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MAP OF LANDSLIDES ON THE COMMUNE SCALE BASED ON SPATIAL DATA FROM AIRBORNE LASER SCANNING

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Abstract: Airborne Laser Scanning (ALS) has proven to be a helpful tool in landslides analysis. The purpose of the study was to determine the ability to identify areas of landslide activity at the commune scale (township scale) based on ALS data. Two researchers, who lacked knowledge concerning the study area, used point clouds to prepare a DEM, and then identified landslides as well as hazardous areas. The second part of the research team, who previously had performed detailed landslide mapping in the study area, had the task of verifying the outcomes of the first stage of research. Combined analysis of mistakes was performed and the capabilities and limitations of the method were established. Mistakes originating in either the vague parts of the point cloud DEM or terrain landslide mapping in forested areas were identified.

Keywords: landslide mapping, airborne laser scanning (ALS), digital elevation model (DEM), Łososina Dolna Commune

1. INTRODUCTION

In recent years, laser scanning has become one of the elementary tools in the analysis of mass movements (Jaboyedoff et al., 2012). Its short time of field source data collection, high accuracy of measurements, and multidimensionality of the obtained information have led to rapid development of laser scanning in environmental research. Opportunities provided by laser scanning are used in geomorphology, (e.g. Jaboyedoff et al., 2012; Owerko et al., 2013), hydrology (e.g.. Milan 2009), forest management (e.g. Alberti et al., 2013; Wężyk et al., 2013), as well as archaeology (e.g. Valzano et al., 2005; Crutchley 2009).

One of the first studies concerning the identification of landslides based on ALS data was done by a Dutch group analyzing landslides in a forested area. The interpretation of the extent of landslides on a DEM by seven independent experts was compared in order to yield new knowledge. The research revealed a substantial discrepancy in the interpretation of the available DEM; areas of landslides delineated by the seven experts accounted for between 116 and 744 ha (Van den Eeckhaut et al., 2007).

Landslide studies based on DEMs obtained from ALS point clouds have been recently significantly improved (e.g. Ardizzone et al., 2007; Bell et al., 2012; Razak et al., 2013; Tarolli 2014, Ciampalini et al., 2016). Automatic delimitations of landslides on detailed DEM is very promising, but still not perfect approach (e.g. Booth et al., 2009; Niculiţă 2015; Pawłuszek & Borkowski 2017). Combining two methods: field mapping and remote sensing data analysis is, so far, the only approach that gives appropriate results. Nowadays, LIDAR based DEM become basic data for landslide analysis, but after over two decades of research there is still many challenges in interpreting terrain models. Comparing field mapping and DEM analysis (Kroh et al., 2014; Leopold et al., 2017; Dolžan & Auflič 2017) shows, that proper landslide mapping based on terrain models requires a more detailed analysis.

Studies using ALS were also conducted in Poland, near the town of Zbyszyce in the Ciężkowickie Foothills (Wojciechowski 2012), town of Gródek nad Dunajcem (Borkowski et al., 2011), as well as in the town of Kłodne in the Limanowa Commune (Wójcik et al., 2011), which is a geographic area adjacent to our study area. LIDAR is used by the Polish Geological

Institute of the National Research Institute for the purpose of monitoring landslides, particularly within the framework of Poland’s System of Landslide Protection SOPO (http://geoportal.pgi.gov.pl/SOPO/aplikacja).

ALS provides the opportunity to pursue large-area studies. The broad accessibility of laser scanning data forces the establishment of a new methodology for the recognition of landslide high risk areas. The application of ALS in Poland as part of the “Information System of National Protection Against Extraordinary Hazards” (Polish acronym: ISOK) creates new opportunities for ALS data. The widespread application of DEMs obtained from the ISOK project as part of environmental studies provides a chance to explore new areas of research. One of these new potential opportunities is the identification of landslide hazard areas in Poland. The scientific description of the research method for such areas enables not only the identification of such areas, but also the verification of “local spatial plans” or local zoning plans in Poland.

The main purpose of the research was to compare the data obtained from common field geomorphological mapping of landslides with the raw spatial data obtained from ALS done within the framework of the ISOK project (point cloud data); to examine the relevance of landslide identification on the commune scale in terms of ALS data analysis. Furthermore, the study aimed to assess the relevance of ALS data and the Database of Topographical Objects (BDOT) for the identification of buildings located on the surface of landslides.

2. STUDY AREA

The study area – the Łososina Dolna Commune (Fig. 1) – is located in the Polish flysch Carpathians on the boundary between the Beskidy Mountains (Beskid Wyspowy) and the Carpathian Foothills (Starkel 1972). The highest peak of the Łososina Dolna Commune in the Beskidy part exceeds 900 m asl (Jaworz, 921 m asl). In the part of the study area located in the foothills, elevations exceed 400 m asl (Ostra Góra 455 m asl).

The Łososina Dolna Commune stretches across the Outer Carpathian geological unit, which consists of flysch rocks dated from the Cretaceous and Paleogene (Burtan and Skoczylas-Ciszewska 1964, Cieszkowski 1992, Burtan et al., 1991, Paul 1997). The Magura Nappe is built mainly of hieroglyph layers (thin layered sandstones and shales with admixture of thick layered sandstones; the proportion of sandstones and shales is 1:1) and magura sandstones (thick 0.7-2.0 m layered sandstones). The foothill part of the community is built of Silesian unit rocks and Michalczów zone rocks which are built mainly of sandstones and shales with admixture of mudstones and marls.

The relief of the Beskid Wyspowy part of the commune is mainly low, middle mountains (Starkel 1972). The slope gradient in the study area ranges from 10 to 35^{o}, relative heights range from 300 to 340 m in the mountain part of the commune and from 140 to 180 m in the foothill part of the commune. Slope length ranges from 0.6 km to about 1 km.

In the foothill part of the study area (Wielickie Foothills), relief is *low-hill-type*, with small patches of the *midsize foothill type* (according to Starkel 1972). Therefore, relative heights range from 120 to 150 m, while slopes are short and range from 5 to 25^{o}.

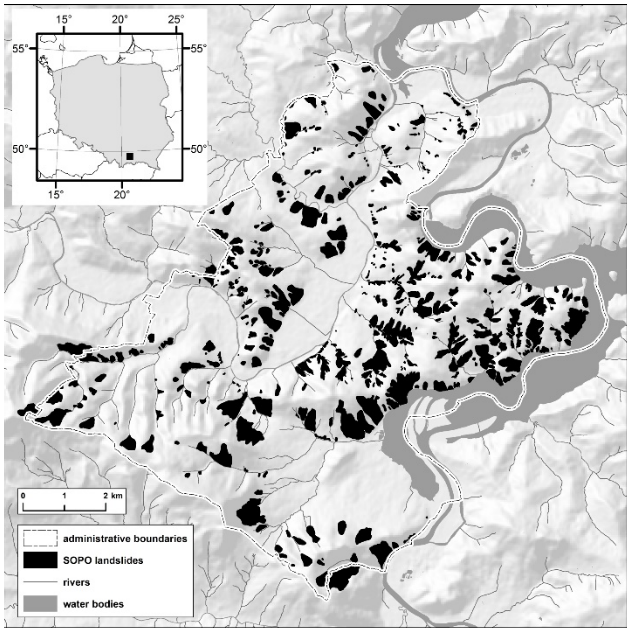

Figure 1. Location of the study area and SOPO landslides inventory.

The Łososina Dolna Commune is located in a main part along the Rożnowski Reservoir, built in 1930 on the Dunajec River. Some parts of the commune are also drained by the Łososina River. The commune is mostly agricultural (54%), while forests occupy 26% of the study area. The area also produces fruit and vegetables. It also attracts some tourists. Residential areas are scattered, but more compact built-up areas are found in valleys and single homesteads can be found at higher elevations (750 m) on slopes, in forest clearings, and along local drainage divides (Gorczyca & Wrońska-Wałach 2011; Gorczyca et al., 2013).

Most of the studied landslides became active prior to the period of fieldwork. The activation of landslides in the Carpathians occurred in 2010 and was the result of high precipitation in May and June in southern Poland. Precipitation during May was 300-350% and during June was 170-180% of 1971-2000 average (which is for May 100-110 mm, and for June 110-120 mm) (Monthly Climate Monitoring Bulletin 2010, http://old.imgw.pl/klimat). Two precipitation periods (several days each) were the most important in the activation of landslides in 2010. The first period occurred from May 15 to May 20 and was associated with rain-bearing low pressure moving along track V-B from the Adriatic Sea to the Balkans and Carpathians. The highest precipitation occurred during this period in the western part of the Polish Carpathians, exceeding 300 mm in total. The next period occurred from May 31 to June 4 and was associated with a low pressure system moving in from the Atlantic Ocean to southern Germany and later on to the Romanian Carpathians. The highest precipitation, exceeding 150 mm per day, was recorded in the study area in the Beskid Wyspowy Mountains as well as the Nowosadecka Basin. A series of clustering precipitation events recorded in the study area along with the coincidence of rainstorms and continuous precipitation contributed to a loss of stability on slopes and a large-scale intensification of mass movements (Gorczyca et al. 2013).

3. METHODS

The general assumptions of laser scanning have already been presented in many previous studies (i.e. Graniczny 2012; Wojciechowski 2012; Heritagem and Large (eds.) 2009). The method that we have decided to apply in the current study we have called "specialist subjectivism." The assumption behind the method was to identify landslide areas only on the basis of a DEM produced using point cloud data. The newly produced maps were then verified. Two researchers who do not know the study area, but are able to analyze point clouds, produced the DEM and then used it to identify landslides. Given the researchers' required qualifications (geographers who frequently have contact with both landslides and their representations in the form of maps or other spatial data), it is difficult to assess the objectivity of the data interpretation in this study. Therefore, subjectivity was assumed in the method presented. Hence, source data were obtained in two different ways: (1) field surveys of landslides, (2) digital analysis of data obtained from laser scanning. Analysis of buildings located on landslides was done via the use of point cloud data obtained from the ISOK project obtained in the framework of INSPIRE (Infrastructure for Spatial Information in the European Community) project and the Topographical Objects Database 10k (BDOT10k). The research procedure is described in detail below.

3.1. Fieldwork

Field surveys in the study area were performed in the years 2010–2011 (Fig, 2, 3). In the following parts of the manuscript field mapping is called SOPO. On maps, areas of existing landslides as well as areas threatened by landslides were presented. (Gorczyca and Wrońska-Wałach 2011). The fieldwork was conducted with the precision of 5m, and included geomorphological and geological mapping and assessment of landslide activity. Also risk assessment for infrastructure and buildings as well as landslide susceptibility for whole commune area were conducted.

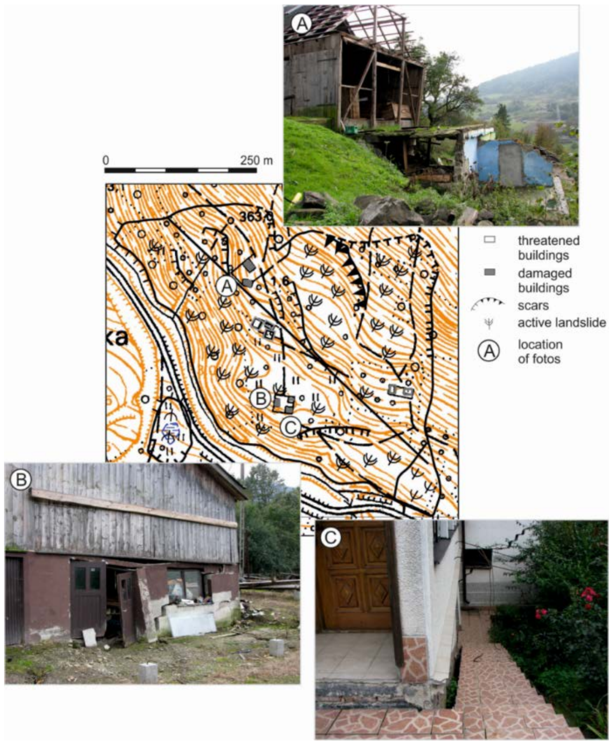

Figure 2. Sample landslide with location of buildings shown; A, B, C – damaged buildings. Sketch by E. Gorczyca.

Topographic map on 1:10 00 scale was the base to present field surveys (Fig 2). The study was done via research methods approved by the Polish Geological Institute of the National Research Institute ("SOPO Landslide Protection Program"; Grabowski et al., 2008). SOPO database, with maps of landslides and their activity together with full documentation (identification cards) are available on public geoportal (http://geoportal.pgi.gov.pl/).

3.2. Digital analysis of data

The study began with the purchase of spatial data – a cloud of points – and a Topographic Objects Database from Poland's Main Office of Geodesy and Cartography. The point cloud from ISOK project has the sampling density four points per square meter. The classes required for the visual interpretation of relief as well as for the assessment of buildings located on landslides were selected from the cloud of points. These included "ground" and "building" categories, as in *.las 1.2 format. A DEM with 0.5 m resolution was generated from the class "ground" via the LasTools operating tool in the ArcGis system. Maps were constructed using the DEM hillshade tool. Shading from four directions (45°,135°, 225°, 315°) were used. The displaying of individual hillshades for landslide extent identification significantly simplified the study. Plotting as well as assessment of landslide extent was done on the desktop monitor (ArcGIS/QGIS). About 48 hours of work was dedicated to this step of analysis in the case of the two researchers working with the DEM. In the following parts of this manuscript, the two researchers will be designated: R1 and R2. Landslides shown on the DEM were surveyed by focusing on relief features such as outstanding concave and convex landforms, both increases and decreases in slope gradient, shape of slope meso-forms, fractures, and other non-anthropogenic linear elements.

Figure 3. Examples of relief interpretations during field research. Foto by E. Gorczyca.

Identification of buildings located on the surface of landslides was performed based on data obtained from two different sources. The one was provided as a point cloud data from ALS and the second was taken directly as a vector layer "building" from BDOT10k. Objects from the point cloud data classified as "building" were converted to shape file format and converted into polygons applying function "Merge" in ArcGIS Software. All polygons smaller than 15 square meters were excluded as no buildings and errors associated with either data collection or transformation. Subsequently, localization of buildings was compared with landslides designated by R1 and R2 researchers using tools "Intersect" in ArcGIS Software.

Data from Topographic Objects Database 10 k (BDOT 10k) are created on the basis of technical requirements established by Poland's Ministry of the Interior and Administration on November 17, 2011. This is currently the most important source of information on topographic objects in Poland, with accuracy and detail corresponding with topographic maps at a scale of 1:10 000. Analysis based on BDOT data was performed in an analogous manner as the analysis described above for the "building" layer. The "BUBD" layer that includes "buildings, structures and devices" was also taken under consideration (Tab 1.). Additional classification work was done following the generation of buildings located on landslides. One class was called "residential buildings," (codes BUBD01-04, Tab. 1). The remaining objects (codes BUBD05-BUBD21), were placed in a second class. The above listed codes are explained in table 1, on basis of the Official Ordinance of the Ministry of the Interior and Administration from November 17, 2011 for topographic objects and a general geographic database as well as standard cartographic work (Journal of Laws 279, Item 1642).

4. RESULTS

Based on fieldwork in 2010-2011, done as part of the SOPO Landslide Protection Program in Łososina Dolna Commune, 572 landslides were documented (Fig. 1) with a total surface area of 1,280 ha. 298 landslides were identified as a fully active, 69 partially active, and 205 inactive landslides. Small in area landslides prevailed. 57% of all documented landslides had an area of less than 1 ha (total area, 102.5 ha), 32% had an area of 1–5 ha (total area, 425.9 ha), 6% had an area of 5–10 ha (total area, 223.46 ha), and 5% had an area of more than 10 ha (total area, 525.43 ha).

Large rock landslides occurred in mountain part of the commune. They were usually inactive and located in forests, on upper part of slope and in headwater areas. In the Łososina Dolna commune the area most predisposed to landslide activity neighbors with the Rożnowski Reservoir. In 2010 active landslides were documented mainly on lower slopes and in small valleys, on abandoned or still cultivated arable land or meadows. A significant part of landslides, are fully active (108 cases with an area of 253 ha) or partially active (12; 118 ha), which causing a substantial threat for transport and housing infrastructure. 23 landslides destroyed or damaged about 80 buildings (Fig. 2). 19 landslides seriously damaged roads, including a national highway no. 75. On 15 landslides power transmission lines were damaged.

Residential houses, commercial buildings, and roads are documented on 160 landslides: 468 houses and 432 commercial buildings were documented to be located on either active or inactive landslides. The large number of new and old buildings situated on the surface of active/partly active landslides is the result of inadequate landslide identification and the lack of local zoning laws. Approximately 100 of landslides were reactivated in 2010. Severe damage to property has been recorded on 49 landslides – almost 140 destroyed or damaged buildings. Active landslides (in 45 cases) in many parts of the commune also damaged road surfaces and embankments. The most important issue was national highway no. 75 which is endangered by nine active landslides and ten periodically active and inactive landslides.

The basis for the spatial accordance of landslides consisted of three shape *.shp layers. A comparison of the area of SOPO landslides with data obtained from the DEM yields quite similar results. The total area of SOPO landslides was 1,280 ha (Table 2). Both researchers analyzing cartographic materials identified a larger area affected by landslides. R1 identified 1,455ha (14% more than SOPO) as landslide areas, while R2 identified 1,549 ha (21% more than SOPO). A high discrepancy occurred when we compared the number of landslides. During the SOPO mapping process, a total of 572 individual landslides were identified. The number of landslides identified on the basis of the DEM employed in the study was different; R1 identified 489 landslides and R2 identified 194 landslides (Table 2).

Table 2. Discrepancies in the surface area and number of landslides obtained based on detailed terrain landslide mapping and identified on a Digital Elevation Model.

	Surface area [ha]	Surface area [%]	No. of landslides
SOPO	1280	100	572
R1	1455	114	489
R2	1549	121	194

Table 1. Coding system used in the Topographic Database and explanation of codes for "buildings" category (on base of Journal of Laws 279, Item 1642).

Code	Category name	Code	Structure class name	Code	Structure name	Number of structures within commune
BU	Buildings, civil structures and facilities	BUBD	Building	BUBD01	single-family residential building	3536
				BUBD02	double-flat buildings	2
				BUBD03	buildings with three or more flats	9
				BUBD04	collective residential buildings	5
				BUBD05	Hotels	13
				BUBD06	touristic accommodation	5
				BUBD07	office buildings	8
				BUBD08	public buildings and facilities	57
				BUBD09	service and terminal buildings	3
				BUBD10	Garages	4
				BUBD11	industrial buildings	23
				BUBD12	warehouse buildings, silo and store tanks	27
				BUBD13	culture objects open for general use	2
				BUBD14	libraries and museum buildings	1
				BUBD15	school and research institute buildings	13
				BUBD16	hospital and medical care buildings	2
				BUBD17	physical culture buildings	1
				BUBD18	farm buildings	2687
				BUBD19	buildings dedicated to religious worship	13
				BUBD21	unclassified buildings	1

Table 3. Discrepancies in the number of buildings located atop landslides in relation with different methods of landslide area identification.

	ISOK data on the number of buildings on landslides	Difference in the number of buildings [%]	BDOT data on the number of buildings on landslides	Difference in the number of buildings [%]
SOPO	1344	100	1121	100
R1	1365	102	1144	102
R2	1405	104	1184	106

When we look at the buildings located on the surface of landslides, the similarity of data obtained using different methods is quite high (Table 3). The smallest number (1,344) of buildings was recorded for landslides identified by SOPO, while the largest for landslides identified by R2 (1,405). The difference between the largest and the smallest number of buildings potentially affected by landslides was 61. The identification of buildings based on BDOT data produced divergent results. A total of 1,121 buildings were identified on landslides discovered via SOPO, while 1,144 buildings were identified on landslides noted by R1 and 1,184 buildings were identified on landslides noted by R2. The difference between SOPO and R2 was 6%. The discrepancy between ISOK and BDOT data and the strong agreement in the number of buildings located on the surface of landslides are discussed below.

5. DISCUSSION

The cause of an abundance of so many landslides in the study area is the presence of faults and joints as well as its location on the boundary between the Magura and Silesian nappes' overthrust. A characteristic feature of the study area is the occurrence of rocks with different mechanical properties (sandstone, shale) relatively close to one another. It may be assumed that favorable rock stratification as well as infiltrating rainwater and snowmelt contributed to the activation of the great majority of these landslides. Another main trigger is river erosion undercutting slopes and landslide foreheads. A factor which additionally affected landslide development and further reactivation in the study area is the construction of the Dunajec River Reservoir in the 1930s (Ziętara 1973). Today, in addition to natural factors, human impact may also play a role in landslide activation in the study area. This includes shocks and vibration coming from road traffic and a lack of drainage due to the paving of roads and other types of manmade construction.

The presented research results require discussion in the context of many aspects including the number of landslides, their surface area and geographic location, number of buildings identified via different methods, and discrepancies in the collected data. Strong discrepancies in the number of landslides identified by SOPO, R1 and R2 are quite interesting and require closer look. In the parts of the studied commune highly transformed by landslides, individual landslides either border or overlap with one another. In such an area, the identification of a single landform and what should by spliced into two or three landforms is difficult and ambiguous. In effect, the identification of boundaries between landslides is quite arbitrary. The question which appeared here is whether there is a need for such delineations.

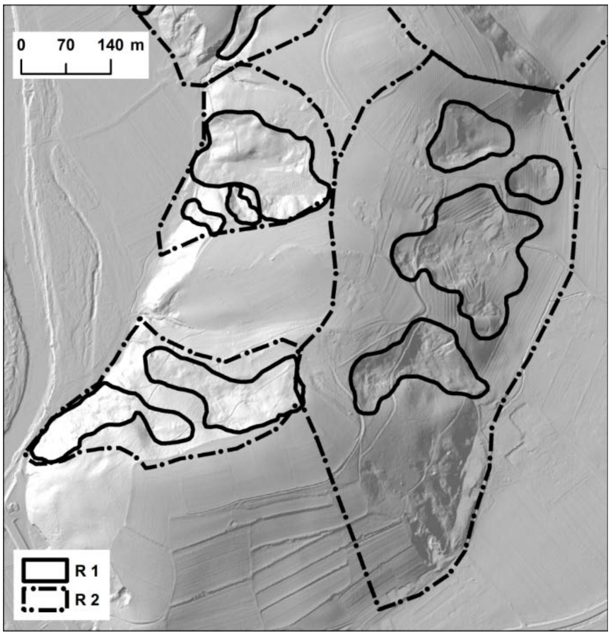

Figure 4. Comparison of the results of landslide tracing by two researchers of which the first was focused on separated landslides and the second was focused on the identification of landslide hazard areas (for explanation see in text). Sketch by P. Struś.

Detailed mapping of individual landslides or their parts is not important at the commune scale of analysis. It is important to recognize; which part of the commune is affected by landsliding. Therefore, different methodological assumptions were produced for the two researchers working on this study. The purpose of R1 was to record single landforms. The R2 was more focused on the location of landslide zones/slopes, as opposed to single landslides – combining landslide areas into uniform polygons (Fig. 4). The discrepancy in the number of landslides with higher compatibility in terms of the landslide area was due to differences in the methodological approach.

Areas recorded by SOPO as landslides were the basis for the quantitative analysis of data. It was assumed that the total area of field-mapped landslides amounts to 100% of landslides in the studied commune. However, an analysis of DEMs shows landslides that were not recorded during the fieldwork, making such assumptions not consistent with reality. During the fieldwork, 1,280 ha of landslides were mapped. SOPO assumptions made it necessary for the field team to survey landslides in terms of their immediate threat to infrastructure and other useful structures found in the study area, which meant that field teams needed to accurately distinguish landslide areas from non-landslide areas in order not to exaggerate the threat to infrastructure.

Researcher R1 recorded 1,455 ha, which is 114% of the area of the base layer; at the same time, R2 recorded 1,549 ha, which gives 121% of the total area mapped in the field. It is worth noting that the approach of the two researchers analyzing DEMs was different. The assumption of R1 was to identify each single landslide; hence, such a layer was the most consistent with fieldwork. Accordingly, a 14% difference appears to be quite small. The compatibility of the conducted delimitation is truly high. A great majority of landslides do not deviate in terms of the boundaries identified by different researchers. On the other hand, overestimation of landslide areas was a consequence of the approach taken by the second researcher (R2). Within area classified by R2 as landslides, many small individual landslides occurred. Such an approach does not provide accurate results, but it may be relevant for the local spatial management plan (i.e. zoning laws), which identifies slopes and landslide areas, but not individual landslides. Combining the areas found between landslides into uniform polygons increases the total area of the studied landslides. In this context, 21% as a difference does not appear to be very high.

Consistency of total landslide area does not have to indicate consistency in terms of particular landslides. To verify such a hypothesis, overlapping areas were identified from maps produced by a field research group (SOPO) as well as both digital mapmakers (R1 and R2). The results of the analysis are presented in Table 4. The area noted as consistent, which means identified by both the SOPO team and R1, stands at 938 ha or 74% of landslides identified by the SOPO team. What follows from this is that 26% of landslides recorded in the field were not identified by R1. Comparison between SOPO and R2 yields 824 ha (65% of SOPO). This is 35% of landslides not noted by R2. Consistency between R1 and R2 stands at either 68% or 64%, depending on the layer taken as a reference.

Table. 4. Landslide surface areas, as identified by different researchers.

	Overlapping area [ha]	% surface area (*1) identified by (*2) [%]	% surface area (*2) identified by (*1) [%]
SOPO (*1) / R1 (*2)	938	74	64
SOPO (*1) / R2 (*2)	824	65	53
R1 (*1) / R2 (*2)	991	68	64

Similarity in the number of buildings located on landslides taken from three different sources suggests high potential usefulness of laser scanning and cloud point data analysis for spatial planning purposes. Despite differences in the area of landslides (21%, see. Table 2), uniformity was noted in terms of the number of landslide-affected buildings. Nevertheless, total differences between layers are higher than they appear to be. Such a uniformity in the number of buildings (Table 3) is partly the result of actual uniformity and partly an effect of the dispersion of errors.

In the study area, we encounter all possible inconsistencies in data. Buildings which were identified as landslide-affected during fieldwork were not identified by the two researchers (R1 and R2). In addition, buildings overlooked in the course of fieldwork were identified by the researchers. Some buildings identified by one of the researchers were not identified by the second researcher and researchers working in the field (Fig. 5). The lower number of landslide-affected buildings (1,364) identified in the course of fieldwork should not be equated with that identified using the DEM. Discrepancies in data are the result of many different factors. Due to the higher reliability and relevancy of BDOT data in comparison with cloud points, the following analysis focuses on it. Data on buildings located on the surface of landslides for the entire studied commune proved to be quite consistent (Table 5). The research team realized that actual results would not be as consistent as averaged data, steps were taken to evaluate the actual consistency level of the data. Thematic layers were superimposed on one another for each digital map used and it was determined which buildings are located on landslide areas.

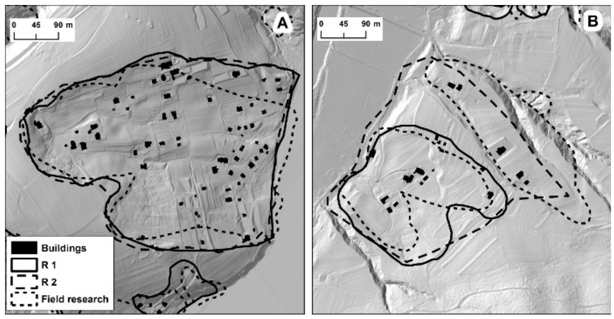

Figure 5. Examples showing consistency (A) and inconsistency (B) in the interpretation of relief and the Digital Elevation Model; differences in the number of buildings threatened by landslide processes. Sketch by P. Struś.

A comparison of SOPO and R1 data showed 851 "consistent" buildings for the entire studied commune, which included 505 residential buildings and 346 buildings of other type (Table 5). In summary, the degree of consistency between SOPO and R1 is 76% in terms of buildings located on the surface of landslides. The corresponding values for residential and non-residential buildings were 77% and 75%. “Inconsistent” buildings or those determined as landslide-type only in SOPO data or only R1 data were respectively 24% of which 153 residential buildings and 117 other ones.

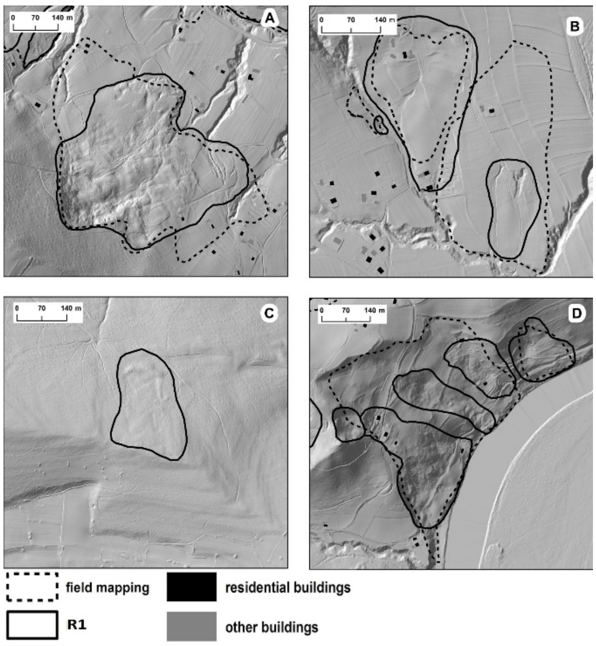

Figure 6. Examples showing wrong interpretations of terrain model. A, B, D – identification of only re-activated part of landslide, C – identification of unexciting landslide caused by lithology. Sketch by P. Struś.

A comparison between SOPO data and R2 data shows significant inconsistency due to different methods of landslide area identification, as discussed in the “Methods” section. Buildings designated “inconsistent” following superimposition of layers constituted 41% of all the studied buildings – 39% of residential buildings and 43% of other buildings. Differences in landslide boundary delimitations in the field and on a DEM may be due to a number of different factors. The first factor may be an actual difference between the landslide shapes identified. Field surveys were done in the period 2010 – 2011, while ALS data were acquired in 2011 and 2013. Hence, it is possible that parts of the studied landslides changed over the two-year period between the field survey and ALS acquisition.

The second factor is technology. The field survey was performed using topographic maps at a scale of 1:10 000 and handheld GPS receivers. The sketching of contour lines on maps, which is both less accurate and more difficult to interpret than DEM data, along with different map projections on different map sheets and different GPS readings may have inevitably produced inaccurate landform boundaries in cartographic materials. In such cases, DEM interpretation may turn out to be a more accurate method.

DEM surveys may also be associated with large errors (Fig. 6). Fieldwork makes it possible to identify landforms that are not readily visible in local relief, but have caused damage to residential buildings or roads. Landslides in shale are particularly difficult to identify using DEM analysis by producing poorly defined landforms. One example of this is shown in Figure 6B whose extent is not visible on a DEM, which made it impossible to correctly identify. However, fieldwork shows that damage to buildings and other infrastructure is present, which suggests the movement of the soil, and thereby an accurate depiction of landslide extent is possible.

The mistake most commonly made by researchers is to focus on the most readily visible landforms. Frequent landslide rejuvenations in the study area lead to highly visible fragments of landslide landforms experiencing this type of movement. The readily observable boundaries of rejuvenated fragments may lead a DEM researcher to lose sight of the broader slope area, and focus only on the most easily identifiable portion. An example of this is shown in Figure 6A and D, where the central part of the landform had experienced movement in 2010, and only this fragment was mapped. The full extent of the landslide is larger, but was not observed on the DEM.

Local geology, especially lithology, can also determine the clarity of landslide boundaries. A readily observable system of rock layers may suggest the presence of landslides at a location where none exist. One example of this is the landslide shown in figure 6C, where the R1 researcher was “led to believe” that a landslide does in fact exist at a location featuring a landform most likely produced via differences in rock layer resistance.

The problems with the research approaches described above are complex in nature. It is difficult to estimate the share of interpretation errors due to each particular factor, and a detailed analysis of these problems requires additional research and the updating of publications on this subject.

Landslides that do not alter relief significantly deserve special attention, as they do become active from time to time. Only certain manmade features can be used to delineate these “hidden” landforms: buildings, plot boundaries, and roads. Several such landslides were identified in the study area. These hidden landslides produce a substantial effect on human activity and are relevant from the point of view of spatial planners. The principal criterion used to identify hidden landslides is cracks in the walls of buildings, which does suggest the shifting of the colluvium. At the same time, it is quite difficult to find other signs of movement in a hidden landslide area.

Another subtle sign of changes in morphology is shifts in plot boundaries including lack of continuity and changes in direction. These subtle changes are not always visible on an DEM due to its preset scanning density. Such areas of the natural environment are proof that even very accurate point cloud data does not fully replace fieldwork.

6. CONCLUSIONS

Rapid development of digital tools provides key support for research and planning work. Airborne laser scanning, accurate terrain models, and topographic object databases constitute very good sources of data. The use of such data opens up new possibilities and creates new avenues for research in the environmental sciences and spatial management.

Research has shown that the vast majority of landslides can be identified using a digital elevation model. The lack of vegetation makes it easier to interpret relief and identify landslide areas more accurately via a delineation of boundaries. Landslide mapping using a DEM is much faster and more effective than field mapping. In addition, DEMs enable a much more accurate determination of boundaries in comparison with work on a general contour map.

Both methods of analysis offer advantages and limitations. Field surveys of landslides are limited by the quality of the base map and visibility of relief sheathed by vegetation, but make it possible to assess landslide activity based on the presence of damage to residential buildings and cracks on roads.

Landslide mapping using a DEM is much faster and more effective than field mapping. In addition, DEMs enable a much more accurate determination of boundaries in comparison with work on a general contour map. Nevertheless, is not providing the information about the activity of landslides and the degree of infrastructure damage, as well as make other interpretational issues, in case which inaccuracies in landslides delimitation could occur. Therefore, those two methods: filed mapping and identification of landslides on the DEM should be integrally conducted.

Every database and field survey creates opportunities, but also yields limitations. It is important to remember that all forms of data including field data and remotely sensed data can and do incorporate substantial error. A lack of understanding of the process that leads to data collection or the mechanisms that govern data processing and updating may lead to significant errors in data interpretation.

The research described in this paper also shows that even the best remotely sensed data are not fully adequate to properly assess landslide risk. The exclusive use of digital data may lead to the omission of subtle landforms that can be observed in the field and do threaten property and infrastructure. This is a much more serious error than an imprecise delineation of landslide boundaries due to a low quality topographic base map. However, the proper use of a digital elevation model can expedite fieldwork by identifying areas that need on-site verification.

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