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The effectiveness of hillshade maps and expert knowledge in mapping old deep-seated landslides

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Abstract

Large deep-seated landslides with a shear surface deeper than 3 m and a mean affected area of 4.2 ha are common features in the Flemish Ardennes. None of these deep-seated landslides are dated, but they are assumed to be rather old (>100 years). Because most of these landslides are located under forest, aerial photo interpretation commonly used for the creation of landslide inventories is not a suitable tool to map the landslides in the Flemish Ardennes. Therefore, an intensive 100-day field survey was carried out by two geomorphologists in a 430-km^2 study area. This resulted in a landslide inventory map, indicating the location of 135 large deep-seated landslides.

But field surveys are time consuming and, thus, very expensive. Therefore, a cheaper and faster mapping technique was tested. A hillshade map was constructed for the study area in a GIS (IDRISI32) from a 5-m resolution digital elevation model (DEM). Seven experts were given 1 h to indicate all the hillslope sections, which they suspected to be possible landslides on a copy of the aforementioned map (scale 1:100,000). In total, this exercise took only 1 day (i.e., 7 person hours).

Large differences in the number of presumed landslides and the extent of the hillslopes thought to be affected by landslides were reported among the seven experts. The polygon and pixel efficiency were introduced to estimate the quality of the landslide maps based on hillshade maps and expert knowledge. Compared to the field survey-based landslide inventory, the quality of the landslide inventories based on the hillshade maps and expert knowledge was relatively low. Experts familiar with the study area obtained somewhat better results than experts who visited the study area only once. A combination of the seven expert maps did not result in a good inventory map because too many unaffected hillslopes were incorrectly indicated as affected by landslides. The results obtained in this study are comparable to an investigation carried out by (Wills, C.J., McCrink, T.P., 2002. Comparing landslide inventories, the map depends on the method. *Environmental and Engineering Geoscience* 8, 279–293). Although the tested method can never replace a detailed field survey, taking

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into account the proposed improvements, it can be used for the creation of a regional inventory map of old landslides in a densely forested area where light detection and ranging (LIDAR) data are unavailable.

Keywords: Old deep-seated landslides; Landslide inventory map; Expert knowledge; DEM; Hillshade map

1. Introduction

In many parts of the world, the surface morphology is marked by traces of old landslides (e.g., see Bentley and Siddle, 1996; Wieczorek and Jäger, 1996; Mather et al., 2003; Soldati et al., 2004). One of these regions is located in Belgium and is called the Flemish Ardennes (Vanmaercke-Gottigny, 1980; Ost et al., 2003). Unfortunately, none of the old large landslides in this region are dated at the moment. As no historical documents describing the initiation of one of these large landslides are found, the landslides are assumed to be at least 100 years old. In Belgium, old landslides are also present in the Pays de Herve (Eastern Belgium), and calibrated ^{14}C dating revealed that some of the landslides were activated at 150±80 AD (Demoulin et al., 2003). Most of these landslides are probably related to local seismic activities in combination with heavy rainfall (Demoulin et al., 2003; Ost et al., 2003).

Different mapping techniques can be used to create landslide inventory maps. At present, aerial photo interpretation in combination with selective ground truthing is the most commonly used technique for the production of regional landslide inventories in sparsely vegetated areas (e.g., see Carrara et al., 1991; Van Westen et al., 1999). Advantages of this method are the stereo viewing capability and the high spatial resolution. Guzzetti et al. (2000) give several parameters which influence the usefulness of aerial photo interpretation. Among them are the land use on the affected sites and the age and freshness of the landslide. Vegetated older slides with subdued topographic expression are often not recognizable on aerial photographs (Carrara et al., 1992; Ardizzone et al., 2002; Wills and McCrink, 2002; McKean and Roering, 2004). The influence of vegetation was investigated by Brardinoni et al. (2003). They found that, in a densely forested region in Vancouver, Canada, up to 85% of the landslides mapped in the field were not visible on aerial photographs. Mather et al. (2003) could not delineate a Pleistocene landslide on aerial photographs because the main characteristics had been partly erased by water erosion on the landslide site. A detailed investigation in the field was needed to identify the feature as a landslide.

Other mapping techniques are based on remote sensing techniques using satellite images (Liu and Woing, 1999; Petley et al., 2002) and light detection and ranging (LIDAR; Singhroy et al., 1998; Wills, 2002; Haugerud et al., 2003; Gold, 2004; McKean and Roering, 2004). Liu and Woing (1999) compared landslide inventory maps based on aerial photographs and on a SPOT mosaic with a 6.25-m spatial resolution for Taiwan. The inventory based on the SPOT mosaic contained only 40% of the landslides on the aerial photograph-based inventory map. About 70% of the indicated area on the SPOT-based landslide inventory was classified incorrectly as landslides. The errors mainly originated from the omission of very large landslides, the incorrect indication of shadows and artificial features and limited knowledge of landslide characteristics of one specialist. Petley et al. (2002) compared a field survey-based landslide inventory with inventories obtained with Landsat ETM+ (30-m spatial resolution) and IKONOS (1-m spatial resolution). Only 17% and 38% of the landslides mapped in the field were also visible on the Landsat ETM+ and the IKONOS satellite images, respectively. Results obtained from LIDAR are more promising. Gold (2004) produced landslide inventory maps for a densely vegetated area using hillshade maps derived from LIDAR and aerial photographs. The maps contained, respectively, 58% and 69% of all the landslides detected in the area. On both inventory maps, about 40% of the total indicated area was falsely classified as a landslide. The lower proportion of correctly indicated landslides on LIDAR images is mainly due to the fact that shallow landslides were easier to detect on the aerial photographs. Deep-seated landslides on the other hand were easier detected on LIDAR-based hillshade maps. Haugerud et al. (2003) could even detect twice as many deep-seated landslides on hillshade maps derived from LIDAR in a densely forested region. Unfortunately, DEMs derived from LIDAR are expensive (Gold, 2004). The high cost explains why, at present, LIDAR is mainly used to study landslides at a local scale (e.g., see McKean and Roering, 2004).

Because 85% of the old landslides in the Flemish Ardennes are partly or completely located under forest, aerial photographs were not useful for the creation of the landslide inventory map. An attempt to detect landslides from aerial photographs failed as only very few often recently reactivated landslides under pasture were visible. Therefore, an intensive field survey was carried out in a 430-km^2 study area by two geomorphologists. The survey resulted in a detailed landslide inventory map. But its creation was time consuming (ca. 100 days) and therefore expensive.

The main purpose of this study is to evaluate a cheaper and faster mapping technique. First, the use of expert knowledge and hillshade maps derived from a detailed DEM for the creation of an inventory map for the old large landslides in the Flemish Ardennes is tested. Our goal is to determine how many of the old large landslides mapped in the field can be determined by the tested technique. In addition, the influence of familiarity with the study area is tested. Then a check is carried out to see whether the landslide maps derived from expert knowledge and hillshade maps reveal the doubtful landslide locations mapped during the field survey. These locations are classified as possible landslide sites (Table 1). The hypothesis is that possible landslides indicated by several experts are more likely to be true landslides than those not indicated. Afterwards, our results are compared with results from similar landslide inventory studies, and finally, some recommendations are drawn for the appropriate use of the tested method.

Table 1
Classification of the deep-seated (>3m) landslides in the study area

Class	Number of landslides	Freshness	Number of landslides
Rotational earth slide	116	Type 1	46
		Type 2	35
		Type 3	35
Complex earth slide (rotational earth slide with flow characteristics in accumulation zone)	6	Type 1	3
		Type 2	2
		Type 3	1
Possible landslide site	13		

See Section 3.1 for more information.

2. Study area

A study area of 430 km^2 was selected in the Flemish Ardennes, a hilly region bordered by the river Scheldt in the west and by the river Dender in the east (Fig. 1). The only natural boundary of the selected study area is the river Scheldt in the west; the other three boundaries are borders of topographical maps. The lithology of the study area consists of loose Tertiary sediments characterized by an alternation of clayey sand layers and clay layers with a dip less than 0.4% to the NNE (Jacobs et al., 1999). During the Quaternary, the Tertiary deposits were covered by Aeolian sediments, i.e., cover sands in the north and loess in the south, of varying thickness. This complex geological situation is responsible for a high variability in soils (I.W.O.N.L., 1987). Several active faults cross or border the study area (De Vos, 1997). Ost et al. (2003) tried to investigate the possibility of seismic shaking as a landslide-triggering factor. They concluded that seismic shaking in combination with large rainfall amounts will have enhanced the probability of landslide initiation or reactivation.

Differential erosion during the Tertiary and Quaternary has created the hilly character of the region. Altitudes range from 10 m a.s.l. in the valley of the river Scheldt to 150 m a.s.l. on the Tertiary hills. More than 98% of hillslopes have gradients less than 20%. Important to note is that hillslope gradients depend on aspect. Slopes with an S to NW aspect are generally steeper than slopes with an N to SE aspect. Due to the alternation of less permeable clays and more permeable sands, perched water tables are a common feature in the Flemish Ardennes. Where the topography cuts a perched water table, springs occur. Land use is determined by lithology, soil type and topography. Croplands are located on the plateaus of the lower hills, and pastures dominate the hillslopes. The

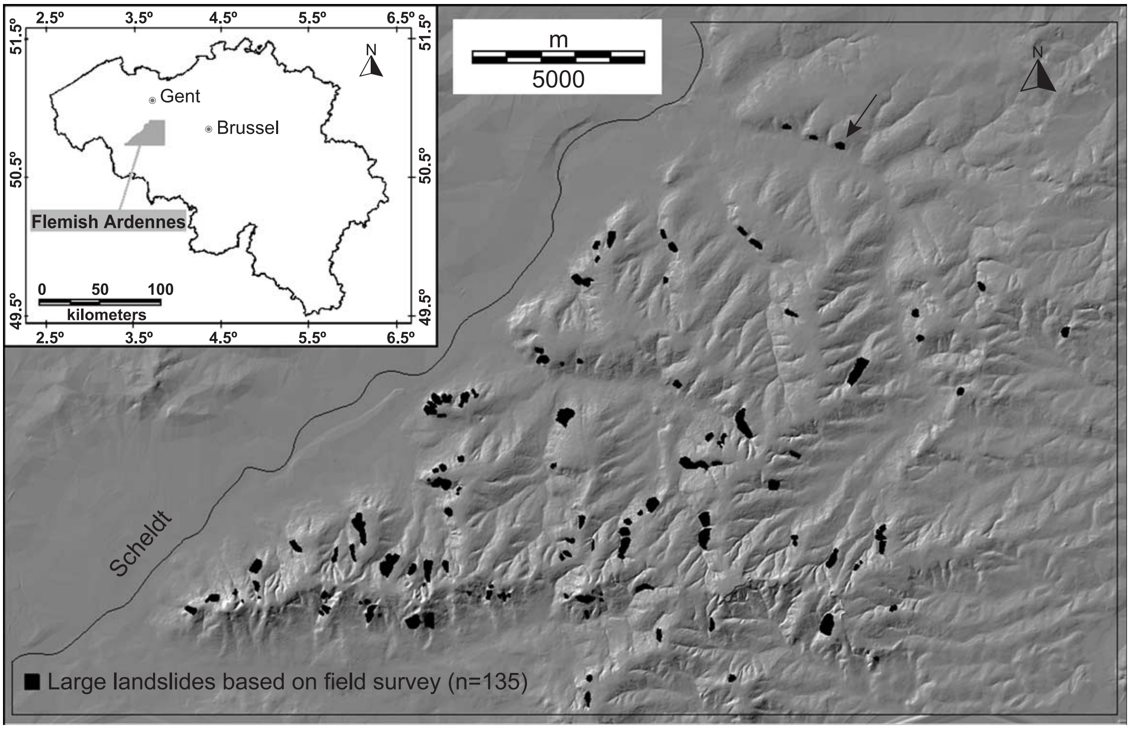

Fig. 1. Location of the study area. The field survey-based landslides (N=135) are shown on the hillshade map with sun elevation angle of 30° and sun azimuth angle of 315°. The black arrow indicates the landslide which was indicated to the experts as an example.

Tertiary hills and the steepest hillslopes are forested (I.W.O.N.L., 1987).

3. Materials and methods

3.1. Landslide inventory map of the Flemish Ardennes based on field survey

During an intensive field survey, the whole study area was checked for the occurrence of landslides. The survey was carried out by two geomorphologists and took about 100 days. Large deep-seated landslides with an average affected area of 4.2 ha and a shear surface deeper than 3 m were indicated on a topographical map (1:10,000) and then stored in a GIS (MapInfo). A typical large deep-seated landslide is shown in Fig. 2. All landslides were classified directly in the field. The classification system is based on Cruden and Varnes (1996). Table 1 gives an overview of the different landslide classes which occur in the study area. The rotational and complex earth slides were subdivided according to their freshness and preservation of the typical landslide characteristics. The terminology suggested by the IAEG Commission on Landslides (1990) is used. For rotational earth slides, these characteristics are, for example, reverse slopes, the main scarp and the foot. To be classified as a type 1 rotational earth slide, a clear rather steep main scarp (>3 m), one or more reverse slopes which are responsible for the presence of an elongated pool parallel to the main scarp and a convex foot, must be present. When, due to erosion, the morphology of the reverse slopes had faded and changed into steps, landslides were classified as type 2. Type 3 landslides were landslides with no relicts of steps in the affected area. The only remnants are a clear main scarp and a hummocky topography.

3.2. Landslide inventory maps of the Flemish Ardennes based on hillshade maps and expert knowledge

The hillshade maps used were subtracted from a 5-m resolution digital elevation model (DEM). This

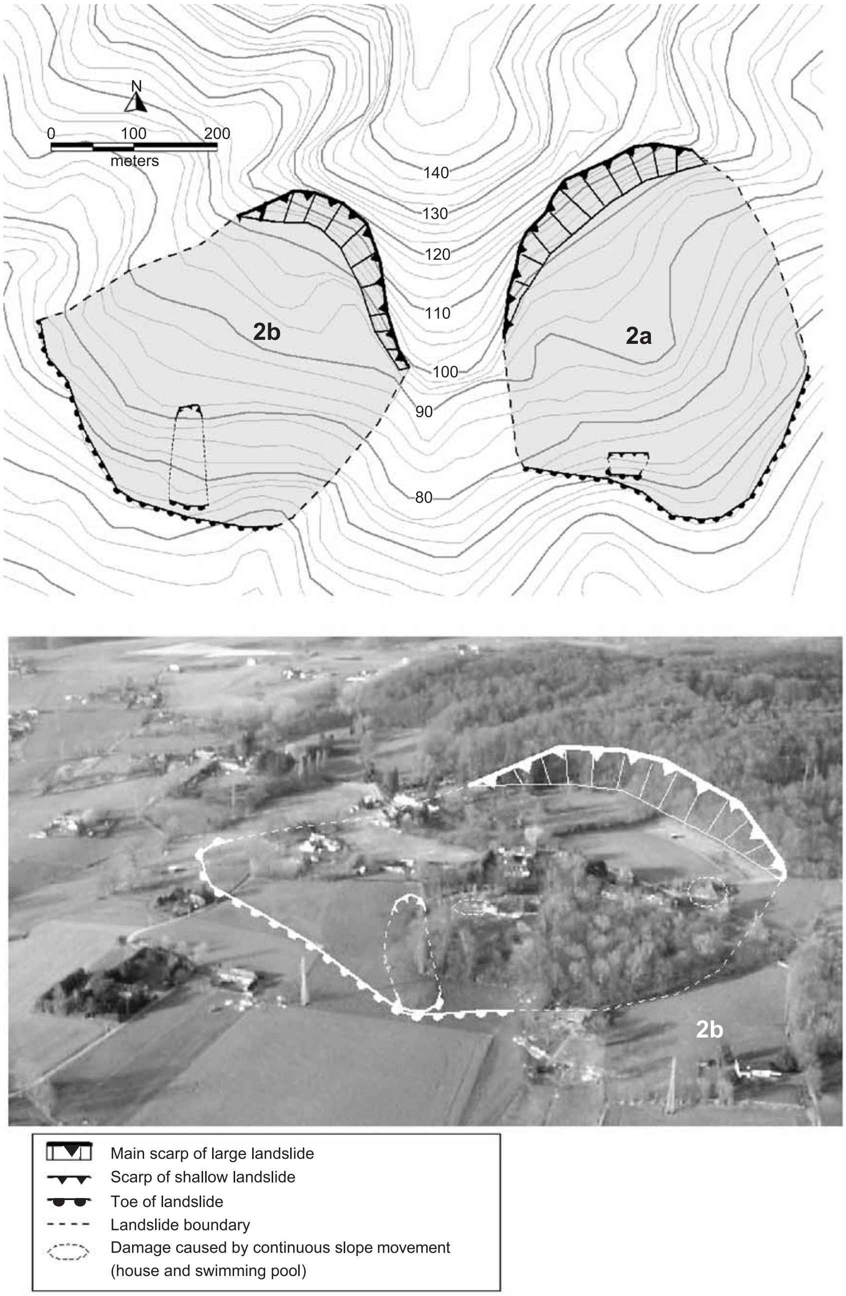

Fig. 2. A typical large deep-seated landslide in the Flemish Ardennes (Wittentak, 13/03/2004, photo by J. Poesen).

DEM was generated from the 1:10,000 scale topographical map (NGI, 1972). After digitizing the contour lines with a 2.5-m interval, an interpolation based on Triangulated Irregular Network was carried out in a raster GIS (IDRISI32). Two different hillshade maps were created, one with a sun elevation angle of 30° and a sun azimuth angle of 315° (Fig. 1) and another with a sun elevation angle of 30° and a sun azimuth angle of 45°. In other words, for the first, the light source was located in the northwest, and for the second, it was located in the northeast. The fact that not all landslides are clearly visible on both aforementioned hillshade maps is clearly visible in Fig. 3.

The interpretation of hillshade maps is quite similar to the interpretation of remote sensing images. It is based on the recognition or identification of elements associated with landslides. The presence of a clear main scarp, an abrupt change in slope and a stepped topography are characteristic features detectable on hillshade maps. As for landslide inventories obtained from aerial photographs, the quality of the resulting landslide map will strongly depend on the experience of the investigator. Therefore, expert knowledge was incorporated in the tested method. Seven experts, all geomorphologists with significant experience in landslide mapping in Europe, East Africa or South America (Table 2), were given 1 h to indicate all the hillslope sections, which showed signs of presumed landslides on an A3-format copy of the two maps (scale: 1:100,000). As an example, one of the 135 field survey-based landslides was indicated on the maps (Fig. 1). Then the maps were scanned, georeferenced, and the indicated areas were digitized.

Two approaches were used to compare the maps based on hillshade maps and expert knowledge and the field survey-based inventory map, i.e., a polygon-based approach and a pixel-based approach. Each approach has its own parameters. The polygon-based approach was carried out in a vector GIS (Mapinfo). For each expert, the number of presumed landslides (N_{PLS}) was determined. Presumed landslides are all the sites indicated by the expert on the hillshade map. In contrast with the true landslides, which were mapped during the field survey, not all presumed landslides sites are in reality affected by landslides. The total area of presumed landslides (A_{PLS}) was obtained by summing up the areas of the presumed landslides. Next, for each expert, the number of correctly indicated landslides

Table 2
The different regions where the experts have investigated landslides and their familiarity with the study area in the Flemish Ardennes

Expert no.	Regions where the experts mapped landslides	No. of visits to the study area (Flemish Ardennes)
Experts familiar with region		
1	Belgium	Regularly
2	Europe, East Africa	Regularly
Experts not familiar with region		
3	Turkey	1
4	Ecuador	1
5	East Africa	1
6	Ethiopia	1
7	Spain	1

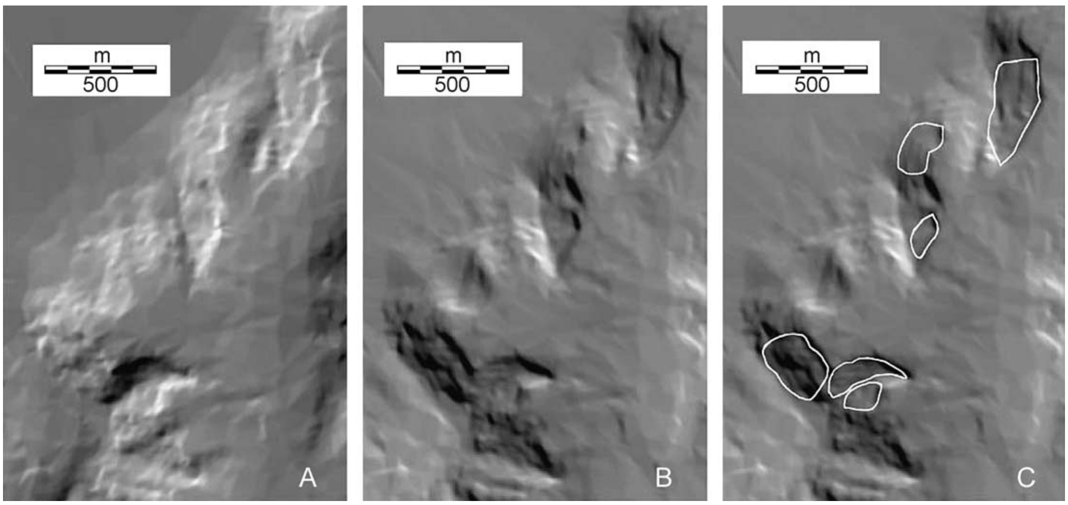

Fig. 3. (A) Hillshade map with sun azimuth angle of 315° for part of the study area. (B) Same part of the study area shown on hillshade map with sun azimuth angle of 45°. (C) Landslides mapped during the field survey. Not all landslides are clearly visible on both hillshade maps.

(N_{INDLS}) was determined. The correctly indicated landslides are the true landslides, which are totally or for more than one-half located within an area indicated as a presumed landslide. As some of the presumed landslides have an area of some tens of ha, several true landslides can be located within one presumed landslide. This explains why the number of correctly indicated landslides can be larger than the number of presumed landslides. Finally, the ratio of the number of correctly indicated landslides and the total number of true landslides (N_{INDLS}/N_{TLS}) was also determined.

The pixel-based approach was carried out in a raster GIS (IDRISI32). The number of presumed landslide pixels (N_{PLSP}), the number of correctly indicated landslide pixels (N_{INDLSP}) and the ratio of the number of correctly indicated landslide pixels and the total number of true landslide pixels (N_{INDLSP}/N_{TLSP}) were determined for each expert.

None of the aforementioned parameters, however, is appropriate to estimate the quality of the landslide maps because the number of correctly indicated landslides and landslide pixels increase with the number of presumed landslides and landslide pixels. The polygon efficiency ($E_{POLYGON}$) takes into account the number of incorrectly indicated presumed landslides and is here defined as

$$E_{POLYGON} = \frac{N_{INDLS} - (N_{PLS} - N_{INDLS})}{N_{TLS}}.$$

It is the ratio of the difference between the correctly and incorrectly indicated landslides and the total number of true landslides mapped in the field. Theoretically, this parameter varies between $-\infty$ and 1. A value of 1 means that an expert has indicated all true landslides without indicating any incorrect landslide. An expert will obtain a negative value for $E_{POLYGON}$ when the number of incorrectly indicated landslides is larger than the number of correctly indicated landslides.

Similarly, a pixel efficiency, E_{PIXEL}, was defined in this study as

$$E_{PIXEL} = \frac{N_{INDLSP}}{N_{PLSP}} \times 100.$$

This pixel efficiency is the ratio of the number of correctly indicated landslide pixels and the total number of presumed landslide pixels. Because of the small scale of the hillshade maps (1:100,000) and the used postprocessing method, it can be argued that this pixel efficiency is too rigid and therefore less useful for this study. It is highly probable that, during the indication as well as during the digitizing of the presumed landslides, small errors were introduced. But small errors of, for example, 1 mm on the hillshade map correspond to 100 m in the field. However, this pixel efficiency was the only way to take into account the total area indicated by the experts.

Table 2 shows that not every expert had the same familiarity with the study area. The first two experts had visited the region several times before the experiment was conducted, while the other five had visited the region only once. Therefore, two different groups of experts were defined, the familiar and the unfamiliar experts.

Finally, the landslide maps of the seven experts were combined. For this compilation map, all the listed parameters were calculated, and the obtained values were compared with the values from the seven maps. To obtain the number of presumed landslides on this combination map, presumed landslides overlapping for more than one-half were considered as one landslide.

4. Results and discussion

4.1. Landslide inventory map of the Flemish Ardennes based on field survey

Fig. 1 shows the location of the 135 field survey-based large landslides or true landslides on the hillshade map with a sun azimuth angle of 315°. Rotational earth slides are dominant (Table 1). Thirteen of these mapped landslides are not very clear in the field and were indicated as doubtful by the two geomorphologists. In total, these 135 landslides occupy 562 ha or 1.3% of the total study area (Table 4).

Although this field survey was carried out very cautiously, the landslide inventory map is incomplete and contains errors. Some old landslides erased by erosion or land leveling were probably overlooked during the field survey, and also, errors in the delineation of the landslide borders have to be taken into account. The second type of error could be especially important for this landslide inventory map because the edges of these old landslides are rather vague.

4.2. Landslide inventory maps of the Flemish Ardennes based on hillshade maps and expert knowledge

The landslide map produced by expert 3 is shown in Fig. 4A as an example. Fig. 4B shows the combination map of the seven experts. A distinction is made between the presumed landslides indicated by the two familiar experts and those indicated by the five unfamiliar experts. The latter group has indicated an area of almost 3360 ha as being affected by landslides (Table 3). This is 7.8% of the study area and four times the area indicated by the familiar experts.

For each expert, the aforementioned comparison parameters can be found in Table 3. Both for the

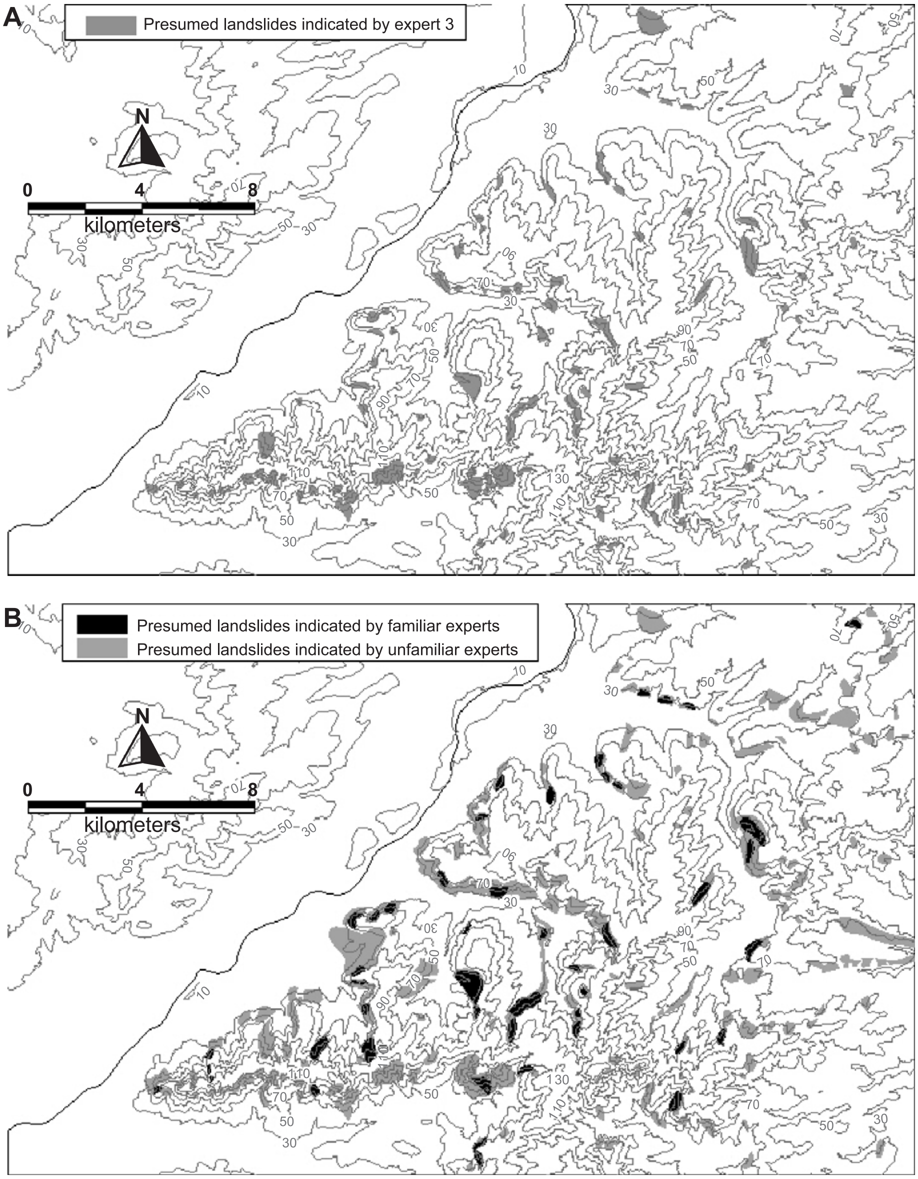

Fig. 4. (A) Landslide map produced by expert 3. The grey polygons are the sites with possible landslides indicated on the hillshade maps. The contours have an equidistance of 20 m. (B) Combination map showing the presumed landslides of the seven experts. A distinction is made between the familiar and unfamiliar experts.

Table 3
The parameters calculated for the landslide inventory maps based on expert knowledge and hillshade maps

Expert	Polygon based					Pixel based	
	N_{PLS}	A_{PLS} (ha)	N_{INDLS}	$N_{INDLS}/N_{TLS}\times100$ (%)	$E_{POLYGON}$	$N_{INDLSP}/N_{TLSP}\times100$ (%)	E_{PIXEL} (%)
Familiar with region							
1	68	422.8	57	42.2	0.34	41.2	51.5
2	50	571.9	53	39.3	0.41	40.8	37.8
Not familiar with region							
3	96	1114	54	40.0	0.09	41.0	19.4
4	102	1115.1	51	37.8	0.00	34.8	16.5
5	91	1526.4	44	32.6	−0.02	21.1	7.3
6	42	160.8	15	11.1	−0.09	5.7	18.9
7	49	500.8	36	26.7	0.17	21.5	22.7
Combination							
Familiar	75	789.8	70	51.9	0.48	55.0	36.8
Not familiar	214	3357.4	93	68.9	−0.21	68.9	10.9
All	234	3536.8	101	74.8	−0.24	73.7	10.8

N_{PLS}—number of presumed landslides; A_{PLS}—total area of presumed landslides; N_{INDLS}—number of correctly indicated landslides; N_{TLS}—number of true landslides (N_{TLS}=135); (N_{INDLS}/N_{TLS})×100—ratio of correctly indicated landslides and total number of true landslides; $E_{POLYGON}$—polygon efficiency or $[N_{INDLS}-(N_{PLS}-N_{INDLS})]/N_{TLS}$; N_{INDLSP}—number of correctly indicated landslide pixels; N_{PLSP}—number of presumed landslide pixels; (N_{INDLSP}/N_{TLSP})×100—ratio of correctly indicated landslide pixels and total number of true landslide pixels (N_{TLSP}=225029), E_{PIXEL}—pixel efficiency or (N_{INDLSP}/N_{PLSP})×100.

polygon-based approach as well as for the pixel-based approach, the results are not satisfactory. There are large differences among the seven experts. The number of presumed landslides ranged from 42 to 102. For the familiar experts and expert 7, the total area of presumed landslides is close to the total affected area based on the field survey (Table 4), whereas the total areas of experts 3, 4 and 5 are two or three times higher. Expert 6 indicated only some very small sites with a total area of 160 ha. The large area indicated by expert 5 also includes hillslopes probably affected by creep. Although common in the study area, features caused by creep cannot be distinguished on the hillshade maps. The two familiar experts indicated 57 and 53 of the 135 true landslides (N_{INDLS}). As mentioned above, a presumed landslide can contain more than one true landslide. This explains the larger number of correctly indicated landslides in comparison with the number of presumed landslides. Experts 3 and 4 were also able to indicate more than 50 true landslides. The results of the other 3 unfamiliar experts were worse.

The low quality of the individual expert maps is reflected by the low values of both the relative proportion of correctly indicated landslides and landslide pixels, as well as the polygon and pixel efficiency. Table 3 shows that the values obtained for the relative proportions of correctly indicated landslides are similar to the relative proportions of correctly indicated landslide pixels. The highest values were ca. 41%. This means that even the familiar experts and expert 3 could only indicate 41% of the true landslides. The pixel efficiency (E_{PIXEL}) takes into account the total number of indicated pixels. This explains the lower efficiency of expert 3 in comparison with the familiar experts. Expert 1 had the highest pixel efficiency. From the 100 presumed landslide pixels, this expert indicated that about 51 pixels were true landslide pixels. The unfamiliar experts have pixel efficiencies of 20% and lower which is far from satisfactory. The main purpose of this experiment was not to identify the 'exact' location of the large landslides in the study area but to identify hillslopes affected by landsliding. This pixel efficiency is a very rigid parameter. The value is strongly affected by the errors at the boundaries on the field-based landslide inventory map and the landslide map based on

Table 4
Comparison of the two methods used to create landslide maps, namely, the field survey and the tested method based on expert knowledge and hillshade maps

	Field survey	Hillshade map+expert knowledge
Number of experts	2	7
Time required to locate the landslides (days)	100	1
Number of landslides		
Ind	135 (1)	15–57 (2)
Comb	n.a.	101 (2)
Total affected area (ha)		
Absolute (ha)		
Ind	562	160–1526
Comb	n.a.	3537
Percent of total study area (42850 ha)		
Ind	1.3	0.4–3.6
Comb	n.a.	8.3
Ratio of correctly indicated landslides and total number of true landslides		
Ind	n.a.	11.1–42.2
Comb	n.a.	74.8
Ratio of correctly indicated landslide pixels and total number of true landslide pixels		
Ind	n.a.	5.7–41.2
Comb	n.a.	73.7
Polygon efficiency		
Ind	n.a.	−0.09–0.41
Comb	n.a.	−0.24
Pixel efficiency (%)		
Ind	n.a.	7.3–51.5
Comb	n.a.	10.8

For the individual experts (Ind), the minimum and maximum values are given.
n.a.—not applicable; Ind—landslide map of 1 individual expert; Comb—landslide map based on the combination of the seven expert maps; (1)—number of true landslides; (2)—number of correctly indicated landslides.

hillshade maps and expert knowledge. As mentioned above, the first map contains errors because of the imprecise boundaries, whereas the second contains errors because of the map scale and the postprocessing method. The polygon efficiency (E_{POLYGON}) is less rigid. Here, the total number of presumed landslides is taken into account instead of the total indicated area. However, Table 3 shows that this parameter also has low values. The familiar experts and expert 7 obtained the best results because they did not indicate many incorrect landslides. But due to the significant number of not indicated true landslides, the polygon efficiencies remained low. The negative values of experts 5 and 6 indicate that the number of incorrectly indicated presumed landslides is larger than the number of correctly indicated presumed landslides.

The combination maps had higher values for the number of correctly indicated landslides and for the relative proportion of correctly indicated landslide pixels. Fifty-two percent or 70 of the 135 true landslides were correctly mapped by the two familiar experts. With a value of 0.48, this combination map has the highest polygon efficiency of all the landslide maps. Therefore, this map can be considered as the best landslide map obtained from expert knowledge and hillshade maps. Together, the unfamiliar experts indicated 93 true landslides. One hundred and one true landslides or almost three-quarters were correctly mapped on the combination map of the seven experts (Fig. 4B). But together with this increase in correctly indicated landslides, there was a decrease in pixel and polygon efficiency resulting from an increase in incorrectly indicated presumed landslides and in area of presumed landslides.

In Section 4.1, it was already mentioned that 13 of 135 field-based landslides were doubtful. Six of these doubtful landslides were indicated by at least one unfamiliar expert. This may be an indication that the sites were truly affected by a landslide.

The results of this experiment show that the tested mapping technique based on expert knowledge and hillshade maps cannot replace the time-consuming field survey because the individual landslide maps, as well as the combination maps, do not contain an acceptable number of true landslides as observed in the field. The area incorrectly classified as unstable by the experts is also too large. To conclude, the most important differences between the two methods used in this investigation are summarized in Table 4.

4.3. Comparison with a similar study by Wills and McCrink (2002)

As the interpretation of topographical maps is more commonly used as a screening tool before more in-depth mapping, little comparable landslide inventories were found. The investigation of Wills and McCrink (2002) is quite similar. For a study area in the Santa Cruz Mountains, CA, these authors compared landslide inventory maps derived from (1) a geological map, (2) aerial photographs, (3) aerial photographs with ground verification (including previously mapped landslides still visible on the photos), (4) topographical maps (1:24,000) and (5) a detailed field survey. For a comparison with our results, only the fourth and fifth inventory maps are interesting. For the fourth inventory map, one geologist tried to distinguish landslide features from irregularities in the contour lines on the topographical map (1:24,000). The mapping and postprocessing took only 80 h, which made it a very cheap mapping technique. The creation of the field survey-based inventory map on the other hand took more than 1100 h and was therefore very expensive.

The results of Wills and McCrink (2002) are similar to those obtained in our study. Using the terminology defined in Section 3.2, the landslide inventory based on the interpretation of the contour lines contained only 393 presumed landslides, whereas 2338 true landslides were mapped during the field survey. The average affected area of the landslides, on the other hand, was much larger for the first inventory map than for the latter (i.e., 10.2 versus 0.6 ha). Especially the map scale, the contour interval (i.e., 40 ft or 12.2 m) and the dense vegetation cover limited the size of the discernable landslides on the inventory derived from the topographical map. The comparison of both inventory maps resulted in an overlap of 49%. This value can be compared with the ratio of the number of correctly indicated landslide pixels to the number of true landslide pixels (Table 3). The results obtained by experts 1 to 4 are somewhat worse than those obtained by Wills and McCrink (2002), but the combination maps have higher ratios. Wills and McCrink (2002) did not take into account the area incorrectly indicated as unstable on the landslide inventory based on the topographical map. Important to note is that, for the densely vegetated area in the Santa Cruz Mountains, the comparison of the first four inventory maps with the field survey-based inventory revealed that the landslide inventory based on the contour lines was the best alternative for the detailed the field survey.

4.4. Improvements and recommendations for future use

Some improvements in the tested technique can probably lead to better results. First, the map should be printed on a larger scale. The hillshade map is produced from a DEM with a 5-m resolution that was created by digitizing the contours of a 1:10,000 topographical map. The scale of the printed hillshade maps was 1:100,000. At a larger scale, the map will be more detailed, and more true landslides will become visible. This is confirmed by the observation that, on a digital version of the hillshade map, the main scarps of some landslides not indicated by the experts are clearly visible at a larger scale. Therefore, a second improvement would be to provide a digital hillshade map to the experts. This enables them to zoom in and out whenever they feel it is needed. In addition, direct digitizing by the experts becomes possible. Although this direct digitizing on a digital hillshade map will entail an increase in the time spent by each of the experts, the associated increase in the production cost of the maps will be less important than the increase in the quality of the maps. Taking into account the suggested improvements, the tested technique could be very useful for the creation of regional inventories of old deep-seated landslides in densely forested areas where vegetation hampers the use of aerial photographs and satellite images. However, for recently initiated or reactivated landslides, landslides with a limited affected area (i.e., smaller than ca. 0.5 ha) and landslides located on hillslopes with few or no trees, the proposed technique cannot replace the use of remote sensing images. Apart from the suggested mapping technique, the parameters introduced in this study, the polygon and pixel efficiency, will also be very useful for the comparison of different landslide inventory maps in similar studies.

There is no doubt that better results could be obtained when the altitudes used for the creation of the hillshade maps are derived from laser altimetry and not from a topographical map (Wills, 2002). The altitudes on topographical maps are often extracted from aerial photographs. For forested areas, the altitude of the soil surface is then defined as the difference between the altitude of the treetops and the average height of the trees. This results in a less accurate altitude under forest and therefore in a decrease of quality of the landslide inventory. However, at present, the availability of laser altimetry data is restricted.

5. Conclusions

A method based on expert knowledge and hillshade maps was tested to produce reliable landslide inventory maps for a large study area characterized by old landslides. The location of these landslides under forest disabled the more commonly used technique of aerial photo interpretation to map the landslides. The results indicate that there are considerable differences between the landslide maps produced by experts familiar with the study area and the corresponding landslides on the one hand and unfamiliar experts who visited the study area only once on the other hand. This difference in familiarity could not be eliminated through the indication of one landslide as an example on the hillshade maps.

The results further indicate that expert knowledge applied to a hillshade map at a scale of 1:100,000 did not result in an acceptable landslide inventory map. Four experts, two familiar and two unfamiliar experts, were able to indicate between 51 and 57 of the 135 true landslides. For these experts, the pixel efficiency ranged from 51.5% to 16.5%. For the two unfamiliar experts, the value of the polygon efficiency approached 0 because the number of incorrectly indicated presumed landslides was almost equal to the number of correctly indicated presumed landslides. With values of 0.34 and 0.41, the familiar experts obtained somewhat better results for the polygon efficiency. The results of the other three experts were worse. After combining the maps of the seven experts, 75% of the true landslides were indicated, but the polygon and pixel efficiency decreased strongly, the first because of the large number of incorrectly indicated presumed landslides and the latter because of the large presumed area (ca. 8% of the total study area). Hence, this approach cannot replace detailed field surveys. The use of hillshade maps at a larger scale (1:10,000–1:20,000), direct digitizing by the experts and more detailed DEMs based on, e.g., laser altimetry could produce more reliable results, especially for the mapping of old deep-seated landslides in densely forested areas.

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References

Ardizzone, F., Cardinali, M., Carrara, A., Guzzetti, F., Reichenbach, P., 2002. Impact of mapping errors on the reliability of landslide hazard maps. Natural Hazards and Earth System Sciences 2, 3–14.

Bentley, S.P., Siddle, H.J., 1996. Landslide research in the South Wales Coalfield. Engineering Geology 43, 65–80.

Brardinoni, F., Slaymaker, O., Hassan, M.A., 2003. Landslide inventory in a rugged forested watershed: a comparison between air-photo and field survey data. Geomorphology 54, 179–196.

Carrara, A., Cardinalli, M., Detti, R., Guzzetti, F., Pasqui, V., Reichenbach, P., 1991. GIS techniques and statistical models in evaluating landslide hazard. Earth Surface Processes and Landforms 16, 427–445.

Carrara, A., Cardinali, M., Guzzetti, F., 1992. Uncertainty in assessing landslide hazard and risk. ITC Journal 2, 172–183.

Cruden, D.M., Varnes, D.J., 1996. Landslide types and processes. In: Turner, A.K., Schuster, R.L. (Eds.), Special Report 247: Landslides, Investigation and Mitigation, Transportation Research Board, National Research Council. National Academy Press, Washington, DC, pp. 36–71.

Demoulin, A., Pissart, A., Schroeder, C., 2003. On the origin of late Quaternary palaeolandslides in the Liège (E Belgium) area. International Journal of Earth Sciences 92, 795–805.

De Vos, W., 1997. Influence of the granitic batholith of Flanders on Acadian and later deformation (Brabant Massif, Belgium). Aardkundige Mededelingen 8, 49–52.

Gold, R.D., 2004. A Comparative Study of Aerial Photographs and LIDAR Imagery for Landslide Detection in the Puget Lowland, Washington. Washington Division of Geology and Earth Resources Open file report 2004–2006, 66.

Guzzetti, F., Cardinali, M., Reichenbach, P., Carrara, A., 2000. Comparing landslide maps: a case study in the Upper Tiber River Basin, Central Italy. Environmental Management 25, 247–263.

Haugerud, R.A., Harding, D.J., Johnson, S.Y., Harless, J.L., Weaver, C.S., Sherrod, B.L., 2003. High resolution Lidar topography of the Puget Lowland, Washington—a bonanza for earth science. GSA Today 13 (6), 9.

IAEG Commission on Landslides, 1990. Suggested nomenclature for landslides. Bulletin of the International Association of Engineering Geology 41, 13–16.

I.W.O.N.L., 1987. Bodemkaart van België: Verklarende tekst bij het kaartblad Ronse 98E. Uitgegeven onder de auspiciën van het Instituut tot aanmoediging van het Wetenschappelijk onderzoek in Nijverheid en Landbouw.

Jacobs, P., De Ceukelaire, M., De Breuck, W., De Moor, G., 1999. Toelichting bij de geologische kaart van België, Vlaams gewest, kaartblad 29 Kortrijk, schaal 1/50000. Ministerie van Economische zaken en Ministerie van de Vlaamse Gemeenschap, pp. 68.

Liu, J.K., Woing, T.C., 1999. A practical approach to creating a landslide database using Taiwan SPOT Mosaic. Proceedings of the 20th Asian Conference on Remote Sensing (ACRS 1999). Hong Kong, available online at: http://www.gisdevelopment.net/aars/acrs/1999/ts12/ts12513.shtml.

Mather, A.E., Griffiths, J.S., Stokes, M., 2003. Anatomy of a fossil landslide from the Pleistocene of SE Spain. Geomorphology 50, 135–149.

McKean, J., Roering, J., 2004. Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry. Geomorphology 47, 331–351.

Ost, L., Van Den Eeckhaut, M., Poesen, J., Vanmaercke-Gottigny, M.C., 2003. Characteristics and spatial distribution of large landslides in the Flemish Ardennes (Belgium). Zeitschrift für Geomorphologie 47 (3), 329–350.

Petley, D.N., Crick, W.D.O., Hart, A.B., 2002. The use of satellite imagery in landslide studies in high mountain areas. Proceedings of the 23rd Asian Conference on Remote Sensing (ACRS 2002). Kathmandu, available online at: http://www.gisdevelopment.net/aars/acrs/2002/hdm/48.pdf.

Singhroy, V., Mattar, K.E., Gray, A.L., 1998. Landslide characterization in Canada using interferometric SAR and combined SAR and TM images. Advances in Space Research 21 (3), 465–476.

Soldati, M., Corsinia, A., Pasuto, A., 2004. Landslides and climate change in the Italian Dolomites since the Late glacial. Catena 55, 141–161.

Vanmaercke-Gottigny, M.C., 1980. Landslides as a morphogenetic phenomenon in a hilly region of Flanders (Belgium). In: De Boodt, M., Gabriels, D. (Eds.), Assessment of Erosion. John Wiley and Sons, Chichester, pp. 475–484.

Van Westen, C.J., Seijmonsbergen, A.C., Mantovani, F., 1999. Comparing landslide hazard maps. Natural Hazards 20, 137–158.

Wieczorek, G.F., Jäger, S., 1996. Triggering mechanisms and depositional rates of postglacial slope-movement processes in the Yosemite Valley, California. Geomorphology 15, 17–31.

Wills, C.J., 2002. Acquisition of a LIDAR survey of the highway 299 corridor, Humboldt County, California and preliminary analysis of its utility for landslide mapping, summary report. California Geological Survey, 16.

Wills, C.J., McCrink, T.P., 2002. Comparing landslide inventories, the map depends on the method. Environmental and Engineering Geoscience 8, 279–293.