to calculate the positioning error index E_i for each pair of corresponding landslides in the two inventories:

$$E_i = \frac{(A_i \cup B_i) - (A_i \cap B_i)}{(A_i \cup B_i)} \quad (1)$$

where A_i is a landslide in Map A and B_i is the corresponding landslide in Map B, and $(A_i \cup B_i)$ and $(A_i \cap B_i)$ are the geometrical union and the geometrical intersection of the two corresponding landslides, respectively. This is different from what was proposed by Carrara et al. (1992) who summed the areas of all the landslides in Map A and Map B to calculate their mapping error index E .

We identified 482 pairs of corresponding landslides for which we calculated the positioning error E_i , with values in the range from 0.5 to 1.00. The average value for the positioning error E_i was 0.44, and the median of the error was 0.41 (dashed line in Fig. 10). We compare these figures to the mapping error $E = 0.19$ computed using the

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method proposed by Carrara et al. (1992). In Fig. 10, for each pair of corresponding landslides, we plot the value of E_i against the area A_L of the landslide shown in Map A (produced using the manual method). Inspection of the plot reveals that the positioning error E_i is largest for the very small landslides and (with a few exceptions) decreases rapidly with increasing landslide area. For slope failures with $A_L < 1 \times 10^5 \text{ m}^2$, the positioning error E_i exhibits a large variability. For landslides having $A_L > 1 \times 10^5 \text{ m}^2$ the positioning error E_i is generally smaller than 0.3, and does not exceed 0.1 for landslides with $A_L > 4.2 \times 10^5 \text{ m}^2$.

Figure 10 shows that large positioning errors are associated to small landslides. When analysing stereoscopic APs visually, small landslides are identified based primarily on their photographic evidence (tone, mottling, pattern, texture) in the photographs, and not based on their morphological characteristics (the presence, association, and pattern of e.g. concavities, convexities, escarpments, back-slopes), which can be very subtle. However, this photographic information is typically not shown in the topographic maps, making it difficult for the interpreter to locate and map accurately the small landslides in the base map. In other words, when the interpreter transfers visually small landslides from the AP to the base map he/she uses a subset of the information available for the detection of the landslide in the AP. Lack of information contributed to the mapping error. Conversely, large landslides typically exhibit a distinct morphological signature (Pike, 1988) that is shown (partially or totally) in the topographic maps, making it simpler for the interpreter to transfer accurately the landslide information to the base map. This reduces the mapping error for large and very large landslides. The same applies to channelled debris flows that occur primarily along channels visible on the topographic maps, and deposit the failed material on debris fans that are also visible on the topographic maps.

5 Discussion

We tested a new semi-automatic procedure to transfer landslide and other geomorphological information captured through API from the original aerial photographs to a digital landslide database in a GIS environment. The new procedure can contribute to the efficient production of accurate LIMs and geomorphological maps over large areas. Considering the entire landslide mapping process exemplified in Fig. 2, the semi-automatic procedure reduces significantly (or avoid completely) the subjectivity introduced by the visual (manual) transfer of the landslide and geomorphological information from the APs to the digital database. This reduces mapping errors, enhancing the quality of a LIM.

In our study area, Map B obtained adopting the new semi-automatic procedure, shows landslides located more accurately than the corresponding landslides in Map A, produced by the traditional manual method. Although “ground truth” i.e. the “true” location, size, and shape of the landslides is not available to us (as it is rarely the case in landslide mapping, Santangelo et al., 2010), and aware of the RMSE of 7.7 m introduced by the ortho-rectification of the APs in Map B (C2 in Fig. 2), we consider Map B as reasonably “correct” in terms of the geographical location, size, and shape of the mapped landslides. As a consequence, we interpret the observed differences (mismatches) in Map A as errors introduced by the visual transfer of the landslide information in the manual procedure (C1 in Fig. 2).

We measured the overall degree of mismatching between the two inventories (Map A vs. Map B) using the error index E (Eq. 1) introduced by Carrara et al. (1992), and obtained a value for the mapping error index $E = 0.19$. This suggests that overall the two maps are rather similar (Ardizzone et al., 2002). Visual inspection of Fig. 7 confirms the impression. However, inspection of Fig. 8 reveals a number of (small and large) local differences between single landslide pairs in the two inventories. To quantify the individual differences, we calculated the positional error E_i for 482 pairs of corresponding landslides in the two inventories. The result revealed positional errors in the range

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$0.05 \leq E_i \leq 1.00$, with an average error $\overline{E}_i = 0.44$. The difference with $E = 0.19$ is significant, and suggests that the lumped measure provided by the mapping error index E of Carrara et al. (1992) overestimates the degree of geographical matching (and underestimates the mismatch) between the two maps.

Our results also revealed that the positional error of single landslides E_i depends on the size A_L of the landslides, with small landslides exhibiting a larger positional error than larger landslides (Fig. 10). Interestingly, the dependence of the positional error on landslide area is well approximated by a power law, $E_i = 8.03 \times A_L^{-0.3}$. This information can be used to estimate the expected positional error of single landslides in LIMs produced manually. We maintain this is important (and new) information for the users of a LIM.

Time is a critical aspect in the production of LIMs. For a LIM covering a large or very large area (thousands of square kilometres) the production of an accurate inventory map can take several months to a few years (Galli et al., 2008; Guzzetti et al., 2012). A significant part of the time used to prepare a LIM is spent in transferring the landslide information from the APs to the digital landslide database. The new semi-automatic procedure reduces significantly the time (and hence the cost) for the production of a LIM.

Table 3 shows a comparison of the time used to prepare our two inventories, using the traditional mapping procedure and adopting the new semi-automatic procedure. In the Table, time is given in hours per one pair of stereoscopic APs (one stereogram), per person. Considering that we analysed five stereograms to prepare the two inventories, in the Table we list the minimum and the maximum time required to complete the mapping of a stereogram. The time required for the API varied significantly, depending on the complexity of the terrain. It was minimum in geomorphologically “simple” areas, where terrain and environmental setting were homogenous, and where landslides were rare or simple to identify and map. The time increased with increasing terrain complexity and local setting, where landslides were abundant, and where multiple generations of landslides were present. The time required for the visual transfer of the information



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from the APs to the digital database depended also on the complexity of the terrain, and on the complexity and quantity of the landslide information drawn on the APs. The time for the ortho-rectification of the scanned APs depended largely on the difficulty of identifying adequate GCPs on the images used for the exterior orientation. The operation was simple (and fast) in urban areas, and difficult (and time consuming) in rural or forested areas where adequate GCPs were difficult to identify. The time required for all geo-coding operations depended on the quantity of the landslides and the other geomorphological features, and on their geographical and topological relationships.

Comparison of the time required for transferring the landslide information from the APs to the GIS database (without geo-coding) reveals that the new procedure (and specifically the ortho-rectification step) accelerated the process by a factor of 4 to 10, compared to the visual (manual) transfer. If geo-coding is considered, the acceleration factor is in the range from 3 to 8 (Table 3). The improvement is significant, and measures the gain in efficiency introduced by the semi-automatic procedure. When the entire mapping workflow is considered (Fig. 2) the gain in efficiency is somewhat lower, but remains significant. The difference (gain) in time for one person to complete the mapping of one stereogram ranged from a minimum of two to a maximum of 13 h. These figures suggest that the new semi-automatic procedure is always convenient (more efficient) than the traditional (manual) procedure, with the efficiency increasing where the geomorphological complexity of the area increases.

In our experiment, the API phase took a total of 31.5 h. Ortho-rectification of the APs took 4.5 h. This compares to 35 h required for the visual transfer of the information with the manual procedure. Automatic vectorization took 4.5 h, which compares to the 22 h for the manual vectorization. Geo-coding required the same amount of time for both procedures (32 h). Overall, exploiting the new semi-automatic procedure the time needed to complete the landslide inventory (Map B) was 40.5 h, which is 44 % of the time (92.5 h) used to prepare the inventory adopting the traditional mapping procedure (Map A). Including the API phase, the time used to cover an area of 93 km² with a detailed (1 : 10 000 scale) geomorphological LIM (Guzzetti et al., 2012) was 72 h



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(nine working days) using the semi-automatic procedure, and was 124 h (15.5 working days) using the manual procedure. In other words, the new procedure increased the interpreter's productivity from 0.32 to 0.55 stereograms per person per day; a 72 % increase. For completing the landslide mapping of one stereogram, a geomorphologist

5 needs two days exploiting the new semi-automatic procedure, and three days using the traditional manual procedure. We acknowledge that these figures are estimates, and subjected to variations depending on the local geological, morphological and land use settings, the quality of the topographic base map, on the number and complexity of the

10 landslides and on their geometrical and topological relationships.

Despite the clear gain in mapping accuracy and efficiency, the new semi-automatic procedure is not free of problems, and care is needed when using the procedure to prepare a LIM. A number of factors influence the geographical accuracy of the landslides shown in a LIM produced exploiting the semi-automatic procedure, including the accuracy of the DEM, of the interior orientation, and of the GCPs used for the exterior

15 orientation. Selection of the GCPs for the exterior orientation is a crucial, and most delicate step of the procedure. Accuracy of this step depends on the geographical accuracy and resolution of the base map, and on the difference in age between the base map and the aerial photographs that need to be ortho-rectified. In our study, the aerial photographs were taken in 2005, and the ortho-photograph (base map) used to select

20 the GCPs was taken in 2007 with a resolution of 0.25 m. This made it simple to identify the GCPs accurately. In other areas, accurate selection of a sufficient number of GCPs may be problematic, limiting the quality of the ortho-rectified image.

Figure 6 shows that the geographical co-registration between the ortho-rectified aerial photographs and the ortho-photograph (base map) used for the exterior orientation is not perfect, and that it is slightly worse along the NS direction than along the EW direction. When a LIM is shown on a base map different from the map used for the

25 ortho-rectification, the differences (including co-registration errors) between the two base maps combine, contributing to degrading the location accuracy of the landslides shown in the new base map. In our study, the co-registration accuracy plots portrayed



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in Fig. 6a and b show that 95 % of the overall co-registration errors are within a range of 9 m along the x axis (E-W direction), and 10.1 m along the y axis (N-S direction). The sum of the total RMSEs for the two base maps (i.e. the RMSE obtained between the orthorectified APs and the ortho-photograph, and the RMSE obtained between the ortho-photograph and the topographic map) is 7.7 m. We consider this is an acceptable error for a 1 : 10 000 scale LIM (~ 0.8 mm on the map).

LIMs are used for many purposes, and their quality affects the results of the investigations performed using the LIMs. This is seldom considered by the investigators (Guzzetti et al., 2012). Supervised remote sensing image classification techniques for the detection and mapping of landslides exploit LIMs in their training phase, and to validate the mapping against independent information (Cheng et al., 2004; Nichol et al., 2006; Borghuis et al., 2007; Yang and Chen, 2010; Lu et al., 2011; Mondini et al., 2011b; Stumpf and Kerle, 2011; Guzzetti et al., 2012). Training performed using LIMs produced using the manual method can affect negatively the ability of the image classifiers to detect and map the landslides. For validation purposes, independent landslide information captured through API is often considered “correct” (Congalton, 1991) i.e. the “ground truth”. Our work demonstrates that (in our study area, but we maintain the same occurs in many other areas) this is not the case, even assuming a hypothetical “error free” API phase. Our results suggest that for training and validation of remote sensing image classifications, LIMs produced through robust ortho-rectification of APs (i.e. using the semi-automatic procedure) provide more accurate results than those obtained using manually prepared LIMs.

Temporal statistics of landslides used e.g. to ascertain landslide hazard (Guzzetti et al., 2005, 2006) or risk (Cardinali et al., 2002; Reichenbach et al., 2004), and to determine landslide erosion or mobilization rates (Guzzetti et al., 2009; Fiorucci et al., 2011), are extracted from multi-temporal or seasonal landslide maps. The accuracy of the temporal calculations depend on the accuracy of the multi-temporal or seasonal maps. Misplaced landslides can result in an overestimation or underestimation of the temporal frequency of landslides in an area (Fig. 7c), introducing errors affecting haz-

ard and risk assessments, and erosion studies. Landslide positioning errors can have serious impacts on the definition of vulnerable elements, leading to locally erroneous estimations of landslide risk. Our results suggest that geographically accurate LIMs prepared adopting the semi-automatic procedure should be preferred to construct accurate multi-temporal or seasonal inventories.

LIMs are also used to determine the statistics of landslide size (area and volume) (Malamud et al., 2004; Guzzetti et al., 2009), and to investigate correlations between the location and abundance of landslides and the local geological structure (Grelle et al., 2011; Marchesini et al., 2013; Santangelo et al., 2015b). Our results revealed that the geographical accuracy of the location (and hence the shape and size) of the landslides depends on the size of the slope failures (Fig. 7c), with larger positional errors expected for small landslides than for large landslides. The positional errors affecting the small landslides may result in biases in the size of the small failures. This may affect the determination of accurate statistics of landslide areas, and particularly the definition of the most common size for the landslides in a study area i.e. the “rollover” size (Stark and Hovius, 2001; Guzzetti et al., 2002; Malamud et al., 2004; Stark and Guzzetti, 2009). On the other hand, statistics of the total (cumulated) landslide area and volume, being controlled by the few largest landslides in an inventory (Guzzetti et al., 2008), are not expected to be biased by the positioning errors inevitably present in the inventories, which our results suggest are reduced for very large landslides (Fig. 10).

Recently, Guzzetti et al. (2012) have pointed out that standards do not exist for the production of LIMs, and that the lack of accepted standards limits the credibility and usefulness of the landslide maps. The results of our work suggest that standards for transferring the information from the APs to a digital landslide map can (and should) be established. We argue that LIMs produced through API should be accompanied by adequate information (metadata) to explain clearly and unambiguously (among other things) how the landslide information was transferred from the APs to the GIS landslide database. For LIMs produced through a visual transfer of the information (e.g. our Map A) the power law dependency shown in Fig. 10 (or similar relationships) can be used to

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quantify (and show) the expected positional errors for the landslides shown in the inventory. For maps produced through a robust ortho-rectification procedure (e.g. our Map B), the total RMSE and plots of co-registration accuracy between the ortho-rectified APs and the reference base map (Fig. 5) should be provided.

6 Conclusions

Preparing accurate landslide inventory maps (LIMs) is crucial to modern landslide research. However, the production of accurate LIMs is time consuming, limiting the ability of investigators to cover large areas. Also, the production of LIMs remains a largely manual (craftsmanship) exercise. This introduces subjectivity and errors in the process, and increases the costs for the production of the LIMs.

We have experimented a new procedure for the semi-automatic mapping of landslides that uses robust ortho-rectification in a GIS environment to transfer accurately and efficiently landslide information drawn by an interpreter on the aerial photographs into a digital landslide database stored in the GIS. The new semi-automatic procedure reduces significantly the time and effort required to prepare a LIM, augmenting the interpreter's efficiency and productivity by a factor of ~ 2 . The semi-automatic procedure results in the production of more accurate LIMs, compared to landslide maps produced manually.

Systematic application of the new procedure in a 93 km² area in NE Sicily, Italy, revealed that a common metric used to evaluate the degree of matching (or mismatching) between two LIMs available for the same area (Carrara et al., 1992; Ardizzone et al., 2002) underestimates (severely, in places) the local mismatch between pairs of corresponding landslides in the two inventories. Our results further revealed a dependency of the positional error of a landslide on the size of the landslide, with small landslides characterized by significantly larger errors than the large and very large landslides. The finding has potential consequences for multiple applications of landslide studies.

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Finally, our results suggest that standards for transferring the information from the APs to a digital landslide map can (and should) be established, contributing to the definition of much needed standards for the production and use of landslide inventory maps (Guzzetti et al., 2012).

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Table 1. Comparison of descriptive statistics of landslide area for the landslide inventories obtained following the traditional manual procedure and the new semi-automatic procedure for transferring landslide information from the aerial photograph to the topographic base map. N_{LT} is the number and A_{LT} is the area of landslides mapped using the manual method (Map A). N_{LO} is the number, and A_{LO} is the area of landslides mapped using the semi-automatic method (orthorectification). L_N , number of landslides. A_{MIN} , A_{MAX} , A_{AVG} , A_{TOT} are minimum, maximum, average, and total landslide area.

Landslide type	L_N (#)		A_{MIN} (m ²)		A_{MAX} (m ²)		A_{AVG} (m ²)		A_{TOT} (m ²)	
	N_{LO}	N_{LT}	A_{LO}	A_{LT}	A_{LO}	A_{LT}	A_{LO}	A_{LT}	A_{LO}	A_{LT}
Slide	390	391	1.66×10^2	4.37×10^2	1.80×10^6	1.84×10^6	6.44×10^4	6.73×10^4	2.51×10^7	2.63×10^7
Earthflow	5	5	2.92×10^3	2.62×10^3	4.03×10^4	3.64×10^4	1.24×10^4	1.24×10^4	6.19×10^4	6.20×10^4
Slide-earthflow	47	48	1.86×10^3	2.87×10^3	7.26×10^5	2.15×10^5	5.52×10^4	5.56×10^4	2.59×10^6	2.67×10^6
Sackung	6	6	3.48×10^5	3.71×10^5	1.2×10^6	0.57×10^6	8.83×10^5	7.77×10^5	5.30×10^6	4.66×10^6
Rock-slide	1	1	7.12×10^4	7.61×10^4	7.12×10^4	7.61×10^4	7.13×10^4	7.61×10^4	7.13×10^4	7.61×10^4
Debris flow	23	24	9.19×10^2	8.09×10^2	8.26×10^5	8.63×10^5	9.55×10^4	9.19×10^4	2.19×10^6	2.21×10^6
Rockfall	10	10	2.49×10^3	3.54×10^3	1.42×10^5	1.53×10^5	3.64×10^4	3.78×10^4	3.64×10^5	3.78×10^5
Soil slide	–	1	–	2.84×10^3	–	2.84×10^3	–	2.84×10^3	–	2.84×10^3
All landslides	482	486	1.66×10^2	4.37×10^2	1.87×10^6	1.86×10^6	7.40×10^4	7.48×10^4	3.57×10^7	3.64×10^7

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Table 2. Comparison of scaling exponent (α) and rollover (size of the most abundant landslide) for the probability distribution functions computed for Map A (manual method) and Map B (semi-automatic method). Best fits computed through maximum likelihood estimation.

	$\alpha + 1$	rollover (m^2)
Map A	2.064	6397
Map B	2.020	5326

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Table 3. Comparison of the time necessary for the entire landslide mapping process (Fig. 2) using the different methods described in the text. Time is given in hours per one complete stereogram, per person. API, Aerial Photo Interpretation. A, visual analysis of the aerial photograph. B, mapping of the landslide information on the aerial photograph. C, visual, manual transfer of the landslide information. D, orthorectification. E, manual vectorization of the scanned landslide information. F, automatic vectorization of the landslide information. G, vector editing. H, geocoding and database editing.

		Time required for landslide mapping (h)							
		API		Transfer		Vectorization		Geo-coding	
		A	B	C	D	E	F	G	H
Time (h)	Min	0.5	2.5	2	0.5	1	0.5	0.5	2
	Max	1	7	10	1	5	1	1	7
		Total time required for the preparation of a landslide database in a GIS (h)							
		Transfer and Vectorization				Mapping			
		Manual		Semi-automatic		Manual		Semi-automatic	
		C + E		D + F		A + B + C + E + G + H		A + B + D + F + G + H	
Time (h)	Min	3		1		8.5		6.5	
	Max	15		2		31		18	

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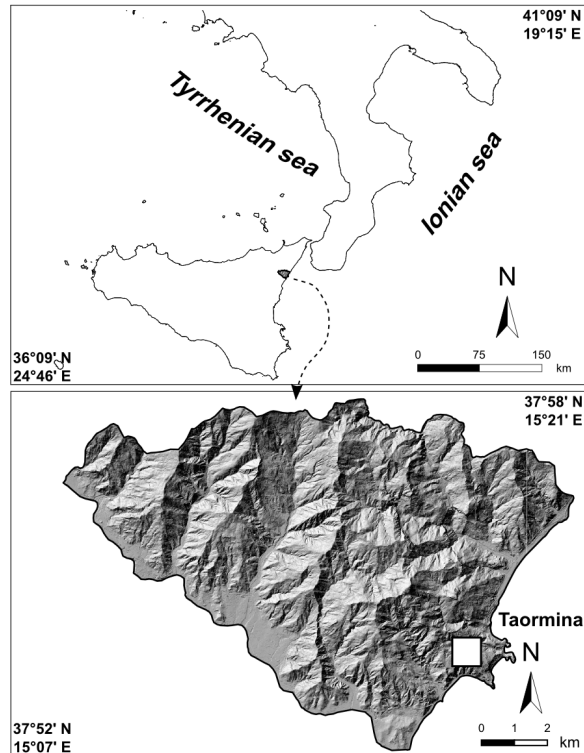


Figure 1. Location map of the study area. The shaded relief was produced from a 2m × 2m LiDAR derived DEM.

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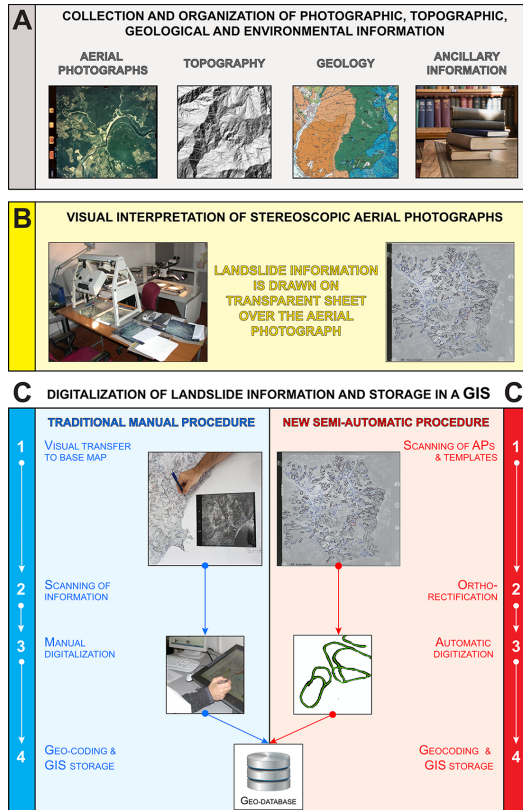


Figure 2. Description of the process of landslide mapping starting from the interpretation of the aerial photographs (API). **(a)** Information useful to the interpretation is collected and organized. **(b)** Aerial photographs are interpreted using a stereoscope. Thematic information is drawn on a transparent plastic sheet (template) placed over the photographs. **(c)** Information is digitalized and stored in a GIS. Blue side and connectors show four steps of the consolidated (traditional) manual procedure; red side and connectors show four steps of the new procedure.

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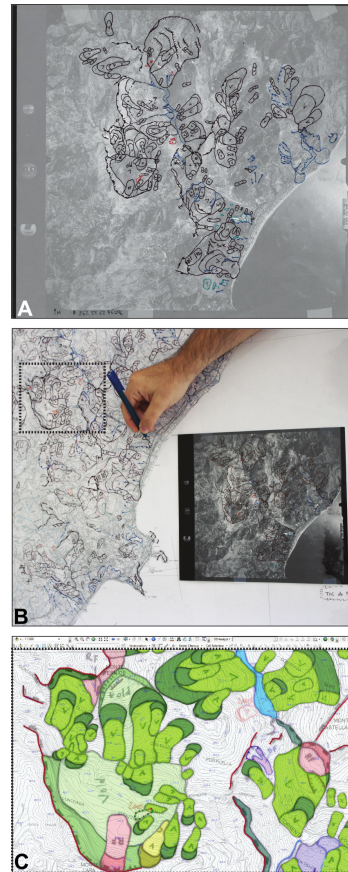


Figure 3. Main steps of the consolidated manual procedure: **(a)** photo-interpreted template, output of API. **(b)** Thematic information visually re-drawn on a transparent plastic sheet placed over a topographic base map. **(c)** Landslide information imported in the GIS, vectorized, and geo-coded.

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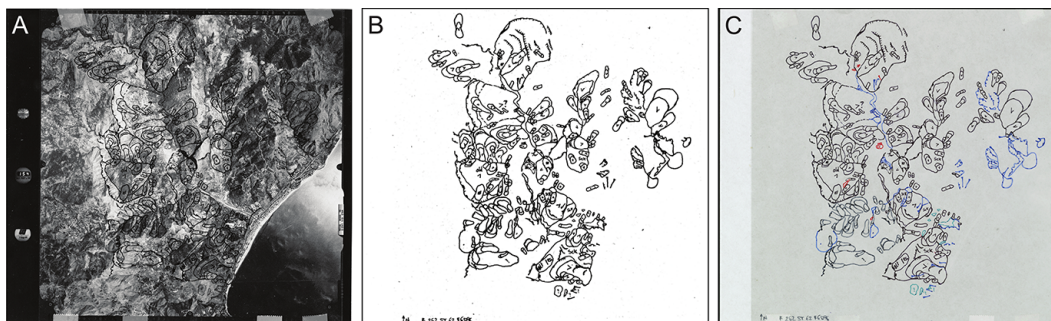


Figure 4. Input layers (scanned aerial photograph and template) required for the application of the orthorectification procedure. **(a)** 8 bit grey tone image of the aerial photograph and its interpreted template. **(b)** 1 bit b/w image of the interpreted template. **(c)** 24 bit colour image of the interpreted template.

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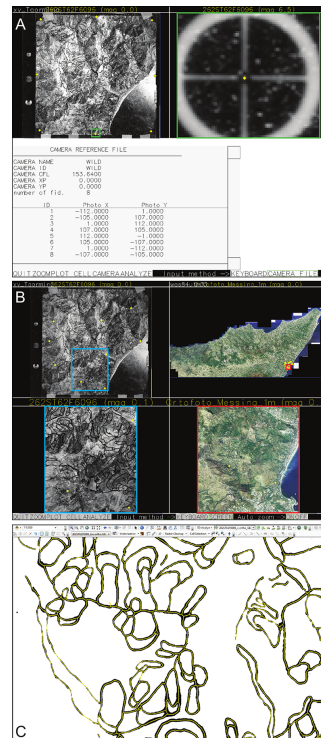


Figure 5. (a) Screenshot of the interior orientation window of the *i.ortho.photo* GRASS GIS tool. Left: input aerial photograph (Fig. 3a). Right: enlargement of a portion of the left image. Yellow diamonds are points chosen for the interior orientation. (b) Screenshot of the exterior orientation window of the *i.ortho.photo* GRASS GIS tool. Left: input aerial photograph (Fig. 3a). Right: reference ortho-photograph. Yellow diamonds are points chosen for the exterior orientation. (c) Screenshot of the automatic vectorization using ArcSCAN tool of ArcGIS 10.1. Black lines are raster-lines of the b/w orthorectified template. Green vector lines results from automatic vectorization.

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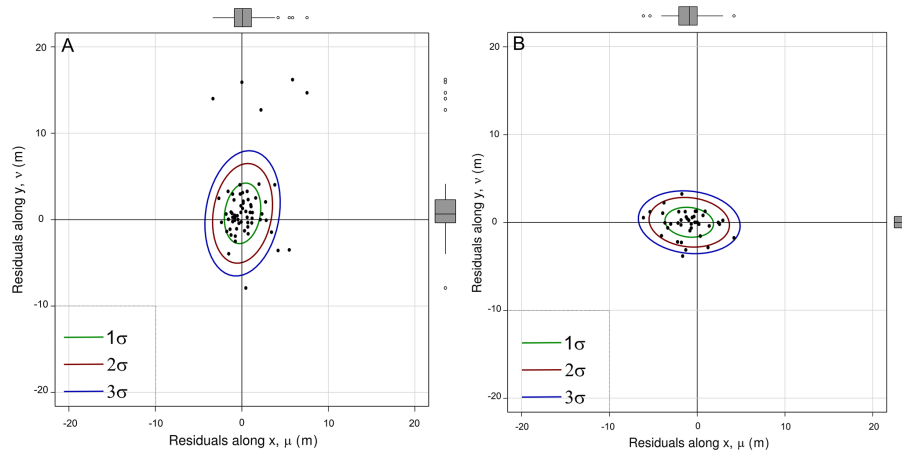


Figure 6. (a) Scatterplot of residuals along x (μ) and y (ν) for 63 GCPs (different from the GCPs used for the exterior orientation) achieved by orthorectification of the aerial photographs. 68 % (1σ , green ellipse) of μ - ν data points is respectively smaller than 1.9 and 3.8 m. 95 % (2σ , red ellipse) of μ - ν data points is smaller than 3.0 and 6.6 m, respectively. 99 % (3σ , blue ellipse) of μ - ν data points is smaller than 4.4 and 7.8 m, respectively. (b) Scatterplot of residuals along x (μ) and y (ν) showing the co-registration of the ortho-photograph used for the exterior orientation of the aerial photographs, and the contour line topographic base map used for the visual transfer (Fig. 3b). For both plots, on the right and upper side of the plots, the boxplots of the residuals are displayed. Data concentration ellipses of 1, 2, and 3σ are shown. All data concentration ellipses computed giving less weight to the outliers.

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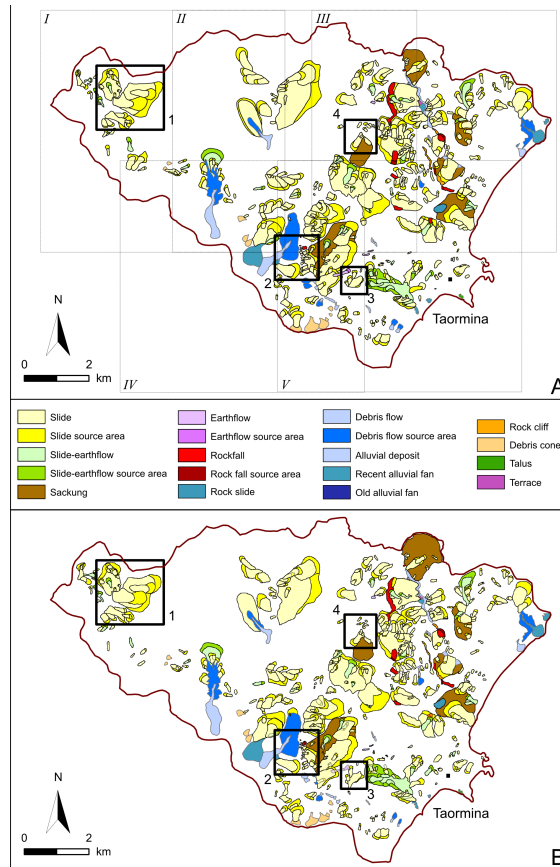


Figure 7. Landslide inventory maps (LIMs) obtained by **(a)** the consolidated manual procedure, and **(b)** the new semi-automatic procedure. Bold black boxes numbered from 1 to 4 indicate the four areas shown in Fig. 8, named from a to d. Thin line boxes with roman numbers indicate the areas covered by the five complete stereograms for which the API was carried out.

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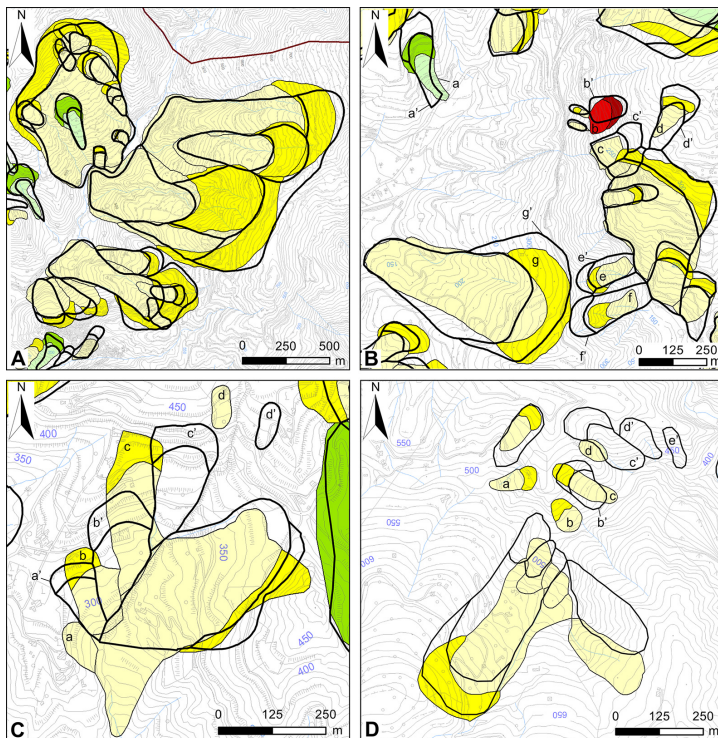


Figure 8. Visual comparison of the two inventory maps resulting by the two different procedures. Black lines are landslides mapped using the manual procedure, coloured polygons are landslides mapped using the semi-automatic procedure. The four images (bold black boxes in Fig. 7) show situations where: **(a)** mapping agreement is substantially acceptable, **(b)** positioning of the landslides is acceptable but not the size, **(c)** positioning of the landslide is not acceptable, and **(d)** mapping agreement is very poor, and commission and omission errors occur. Lower case letters refer to the corresponding landslides mapped using the semi-automatic and the manual (lower case letters with apex) procedure. See text for explanation.

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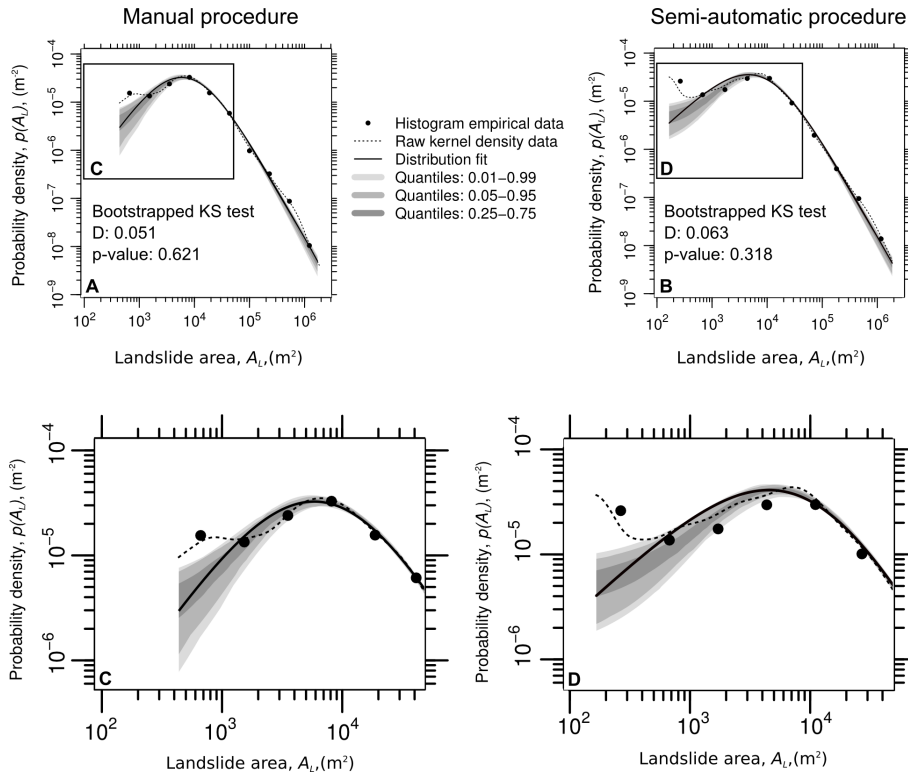


Figure 9. Comparison of the Inverse Gamma (Malamud et al., 2004) probability density function (pdf) computed for Map A and Map B. **(a)** Pdf of the inventory obtained by the manual method (Map A). **(b)** Pdf of the inventory obtained by the orthorectification method (Map B). **(c)** Enlargement of **(a)**, and **(d)** enlargement of **(b)** are provided for helping visual comparison of the two distributions.

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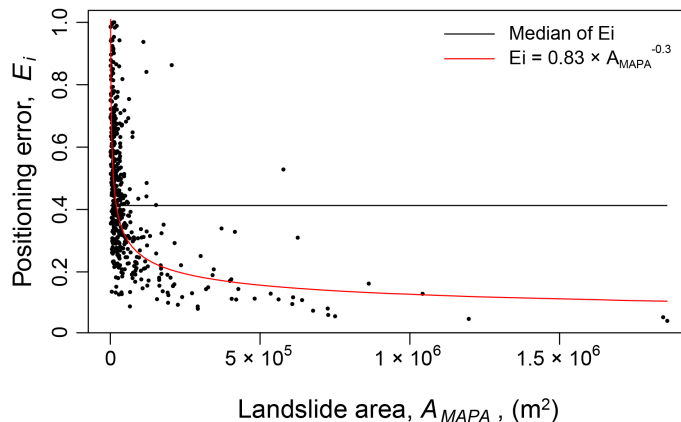


Figure 10. Scatterplot of positioning error index (E_i) against the landslide area mapped using the traditional procedure (A_{MAPA}). The plot shows a heavy tailed distribution of E_i that decays with increasing landslide area, following a power-law (red line). Both axes are in linear scale. The median value of E_i (0.41) is displayed by a black line.

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