Subj.: Re-submission of manuscript nhess-2017-111

Dear Paolo Tarolli,

This cover letter is to go with our electronic re-submission of the manuscript *Criteria for the optimal selection of remote sensing images to map event landslides* by Federica Fiorucci, Daniele Giordan, Michele Santangelo, Furio Dutto, Mauro Rossi, Fausto Guzzetti.

We are grateful to you and to the reviewer for their constructive comments that helped us to improve the work.

In preparing the new version of our work, we considered all the comments and suggestions made by the referee, which were pertinent and helpful.

To respond to the requests of both the reviewers we modified the Abstract, and all the other sections according to the reviewer requests.

We provide a list of our responses to the referee's comments, including details on the changes made to the text.

Overall, we consider this new version of the manuscript significantly improved. We hope the paper can be accepted for publication in the Special Issue: *The use of remotely piloted aircraft systems (RPAS) in monitoring applications and management of natural hazards*.

We look forward to hearing a decision from you soon.

Sincerely,
Federica Fiorucci, on behalf

Answares to Reviwer 3

The paper is an interesting contribution to the journal. However, it should be pointed out more carefully that it is a showcase of a technical application.

AC- We thank the reviewer for pointing out the value of the contribution to the journal. However, we disagree in considering it as a showcase of a technical application, since the experiment was designed to evaluate the impact of images characteristics on landslide mapping. For how the experiment was conceived and developed, the findings are general and applicable to all the cases similar to the setting of the experiment.

Overall, I only have few major points to highlight and some minor issues as they arose during the reading of the research.

1.The title speaks about criteria for the selection of images. However, the criteria are not well defined in the manuscript, and they are only slightly mentioned at the very end of the conclusions. If the point of the manuscript is indeed to present some criteria for selection, these criteria should appear more clearly (e.g. in a list? A well define paragraph?)

AC- In the paper, the criteria are well explained in **Table 3**, and commented in the Discussion section and resumed in the "Concluding remarks" section. The reason why they appear in the "Discussion" section, is that the criteria are a consequence of the results of the experiment. The text in the Discussion section extensively comments on the advantages and limitation of using the different types of images taken into account in the experiment for landslide mapping purposes. The section reads:

> "For event landslide mapping, selection between ultra-resolution pseudo-stereoscopic UAV images and very-high resolution stereoscopic satellite images depends on (i) the extent of the investigated area, (ii) the available resources, including time and budget, and (iii) the accessibility to the study area. The selection is largely independent from the landslide signature, at least for landslides similar to the Assignano landslide. From an operational perspective, modern multi-rotor UAVs allow for the acquisition of ultra-resolution images over small areas in a limited time, and at very low costs. UAV-based surveys are flexible in their acquisition planning, and partly independent from the local lighting conditions, including the cloud cover. As a drawback, UAVs are strongly (and negatively) affected by wind speed and weather conditions, they allow for a limited flight time (currently approximately 20 minutes in optimal conditions), which is reduced in bad weather conditions and in cold environments, and typically have limited data storage capacity. Further, it must be possible for the pilot to be at the same time near to the area to be surveyed and to maintain a safe distance from the UAV, a condition that may be difficult to attain in remote or in mountain areas. Collectively, the intrinsic advantages and limitations of modern UAVs make the technology potentially well suited for the acquisition of ultra-resolution images for event, seasonal, and multi-temporal mapping of single landslides, of multiple landslides in a single slope, or in a relatively small area (a few hectares). The use of UAV images was recently proposed by Turner et al. (2015) for determining the landslide dynamics, exploiting time series of images that can be constructed using UAVs. The result is achievable thanks to centimetre co-registration accuracy of the UAV images. Use of UAVs becomes impracticable with the increasing extent of the study area, largely due to (i) the operational difficulty of flying UAVs over large areas (more than a few square kilometres), and (ii) the acquisition and image processing time and associated cost, which increase rapidly with the size of the study area (Table 3). On the other hand, very-high resolution, stereoscopic satellite images have also advantages and limitations for the production of event, seasonal and multi-temporal landslide inventory maps (Guzzetti et al., 2012). The main advantage of the satellite images is that they cover large or very large areas (tens to hundreds of square kilometres) in a single frame with a sub-metre resolution well suited for landslide mapping through the expert visual

interpretation of the images (Ardizzone et al., 2013). On the other hand, limitations remain due to distortions caused by different off-nadir angles in successive scenes, and to difficulties – in places severe – to obtaining suitable (e.g., cloud-free) images at the required time intervals. This is particularly problematic for the production of seasonal and multi-temporal landslide maps. Information on the photographic or morphological signature of the typical, or most abundant, landslides in an area, is important to selecting the optimal characteristics of the images best suited for the production of an event, seasonal or multi-temporal landslide inventory map. Use of images of non-optimal characteristics for a typical landslide signature in an area may condition the quality (completeness, positional and thematic accuracy) of the landslide inventory. Where possible, we recommend that the acquisition of images used for the production of event, seasonal or multi-temporal landslide inventory maps is planned considering the typical landslide signature, in addition to the purpose (event inventory, planning of monitoring systems), scale of the mapping (regional or slope scale), and the size and complexity of the study area (Table 3)."

Moreover, for more clarity we added a text at the end of the "Introduction "section that reads:

"Arguably, the combination of images characteristics, the prevalent landslide signature, the size of the study area, and the available resources define the criteria for the optimal selection of remote sensing images for landslide mapping."

2. English needs polishing and revision. Many times the authors overuse 'i.e.' or they use sentences in a 'personal' approach ("we did this", "we highlight that", rather than describing what the research indicates), and many sentences are very long and hard to follow.

AC- We thank this Reviewer (R3) for this comment. Most of the 'i.e' were removed, and most of the sentences with a personal approach were converted in an impersonal form. We also revised the text, removing and simplifying the very long sentences.

3. The work does not compare eight maps. It compares seven maps. The dGPS survey is the benchmark (or ground truth), so it is misleading to include it in the list.

AC-Thank you for the suggestion.

The text was modified accordingly.

4. One of the main findings of this work is that a photographic landslide signature is best mapped with higher resolution images, while morphometric signatures are better identified with stereoscopic images. However, the reader does not know what photographic signatures VS morphometric ones are (this is never described in the manuscript).

AC- We thank the Reviewer for this comment. We described more clearly what morphological and photographical signature are in the following sentences (which give also credits of other works in the literature):

In the "Introduction" section we state:

"Heuristic visual mapping of landslide features is based on the systematic analysis of photographic characteristics such as colour, tone, mottling, texture, shape, and morphological characteristics such as size, curvature, concavity and convexity (Pike, 1988). The mentioned photographic and morphological characteristics encompass all the possible landslide features that can be used for the (visual) image interpretation.."

In the "Study area" section, we state:

"The landslide signature (Pike, 1988) is different in the different parts of the landslide. In the source and transportation area the signature is predominantly photographical (radiometric), whereas in the landslide deposit it is mainly morphological (topographic). The photographic signature consists in all the landslide features that can be detected by the analysis of the photographical characteristics of a given image: colour, tone, pattern and mottling of a given image (Guzzetti et al., 2012). The morphological signature consists in all the landslide features that can be detected by the analysis of the topography, therefore, features such as curvatures, shape, slope, concavity and convexity are always taken into account (Guzzetti et al., 2012). The differences within the landslide allowed to separate the source and transportation area from the deposition area."

5. The discussion chapter can be shortened and reorganised; much of it is a repetition of the previous chapter, while the reader would expect to find here some additional considerations about the meaning of the results.

AC- As suggested by the reviewer, we shortened the discussion section, removing most of the first paragraph. Moreover, to increase the readability of the paragraph, all the values between brackets related to the Error value (a repetition of the results) were removed. Admittedly, we disagree for what concerns the considerations on the meaning of the results, which are quite extensively described in the text.

Minor comments

Abstract

The abstract needs rewording. It should be more research-oriented, and less of a description of the team effort. E.g. first sentence 'we executed....' Could be rephrased to 'this paper presents...'

The work, furthermore, does not compare eight maps, but rather seven different maps as compared to a reference dGPS survey. The so called '8th map', being the ground-truth, is not part of the considered dataset, but it is the benchmark used to compare all the others.

AC-Thanks to R3 for the suggestion. We reorganized the abstract removing most of the personal form sentences.

Lines 19 to 24 report a very long sentence, that needs rephrasing. E.g. "Six maps were obtained through expert knowledge by visual interpretation of images from different sources taken on April 14, 2014. The dataset comprised monoscopic and pseudo-stereoscopic (2.5D) ultra-resolution (0.3 × 0.3 m) images derived using a Canon EOS M photographic camera mounted on a CarbonCore 950 hexacopter, and monoscopic and stereoscopic true-colour and false-colour- composite images (1.84 × 1.84 m resolution) taken by the WorldView-2 satellite."

AC- In the present version of the abstract this sentence has been removed.

Introduction

Line 48 > 'to support' should be changed to 'supporting the installation of...'

AC-We thank R3 for this suggestion. We corrected the text accordingly.

Line 52 to 58 > "...through field surveys (Santangelo et al., 2010) or the heuristic visual interpretation of monoscopic or stereoscopic aerial or satellite images (Brardinoni et al., 2003; Fiorucci et al., 2011; Ardizzone et al., 2013), of LiDAR-derived images (Ardizzone et al., 2007; Van Den Eeckhaut et al., 2007; Haneberg et al., 2009; Giordan et al., 2013; Razak et al., 2013; Niculita et al., 2016, Petschko et al., 2016), or of ultra-resolution images acquired by Unmanned Aerial Vehicles (UAV, Niethammer et al., 2010, Giordan et al., 2015a, 2015b; Torrero et al., 2015, Turner et al., 2015).

AC-Sincerely, we don't' understand the comment. It seems there is no request/observation.

Line 59 > of the mentioned parameters, which are photographic characteristics, and which ones are morphological? Please explain, also considering that one of the main findings of this work is that a photographic landslide signature is best mapped with higher resolution images, while morphometric signatures are better identified with stereoscopic images.

AC-Correct. We split the sentence in two sentences to clarify what photographical and morphological signatures are. The sentence now reads:

> "The heuristic visual mapping of landslide features is based on the systematic analysis of image photographic characteristics such as colour, tone, mottling, texture, shape, and morphological characteristics such as size and curvature, concavity and convexity (Pike, 1988). These photographic and morphological characteristics encompass all the possible landslide features that can be used for the (visual) interpretation of the available imagery."

Line 66 > maps prepared to exploit one or more of the mentioned techniques are inevitability incomplete. Is that true? Shouldn't we affirm that they "can be" incomplete, rather than making such a strong statement?

AC- We are aware that this statement is strong. But we underline that this is a logical consequence of the consideration that any technique or images have intrinsic limitation. If this is true, this means that these images will be somewhat "blind" for some landslides (e.g., due to the size, type, surrounding land cover), for example due to the spatial or spectral resolution, or lack of three-dimensional information. Nevertheless, we understand that such a strong clause could be better explained and supported in the text. Now, the text quoted by the Reviewer reads:

> "All these mapping techniques have inherent advantages and intrinsic limitations, which depend on the characteristics of the images, including their spatial and spectral resolutions (Fiorucci et al., 2011). The limitations affect differently the mapping, based on the size and type of the investigated landslides. As a result, images from single sources or the single mapping techniques are "blind" to some landslides, which inevitably results in incomplete landslide inventory maps. Furthermore, maps also can contain errors in terms of the position, size and shape of the mapped landslides (Guzzetti et al., 2000; Galli et al., 2008, Santangelo et al., 2015a)."

Line 76 > 'images of different types' > 'images from different sources'

AC- We thank R3 for this suggestion. We acknowledge the problem, and we changed the text.

Line 77 > as I mentioned in the abstract, technically you do not compare eight maps, but rather seven maps. The dGPS is the ground truth.

AC-We thank R3 for this suggestion. We corrected accordingly.

Line 80 > on board OF a UAV.

AC- We thank R3 for this suggestion. We corrected the error accordingly.

Study area

Line 96 > " and A third located…"

AC- We thank R3 for this suggestion. We corrected the error accordingly.

Image acquisition

What software has been used for the SFM technique?

AC- the software used is Agisoft Photoscan. We added this specification in the text.

Line 124: "i.e. the same day…" does not make sense. The same day is not an example, thus, i.e. is not needed

AC- We thank R3 for this suggestion. We removed i.e. from the sentence.

Landslide mapping

Again, you do not compare eight maps. You compare seven maps and use one survey as a benchmark.

Line 147: i.e. is overused. 'who carried out the field activities (the reconnaissance field mapping and the RTK-DGPS survey) were not involved…"

AC- We thank R3 for this suggestion. We removed i.e. from the sentence.

Field mapping

Line 173 again overuse of 'i.e.' > the figure is not an example

AC- We thank R3 for this suggestion. We removed i.e. from the sentence.

Mapping through images

Line 201 again overuse o f i.e. > the TC and FCC images are not an example of the images used. They are indeed the images used.

AC- We thank R3 for this suggestion. We removed i.e. from the sentence.

Why the need of d raping the UAV image to google earth? The survey itself allows for the creation of a DSM, why using further sources (google) to interpret the images?

AC- The reason why the ultra-high resolution UAV image was draped on Google earth is technological and is explained in the following sentence of section 4.2.:

> "To interpret visually the ultra-resolution UAV image, the interpreter overlaid ("draped") the image on Google Earth™. For the purpose, we first treated the UAV image with the gdal2tiles.py software to obtain a set of image tiles compatible with Google Earth™ terrain visualization platform. To the best of our knowledge, the platform is the only free 2.5D image visualisation environment that allows the editing of vector (point, line, polygon) information. Other commercial (e.g., ArcScene) and open source (e.g., ParaView, GRASS GIS), 2.5D visualization tools do not provide editing capabilities. Google Earth™ is a user-friendly solution for mapping single landslides, and for preparing landslide event inventories for limited areas, with the possibility for the user to visualize a landscape from virtually any viewpoint, facilitating landslide mapping. We refer to the representation of the Assignano landslide obtained through the visual interpretation of the ultra-resolution UAV image as "Map H".

Results.

Lines 23 5-238: I disagree. Visually, Fig. 5F is not that different from 5G or H: F underestimates the lower part of the landslide and misses some features in the top part. I would say that visually the most similar is 5E.

AC- We agree that the most similar is the map E as evident also from the value of the error index (fig--). The text was changed accordingly.

Discussion

Lines 318 t o 332 are not needed: they are a summary of what has already been said before. I think the whole chapter until line 397 can be shortened because much of it is a repetition o f the previous one.

AC- We thank R3 for this suggestion. The suggestion was accepted and the text modified accordingly.

The authors should focus more on either explaining the numbers or discussing them in general as compared to other works or examples.

AC- We thank R3 for this suggestion. However, as stated in the introduction, the literature is rather poor in providing examples of similar studies to be compared to the present work. We cited all the papers in our knowledge:

> “Our results are similar to the results of tests performed to compare field-based landslide maps against GPS-based surveys of single landslides (Santangelo et al., 2010), the visual interpretation of very-high resolution stereoscopic satellite images (Ardizzone et al., 2013), or the semi-automatic processing of monoscopic satellite images (Mondini et al., 2013), and confirm the inherent difficulty in preparing accurate landslide maps in the field, unless the mapping is supported by a GPS survey or a similar technology.”

Concluding remarks

Lines 457-468 are not needed. All of this has already been explained throughout the manuscript.

AC- We thank R3 for this suggestion. We removed most of the text as suggested by the reviewer.

Line 465-47 should also be mentioned in the study area description, explaining what photographi c and morphological signatures are.

AC-We corrected the text according to the suggestion.

There is no need to explain the results as a list (First….second…third), unless the authors make a short bullet point list of the main findings, and then further discuss them.

AC-We agree, we removed the list.

Line 512 and following. This whole part can be rephrase d without using the personal point of view (e.g. We maintain, We emphasise…’ You can simply state that ‘ although the study was conducted on a single landslide, the findings are general and…

AC-We corrected the text according to the suggestion.

[…]. The technique and imagery used to prepare landslide inventory maps should be selected depending on…”

AC- We corrected the text according to the suggestion.

Criteria for the optimal selection of remote sensing optical images to map event landslides

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Abstract

Landslides leave discernible signs on the land surface, most of which can be captured in remote sensing images. Trained geomorphologists analyse remote sensing images and map landslides through heuristic interpretation of photographic and morphological characteristics. Despite a wide use of remote sensing images for landslide mapping, no attempt to evaluate how the images characteristics influence landslide identification and mapping exists. This paper presents an experiment to determine the effects of optical image characteristics, such as spatial resolution, spectral content and image type (monoscopic or stereoscopic), on landslide mapping. We considered eight maps of the same landslide in Central Italy: (i) six maps obtained through expert heuristic visual interpretation of remote sensing images, (ii) one map through a reconnaissance field survey, and (iii) one map obtained through a Real Time Kinematic (RTK) differential Global Positioning System (dGPS) survey, which served as a benchmark. The eight maps were compared pairwise and to a benchmark. The mismatch between each maps pair was quantified by the error index, *E*. Results show that the map closest to the benchmark delineation of the landslide was obtained using the higher resolution image, where the landslide signature was primarily photographical (in the landslide source and transport area). Conversely, where the landslide signature was mainly morphological (in the landslide deposit) the best mapping result was obtained using the stereoscopic images. Albeit conducted on a single landslide, the experiment results are general, and provide useful information to decide on the optimal imagery for the production of event, seasonal and multi-temporal landslide inventory maps~~We executed an experiment to determine the effects of optical image characteristics on event landslide mapping. In the experiment, we compared eight maps of the same landslide, the Assignano landslide, in Umbria, Central Italy. Six maps were obtained through the expert visual interpretation of monoscopic and pseudo-stereoscopic (2.5D), ultra-resolution (3 × 3 cm) images taken on 14 April 2014 by a Canon EOS M photographic camera flown by an CarbonCore 950 hexacopter over the landslide, and of monoscopic and stereoscopic, true-colour and false-colour composite, 1.84 × 1.84 m resolution images taken by the WorldView-2 satellite also on 14 April 2014. The seventh map was prepared through a reconnaissance field survey aided by a pre-event satellite image taken on 8 July 2013, available on Google Earth™, and by colour photographs taken in the field with a hand-held camera. The images were interpreted visually by an expert geomorphologist using the StereoMirror™ hardware technology combined with the ERDAS IMAGINE® and Leica Photogrammetry Suite~~

~~(LPS) software. The eighth map, which we considered our reference showing the "ground truth", was obtained through a Real Time Kinematic Differential Global Positioning System (GPS) survey conducted by walking a GPS receiver along the landslide perimeter to capture geographic coordinates every about 5 m, with centimetre accuracy. The eight maps of the Assignano landslide were stored in a Geographic Information System (GIS), and compared adopting a pairwise approach. Results of the comparisons, quantified by the error index *E*, revealed that where the landslide signature was primarily photographical (in the landslide source and transport area) the best mapping results were obtained using the higher resolution images, and where the landslide signature was mainly morphometric (in the landslide deposit) the best results were obtained using the stereoscopic images. The ultra-resolution image proved very effective to map the landslide, with results comparable to those obtained using the stereoscopic satellite image. Conversely, the field-based reconnaissance mapping provided the poorest results, measured by large mapping errors, and confirmed the difficulty in preparing accurate landslide maps in the field. Albeit conducted on a single landslide, we maintain that our results are general, and provide useful information to decide on the optimal imagery for the production of event, seasonal and multi-temporal landslide inventory maps~~.

1 Introduction

Accurate detection of ~~single~~ individual landslides has different scopes, including landslide mapping (Di Maio and Vassallo, 2011; Manconi et al., 2014; Plank et al., 2016), landslide hazard analysis and risk assessment (Allasia et al., 2013), to ~~to support the installation~~support the installation of landslide monitoring systems (Tarchi et al., 2003; Teza et al., 2007; Monserrat and Crosetto, 2008; Giordan et al., 2013), and for landslide geotechnical characterization and modelling (Gokceoglu, 2005; Rosi et al., 2013). Mapping of ~~single~~ individual landslides can be executed using the same techniques and tools commonly used by geomorphologists to prepare landslide inventory maps~~ i.e.,~~. Such techniques and tools includes: a) ~~through~~ field survey~~s~~ (Santangelo et al., 2010)~~ or~~, b) ~~the~~ heuristic visual interpretation of monoscopic or stereoscopic aerial or satellite images (Brardinoni et al., 2003; Fiorucci et al., 2011; Ardizzone et al., 2013), c) ~~of~~ LiDAR-derived images (Ardizzone et al., 2007; Van Den Eeckhaut et al., 2007; Haneberg et al., 2009; Giordan et al., 2013; Razak et al., 2013; Niculita et al., 2016, Petschko et al., 2016), ~~or of~~d) ultra-resolution images acquired by Unmanned Aerial Vehicles (UAV, Niethammer et al., 2010, Giordan et al., 2015a, 2015b; Torrero et al., 2015, Turner et al., 2015). ~~The h~~Heuristic visual mapping of landslide features is based on the systematic analysis of ~~image~~ photographic ~~and morphological~~ characteristics such as colour, tone, mottling, texture, shape, and morphological characteristics such as size,~~, curvature~~ curvature, concavity and convexity (Pike, 1988). ~~These~~ The mentioned photographic and morphological characteristics encompass~~es~~ all the possible landslide features that can be used for the (visual) image interpretation~~ of the available imagery~~.

All these mapping techniques have inherent advantages and intrinsic limitations, which depend on the characteristics of the images, including their spatial and spectral resolutions (Fiorucci et al., 2011). The limitations affect differently the mapping, based on the size and type of the investigated landslides~~, and on the characteristics of the images, including their spatial and spectral resolutions (Fiorucci et al., 2011)~~. As a result, an ~~a~~ image~~s of~~ from a single sources or a ~~the~~ single mapping technique~~s~~ are "blind" to some landslides features~~,~~. This ~~which~~ inevitably results ~~landslide maps prepared exploiting one or more of the mentioned techniques are inevitably~~ in ~~i~~an incomplete landslide inventory maps~~ incomplete~~. Furthermore, maps ~~also~~ can ~~, and~~ contain errors in terms of the position, size and shape of the mapped landslides (Guzzetti et al., 2000; Galli et al., 2008, Santangelo et al., 2015a).

A few attempts ~~have been made~~exist to evaluate the errors associated to different types of landslide inventory maps (Carrara et al., 1992; Ardizzone et al., 2002, 2007; Van Den Eeckhaut et al., 2007; Fiorucci et al., 2011; Santangelo et al., 2010; Mondini et al., 2013). Most of the~~se attempts~~m compare ~~landslide~~ maps prepared using aerial or satellite images ~~to~~ to maps obtained~~maps obtained~~ through reconnaissance field mapping (Ardizzone et al., 2007; Fiorucci et al., 2011) or GPS surveys (Santangelo et al., 2010). Conversely, only a few authors have attempted to evaluate how ~~the influence of different types of imagery~~the characteristics of images acquired from different sources influence ~~on~~ landslide detection and mapping (Carrara et al., 1992).~~–~~

In this work, we evaluate how images of different types and characteristics influence event landslide mapping. We do ~~this~~ so by comparing ~~eight~~the ~~–~~maps ~~of a~~prepared for one~~ single,~~ rainfall-induced landslide ~~near the village of Assignano, Umbria, central Italy~~in a pairwise approach, including a benchmark map. The s~~S~~even maps ~~of the same landslide~~ were obtained using different techniques and images, including (i) a reconnaissance field survey, (ii) the interpretation of ultra-resolution images taken by an optical camera on-board of ~~an~~ a UAV, and (iii) the visual interpretation of Very High Resolution (VHR), monoscopic and stereoscopic, multispectral images taken by the WordView-2 satellite. These ~~maps were compared~~comparisons included ~~to~~ an eighth map, obtained through dGPS survey, considered as ~~to be~~ the benchmark showing the “ground truth” ~~i.e., the “true” position, shape and extent of the Assignano landslide~~. Based on the results of the ~~map~~ comparison, we infer the ability of different optical images, with different spectral and spatial characteristics and type (monoscopic or stereoscopic), to portray the landslide features that can be exploited for the visual detection and mapping of landslides. Arguably, the combination of images characteristics, the prevalent landslide signature, the size of the study area, and the available resources define the criteria for the optimal selection of remote sensing images for landslide mapping~~We maintain that the results obtained in our test case are general, and should be considered for the optimal selection of images for the detection and mapping event landslides~~.

Formattato: Barrato

2 The Assignano landslide

For our study, we selected the Assignano landslide, a slide-earthflow (Hutchinson, 1970) triggered by intense rainfall in December 2013 in the northwest-facing slope of the Assignano village, Umbria, central Italy (**Fig. 1**). The landslide ~~develops~~ developed in a crop area, where a layered sequence of sand, silt and clay deposits crop out (Santangelo et al., 2015b). The slope failure is about 340 m long, 40 m wide in the transportation area, and 60 m wide in the deposition area, and is characterized by three distinct source areas, two located on the south-western side of the landslide and a third located on the north-eastern side of the landslide. The source and transportation area has an overall length of about 230 m, and a width increasing from 10 to 40 m from the top of the source area to the bottom of the transportation area. Elevation in the landslide ranges from 276 m along the landslide crown, to 206 m at the lowest tip of the deposit. The source and transportation area is bounded locally by sub-vertical, 2 to 4-m high escarpments. In the landslide, terrain slope averages 11°, and is steeper (12°) in the source and transportation area than in the deposition area (9°). The landslide signature (Pike, 1988) is different in the different parts of the landslide. In the source and transportation area the signature is predominantly photographical (radiometric), whereas in the landslide deposit it is mainly ~~morphometric~~ morphological (topographic). The photographic signature consists in all the landslide features that can be detected by the analysis of the photographical characteristics of a given image: colour, tone, pattern and mottling of a given image (Guzzetti et al., 2012). The morphological signature consists in all the landslide features that can be detected by the analysis of the topography, therefore, features such as curvatures, shape, slope, concavity and ~~The~~convexity are always taken into account (Guzzetti et al., 2012). The differences within the landslide allowed to separate the source and transportation area from the deposition area. ~~differences allow to separate the source and transportation area from the deposition area.~~

Formattato: Citation, Italiano (Italia)

Formattato: Citation, Inglese (Regno Unito)

3 Image acquisition

On 14 April 2014, we conducted an aerial survey of the Assignano landslide using a “X” shaped frame octocopter with eight motors mounted on four arms (four sets of CW and CCW props) with a payload capacity of around one kilogram, and a flight autonomy of about 20 minutes. The UAV was equipped with a remotely controlled gimbal hosting a ©GoPro Hero 3 video camera and a Canon EOS M camera. We controlled the flight of the UAV manually, relaying on the real-time video stream provided by the ©GoPro. ~~We kept t~~The operational flight altitude of the UAV was kept in the range between 70 and 100 m above the ground. This allowed the Canon EOS M camera to capture 97 digital colour images of the landslide area with a ground resolution of about 2-4 cm, with the single images having an overlap of about 70% and a side-lap of about 40%. For the accurate geocoding of the images, ~~we positioned~~ 13 red-and-white, four-quadrants square targets, 20 cm × 20 cm in size were positioned~~,~~ outside and inside the landslide. ~~We obtained t~~The geographical location (latitude, longitude, elevation) of the 13 target centres was obtained using a Real Time Kinematic (RTK) Differential Global Positioning System (~~DGPS~~dGPS), ~~,~~ with a horizontal error of less than 3 cm. ~~We processed t~~The 97 images were processed using commercial, structure-from-motion software (Agisoft Photoscan©) to obtain (i) a 3D point cloud, (ii) a Digital Surface Model (DSM), and (iii) a digital, monoscopic, ultra-resolution (ground sampling distance is 3 × 3 cm) ortho-rectified image in the visible spectral range, which we used for the visual mapping of the Assignano landslide (**Table 1**).

To map the landslide, ~~we also used a~~ a stereoscopic pair of WorldView-2 satellite~~VHR images taken on 14 April 2014 i.e., the same day of the UAV survey, by the WorldView-2 satellite that operates at an altitude of 496 km,~~ was used. ~~and collects~~The satellite stereo pair was taken on 14 April 2014 (the same day of the UAV survey). It has a spatial resolution of 46-cm in panchromatic, and 1.84-m in ~~eight-band,~~ multispectral~~,~~, with ~~(coastal blue, blue, green, yellow, red, red edge, and near infrared 1, near infrared 2) imagery at~~ a 11-bit dynamic range~~, in the spectral range 0.400 – 1.040 μm~~. For the satellite imagery, the rational polynomial coefficients (RPCs) ~~are~~ were available, allowing for accurate photogrammetric processing of the images. ~~We used t~~The RPCs were used to generate 3D models of the terrain from the stereoscopic image pair. Exploiting the characteristics of the satellite image, ~~we prepared~~ four separate images for landslide mapping were prepared, namely, (i) a monoscopic, "true colour" (TC) image, (ii) a monoscopic false-colour-composite (FCC) image obtained from the composite near infrared, red and green (band 4,3,2), (iii) a TC stereoscopic pair, and (iv) a FCC stereoscopic pair. ~~We prepared~~ A total of four ~~separate~~ maps of the Assignano landslide were prepared through the visual interpretation of the four images (**Table 1**). Both satellite and UAV images are free from deep shadows (**Fig. 2**).

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To compare the images obtained by the UAV and the WorldView-2 satellite, we co-registered the images, and ~~we~~ evaluated the co-registration on seven control points (**Fig. 3**), obtaining a Distance Root Mean Square error, DRMS = 0.53 m, and a Circular Error Probability, $CEP_{50\%}$ = 0.42 m, which ~~we~~ was considered adequate for landslide mapping, and for the maps comparison.

4 Landslide mapping

We prepared eight maps of the Assignano landslide using different approaches, images and datasets, including two maps prepared through field surveys, four maps prepared through the visual interpretation of monoscopic and stereoscopic satellite images, and two maps prepared through the visual interpretation of the orthorectified images taken by the UAV (**Table 1**).

The field mapping and the image interpretation were carried out by independent geomorphologists. The two geomorphologists who carried out the field activities ~~(i.e., ~~the reconnaissance field mapping and the RTK-~~DGPS~~dGPS survey)~~,~~ were not involved in the visual interpretation of the satellite and the UAV images. Equally, the geomorphologist who interpreted visually the satellite and the UAV images did not take part in the field activities. Visual interpretation of the remotely-sensed images was performed by a single geomorphologist to avoid problems related to different interpretation skills by different interpreters (Carrara et al., 1992). ~~We then compared t~~The eight ~~resulting~~ maps of the Assignano landslide were then compared adopting a pairwise approach to quantify and evaluate the mapping differences.

The geomorphologist who interpreted visually the images was shown first the 1.84-m resolution, monoscopic satellite image, next the 1.84-m resolution stereoscopic satellite pair, and lastly the 3-cm resolution UAV images. The monoscopic and the stereoscopic satellite images were first shown in TC and then in FCC. Lastly, the interpreter was shown the draped ultra-resolution UAV image. Selection of the sequence of the images given to the geomorphologist for the expert driven visual interpretation was based on the assumption that for landslide mapping (i) the ultra-resolution monoscopic images provide more information than the 1.84-m monoscopic or stereoscopic images, (ii) for equal spatial resolution images, stereoscopic images provide more information than monoscopic images, and (iii) for equal image type (monoscopic, stereoscopic), the FCC images provide more information than the TC images. To prevent biases related to a possible previous knowledge of the landslide, the interpreter was not shown the results of the reconnaissance field mapping.

4.1 Field mapping

Field mapping of the Assignano landslide consisted in two synergic activities, (i) a reconnaissance field survey, and (ii) a RTK ~~DGPS~~ dGPS aided survey. First, the reconnaissance field survey was conducted by two geomorphologists (FF and MR) who observed the landslide and took photographs of the slope failure from multiple viewpoints, close to and far from the landslide. The geomorphologists ~~draw~~ drew in the field a preliminary map of the landslide exploiting the most recent satellite image available at the time in Google Earth™, which was a pre-event image taken on 8 July 2013 ~~i.e.~~ (**Fig. 4**~~), before the landslide occurred~~). The reconnaissance field mapping was then refined in the laboratory using the ground photographs taken in the field. We refer to this reconnaissance representation of the Assignano landslide as "Map B".

Next, the same two geomorphologists (FF and MR) conducted an RTK ~~DGPS~~ dGPS aided survey walking a Leica Geosystems GPS 1200 receiver along the landslide boundary, capturing 3D geographic coordinates every about 5 m, in 3D distance. For the purpose, ~~we used t~~the SmartNet ItalPoS real-time network service was used to transmit the correction signal from the GPS base station to the GPS roving station. The estimated accuracy obtained for each survey point measured along the landslide boundary was 2 to 5 cm, measured by the root mean square error (RMSE), on the ETRF-2000 reference system. ~~We refer to t~~The cartographic representation of the Assignano landslide produced by the RTK ~~DGPS~~dGPS survey is referred to as "Map A", and is ~~. We~~ considered~~ this map~~ as the ~~"ground truth", and we use it as a~~ benchmark against which to compare the other maps. ~~We acknowledge that m~~Mapping a landslide by walking a GPS receiver around its boundary is an error prone operation e.g., because in places the landslide boundary is not sharp, or clearly visible from the ground (Santangelo et al., 2010). ~~However~~Nevertheless,~~,~~ ~~we maintain~~ this is the most reasonable working assumption (Santangelo et al., 2010). Furthermore, ~~, and that~~ the geometrical information obtained by walking a GPS receiver along the landslide boundary was superior to the information obtained through the reconnaissance field mapping (Map B) ~~(Santangelo et al., 2010)~~.

4.2 Mapping through image interpretation

A trained geomorphologist (MS) used the three monoscopic images (~~i.e.,~~ the TC and FCC monoscopic satellite images, and the monoscopic ultra-resolution UAV image) to perform a heuristic, visual mapping of the Assignano landslide. For this purpose, the interpreter considered the photographic (colour, tone, mottling, texture) and ~~geometrical~~ geometric (shape, size, ~~curvature,~~ pattern of individual terrain features, or sets of features) characteristics of the images (Antonini et al., 1999). In this way, the geomorphologist prepared (i) "Map C" interpreting visually the monoscopic~~,~~ TC satellite image, (ii) "Map D" interpreting visually the monoscopic~~,~~ FFC satellite image, and (iii) "Map G" interpreting visually the monoscopic~~,~~ TC UAV image (**Table 1**).

Next, the interpreter used the two stereoscopic satellite images (~~i.e.,~~ the TC and FCC images) to prepare “Map E” and “Map F” (**Table 1**). In the stereoscopic images, the photographic and morphological information is combined, favouring the recognition of the landslide features through the joint analysis of photographic (colour, tone, mottling, texture), geometrical (shape, size, pattern of features), and morphological terrain features (curvature, convexity, concavity). To analyse visually the stereoscopic satellite images, the interpreter used the StereoMirror™ hardware technology, combined with the ERDAS IMAGINE® and Leica Photogrammetry Suite (LPS) software. To map the landslide features in real-world, 3D geographical coordinates, the interpreter used a 3D floating cursor (Fiorucci et al., 2015).

~~To interpret the ultra-resolution UAV image, the interpreter overlaid (“draped”) the image on Google Earth™. For the purpose, we first treated the UAV image with gdal2tiles.py software to obtain a set of image tiles compatible with the Google Earth™ terrain visualization platform.~~ To interpret visually the ultra-resolution UAV image, the interpreter overlaid (“draped”) the image on Google Earth™. For the purpose, we first treated the UAV image with the gdal2tiles.py software to obtain a set of image tiles compatible with Google Earth™ terrain visualization platform. To the best of our knowledge, the platform is the only free~~,~~ 2.5D image visualisation environment that allows the editing of vector (~~i.e.,~~ point, line, polygon) information. Other commercial (e.g., ArcScene) and open source (e.g., ParaView, GRASS GIS), 2.5D visualization tools do not provide editing capabilities. Google Earth™ is a user-friendly solution for mapping single landslides, and for preparing landslide event inventories for limited areas, with the possibility for the user to visualize a landscape from virtually any viewpoint, facilitating landslide mapping. ~~We refer to t~~The representation of the ~~Assignano~~ landslide obtained through the visual interpretation of the ultra-resolution UAV image is referred to as “Map H”.

For the visual interpretation of the satellite and the UAV images, the interpreter adopted a visualization scale in the range from 1:1000 to 1:6000, depending on the image spatial resolution (**Table 1**). The scale of observation was selected to obtain the best readability of each landslide feature and the surroundings~~, which is a common practice in image visual analysis for landslide mapping (Fiorucci et al., 2011)~~. ~~Hence, e~~Despite ~~ven if~~ the maps were produced at slightly different observation scales, the differences arising from the comparison are due to actual features (e.g.~~i.e.~~, the image resolution and radiometry), and not to the different observation scales.

5 Results

Using the described mapping methods, and the available satellite and UAV images (**Table 1**), we prepared eight separate and independent cartographic representations of the Assignano landslide, shown in **Fig. 5** as Map A to Map H.

Considering the entire landslide, visual inspection of **Fig. 5** reveals that the map~~s~~ most similar to the benchmark (Map A) ~~are~~ is Map E, prepared examining the true colour (TC) stereoscopic satellite image~~,~~. ~~and Map F, prepared examining the false colour composite (FCC) stereoscopic satellite image.~~ Conversely, the largest differences were observed for the landslide maps obtained through the reconnaissance field survey (Map B), and the visual interpretation of the monoscopic satellite images (Map C and Map D). Considering only the source and transportation areas (dark colours in **Fig. 5**), interpretation of the UAV ultra-resolution images resulted in the landslide maps most similar (Map G and Map H) to the benchmark (Map A). It is worth noticing the systematic lack in the mapping of one of the two secondary landslide source areas located in the SW side of the landslide, which was recognized only from the visual inspection of the ultra-resolution orthorectified images taken by the UAV. In the field, this secondary source area was characterized by small cracks along the escarpment and a limited disruption of the meadow, making it particularly difficult to be detected and mapped. We argue that only the ultra-resolution images allowed for the detection of the cracks. Considering only the landslide deposit (light colours in **Fig. 5**), the landslide mapping that was more similar to the benchmark (Map A) was obtained interpreting the TC, stereoscopic satellite images (Map E). We also note that in most of the maps the landslide deposit was mapped larger (Map G, Map H) or much larger (Map B, Map C and Map D) than the benchmark (Map A).

Table 2 lists geometric measures of the mapped landslides, including the planimetric measurement of length, width and area (i) of the entire landslide, (ii) of the landslide source and transportation area (dark colours in **Fig. 5**), and (iii) of the landslide deposit (light colours in **Fig. 5**). The length and width measurements were obtained in a GIS as the length and the width of the minimum oriented rectangle encompassing (i) the entire landslide, (ii) the landslide source and transportation area, and (iii) the landslide deposit. Our benchmark (Map A) has a total area $A_L = 1.1\times10^4$ m^2, and is L_{LS} = 362 m long and W_{LS} = 71 m wide. Amongst the other seven maps (Map B to Map H in **Fig. 5**), the largest landslide is shown in Map B, obtained through the reconnaissance field mapping, and has $A_L = 1.91\times10^4$ m^2, 71.1% larger than the benchmark. Conversely, the smallest landslide is shown in Map F, with $A_L = 1.1\times10^4$ m^2, 4.6% smaller than the benchmark. The longest and largest landslide is found in Map C, with L_{LS} = 405 m (11% longer than the benchmark) and W_{LS} = 113 m (60% wider than the benchmark).

Considering the source and transportation area, in Map A (the benchmark) $A_{LS} = 5.4\times10^3$ m^2, L_{LS} = 228 m, and W_{LS} = 52 m. The largest representation of the source and transportation area is found in Map B (reconnaissance field mapping) with $A_{LS} = 7.4\times10^3$ m^2, 36.9% larger than the benchmark, and the smallest source and transportation area is found in Map G, with $A_{LS} = 5.2\times10^3$ m^2, 3.6% smaller than the benchmark. The longest source and transportation area is found in Map F, with L_{LS} = 239 m, 5% longer than the benchmark, and the shortest source and transportation area is shown in Map C, with L_{LS} = 206 m, 9.7% shorter than the benchmark. The largest source and transportation area is shown in Map B, W_{LS} = 60 m, 15.7% wider than Map A, and the narrowest source and transportation area is in Map C, L_{LS} = 44 m, 15.3% narrower than the benchmark. Considering instead only the landslide deposit, our benchmark (Map A) has $A_{LD} = 5.7\times10^3$ m^2, L_{LS} = 153 m, and W_{LS} = 61 m. The largest deposit is shown in Map B (reconnaissance field mapping) and has $A_{LD} = 1.2\times10^4$ m^2, 103.4% larger than the benchmark, whereas the smallest landslide deposit is shown in Map F, with $A_{LD} = 4.6\times10^3$ m^2, 19.8% smaller than the benchmark. Analysis of the length and width of the landslide deposit reveals that Map C shows the longest deposit, L_{LS} = 206 m, 35% longer than the benchmark, and Map H shows the shortest deposit, L_{LS} = 122 m, 20.2% shorter than the benchmark. Similarly, the largest landslide deposit is shown in Map C, W_{LS} = 112 m, 82.8% wider than the benchmark, and the narrowest landslide deposit is portrayed in Map E, W_{LS} = 56 m, 8.2% less than the benchmark.

To compare quantitatively the different landslide maps, we use the error index *E* proposed by Carrara et al. (1992), adopting the pairwise comparison approach proposed by Santangelo et al. (2015a). The index provides an estimate of the discrepancy (or similarity) between corresponding polygons in two maps, and is defined as:

$$E = \frac{(A\cup B)-(A\cap B)}{(A\cup B)};\ 0 \le E \le 1, \tag{1}$$

where, A and B are the areas of two corresponding polygons in the compared maps, and ∪ and ∩ are the geographical (geometric) union and intersection of the two polygons, respectively. *E* spans the range from 0 (perfect matching) to 1 (complete mismatch).

We compared the eight maps of the Assignano landslide (**Fig. 5**) adopting a pairwise approach, and considering first only the landslide source and transportation area, next only the landslide deposit, and lastly the entire landslide. **Fig. 6** summarizes the 84 values of the error index E, 28 for the landslide source and transportation area (**Fig. 6 I**), 28 for the landslide deposit (**Fig. 6 II**), and 28 for the entire landslide (**Fig. 6 III**). On average, the source and transportation area exhibits values of the error index smaller than the values found in the landslide deposit. This indicates that in the source and transportation area the landslide maps are more similar than in the landslide deposit. Inspection of **Fig. 6 I**, reveals a decrease of the error index in the source and transportation area for the maps obtained interpreting the available images (from Map C to Map H), compared to our benchmark obtained through the RTK ~~DGPS~~dGPS survey ($0.15 \leq E \leq 0.38$), with Map G obtained interpreting the TC, monoscopic, ultra-resolution UAV image. In the landslide deposit (**Fig. 6 II**), the minimum difference ($E = 0.21$) was found comparing the benchmark to Map E, obtained through the interpretation of the stereoscopic TC satellite image, and the largest difference ($E = 0.52$) was found comparing the benchmark to Map C, prepared interpreting the TC, monoscopic, satellite image.

Comparison of the maps obtained through the interpretation of the monoscopic images (Map C and Map D), and the maps obtained through the interpretation of stereoscopic (Map E and Map F) or ultra-resolution images (Map G and Map H), reveals high values of the error index, which is slightly worse in the landslide deposit. This is evident in the source and transportation area ($0.31 \leq E \leq 0.44$) (**Fig. 6 I**), and in the landslide deposit ($0.43 \leq E \leq 0.63$) (**Fig. 6 II**). Map C and Map D are very similar, with a mapping error $E = 0.17$. Maps obtained through the interpretation of stereoscopic satellite images (Map E and Map F, prepared using TC and FCC images, respectively), and maps prepared by interpreting the UAV images (Map G and Map H), exhibit a generally low value of E. In particular, $0.14 \leq E \leq 0.26$ in the landslide source and transportation area, and $0.15 \leq E \leq 0.38$ in the landslide deposit. The reconnaissance field mapping (Map B) exhibited the largest differences compared to all the other maps ($0.63 \leq E \leq 0.45$) in the landslide source and transportation area, and $0.44 \leq E \leq 0.73$ in the landslide deposit. The large values of E in the landslide deposit is probably due to lack of visibility of part of the landslide toe in the field.

6 Discussion

In this section, the~~We discuss the~~ ability of the different images ~~used to detect and map the Assignano landslide (**Fig. 1**)~~ to resolve the landslide photographical and morphological signatures is discussed, considering separately (i) the image spatial and (ii) spectral resolutions, and the (iii) image type ~~i.e.,~~ (monoscopic, stereoscopic, or pseudo-stereoscopic). ~~We treat e~~Each of ~~the~~ these three factors is considered separately, keeping the other two factors constant. ~~To evaluate the influence of the image spatial resolution on landslide mapping, we compare to our benchmark (Map A) two true-colour (TC) monoscopic maps (Map C and Map G), and two TC stereoscopic maps (Map E and Map H). Next, to evaluate the influence of the image spectral resolution on the landslide mapping, we compare to the benchmark (Map A) the TC and the false-colour composite (FCC) monoscopic maps (Map C and Map D), and the corresponding TC and FCC stereoscopic maps (Map E and Map F). Lastly, to assess the influence of the type of image (i.e., monoscopic, stereoscopic, pseudo-stereoscopic) on the landslide mapping, we compare to the benchmark (Map A) the monoscopic (Map C) and the stereoscopic (Map E) TC maps (**Fig. 7A**), the two FCC maps (Map D and Map F) (**Fig. 7B**), and the maps obtained interpreting the ultra-resolution images captured by the UAV (Map G and Map H). **Fig. 6** summarizes the mapping errors E obtained by the pairwise comparisons of the eight landslide maps shown in **Fig. 5**~~.

~~We first evaluate the role of the image spatial resolution in the production of the different maps of the Assignano landslide.~~ Inspection of **Fig. 6 I** reveals that the maps of the landslide source and transportation area obtained from images characterized by the highest spatial resolution (~~i.e.,~~ Map G and Map H) exhibits the smallest errors ~~($E \leq 0.16$),~~ when compared to the benchmark ~~(Map A)~~. The mapping error obtained for Map C (TC, monoscopic~~, $E = 0.38$~~) is 2.5 times larger than the error obtained using the ultra-resolution orhtorectified images taken by the UAV ~~(Map G, $E = 0.15$, and Map H, $E = 0.16$)~~, whereas the error obtained from Map E (TC, stereoscopic~~, $E = 0.23$~~) is smaller, and about 1.5 times larger than the error obtained for Map H (TC, pseudo-stereoscopic~~, $E = 0.16$~~). In the landslide deposit (**Fig. 6 II**), the map obtained exploiting the monoscopic, TC satellite image ~~(Map C)~~ exhibits an error ~~$E = 0.52$,~~ 1.7 times larger than the error obtained using Map G (TC, monoscopic UAV~~, $E = 0.30$~~). Conversely, the error is smaller in the map obtained from the 2-m spatial resolution, stereoscopic TC satellite image (Map E~~, $E = 0.21$~~) than from the 3-cm spatial resolution, pseudo-stereoscopic image taken by the UAV (Map H~~,~~

~~*E* = 0.30~~). Collectively, the pairwise comparisons highlight~~s~~ an improvement of the quality of the mapping of the landslide features that exhibits a distinct photographical signature, most visible in the source and transportation area of the Assignano landslide, with an increase of the image spatial resolution (**Fig. 6**). Use of the ultra-resolution image captured by the UAV did not result in an improvement of the mapping in the deposition area of the Assignano landslide~~;~~, where the landslide exhibits a distinct morphological signature. ~~We f~~Furthermore, ~~observe that~~ most of the landslide parts that were not identified in the maps prepared using the satellite image are covered by vegetation, locally bounded by small and thin cracks with an average width smaller than the size of the 2 × 2 m pixel. In the satellite image, the cracks are located in pixels containing a mix of vegetation and bare soil, making it difficult for the interpreter to recognize the cracks.

Next, we evaluate the effectiveness of the image spectral resolution, and for the purpose we examine the mapping errors of Maps C and Map E (TC), and of Map D and Map F (FCC). The mapping of the source and transportation area prepared using the false-colour-composite (FCC) images (Map D and Map F) resulted in smaller errors than the mapping prepared using the corresponding true-colour (TC) images (Map C and Map E), for both monoscopic and stereoscopic images (**Fig. 6 I**). In the source and transportation area, the false-colour-composite emphasized the presence or absence of the vegetation, and contributed locally to highlight the typical photographical signature of the landslide~~, which helped the photo-interpreter to detect and map the slope failure~~. Conversely, in the landslide deposition area (**Fig. 6 II**) use of the FCC images did not result in a systematic reduction of the mapping error, when compared to the TC images. We conclude that use of the additional information contributed by the Near Infrared (NIR) band in the 1.84-m resolution satellite image did not improve the quality of the mapping. On the other hand, the contribution of the NIR in the 3-cm UAV image remains unknown.

~~Next~~Lastly, ~~we evaluate~~ the influence of the image type (~~i.e.,~~ monoscopic, stereoscopic, pseudo-stereoscopic) on the mapping error was evaluated by comparing (i) the TC images (Map C and Map E), (ii) the FCC images (Map D and Map F), and (iii) the ultra-resolution UAV image (Map G and Map H). Comparison of the TC, monoscopic (Map C) and stereoscopic (Map E) images revealed a mapping error for the entire landslide ~~*E* = 0.48~~, with the mismatch larger in the deposition area ~~(*E* = 0.59)~~ than in the source and ~~transpiration~~ transportation area ~~(*E* = 0.45)~~(~~(~~**Fig. 6**). A similar result was obtained comparing the FCC, monoscopic (Map D) and stereoscopic

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(Map F) images, with a mapping error for the entire landslide~~ E = 0.44~~, and again the mismatch is larger in the deposition area (E = 0.60) than in the source and transpiration area (E = 0.36). In the deposition area, where the morphological signature of the Assignano landslide is strongest, the mapping error obtained comparing ~~our ~~the benchmark (Map A) to the landslide maps prepared using the monoscopic images (Map C and Map D) is 2 times larger than the error observed for the maps prepared using the corresponding stereoscopic images (Map E and Map F). The differences are smaller in the source and transportation area, where the morphological signature of the landslide is less distinct. C~~Direct c~~omparison of Map E (TC, stereoscopic) and Map F (FCC, stereoscopic) for the entire landslide reveals a very small mapping error~~ (E = 0.15)~~, indicating the similarity of the two maps, which were also very similar to the benchmark (Map A)~~, $E \leq$ 0.20~~.

Comparison for the entire landslide of the maps prepared using the ultra-resolution images captured by the UAV (Map G and Map H) exhibits the smallest error of all the pairwise comparisons ~~(E = 0.08) ~~(**Fig. 6 III**), indicating the large degree of matching between the two maps. The degree of matching is only marginally smaller in the source and transportation area, and in the deposition area~~ (E = 0.15)~~. When compared to ~~our ~~the benchmark (Map A), Map G and Map H exhibit a small error ~~(E = 0.19) ~~for the entire landslide, which is larger in the deposition area ~~($E \leq$ 0.30) ~~and slightly smaller in the source and transportation area~~ ($E \leq$ 0.15)~~. Interestingly, the mismatch with Map A (the benchmark) is lower for the monoscopic (Map G) than for the pseudo-stereoscopic (Map H) map. The finding highlights the lack of an advantage in using a pseudo-stereoscopic (2.5D) image for mapping the ~~Assignano ~~landslide. We attribute this result to the low resolution of the (pre-event) DEM used to drape the ultra-resolution image for visualization purposes, which did not add any significant morphological information to the expert visual interpretation.

Joint analysis of **Fig. 5B** and **Fig. 6** reveals that, when compared to ~~our ~~the benchmark (Map A), the reconnaissance field mapping (Map B) exhibited the largest mapping error of all the performed pairwise comparisons, with E = 0.45 in the source and transportation area, E = 0.67 in the landslide deposit, and E = 0.55 for the entire landslide. ~~We note than an error of E = 0.50 indicates that 50% of the landslide area in one map (Map B, in this case) does not overlay with the other map (Map A, the benchmark, in this case). ~~Our results are similar to the results of tests performed to compare field-based landslide maps against GPS-based surveys of single landslides (Santangelo et al., 2010), the visual interpretation of very-high resolution stereoscopic satellite images (Ardizzone et al., 2013), or the semi-automatic processing of monoscopic satellite images (Mondini et al., 2013), and confirm the inherent difficulty in preparing accurate landslide maps in the field, unless the mapping is supported by a GPS survey or a similar technology.

~~Our~~ The experiment showed that the mapping of the Assignano landslide obtained exploiting the ultra-resolution images captured by the UAV (Map G and Map H) was comparable to the maps obtained using the high resolution stereoscopic satellite image (Map E and Map F), and to the ground-based RTK ~~DGPS~~dGPS survey (Map A, the benchmark). The ~~We conclude that~~ ultra-resolution images ~~captured by an UAV~~ and the stereoscopic satellite images are well suited to map event landslides, at least in physiographical settings similar to the one of ~~our~~ this study area, and for landslides similar to the Assignano landslide (slide-earthflow~~**Fig. 1**~~). ~~–~~

For event landslide mapping, selection between ultra-resolution pseudo-stereoscopic UAV images and very-high resolution stereoscopic satellite images depends on (i) the extent of the investigated area, (ii) the available resources, including time and budget, and (iii) the accessibility to the study area. The selection is largely independent from the landslide signature, at least for landslides similar to the Assignano landslide. From an operational perspective, modern multi-rotor UAVs allow for the acquisition of ultra-resolution images over small areas in a limited time, and at very low costs. UAV-based surveys are flexible in their acquisition planning, and partly independent from the local lighting conditions, including the cloud cover. As a drawback, UAVs are strongly (and negatively) affected by wind speed and weather conditions, they allow for a limited flight time (currently approximately 20 minutes in optimal conditions), which is reduced in bad weather conditions and in cold environments, and typically have limited data storage capacity. Further, it must be possible for the pilot to be at the same time near to the area to be surveyed and to maintain a safe distance from the UAV, a condition that may be difficult to attain in remote or in mountain areas. Collectively, the intrinsic advantages and limitations of modern UAVs make the technology potentially well suited for the acquisition of ultra-resolution images for event, seasonal, and multi-temporal mapping of single landslides, of multiple landslides in a single slope, or in a relatively small area (a few hectares). The use of UAV images was recently proposed by Turner et al. (2015) for determining the landslide dynamics, exploiting time series of images that can be constructed using UAVs. The result is achievable thanks to centimetre co-registration accuracy of the UAV images. Use of UAVs becomes impracticable with the increasing extent of the study area, largely due to (i) the operational difficulty of flying UAVs over large areas (more than a few square kilometres), and (ii) the acquisition and image processing time and associated cost, which increase rapidly with the size of the study area (**Table 3**). On the other hand, very-high resolution, stereoscopic satellite images have also advantages and limitations for the production of event, seasonal and multi-temporal landslide inventory maps (Guzzetti et al., 2012). The main advantage of the satellite images is that they cover large or very large areas (tens to hundreds of square kilometres) in a single frame with a sub-metre resolution well suited for landslide mapping through the expert visual interpretation of the images (Ardizzone et al., 2013). On the other hand, limitations remain due to distortions caused by different off-nadir angles in successive scenes, and to difficulties – in places severe – to obtaining suitable (e.g., cloud-free) images at the required time intervals. This is particularly problematic for the production of seasonal and multi-temporal landslide maps. Information on the photographic or morphological signature of the typical, or most abundant, landslides in an area, is important to selecting the optimal characteristics of the images best suited for the production of an event, seasonal or multi-temporal landslide inventory map. Use of images of non-optimal characteristics for a typical landslide signature in an area may condition the quality (~~i.e.,~~ completeness, positional and thematic accuracy) of the landslide inventory. Where possible, we recommend that the acquisition of images used for the production of event, seasonal or multi-temporal landslide inventory maps is planned considering the typical landslide signature, in addition to the purpose (event inventory, planning of monitoring systems), scale of the mapping (~~i.e.~~ regional or slope scale), and the size and complexity of the study area (**Table 3**).

7 Concluding remarks

~~We executed an~~The experiment aimed at determining and measuring the effects of the image characteristics on event landslide mapping. ~~In the experiment, we compared landslide maps obtained (i) through the expert visual interpretation of an ultra-resolution image taken by an UAV with a ground resolution of 3 × 3 cm, and monoscopic and stereoscopic true-colour and false-colour composite (1.84 × 1.84 m) images taken by the WorldView-2 satellite, (ii) a reconnaissance field survey of the landslide, and (iii) an accurate survey of the landslide obtained by walking a GPS receiver along the landslide boundary. We conducted the experiment on a~~The study was conducted on a slide-earthflow ~~the Assignano landslide~~ (**Fig. 1**) triggered by intense rainfall in December 2013 in the northwest-facing slope of the Assignano village, Umbria, central Italy. The landslide exhibited a predominant photographical (radiometric) signature in the source and transport area, and a more distinct morphological (topographic) signature in the deposition area. ~~The results of our mapping experiment allow for the following conclusions.~~

Increasing the spatial resolution allows to reduce the error of landslide mapping where landslides show mainly a photographical signature. Such a behaviour was observed in the ~~First, in the~~ landslide source and transport area~~, –~~. ~~where the signature of the slope failure was primarily photographical (radiometric), mapping errors (Carrara et al., 1992; Santangelo et al., 2015a) decreased with the increase of the spatial resolution of the images used for the expert visual detection and mapping of the landslide. In the same area~~Here, the image photographic (radiometric) characteristics (true-colour, false-colour-composite) and the image type (monoscopic, stereoscopic) played a minor role in augmenting the quality of the landslide maps. Conversely, in the deposition area, where the signature of the landslide was primarily morphological (topographical), mapping errors decreased using stereoscopic satellite images that allowed detecting topographic features distinctive of the landslide.

FCC and TC in the stereoscopic satellite images give similar values of the error. This indicates that the spectral resolution of the images does not provide useful information to recognize and map the landslide morphological features. On the other hand, the high spatial resolution provided by the UAV images reduces the error, when compared to the monoscopic satellite imagery. However, the error obtained using the UAV images remains higher than that obtained using stereoscopic satellite images, despite the latter having a pixel one order of magnitude larger than the UAV images. We conclude that the increase in the spatial resolution improves the ability to map morphological features when using monoscopic images.

~~Second, use~~Use of the stereoscopic satellite images resulted in more accurate landslide maps (lower error index E) than the corresponding monoscopic images in the landslide deposition area, where the signature of the landslide was primarily ~~morphometric~~ morphological~~(topographic)~~. This was expected, as the stereoscopic vision allowed to better capture the 3D terrain features typical of a landslide (Pike, 1988), including curvature, convexity and concavity. Conversely, visual examination of the false-colour-composite images resulted in more accurate maps than the corresponding true-colour images in the landslide source and transport area, where the signature of the landslide was primarily photographic~~ (radiometric)~~. ~~This was also expected (Guzzetti et al.,~~

~~2012).~~ Expert visual interpretation of pseudo-stereoscopic ultra-resolution image failed to provide better results than the corresponding monoscopic ultra-resolution image, most probably because the DEM used to drape (overlay) the image on the terrain information was of low resolution.

~~Third, t~~The ultra-resolution (3 × 3 cm) image captured by the ~~the photographic camera flown on-board the~~ Unmanned Aerial Vehicle (UAV) proved to be very effective to detect and map the landslide. The expert visual interpretation of the monoscopic ultra-resolution image provided mapping results comparable to those obtained using the about 2-m resolution~~,~~ stereoscopic satellite image.

~~Fourth, a~~A comparative analysis of the technological constrains and the costs of acquisition and processing of ultra-resolution imagery taken by UAV, and of high, or very-high resolution imagery taken by optical satellites, revealed that the ultra-resolution images are well suited to map single event landslides, clusters of landslides in a single slope, or a few landslides in nearby slopes in a small area (up to few square kilometres, Giordan et al., 2017)~~-~~, and proved unsuited to cover large and very large areas where the stereoscopic satellite images provide the most effective option (Boccardo et al., 2015).

~~Fifth, our~~The field-based reconnaissance mapping (Map B) provided the least accurate mapping results, measured by the largest mapping error ~~(E = 0.55 for the entire landslide)~~ when compared to the benchmark map ~~(**Fig. 6**)~~. ~~Our r~~Results confirm the inherent difficulty in preparing accurate landslide maps in the field through a reconnaissance mapping (Santangelo et al., 2010).

Although ~~we conducted our~~the study was conducted on a single landslide (**Fig. 1**), ~~we maintain that~~ the findings are general, and can be useful to decide on the optimal imagery and technique to be used when planning the production of a landslide inventory map. ~~We emphasize that the~~The technique and imagery used to prepare landslide inventory maps should be selected depending on multiple factors, including (i) the typical or predominant landslide signature (photographic or morphological), (ii) the scale and size of the study area (a single slope, a small catchment, a large region), and (iii) the scope of the mapping (event, seasonal, multi-temporal, Guzzetti et al., 2012).

8 Acknowoledgements

FF and MS were supported by a grant of Italian Dipartimento della Protezione Civile. We thank Andrea Bernini and Mario Truffa, Servizio Protezione Civile della Città Metropolitana di Torino, for flying the UAV over the Assignano landslide. Federica Fiorucci and Michele Santangelo designed the experiment and wrote this paper; Michele Santangelo mapped the landslide on the images, Mauro Rossi performed GPS survey, Daniele Giordan produced the UAV images. Fausto Guzzetti supervised the work, Federica Fiorucci, Daniele Giordan, Mauro Rossi, and Furio Dutto participated to field activities.

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Table 1. Characteristics of the images used to identify and map the Assignano landslide (**Fig. 2**). O: order in the sequence of images shown to the interpreter. Platform used to capture the image: W, WorldView-2 satellite; U, UAV. Resolution (ground resolution)~~, in metre~~. Spectral (image spectral composite): TCC, True Colour Composite (Red, Green, Blue); FCC, False Colour Composite (Near infrared, Red, Green). Type (image type): M, monoscopic; S, stereoscopic; P, pseudo-stereoscopic. Map: Corresponding landslide map (**Fig. 5**).

O	Platform	Resolution (m)	Spectral	Type	Map
1	W	1.84	TC	M	C
2	W	1.84	FCC	M	D
3	W	1.84	TC	S	E
4	W	1.84	FCC	S	F
5	U	0.03	TC	M	G
6	U	0.03	TC	P	H

Tabella formattata

Table 2. Comparison of the total landslide area (A_L), the landslide source and transportation area (A_{LS}), the landslide deposit (A_{LD}), the width and length of the entire landslide (W_L, L_L), of the source and transportation area (W_{LS}, L_{LS}), and of the deposit (W_{LD}, L_{LD}), for eight separate and independent cartographic representations of the Assignano landslide. EL, entire landslide; ST, landslide source and transport area; LD, landside deposit. See **Table 3** for the characteristics of the single maps.

		Map A	Map B	Map C	Map D	Map E	Map F	Map G	Map H
Landslide area (m^2)									
EL	A_L	1.11×10^4	1.91×10^4	1.53×10^4	1.52×10^4	1.09×10^4	1.06×10^4	1.19×10^4	1.16×10^4
ST	A_{LS}	5.40×10^3	7.40×10^3	3.64×10^3	4.02×10^3	5.71×10^3	6.03×10^3	5.21×10^3	5.70×10^3
LD	A_{LD}	5.73×10^3	1.17×10^4	1.16×10^4	1.12×10^4	5.15×10^3	4.59×10^3	6.70×10^3	5.87×10^3
Landslide length (L_L, m) and width (W_L, m)									
EL	W_L	70.7	97.8	113.4	109.9	61.4	61.25	89.9	85.3
	L_L	362.0	387.5	404.7	391.2	354.6	359.5	343.3	349.1
ST	W_{LS}	51.5	59.6	43.6	49.2	51.92	54.3	49.5	50.5
	L_{LS}	227.9	229.7	205.9	208.0	239.0	239.2	234.7	237.3
LD	W_{LD}	61.0	98.69	111.5	109.0	56.0	57.6	89.9	81.9
	L_{LD}	152.7	172.1	206.2	203.5	129.8	134.7	139	121.8

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Table 3. Comparison of the estimated cost, acquisition and pre-processing time, and storage requirement for an area of 4 km^2 (2 km × 2 km) and for an area of 100 km^2 (10 km × 10 km), for monoscopic and stereoscopic satellite images, and for an area of 15 km^2 for photographic images captured by an UAV.

	Satellite monoscopic		Satellite stereoscopic		UAV	
	4 km^2	100 km^2	4 km^2	100 km^2	4 km^2	15 km^2
Acquisition cost (€)	1.500	1.500	3.500	3.500	1.000	3.000
Pre-processing cost (€)	50	50	50	50	250-300	3.000
Acquisition time (day/person)	7-60	7-60	7-60	7-60	1	4
Pre-processing time (hr/person)	1	1	1	1	5-6	20-24
Storage (GB)	0.5	0.5	1	1	12	50
Resolution (m)	2	2	2	2	0.02	0.02
Morphologic signature	no	no	yes	yes	yes	yes
Photographic signature	yes	yes	yes	yes	yes	yes

Figure captions

Figure 1. The Assignano landslide, located near Collazzone, Umbria, central Italy. (A) global view of the landslide. (B) detail of the landslide source area. (C) detail of the landslide transportation area. (D) detail of the landslide deposit. Base image obtained overlaying ("draping") the image on Google Earth™. Red line is the boundary of the landslide obtained using the RTK ~~DGPS~~dGPS (benchmark).

Figure 2. Images used to map the Assignano landslide. (A) TC WordView-2 satellite image, (A-I) detail of the source area and (A-II) detail of the landslide deposit. (B) WordView-2 satellite image in FCC, (B-I) detail of the source area and (B-II) detail of the landslide deposit. (C) UAV monoscopic image and C-I a detail of the source area and C-II a detail of the deposition area.

Figure 3. Position of the seven GCPs used to evaluate the co-registration of WordView-2 satellite image (A) and UAV image (B). Corresponding points are illustrated with the same symbol. Differences of the coordinates of the corresponding points along X (~~i.e.,~~ E-W direction, ΔX) and along Y (~~i.e.,~~ N-S direction, ΔY) are provided in metres on the left of the figure.

Figure 4. (A) Overview of the Assignano landslide area in Google Earth™ taken on 8 July 2013. Photo shooting points and photograph taken (B) close to the landslide and (C) from a viewpoint.

The photographs taken in the field and the Google Earth™ image were used to prepare the reconnaissance field map.

Figure 5. Eight independent cartographic representations of the Assignano landslide, "Map A" to "Map H". Map A obtained through a RTK ~~DGPS~~dGPS survey is considered the "benchmark", and shown as a thick black line in the other maps. Map B obtained through reconnaissance field mapping. Map C to Map F obtained through the expert visual interpretation of the satellite images. Map G and Map H obtained through the expert visual interpretation of the orthorectified image taken by the UAV. See **Table 1** for image characteristics. Dark colours show the landslide source and transportation area. Visual inspection of the images reveals the maps most similar to the benchmark.

Figure 6. The error index (*E*) proposed by Carrara et al. (1992), was used to compare quantitatively the different landslide maps. (I) Error index matrix for the landslide source and transportation area. (II) Error index matrix for the landslide deposit. (III) Error matrix for the entire landslide. *E* spans

the range from 0 (perfect matching) to 1 (complete mismatch).

Figure 7. Comparison of landslide maps prepared for the Assignano landslide, Umbria, Central Italy. (A) Landslide map obtained from a monoscopic (Map C, dark yellow line) and a stereoscopic (Map E, light blue line), true-colour (TC) WordView-2 satellite image (base image), and a mapping of the landslide obtained by walking a GPS receiver along the landslide boundary (Map A, black line). (B) Landslide map obtained from a monoscopic (Map D, yellow line) and a stereoscopic (Map F, cyan line), false-colour-composite (FCC) WordView-2 satellite image, and a mapping obtained by walking a GPS receiver along the landslide boundary (Map A, black line). (C) Landslide map obtained from field survey (Map B, pink line) and from a monoscopic, TC, ultra-resolution image captured by an UAV (Map G, purple line), and the mapping obtained by walking a GPS receiver along the landslide boundary (Map A, black line).

761 **Figure 1**

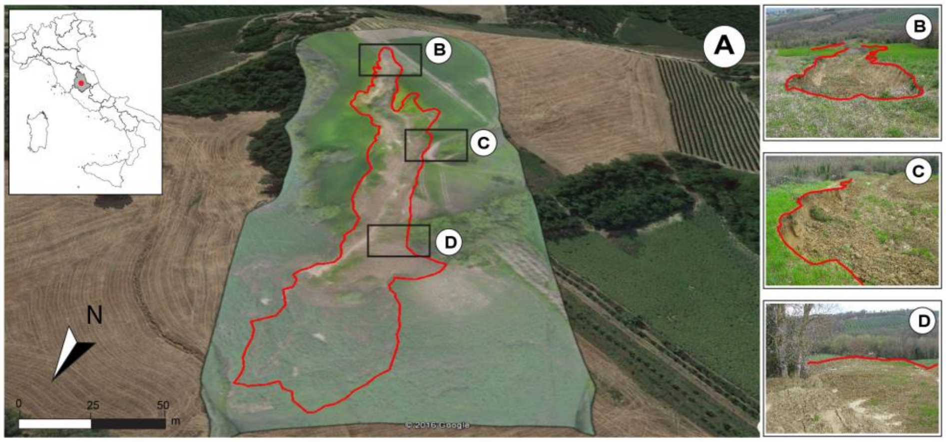

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Figure 2

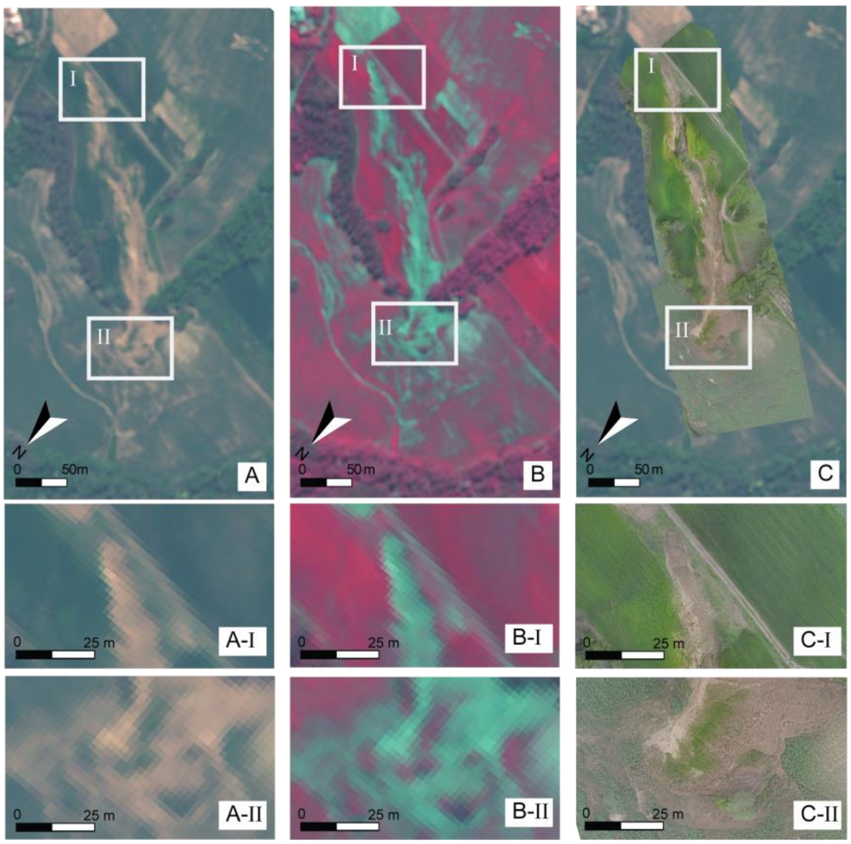
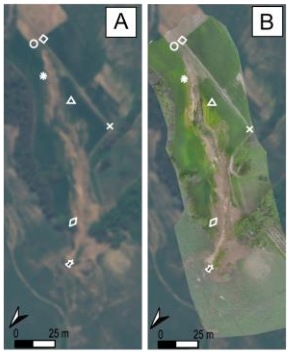
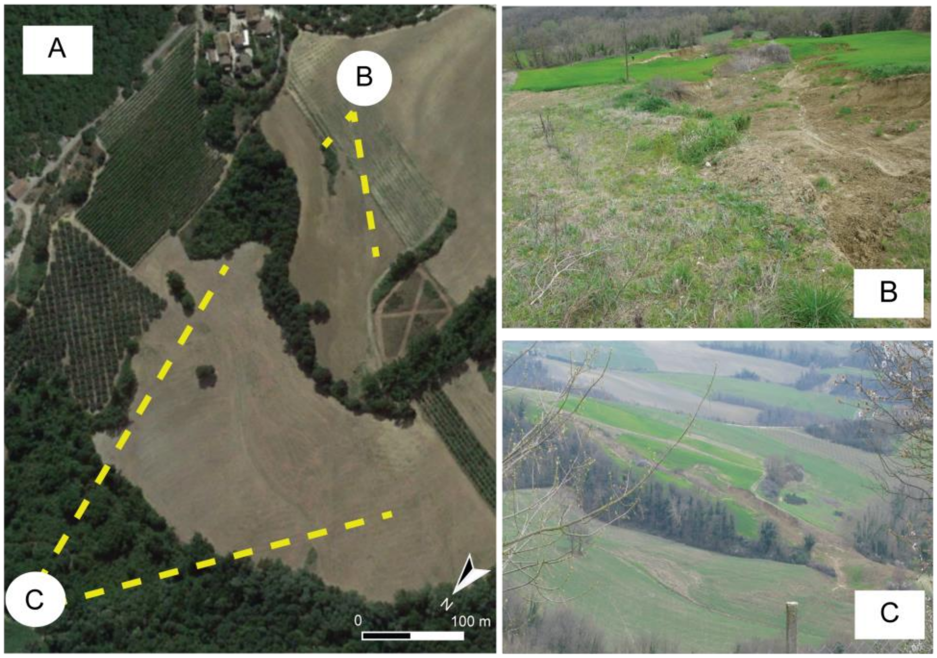


Figure 3

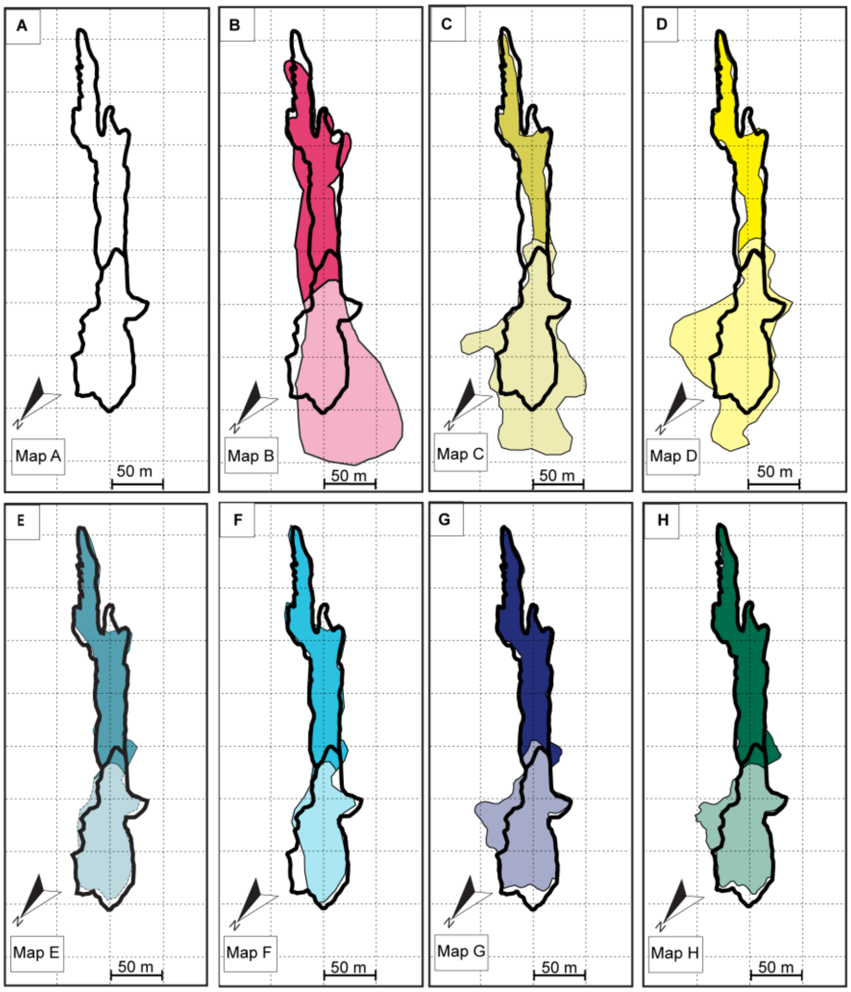


	A-B ΔX (m)	A-B ΔY (m)
◇	-1.1	1.1
○	0.3	1.3
△	-0.4	1.2
✳	1.7	-1.8
✖	2.1	2.9
▱	0.3	1.3
✦	-0.8	-2.4

Figure 4

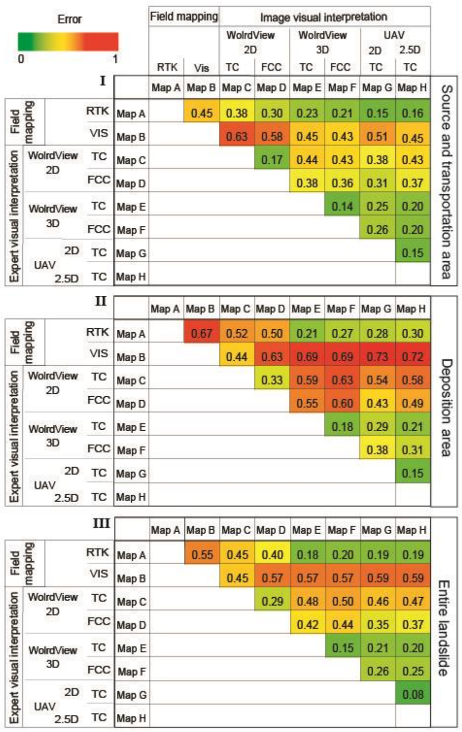


771 **Figure 5**

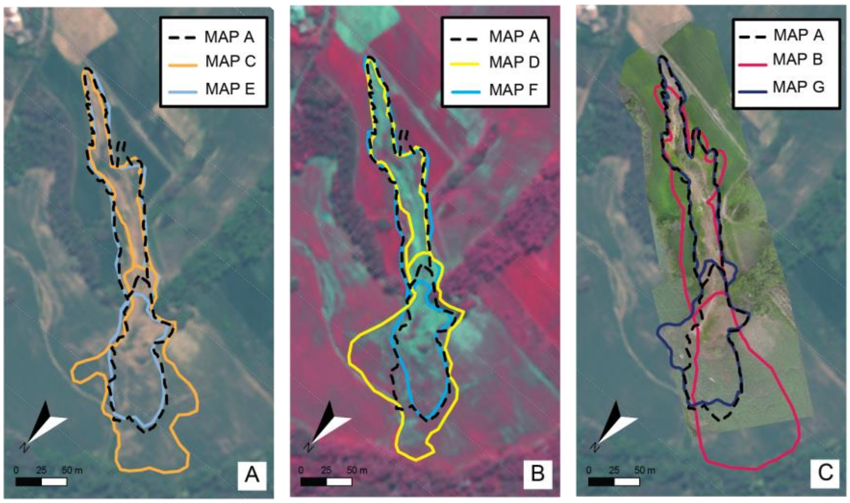


772

Figure 6


Error
0
1
Field mapping
Image visual interpretation
WolrdView 2D
WolrdView 3D
UAV
2D
2.5D
RTK
Vis
TC
FCC
TC
FCC
TC
TC
I
Map A Map B Map C Map D Map E Map F Map G Map H
Field mapping RTK Map A 0.45 0.38 0.30 0.23 0.21 0.15 0.16
VIS Map B 0.63 0.58 0.45 0.43 0.51 0.45
Expert visual interpretation WolrdView 2D TC Map C 0.17 0.44 0.43 0.38 0.43
FCC Map D 0.38 0.36 0.31 0.37
WolrdView 3D TC Map E 0.14 0.25 0.20
FCC Map F 0.26 0.20
UAV 2D TC Map G 0.15
2.5D TC Map H
Source and transportation area
II
Map A Map B Map C Map D Map E Map F Map G Map H
Field mapping RTK Map A 0.67 0.52 0.50 0.21 0.27 0.28 0.30
VIS Map B 0.44 0.63 0.69 0.69 0.73 0.72
Expert visual interpretation WolrdView 2D TC Map C 0.33 0.59 0.63 0.54 0.58
FCC Map D 0.55 0.60 0.43 0.49
WolrdView 3D TC Map E 0.18 0.29 0.21
FCC Map F 0.38 0.31
UAV 2D TC Map G 0.15
2.5D TC Map H
Deposition area
III
Map A Map B Map C Map D Map E Map F Map G Map H
Field mapping RTK Map A 0.55 0.45 0.40 0.18 0.20 0.19 0.19
VIS Map B 0.45 0.57 0.57 0.57 0.59 0.59
Expert visual interpretation WolrdView 2D TC Map C 0.29 0.48 0.50 0.46 0.47
FCC Map D 0.42 0.44 0.35 0.37
WolrdView 3D TC Map E 0.15 0.21 0.20
FCC Map F 0.26 0.25
UAV 2D TC Map G 0.08
2.5D TC Map H
Entire landslide

777 **Figure 7**



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