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Use of Unmanned Aerial Vehicles (UAVs) for Updating Farmland Cadastral Data in Areas Subject to Landslides

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Abstract: The purpose of this study was to verify the applicability of unmanned aerial vehicles (UAVs) to update cadastral records in areas affected by landslides. Its authors intended to compare the accuracy of coordinates determined using different UAV data processing methods for points which form the framework of a cadastral database, and to find out whether products obtained as a result of such UAV data processing are sufficient to define the extent of changes in the cadastral objects. To achieve this, an experiment was designed to take place at the site of a landslide. The entire photogrammetry mission was planned to cover an area of more than 70 ha. Given the steep grade of the site, the UAV was flown over each line at a different, individually preset altitude, such as to ensure consistent mean shooting distance (height above ground level), and thus, appropriate ground sample distance (GSD; pixel size). The results were analyzed in four variants, differing from each other in terms of the number of control points used and the method of their measurement. This allowed identification of the factors that affect surveying accuracy and the indication of the cadastral data updatable based on an UAV photogrammetric survey.

Keywords: unmanned aerial vehicle (UAV); cadastre; cadastral records; landslides; mass wasting

1. Introduction

In recent years, the use of unmanned aerial vehicles (UAVs) steadily grew in many countries, including Poland, primarily as a result of rapid developments in the field of unmanned flight and drone-borne sensors for geospatial data collection. One impediment to the wider spread of UAVs is airspace regulation [1,2]. Currently, legislative and regulatory authorities worldwide are faced with the challenge of striking a balance between different UAV-related economic, information, and safety needs [3,4]. If regulatory constraints are adjusted to respond better to actual social needs, UAVs may find use in a greater number of industries [5].

Studies were already published regarding applications of UAV-collected data in areas such as forestry and agriculture. Guerra-Hernández et al. [6] tested the applicability of this technology to the stock-taking of forests. In Japan, UAV-based remote sensing was successfully used to monitor real-time wheat growth status, and to map within-field spatial variations of wheat yield for smallholder wheat growers [7]. In Brazil, UAVs were deployed over sugarcane fields. Wachholz de Souza et al. [8] described an object-based image analysis (OBIA) procedure for UAV images, designed to map and extract information about skips in sugarcane planting rows. German researchers examined the prospects of monitoring biophysical parameters and nitrogen content in wheat crops using images taken from UAVs [9], while their Swedish colleagues researched ways to identify aquatic plants which serve important environmental functions, and thus, should be monitored to detect changes in ecosystems [10]. In Reference [11], high-resolution thermal imagery acquired by an unmanned aerial vehicle was used to map plant water stress and its spatial variability. This technology can also be applied widely in engineering [12,13] and environmental protection. An interesting application is presented in Reference [14], which describes the integration of an off-the-shelf laser-based methane detector into a multi-rotor UAV, and demonstrates its efficacy in generating an aerial methane concentration map of a landfill. In order to perform plant protection operations, an automatic spraying system based on unmanned aerial vehicles (UAVs) was designed in China [15].

Nevertheless, the authors of this article were mostly interested in landslides. Most publications focus on applying UAVs to monitoring and assessing landslide dynamics [16–21]. The UAV demonstrated its capability for producing valuable landslide data, but improvements are required to reduce data processing time for the efficient generation of ortho-mosaics based on photogrammetric digital terrain models (DTMs), in order to minimize geo-referencing errors.

This study, however, addresses a different issue, namely the collection of spatial data for creating and updating cadastral databases with respect to landslide sites. The potential applicability of UAVs to the acquisition of such data was already indicated in the literature [22–25]. According to Reference [26], with the exception of Reference [27], cadastral mapping is not mentioned in review papers on application fields of UAVs [3,28,29]. As is suggested in Reference [26], this might be due to the small number of case studies within this field, the often highly prescribed legal regulations relating to cadastral surveys, and the general novelty of UAV use in mapping. Nevertheless, all existing case studies underline the high potential of UAVs for cadastral mapping, in both urban and rural contexts, for developing and developed countries.

This study was designed to answer the question of whether the statutorily required accuracy is attainable for difficult-to-access landslide sites where considerable differences in terrain elevation may hinder the use of photogrammetric data for updating cadastral databases. Analyses were conducted to compare the accuracy of different UAV data processing methods in determining the coordinates of points which form the framework of a cadastral database. Relevant tests were carried out with a varying number of ground control points (GCP) used for developing an orthophoto map and a digital surface model (DSM), as well as with varying accuracy of determining the coordinates of such points (static or kinematic Global Navigation Satellite Systems (GNSS) survey of control points).

2. Materials and Methods

2.1. Cadastral Data Requirements

As Reference [30] points out, many countries around the world recognize and appreciate the value of accurate digital cadastral databases. Theoretically, an accurate, efficient, and up-to-date cadastral database offers a better basis for the planning and implementation of a variety of real estate applications. Poland is no exception in this regard. As defined in Polish law, the cadastre is a uniform, nation-wide, and importantly, regularly updated set of data on land, buildings, and building units, as well as on their owners and users [31]. The profile of the Polish cadastre is presented in Figure 1.

The cadastral database, which is maintained by means of an information technology (IT) system, is part of the European Union's spatial information infrastructure, established under Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE). In Poland, the directive was implemented by the Act on Spatial Information Infrastructure of 4 March 2010 [32,33].

Regardless of the purpose of creating the spatial information infrastructure in the European Union, in Poland, the real estate cadastre provides information that is necessary for economic planning, spatial planning, tax and benefit assessment, property denotation in land and mortgage registers, public statistics, real estate management, and agricultural farm records [31]. Therefore, the data that are entered into the database must be absolutely reliable [34]. This means that any entry into the cadastral database can only be made based on relevant documents. These include, e.g., notarial deeds, final and legally binding court decisions, final administrative decisions, official copies of land and mortgage registers, etc. Technical surveys, although essential, cannot form the basis for entering data into the real estate cadastre [34].

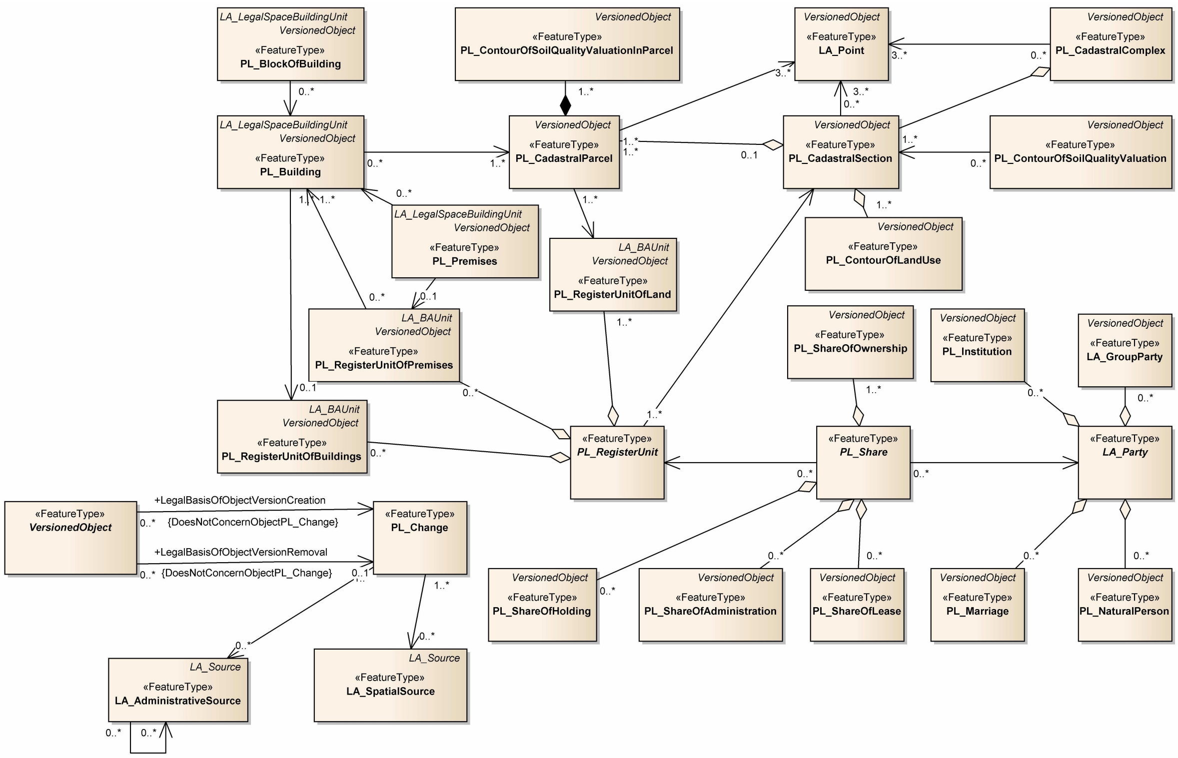


Figure 1. The profile of the Polish cadastre based on the Land Administration Domain Model [35].

2.2. Accuracy Requirements

As UAV data acquisition is a universal method, the study of whether it can be applied to obtain landslide data with sufficient accuracy was preceded by research into accuracy requirements in other countries. The first conclusion of the research was that not all applicable laws and regulations define the accuracy of positioning boundary points.

According to Reference [36], in Australia, the accuracy required for determining boundaries depends on the needs and nature of the site being surveyed. In this case, accuracy levels achievable thanks to modern technologies are balanced with user requirements. According to Reference [37], the recommended accuracy for rural areas is 0.15 m. However, Reference [36] points out that setting a single value for all kinds of land areas could be impractical.

An interesting solution was adopted in the Netherlands. According to Reference [38], when ownership of one or more parts of a parcel changes, buyers and sellers are legally obliged to identify the new boundaries. After verification, the new cadastral situation is created through surveying and cartographical activities. As a result, the new situation is represented in the cadastral registration with an accuracy of 0.06 m or greater [39].

According to Reference [30], in Malaysia, the accuracy of determining boundary points is regulated by law. The permissible tolerance is 0.05 m for urban areas and 0.10 m for farmland.

Reference [40] concludes that, in different countries, the standards of accuracy documented in manuals of survey instruction provide for varying "classes of surveys" or zones. The class of survey addresses issues, such as the difficulty of terrain and the value of the land being surveyed, and influences the expected standard of accuracy. The author also indicates that the point position as determined on the ground from any of the control points should be within a given tolerance (for example, in Zone 1—0.03 m, Zone 2—0.07 m). Accordingly, in Germany, the statutorily required accuracy depends on the zone in which the property is located.

A similar solution was adopted in Switzerland. According to Reference [22], the statutorily required accuracy for cadastral surveying is defined in the technical ordinances on official cadastral surveying [41,42]. In Swiss cadastral surveying, the territory is divided into five zones with different levels of surveying tolerances, specified in Article 3 of Reference [41]. The accuracies for points (e.g. building points, boundary points, and land cover) for the different tolerance levels are listed in Articles 27–32 [41]. For instance, the accuracy of a boundary point in zone TS2 (built-up areas and construction zones) is 0.035 m, while it is only 0.07 m in zone TS3 (intensively used agricultural and forested areas).

According to Reference [43], the accuracy of boundaries in the Polish land cadastre is determined by the mean error of the boundary point position. This error is related to the fundamental geodetic control network of class one. This horizontal control network is composed of ASG-EUPOS (active geodetic network) reference stations, which belong to the EPN (EUREF permanent network). Ultimately, the error should not exceed 0.10 m and 0.30 m, respectively [44]. The horizontal survey of points which provide numerical descriptions of plot boundaries, structure boundaries, or building outlines must be conducted in such way as to ensure that the positions of such points are measured in relation to the nearest control network points with an accuracy of no less than 0.10 m. For boundaries of land use classes and soil quality classes, the accuracy is 0.50 m [45]. With regards to surface area measurements, the prescribed accuracy for plots, buildings, and boundaries of land use classes and soil quality classes is 1 m^2 [46].

2.3. Updating the Cadastre with Respect to Landslide Sites

A cadastral database can become out of date owing to a wide range of factors, including natural causes. Obviously, the elements most prone to becoming out of date are those which tend to change substantially over time [47]. Factors which may outdate information stored in a cadastral database include mass wasting, defined as natural or human-caused sliding, creeping, or falling of superficial layers or rock, weathered material, or soil [48]. Landslides usually have catastrophic consequences, including degradation of land and the razing of buildings and infrastructure. On farmland and in forests, crops and vegetation are destroyed. Restoring land hit by such a disaster to its previous condition is extremely difficult or even impossible. Long-term consequences of a landslide must be recorded in relevant spatial databases, including the cadastre.

The relevant cadastral database may require both its land and building records to be updated with respect to the site where the landslide occurred.

The landslide does not directly affect the extent of rights to real estate, i.e. it does not change the owner by virtue of law, but it may be related to the following changes [31,49]: of property rights to real estate and entities of these rights, configuration of boundaries, land uses and contours of soil quality classes, as well as of statuses of buildings and premises.

Changes in holders of the rights may occur exclusively in the areas where the principles of the reconstruction, renovation, and demolition of building structures, as well as special principles of land development and the procedure for real estate acquisition related to landslides, are specified by the Prime Minister in the form of a regulation [49]. This is the case when the Commune Council, guided by the need to ensure the safety of people and property, enacts a total ban on development in areas threatened by mass wasting and areas where mass wasting occurs, or where the reconstruction of building structures is subject to special conditions. Owners of the properties covered by such a restriction or limitation may either claim compensation for the damage they suffered, or demand that the commune purchase their property.

In order to allow reconstruction works under special conditions, the so-called local recovery plan is adopted. This plan includes, e.g., decisions on the method and implementation of investments related to linear infrastructure that is contained in this plan, as well as decisions regarding the purchase or expropriation of real estate that is essential for the implementation of investments included in the local recovery plan.

Real properties covered by the local recovery plan may also be sold, let into perpetual usufruct, lease or lending, without a tender procedure, to owners and perpetual usufructiaries of the real properties covered by the ban or restriction of development. Any change in the rights to a real property entails the necessity of introducing new data into the cadastral database (title transfer).

The configuration of boundaries are subject to change when the title transfer relates only to parts of the real estate [50] that cannot be utilized in the current manner, or which are necessary to eliminate the consequences of the natural disaster. Such a fragment of the plot is parceled out through a surveying legal procedure of plot division.

Areas with newly formed natural landmarks such as escarpments, steep slopes, faults, rocks, debris, sinkholes, landslide scars, or screes should be marked as wasteland [44]. Such sites may require changes in land use classes and soil quality classes, and marking of individual areas. In addition, the surface area of new land use classes must be determined, based on their numerical description (change in land use classes). Table 1 lists selected land plot attributes recorded in the Polish cadastre, which may change following a landslide.

Table 1. Land plot attributes that may change as a result of a landslide.

Item	Plot Attribute	Title Transfer	Plot Division	Change in Land Use Classes
1	Identifier of the parcel		+	
2	**Numerical description of boundaries ***		+	
3	**Surface area ***		+	
4	**Surface area of land use classes and soil quality classes ***		+	+
5	Land value and valuation date		+	+
6	Land registration unit number	+		
7	Land and Mortgage Register reference	+		
8	Reference to documents defining other rights to the plot	+		
9	For public road plots—road numbers			+
10	For landmark plots such as water courses, reservoirs, parks, or other natural landmarks—names of such landmarks			+

* Data obtainable through unmanned aerial vehicle (UAV) survey.

For buildings, the easiest changes to record are the complete destruction or destruction of an independent part of a building. If a building is partially destroyed, its data may change as a result of later reconstruction, extension, redevelopment, conversion, etc. [51]. If only one part of a building is destroyed while the other remains usable, it seems reasonable to adjust all geometric data of such a building. It must also be borne in mind that new buildings may be erected on a landslide site. In such a case, which is rather exceptional, an entirely new structure, with all its attributes and a new classification for the plot it would be erected on, would be entered into the relevant cadastral database. Complete destruction or construction of a new building may also lead to changes in land use classes and assigned soil quality classes. Table 2 presents selected attributes which are recorded in the Polish cadastre with respect to buildings and building units, and which may change as a result of their complete or partial destruction.

Table 2. Building attributes that may change as a result of a landslide.

Item	Building Attribute	Destruction	Partial Destruction	Reconstruction
1	Identifier of the building	+		
2	**Building's status ***	+	+	
3	**Numerical description of the building's outline ***		+	
4	Value of the building		+	
5	Date constructed, and, if applicable, date reconstructed			+
6	Degree of certainty which the dates referred to in item 5 are determined with			+
7	scope of redevelopment/conversion			+
8	Number of aboveground/underground stories		+	
9	**Building footprint ***		+	
10	Usable area of the building determined on the basis of survey or information included in the relevant planning permission		+	
11	Total usable area of the following: units which are independent properties, units which are not subdivided from the main property, rooms comprising units		+ + + +	
12	Number of independent units disclosed in the cadastre		+	
13	Information on whether the building has been commissioned in whole or in part			+
14	Identification of the commissioned part of the building			+
15	Date the building or part thereof was commissioned			+
16	Total number of rooms in a residential building		+	
17	Demolition date for the following: the whole building part of the building	 + 	 +	
18	Reasons why the building or part thereof was demolished	+	+	
19	Information on whether the building is equipped with high-speed-ready in-building infrastructure			+

* Data obtainable through UAV survey.

All the changes listed above must be recorded under separate administrative procedures regulated in References [31,43], and are discussed, e.g., in References [52–54], and each affects the value of the property, which also needs to be included in the cadastre. A landslide may result in a situation where changes must be made to reflect more than one of the events described above (e.g., destruction of a building combined with a change in land use classes and soil quality classes, as well as in their respective identification symbols). Unfortunately, not all of the attributes listed in the tables above can be changed on the basis of UAV-collected data. Those that can be updated based on a photogrammetric survey are written in bold letters. Also, if a destroyed building included any units recorded in the cadastre, their destruction can be easily updated in the relevant database. However, no details of such units can generally be inferred from UAV-acquired data.

2.4. Survey Site

In May and June 2010, heavy precipitation triggered landslides which caused extensive damage across large areas of Poland [55]. One such landslide was selected for the UAV survey in question. It occurred in June 2010 in Kłodne, Poland (Municipality of Limanowa, County of Limanowa, the Lesser Poland Voivodship), and covers part of the southern slope of the Chełm Mountain in the Beskid Wyspowy mountain range. It was one of the largest and most dangerous landslides activated in the Polish Carpathians in recent years. Its site is classified as farmland, and therefore, should be afforded special protection as postulated by References [56–61]. The site before and after the landslide is presented in Figure 2.

(a) (b)

Figure 2. Survey site: (a) April 2010—before landslide [62]; (b) October 2014—after landslide [63].

Given the size of the area affected by mass wasting (approximately 50 ha), the extent of the damage caused, and the threat to the remaining buildings and infrastructure, the landslide was studied by many scientific and research institutions, including the Polish Geological Institute (National Research Institute) since 2010 [64], and students and employees of the Faculty of Geology, Geophysics, and Environmental Protection and of the Faculty of Mining, Surveying, and Environmental Engineering of the AGH University of Science and Technology of Kraków since 2013 [65,66]. All the previous research was conducted to determine the current external boundaries of the landslide, as well as its stability, and found that the landslide did not remain active. Since 2013, practically no movement of soil is noticeable.

2.5. Study Methods

Case studies discussed in the literature are mostly focused on the compliance of UAV-collected data with applicable local standards and requirements [22,24,38]. Reference [22] compares cadastral data from UAV-borne sensors with data collected using conventional methods. The study concludes that the factors that reduce the attainable accuracy of UAV-collected data are the quality and calibration of the camera, image quality, and the definition of ground control points (whether natural or artificial).

It also points to the high flexibility of UAV systems, which enable additional information to be obtained easily, including elevation models and three-dimensional (3D) objects. The article emphasizes that UAV-based methods have enormous data collection potential, and, in areas with limited accessibility, such as those following a natural disaster, offer a valuable alternative to traditional survey methods (such as tacheometry or GNSS).

The study presented in Reference [38] was conducted in 2012 after the Dutch Product Innovation Department of Kadaster decided to seriously investigate the suitability of aerial images captured by UAV for the identification of property boundaries by executing a practical evaluation. The first experiment was carried out at the Pyramid of Austerlitz, a flat sandy area surrounded by forest with a 30-m-high pyramid, built as a victory monument by troops of Napoleon. This was the learning phase of the study, aimed at becoming acquainted with the technology. Although the target accuracy of 0.06 m was not attained, enough experience was gained to identify the factors affecting the accuracy of measurements taken using UAVs, including the quality of the camera, the camera calibration, the number and location of ground control points, and the processing software used. With modified equipment parameters and increased density of control points, the other two experiments yielded sufficiently accurate results. It must, however, be borne in mind that, except for the Pyramid of Austerlitz, the other two survey sites in the above study were flat areas of developed land, while the experiment discussed in this article was conducted at the site of a landslide with considerable differences in terrain elevation, crags, and ridges. Other research involving UAV surveying includes studies conducted to record narrow tourist trails in areas with large difference in terrain elevation in the Polish Tatra Mountains [67], which partly comprised the analysis of the accuracy of UAV-based photogrammetric products. This process involved all points of the photogrammetric control (both control points and check points). The following mean errors for point coordinates were obtained: m_x = 29 mm, m_y = 29 mm, and m_h = 31 mm, which correspond to the error of the horizontal point position, m_{xy} = 41 mm, and the error of spatial position, m_{xyh} = 51 mm. The worst results of root-mean-squared errors were obtained for areas with a small number of control points, which were difficult to set up due to field conditions (steep slopes and exposure).

Figure 3 shows a general processing diagram for typical aerial photogrammetry products developed from UAV-collected data.

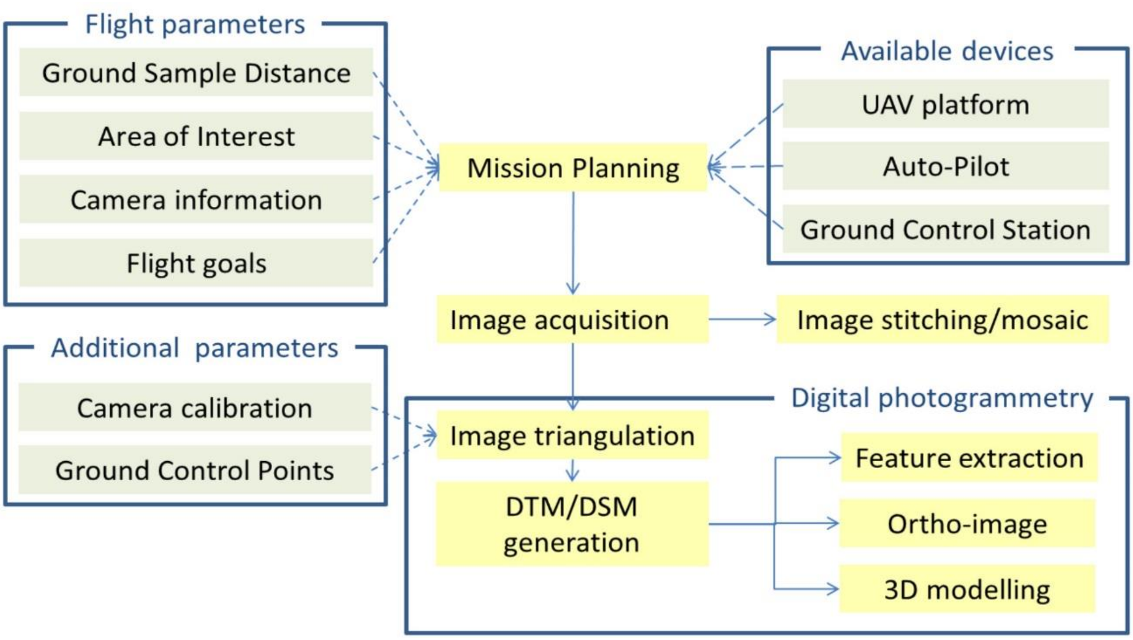


Figure 3. Processing diagram for typical aerial photogrammetry products developed from unmanned aerial vehicle (UAV)-collected data [68].

The UAV selected for conducting the photogrammetric flight was a DJI S1000 octocopter with a maximum take-off weight of 11 kg. The platform was fitted with a Sony ILCE A7R camera equipped with a Sony Zeiss Sonnar T* FE 35 mm F2,8 ZA lens whose position was stabilized with a Zenmuse Z15-A7 gimbal. The size of the sensor used in the digital camera was 35.9 mm $\times$ 24.0 mm.

The photogrammetric mission plan was prepared, taking into account the specification of the surveying equipment used, the characteristics of the site, and the target ground sample distance (GSD) of 20 mm. On the basis of these parameters, the flight altitude was preset at 145 m. The assumed forward overlap was 80%, while the assumed side overlap was 60%. Given the UAV flight duration, the mission was divided into three parts. The measurements were taken along a total of 22 flight lines, covering a total area of more than 70 ha.

Given the steep grade of the site, the UAV was flown over each line at a different, individually preset altitude, such as to ensure consistent mean shooting distance (height above ground level), and thus, appropriate GSD (pixel size) (Figure 4). During the survey, 465 photographs were taken, and 388 of those were selected for further processing. The key flight parameters are presented in Table 3.

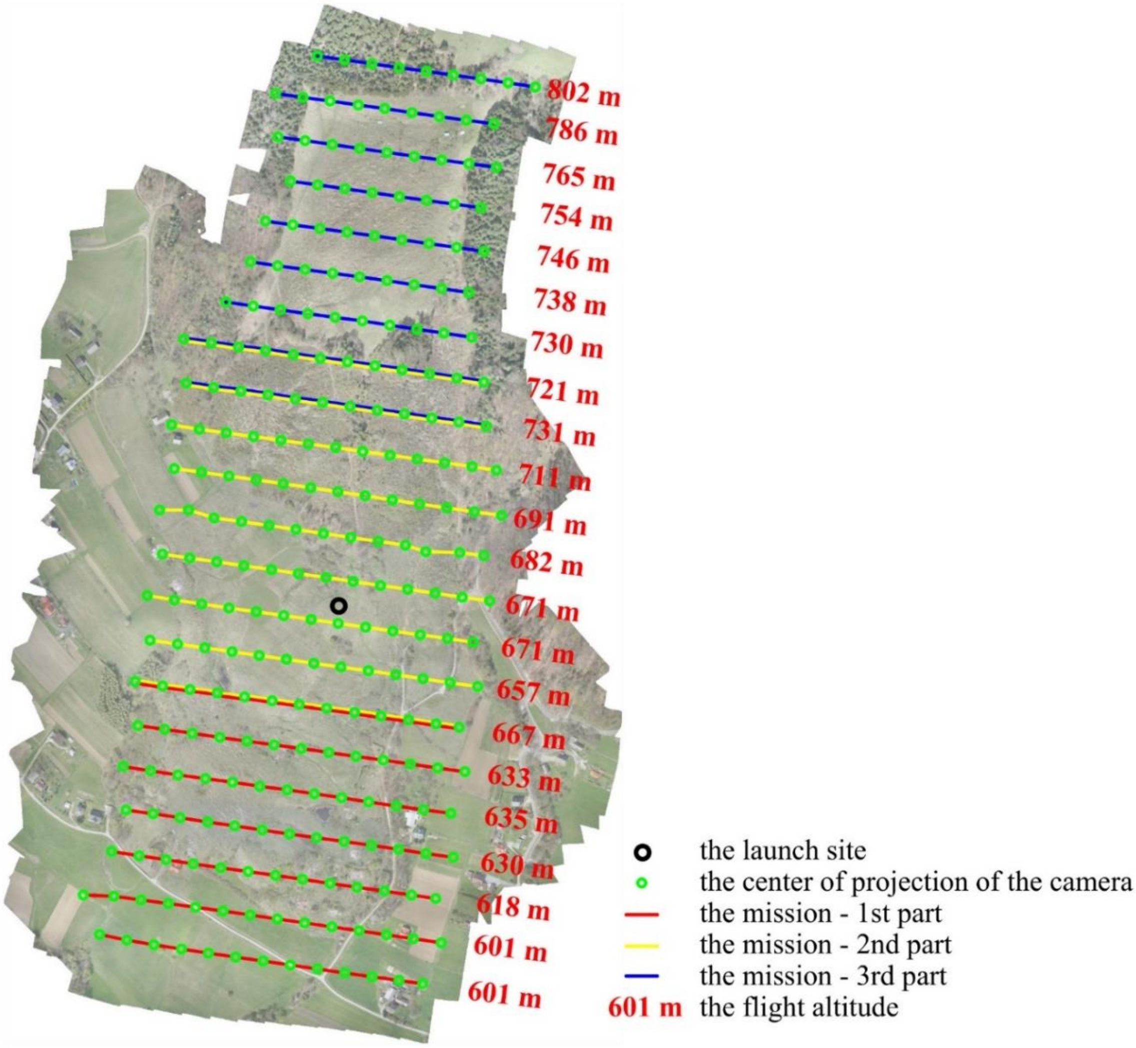


Figure 4. Plan of photogrammetric flight over the landslide.

Table 3. Technical specification of flight planned over the Kłodne landslide.

Ground sample distance (GSD; pixel size) (cm)	2.0
Forward overlap (%)	80
Side overlap (%)	60
Flight altitude (m)	145
Distance between photographs (m)	20
Distance between lines (m)	60
Ground footprint of one image (m)	148.3 × 99.0
Total number of lines	22
Total survey area (ha)	70

A total of 33 points, comprising 15 control points and 18 check points, were established throughout the survey site. Their locations are presented in Figure 5. The coordinates of the points were determined using two methods, static GNSS and real time kinematic (RTK) GNSS, both with reference to an ASG-EUPOS reference station.

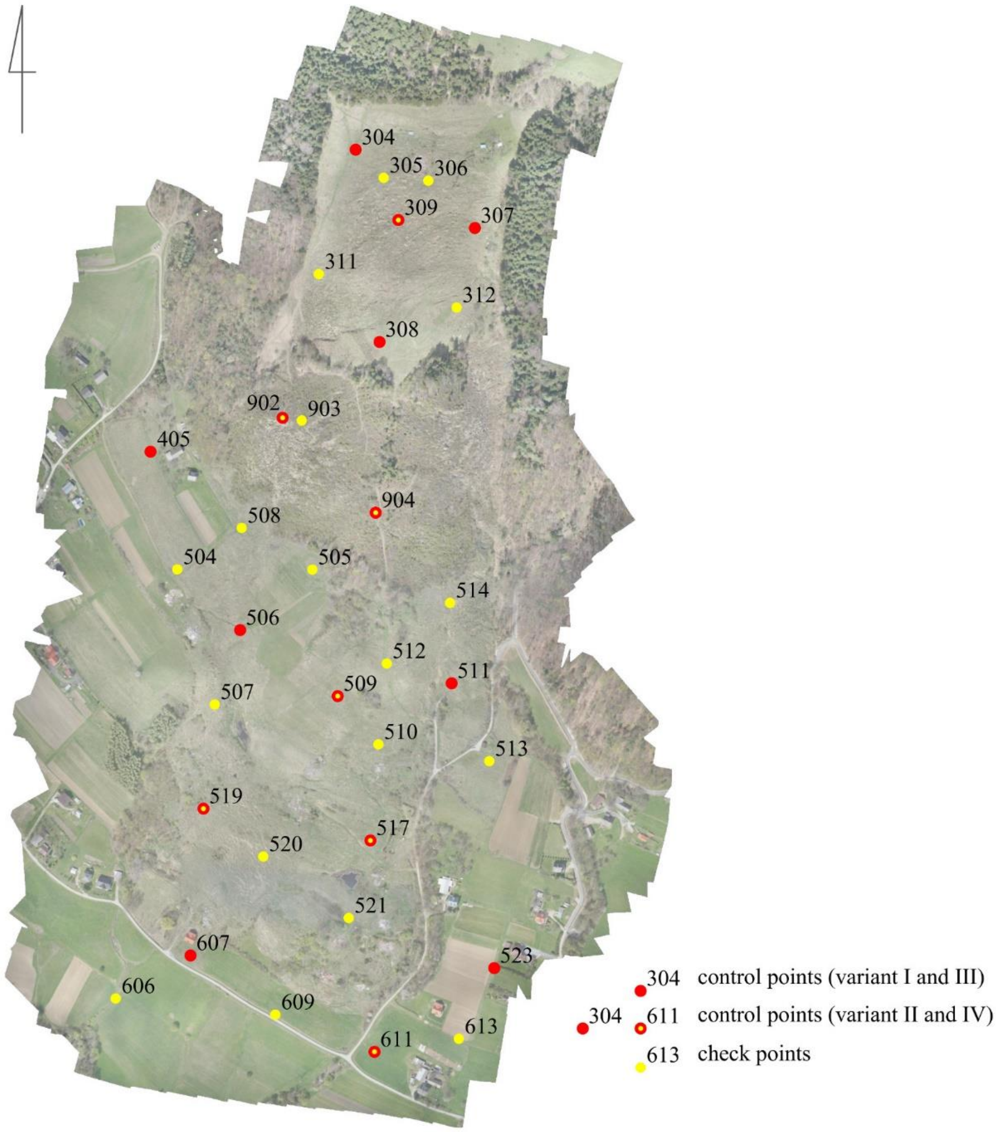


Figure 5. Locations of control points and check points.

The static survey was conducted at the Kłodne landslide together with members of the Dahlta Student Club of Surveyors as part of their seventh measurement cycle. Two types of GNSS receivers were employed for the survey, namely a Leica GPS500 and a Leica GPS1200. Measurements were taken during 11 sessions, each lasting 40–45 min and together covering 43 points (including 33 points used for this study). Static GNSS data were referenced to the ASG-EUPOS Nowy Sącz (NWSC) reference station and post-processed using the Leica Geo Office 8.0 software. The RTK measurements were taken with a Leica Viva CS10 receiver using an RTK correction signal from the Nowy Sącz reference station. The logging interval was 1 s, and the measurement of each point included no fewer than 30 epochs.

3. Results and Discussion

The respective mean errors of determining the coordinates of the control points and the check points were as follows:

- m_{xy} = 30 mm and m_h = 50 mm for RTK GNSS;
- m_{xy} = 5 mm and m_h = 15 mm for static GNSS.

These values were determined in relation to the base control network, which includes ASG-EUPOS reference stations.

A comparison of coordinates determined using two independent methods (Table 4) shows that the obtained values were free of gross errors, and that the maximum difference in the coordinates did not exceed 0.050 m.

Table 4. Comparison of coordinates of points determined using static GNSS and RTK GNSS.

Parameter	ΔX	ΔY	ΔH
Average difference (m)	0.020	0.022	0.002
Maximum difference (m)	0.007	0.044	0.046
Minimum difference (m)	−0.036	−0.009	−0.026
Standard deviation (m)	0.010	0.014	0.014

The UAV-collected data were processed using the Agisoft PhotoScan Professional software [69] in four variants (Table 5), differing from each other in terms of the number of control points used (Figure 5) and the method of their measurement.

Table 5. Survey data processing variants.

VARIANT 1	VARIANT 2
8 control points surveyed using RTK GNSS	15 control points surveyed using RTK GNSS
VARIANT 3	**VARIANT 4**
8 control points surveyed using static GNSS	15 control points surveyed using static GNSS

The first step of image processing was to align the images. At this stage, the images were uploaded to the software and were given the initial orientation by adding approximate coordinates of image projection centers. The alignment was competed using an accuracy parameter set to "high". It ensured the use of the original image resolution. Additionally, control points were indicated on the images. This was preceded by uploading coordinates of the terrestrial photogrammetric control to the software. Each marker was indicated on all photos where it was visible. The block of photographs for each variant was finally aligned, and, at the same time, the camera calibration parameters were determined.

In this process, the following values were determined: the principal distance (c), the location of the principal point (c_x and c_y), and the distortion parameters (k_1, k_2, k_3, and p_1 and p_2). As a result of the alignment, the root-mean-squared errors of the control points were obtained (Table 6).

Table 6. Comparison of control point mean-squared errors for all of the data processing variants.

Block Type	m_X (m)	m_Y (m)	m_H (m)	m_{XY} (m)	m_{XYH} (m)
VARIANT 1	0.037	0.031	0.083	0.048	0.096
VARIANT 2	0.023	0.026	0.055	0.035	0.065
VARIANT 3	0.021	0.020	0.038	0.029	0.048
VARIANT 4	0.016	0.020	0.032	0.026	0.042

The assumed control point identification error at the data processing stage (interpretation error) was 1 pix (20 mm). Accordingly, the ultimate marker (control point) mean spatial error was 60 mm for RTK GNSS, and 25 mm for static GNSS.

It must be noted that both the number of photogrammetric control points used, as well as the survey method applied to measure them, affects the obtained error values. The control point mean-squared error for Variant 1, which was considered to be the least accurate (eight control points surveyed using RTK GNSS), was more than twice the analogous parameter determined for Variant 4 (15 control points surveyed using static GNSS). However, none of the errors was greater than 0.100 m. The obtained values of spatial errors were considerably affected by altitude errors, which were negligible for the purposes of updating a cadastral database. The mean-squared errors of the planar coordinates showed a similar tendency and range from 0.026 m (Variant 4) to 0.048 m (Variant 1).

The final step of image processing in the Agisoft PhotoScan software was to create dense point clouds with the method of dense matching. Then, DSMs were created. These were used as a basis to conduct orthorectification of images and to create orthophoto maps. As a result of the data processing conducted, four orthophoto maps with a GSD of 19.7 mm and four DSMs with a resolution of 39.5 mm were generated in the PL-2000/7 rectangular planar coordinate system.

In order to determine the accuracy of the obtained photogrammetric products and their suitability for updating a cadastral database, the positions of 18 check points on the orthophoto map were measured, with their altitude coordinates read from the DSM. The obtained coordinates were compared with the data received by means of the direct static GNSS and RTK GNSS surveys. The comparison of the coordinates was carried out for the datasets marked by (+) in Table 7. The computed accuracy assessment parameters for check points surveyed using static GNSS, compared to an aligned block of photographs, are presented in Table 8. Similar calculations for check points surveyed using RTK GNSS are presented in Table 9.

Table 7. List of data analysis performed on datasets.

Data Set	Coordinates of Check Points Measured on Photogrammetric Products			
	VARIANT 1	VARIANT 2	VARIANT 3	VARIANT 4
Coordinates of check points surveyed using static GNSS	+	+	+	+
Coordinates of check points surveyed using RTK GNSS	+	+	−	−

Table 8. Average differences in coordinates and their maximum and minimum values for check points surveyed using static GNSS, compared to an aligned block of photographs.

Parameter	VARIANT 1			VARIANT 2			VARIANT 3			VARIANT 4		
	ΔX	ΔY	ΔH	ΔX	ΔY	ΔH	ΔX	ΔY	ΔH	ΔX	ΔY	ΔH
Average difference (mm)	−7	16	−50	−6	18	3	12	−4	−14	11	−3	6
Maximum difference (mm)	55	80	82	49	60	73	67	37	43	60	38	95
Minimum difference (mm)	−71	−67	211	−71	−52	−89	−34	−72	−86	−39	−54	−72
Standard deviation (mm)	36	35	84	34	28	48	29	26	44	30	23	42

Table 9. Average differences in coordinates and their maximum and minimum values for check points surveyed using RTK GNSS, compared to an aligned block of photographs.

Parameter	VARIANT 1			VARIANT 2		
	ΔX	ΔY	ΔH	ΔX	ΔY	ΔH
Average difference (mm)	10	−3	−52	11	0	1
Maximum difference (mm)	62	71	78	56	50	87
Minimum difference (mm)	−51	−87	−206	−47	−72	−79
Standard deviation (mm)	32	37	85	30	33	47

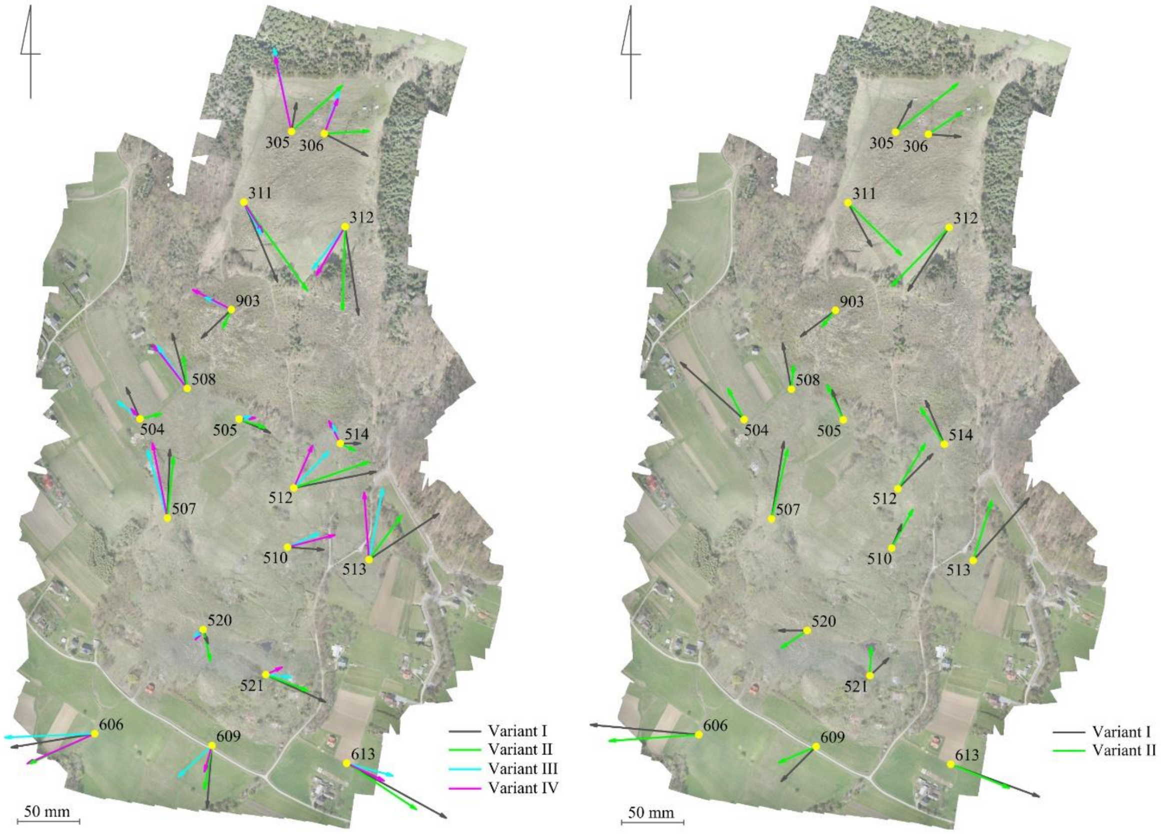
It must be noted that, regardless of the check point survey method, the standard deviation of the differences in spatial coordinates did not exceed 0.100 m for any of the calculation variants, or 0.050 m for the planar coordinates. Such values met the accuracy requirements for determining the coordinates of boundary points laid down in applicable Polish laws and regulations [45]. The mean difference in the coordinates is also worth noting, as it may indicate the occurrence of a systematic error. In Variants 2, 3, and 4, this parameter was near 0 for each coordinate, while, in Variant 1, it was −0.050 m for the altitude coordinate, which is a significant value. Analysis of the maximum and minimum differences in the coordinates shows that they ranged from −0.100 m to 0.100 m except for Variant 1, for which the obtained results were the most unsatisfactory (as much as −0.200 m for ΔH).

When studying the obtained results, one must consider the locations of the check points in relation to the control points (Figure 5). Some of the check points were located on or even outside the external boundary of the survey area as defined by the extreme control points (points 606, 609, 613, 513, 507, 305, 306, 311, and 312). Such locations were chosen intentionally, in order to see how the corresponding deviations would trend. It was at precisely those points that the maximum/minimum differences in coordinates were recorded for Figure 6.

For planar coordinates, the greatest east–west deviation was recorded for point 606. Depending on the calculation variant, it ranged from −0.087 m to −0.052 m. The greatest north–south deviations occurred for points 507, 311, and 312, from 0.062 m to 0.049 m for point 507, from 0.024 m to 0.071 m for point 311, and from 0.034 m to 0.071 m for point 312. For point 305, similar results (0.067 m and 0.060 m) were obtained only in Variants 3 and 4.

When ready, the orthophoto map was compared with the cadastral database. In order to carry out relevant spatial analysis, the boundary of the landslide was outlined on the orthophoto map. It was established in line with the landslide visible in the photographs. If the boundary of the landslide ran close to cadastral boundaries, it was drawn over the boundaries of relevant plots in order to prevent the creation of new objects with a small surface area in the cadastre.

It should be emphasized here that any interference with the cadastral database must be preceded by appropriate settlements that are carried out in the field with the owners of the subject properties. Entities of the real estate cadastre express their consent for entering new objects into the database or updating the existing ones, by signing relevant documents that are necessary to carry out surveying and legal procedures.



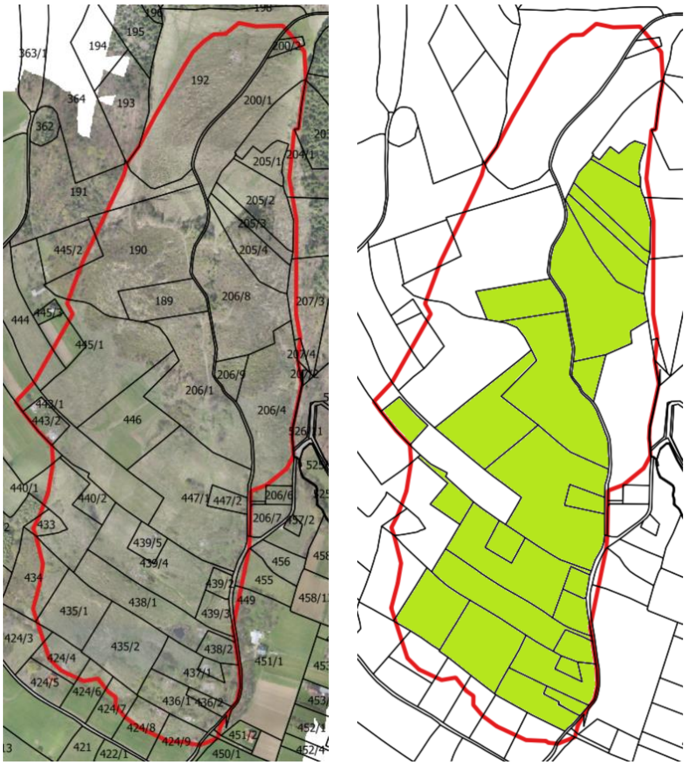
(**a**) (**b**)

Figure 6. Differences in coordinates for check points compared to an aligned block of photographs: (**a**) check points surveyed using static GNSS; (**b**) check points surveyed using RTK GNSS.

Given the fact that the survey was conducted following the demolition of all the designated buildings, this study focused solely on plots of land. Once the vectorized outline of the landslide was imposed on the cadastral map (Figure 7), it was found that the landslide covered 25 plots in whole and 34 plots in part. These analyses were carried out manually. There are studies aimed at exploring options for automatically delineating boundaries for UAV-based cadastral mapping [26,70]. However, in the opinion of the authors, the algorithms described in Reference [70] to extract boundaries automatically would be ineffective in the case of areas subject to landslides. Cadastral boundaries in areas affected by landslides are assumed to be not visible, as they may not coincide with natural or manmade object contours.

For the plots which were entirely covered by the landslide, data should be changed with respect to land use classes and soil quality classes, i.e., such plots should be marked as wasteland, excluded from soil classification. With regards to the other plots, their land use classes and soil quality classes should be properly adjusted. Under applicable Polish laws and regulations [45], this means that the boundary of the landslide running over relevant plots should be surveyed with an accuracy of at least 0.50 m in relation to the nearest points of the geodetic control network and the survey network, which can be attained with a large margin of error on the basis of UAV-acquired data.

Unfortunately, this process cannot be automated due to the fact that surveys using UAV technology are only a part of the surveying and legal procedures that lead to the introduction of changes in the cadastral database.



(**a**) (**b**)

Figure 7. (**a**) Outline of the landslide over plots of land; (**b**) plots wholly covered by the landslide.

If the landslide is declared undevelopable land area, it will be possible to register future changes with respect to all or part of the properties covered by the landslide. In such a case, the outline of the landslide, which would become a new boundary, would have to be surveyed with an accuracy of 0.10 m in relation to the nearest points of the geodetic control network and the survey network [45], which is also attainable, as proven above.

Given the accuracy of the generated orthophoto map, it can be concluded that UAV-collected data may be sufficiently accurate to be used in surveying and legal procedures aimed at updating the cadastral database.

4. Conclusions

As UAV photogrammetry became immensely popular, it is unsurprising that attempts were also made to apply it to the maintenance of a cadastre. The research described in this article proved that an orthophoto map and a DSM developed with due care based on UAV-acquired data may be used to update cadastral data, including those with respect to areas affected by landslides. To enable that, a photogrammetric control network needs to be established over the entire site of the survey. The coordinates of the control points in the case under discussion were determined using two independent methods, static GNSS and RTK GNSS. Analysis of the obtained results showed that the accuracy of UAV photogrammetry products did not, in practice, depend on which of these data collecting and processing methods were used. Results were slightly improved in Variants 3 and 4, where the coordinates of the control points were established using static GNSS. However, given the amount of time and labor required for conducting such a survey, this method cannot be considered to produce significantly better results than RTK GNSS. A more important factor contributing to the accuracy of photogrammetry products was the number of control points used. Although for Variants 1 and 3, where only eight control points were used, the attained accuracy of the orthophoto map and the DSM satisfied the applicable Polish legal requirements [45], i.e., the maximum deviations for individual check points did not exceed 0.100 m. Such a level of accuracy may be insufficient to ensure compliance with legal requirements imposed in other countries, e.g., Switzerland or the Netherlands. It is, therefore, advised that a greater number of photogrammetry control points be used in order to increase the certainty that the photogrammetric products generated are correct and as accurate as is required.

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