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ORIGINAL ARTICLE

Study of karst manifestations in Solotvyno based on aerial photography from a UAV

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Abstract

This article is devoted to the study of surface karst manifestations on the territory of inactive salt mines of Solotvyno, Transcarpathian region, Ukraine. The historical development of the salt mine from the moment of the creation of the first mine (the end of the 18th century) to the present is considered. Based on the results of previously published studies, monitoring of karst manifestations from 2010 to 2020 was implemented. The last stage of monitoring in 2021 was the aerial survey of the territory obtained by the Arrow UAV using the Sony QX1 camera. Pix4Dmapper software was used for image processing. The aim of the work is to estimate the scale of destructive geological processes by the method of photogrammetry. During the execution of the work, the methods of processing materials of aerial photography, analysis of developments in the direction of photogrammetry were applied. As a result of the study, the volume-planar characteristics of karst formations on the territory of Solotvyno were calculated using the photogrammetry method. This scientific work is relevant for assessing the scale of the development of degenerative geological processes on the territory of Ukraine, in particular within the Transcarpathian region. The practical significance of the obtained results lies in their application in order to ensure environmental monitoring. The results of the study can be used to predict the impact on economic and infrastructure objects, followed by the development of a plan of specific actions for prevention, localization and work with the consequences of man-made processes in the adjacent territory.

Key words: geodesy, UAV, karst, monitoring, photogrammetry, aerial photography, orthomosaic.

1 Introduction

The first comprehensive source of coverage of karst phenomena and geological processes was the work by Korotkevych (1970), where the problem of hydrogeological processes in Solotvyno was described. Gradually, specialists from the VIOGEM Institute (Belgorod), the Ukrainian Research Institute of the Salt Industry (UkrRISI, Bakhmut) and the Ukrainian Research and Design Institute of Mining Geology, Geomechanics and Surveying (UkrNIMI, Donetsk), Institute of Geology of the National Academy of Sciences of Ukraine (Dyakiv and Haydin, 2021) were involved in solving the problems of the salt mines.

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1.1 Analysis of literary sources regarding the topic of the work

In Trofymchuk et al. (2020) the authors conducted a retrospective analysis and studied the dynamics of destructive phenomena on the territory of Solotvyno, using satellite imagery. Using the survey data for 2017 and 2019, respectively, a deformation map was created in the ArcGIS software. These materials reflect the dynamics of movements and their direction, as well as infrastructure facilities that have fallen into the zone of influence of dangerous geological processes. However, the authors did not compare the scale of destructive phenomena according to the obtained survey materials by years, and did not calculate the areas affected by these phenomena.

The authors of the work Pakshin et al. (2021) processed the materials of satellite images in order to establish the main patterns of deformations of the earth's surface and predict the development of dangerous geological processes within the Solotvyno and nearby territories. On the basis of the processing results, digital maps were created. The accuracy of estimating the average speed of vertical movements of objects was 2 – 4 mm/year using the "Persistent Scatterers (PS)" method and 6 – 15 mm/year using the "Small Baseline Subset (SBAS)" method. Information products (raster and vector) were created, which made it possible to analyze changes in spatial and temporal measurements. The magnitudes and areas of concentrated deformations of the earth's surface within the zone of anthropogenic and natural karst development were determined. An assessment of the anthropogenic hazard of the Solotvyno salt-dome structure and the surrounding areas has been given. It has been established that mines No. 7, 8, 9 pose an anthropogenic threat to the safety of Solotvyno residents. In general, the study was quite extensive and qualitative in terms of the problem of the village.

In the materials Shekhunova et al. (2019), the authors describe the process of creating a zoning scheme for dangerous geological processes and their consequences within Solotvyno. This scheme is based on geodetic survey materials, remote sensing data and the authors' systematic field observations. The authors managed to rank the territory according to the scale of influence of karst, sufosis and erosion phenomena. This work is not considered finished, as stated by the authors, and the obtained results are the basis for further observations and their inclusion in the scheme. The future scheme is proposed to be the basis for ensuring the safety of Solotvyno. However, at present, the scheme requires further monitoring.

In Yakimchuk et al. (2021) the authors conducted a study using remote sensing materials to identify relative changes in the environment for two channels based on the materials taken in 2015 and 2019. A map was also created with selected manifestations of exogenous processes and the territory of the salt mine, such as: landslides, sinkholes, karst fields and swampy areas. Based on the research materials, an extensive analysis of the movements of the earth's crust within the mining zone was carried out.

1.2 Development of the salt industry in Solotvyno

The Solotvyno rock salt deposit is geographically located in the south-west of Ukraine, not far from the border with Romania, within the Carpathian internal depression. The administrative position corresponds to the territory of the Tyachiv district of the Transcarpathian region. The highest part of the village rises to 325 m above sea level on the southern slopes of the Magura Mountains, the lowest part in the Tysa floodplain is a little more than 250 m. The average height above sea level is about 280 m. The area of the salt dome is located between the Vygorlat-Hutinsky volcanic ridge and the sedimentary flysch zone of the northeastern Carpathians. From a geomorphological point of view, the Solotvyno deposit is located in a valley on the right bank of the Tysa River (Zaton district, an old watered area, where a salt lake is located). The deposit

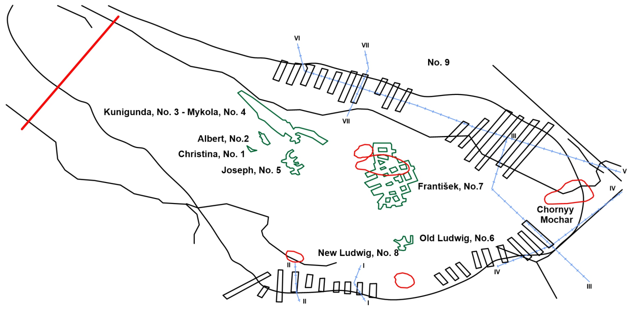

Figure 1. Scheme of the salt mines of the Solotvyno deposit (Dyakiv and Haydin, 2021)

is located within the climatic range where the rainfall is almost double the amount of evaporative water. The average long-term precipitation is 873 mm, of which 45% falls from May to August and the fixed maximum is 294 mm (Kalynych et al., 2017).

The creation and development of the city of the same name as the deposit is inextricably linked with the beginning of the development of rock salt deposits on its territory. Based on archival data, exploitation of the deposits underground began about 245 years ago. The first underground mine in Solotvyno dates back to 1777 and was named Khrystyna. It existed until 2010. In total, 9 mines operated on the territory of the town at different times. Throughout the history of the exploitation of salt formations, an extensive arsenal of methods of extracting mineral resources was used, which were represented by open pit and mine methods (Ivanov, 2007).

At first, the technology was based on the brine mining method, which is a high concentration of salt (NaCl) in water (H_2O), which over time developed into the usual underground mining using various tools (Shekhunova et al., 2019). Also, salt was mined from cone-shaped pits up to 20 m deep, and over time their depth reached 150 m.

Industrial salt extraction began in the middle of the 18th century. In the best years of the period – the 80s of the XX century – production reached 500 thousand tons per year, which covered a significant part of the needs of the salt market (Dyakiv and Haydin, 2021). In total, nine different mines operated in Solotvyno, of which mines No.1 – No.6 were the oldest and smallest. They were operated until the 1930s. Mine No. 7 worked until 1953. The layout of salt mines is shown in Figure 1. Considering the location of mine No. 7 on the site with a satisfactory functional type of salt rock, the underground production was quite long.

The total volume of the two horizons available for production is 1.7 million m^3. The mine was operated with a constant inflow of water and had five levels of drainage works. This is evidenced by the fact that the central part of the deposit up to 100 m deep was destroyed by man-made karst (Bosevska and Khrushchov, 2011). Territorially, it is located east of the center of the salt dome.

Mine No. 8 is located in the southern part of the dome and existed for 125 years; operation was carried out until 2007. Four horizons were developed, which in total amounted to approximately 8 million m^3; preparatory work was also carried out for the development of the fifth horizon. The height of the chambers varies from 45 meters for the upper and up to 65 m for the lower horizons. The development of the mine took place with the constant involvement of the drainage system. However, despite the above-mentioned measures, the volume of water inflows constantly increased (Bosevska, 2009).

Mine No. 9 is located in the northern part of the dome and is laid at a mark of 430 m. Only one horizon was mined at an absolute mark of 146 m. The mined rock volumes were approximately 4 million m^3. Above this development horizon was the underground department of the Ukrainian Allergological Hospital, which had a system of connections with the mine in the form of trunks. From

Table 1. Information about the mines which operated on the territory of the Solotvyno deposit (Bosevska, 2009)

Name of the mine	Commissioning	Decommissioning	Year of liquidation	Reasons for liquidation and method
Christina, No. 1	1778	1781	unknown	low salt quality; covered with soil
Albert, No.2	1781	1789	1870	water breakthrough due to roof collapse; natural flooding
Kunigunda, No. 3	1789	1905	1925	water breakthrough due to roof collapse; natural flooding; later covered with soil
Mykola, No. 4	1789	1905	1925	water breakthrough due to roof collapse; natural flooding, later covered with soil
Joseph, No. 5	1804	1850	1895	low salt quality; natural flooding
Old Ludwig, No.6	1804	1810	1930	low salt quality; partial filling with soil
František, No.7	1809	1953	1970	weakening of the supporting and interhorizontal cells, collapse of the chamber roof, water breakthrough;
New Ludwig, No. 8	1886	2007		combined flooding (natural and partly artificial)
No. 9	1975	2008	2010	operational work has not been carried out since 2006 due to the state of emergency and difficult hydrogeological conditions; is flooded; is in the conservation stage

the beginning, the eastern part of the field began to suffer from excessive water inflows while, in turn, the opposite part of the deposit was not subject to flooding. The first collapse in the mine occurred in 1973 in the central part of the salt dome. As a result of the violation of the protective layers, the incoming water activated processes inside the salt dome which resulted in significant subsidence and collapse of its central part. The brines increased their volume at a rapid pace. In 2006, the indicators reached values of 200 m^3/h. In 2008, this indicator increased to 550 m^3/h. There was constant pumping of water volume. According to the results of the conducted research, it was found that the pumped water was on the verge of full saturation, amounting to 300 g/l. From these values, it was concluded that the water massifs had dissolved the salt massif for a long time. Subsequently, the phenomena of soil subsidence on the surface and the destruction of mine structures led to the global degradation of the relief. According to the latest information, the mine is completely filled with water, the level above which is in balance with the mark of the depth of underground water.

Salt lakes were formed at the place where the dome of the Solotvyno rock salt massif came to the surface in Solotvyno, Transcarpathian region. The largest of them is Lake Kunigunda (depth from 1 to 8 m, area ~800 m^2), which contains oil and weakly alkaline silt mud. The lake is a natural health center (Parlah et al., 2003).

The largest man-made objects that worked in the 20th – 21st centuries are concentrated mainly in the western part of the structure. These are nine mines, water discharges (mines, pits, tunnels), ventilation (shafts), old drainage structures, a dam, etc. The years of exploitation of deposits according to the source Bosevska (2009) are shown in Table 1.

1.3 The results of the development of industry and the study of the problems of the village

For more than a decade, the Solotvyno rock salt deposit has been degeneratively changing due to an extraordinary environmental situation. As a result of negative processes, there has been a loss of operating mines and a complete emergency shutdown of the state enterprise "Solotvyno Salt Mine". There is a merciless degradation of the landscape, which is manifested in the development of gigantic failures even outside the limits of production itself.

In the article by Trofymchuk et al. (2020), the space images of the Solotvyno territory for 2017 and 2019, respectively, was compared. The results showed that the progress of karst formation processes takes place mainly in the southern direction and to the north towards the slope of Mount Magura. The authors constructed a map of geodynamic influence and predicted potentially dangerous zones that may be subject to destructive influence.

The ecological disaster in Solotvyno gained publicity among the public and mass media due to the scale of the impact on the economic and social component. The Ministry of Emergency Situations was involved in the problem (Instruction of the President of Ukraine, 2010). As a result, the expert opinion of the Ministry of Emergency Situations (protocol No. 14 dated 2010-12-03, letter No. 02-17292/165 dated 2010-12-09) determined the environmental situation related to the territory of (SE) "Solotvyno Salt Mine" as an emergency at state levels.

Despite the cessation of general mining, the company "Speleocenter Solotvyno" LLC received a special permit for the use of subsoil (No. 6190 dated 2017-03-15).

With the flooding of mines No. 8 and No. 9, Ukraine lost not only a promising location for salt production. Due to negative processes, the underground sanatorium of the Republican Allergological Hospital, unique in Europe, was lost. The powerful massifs of the salt mine and underground corridors served as a resource for the underground department of the Transcarpathian Regional Allergological Hospital. Allergic diseases, lesions of the respiratory tract, and, in particular, bronchial asthma, were treated there. Descents into the mines were carried out annually for the purpose of rehabilitation and strengthening of health.

In addition to medical facilities, the Solotvyno underground low-frequency laboratory of the Institute of Nuclear Research of the National Academy of Sciences of Ukraine was flooded, where a number of radioactive anomalies were studied. These enterprises functioned in close connection with the deposits. Mining of salt, carrying out scientific activities and treatment of patients gradually stopped functioning starting from 2006 – 2008. Due to insufficient funding from the responsible authorities, it was not possible to carry out the necessary measures for technical support and equipment conversion. And this led to further destruction. In addition, due to the neglect of the situation, the process of landscape degradation has accelerated. Currently, the phenomenon of karst processes is spreading beyond the mining district, which, in turn, threatens the future development of the village. In recent years, the size of existing karst formations has increased by 50 – 70%. Important objects of the village infrastructure, including two schools, a hospital, a network of centralized water supply and drainage, and a power line, fell into the zone of potential disaster.

Under the leadership of the State Environmental Inspection, periodic monitoring of the condition of surface waters of the Tysa River has been carried out. To conduct these observations, 6 sites were established, among them 4 are international and observed together with bordering neighboring countries. Water sampling takes place in the Solotvyno and Tyachiv basins (Ukraine – Romania), Vylok and Chop/Zagon (Ukraine – Hungary) and Chop/Mali Trakany (Ukraine – Slovak Republic).

In 2016, the Advisory Mission of the EU Civil Protection Mechanism (EUCPT) operated in order to assess the situation on the territory of the mines of the Solotvyno Salt Mine enterprise. The mission's activities were implemented with the support of the Ministerial Commissariat for the EU Strategy for the Danube Region, the Ministry of Foreign Economy and Foreign Affairs of Hungary, the Ministry of Foreign Affairs of Ukraine, the Representation of Ukraine to the EU, the Transcarpathian Regional Council and the Transcarpathian Regional State Administration. Specialist forces prepared materials for the Advisory Mission, which aimed to contribute to the creation of a concrete plan of action to resolve the emergency situation.

In the process of preparing materials from the National Academy of Sciences of Ukraine for the implementation of the mission with the aim of obtaining express information for the assessment of the current state of the mountain massif over the worked-out space of the deposit, the determination of local heterogeneities and the forecast of the development of dangerous geological processes, the stressed state was investigated by the method of natural pulses of the Earth's electromagnetic field (PIEMZ, Natural Pulse Electromagnetic Field of the Earth – NPEMFE (Yakovlev et al., 2016)).

The current situation at the SE "Solotvyno Salt Mine" is critical and requires the attention of the state to regulate negative phenomena, the development of which threatens the lives and health of the residents of Solotvyno. Available data on the topic of the problem indicate that endogenous processes are spreading beyond the former mining area. It is necessary to conduct regular monitoring missions to track the dynamics of the development of destructive phenomena on the territory of the village.

2 Monitoring of karst processes on the territory of Solotvyno by photogrammetric methods

The advantage of using unmanned aerial vehicles (UAVs) over the use of space satellites and aerial manned vehicles is the possibility of shooting from low heights and directly in the vicinity of objects, obtaining high-resolution images, using them in emergency zones without risk to life and health of the pilot and profitability (Hlotov et al., 2018). The use of UAVs allows you to quickly carry out digital aerial photography of small land plots with the aim of drawing up orthophoto plans of various scales for the performance of land monitoring tasks. An important issue is the timely updating of cartographic materials (Hlotov and Gunina, 2016).

For the task of performing aerial photography, a light backpack UAV "Arrow" of Ukrainian production was involved. The device was developed by Volodymyr Hlotov, professor of the Institute of Geodesy of the Lviv Polytechnic National University, in cooperation with the ABRIS Design Group. The body of the UAV is made of carbon fiber and fiberglass, which is resistant to the influence of external factors. As for the safety system, the model is designed with a parachute system and uses rubber dampers to minimize damage during landing (Hlotov et al., 2018). The general appearance of the UAV before its launch is shown in Figure 2

Figure 2. General view of the Arrow UAV before launch

In general, the model is designed to work in stable, rain-free weather conditions in the temperature range from −25 to +40°C. Based on the values of the operating altitude and flight speed, it is quite realistic to obtain high-quality shooting materials with a resolution of 2 cm/pixel. The device has a system for determining the values of the wear angle during flight, which also compensates for the displacement. The total weight when fully equipped is 8 kg, which allows you to deliver the device to the shooting location without the involvement of special transport and to use it in mountainous terrain. The technical characteristics of the UAV "Arrow" are given in Table 2.

2.1 Design and execution of aerial photography

FlightPlanner is an aerial photography planning program for fully automated flights from takeoff to landing. Intelligent software calculates the local wind speed and direction and terrain features (topography) in real-time to calculate flight and plan aerial mapping with extreme accuracy. FlightPlanner also programs and manages onboard equipment during the flight.

In the field, the operator will easily perform pre-flight procedures guided by step-by-step instructions.

For aerial photography, a shooting resolution of ~8 cm was chosen, with longitudinal and transverse overlap of 80% and 70%, respectively. This percentage of overlap is needed to improve the creation of the point cloud of karst. These parameters have been configured in the program window.

Also, when setting up the flight, it is necessary to correctly choose the starting and landing place of the UAV (Figure 3). One of the biggest disadvantages of working in densely built-up areas is the lack of open spaces. Since the UAV lands by parachute, it needs a spacious area of about 100 by 100 meters to prevent it from hitting trees, roofs, poles, etc.

Figure 3 shows the UAV route (green line). The red markers show the launch and landing sites of the UAV. The yellow semi-transparent area shows the survey area, and blue rectangles show the design locations for laying the edges of the images on the terrain. This software product takes into account the specifics of the terrain and the UAV rises to different heights in order to avoid multi-scale images. In the project, this is not critical, because the range of relief change is approximately thirty meters, although there is a slight variation in scale. Therefore, these facts should be taken into account when using another UAV.

After designing, a navigation file is created with waypoints placed sequentially. Before the flight, pre-flight preparation is carried out.

Table 2. Technical characteristics of the Arrow UAV

Characteristics	Parameters
Takeoff weight, kg	4.8
Camera	Sony QX1
Sensor type	APS-C 20MP
Lens type	variable
Battery capacity, Ah	16
Minimum flight speed, km/h	50
Cruise flight speed, km/h	60 – 80
Maximum flight time, min	100
Maximum flight range, km	100
The maximum controlled distance from the base, km	15
Maximum flight height, m	5000
Minimum operating flight altitude, m	75
Maximum image resolution, cm/pixel	2
Speed of climb (at sea level, in ISA conditions), m/s	6
Hand start	yes
Automatic start (from LuckyLaunch catapult)	yes
Automatic parachute landing	yes
Recommended launch pad dimensions, m	50x30
Dimensions in transport configuration, cm	120x25x25
Flight preparation time, min	10
Limit wind speed, m/s	12

Figure 4 shows the window of the Mission Planer program, which controls all UAV systems.

The survey was carried out in November 2021 in sunny weather with a moderate surface wind of up to 5 m/s. The survey took place in regular mode; as a result of aerial photography, 503 images were obtained.

2.2 Creating a point cloud and an orthomosaice in the Pix4D software package

An orthomosaic is a digital image of the area obtained by aerial photography and reduced to a given coordinate system. That is, an orthomosaic is not only a visual representation of the earth's surface, but also the basis for creating topographic maps and plans. The technological scheme of creating an orthomosaic is presented in Figure 5; processing has high quality options in each step.

The orthomosaic and the digital terrain model, which were created in the Pix4D software package, are shown in Figure 6.

As a result, the orthomosaic with a resolution of 8.4 cm was created, which corresponds to the technical specifications of the customer. For binding and control, 28 reference points were used; according to the quality report the mean square error of their placement does not exceed 149 mm.

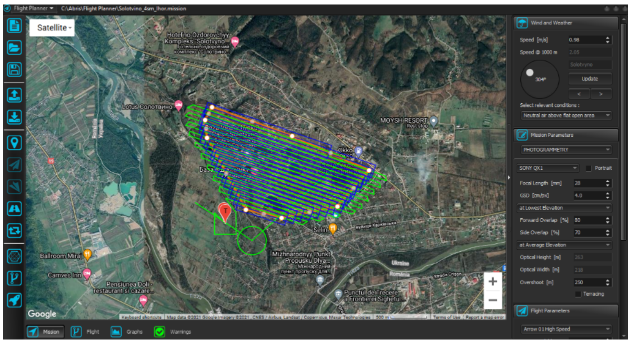

Figure 3. Designed flight routes.

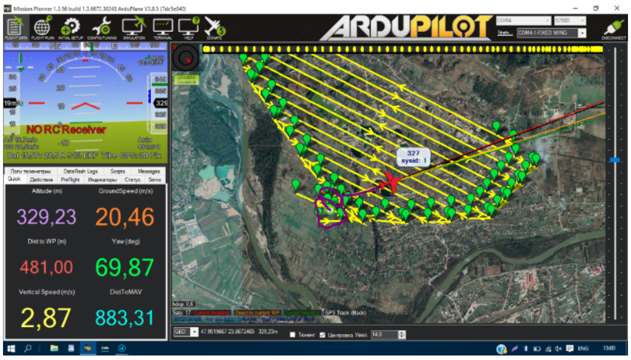

Figure 4. The window of the Mission Planer program

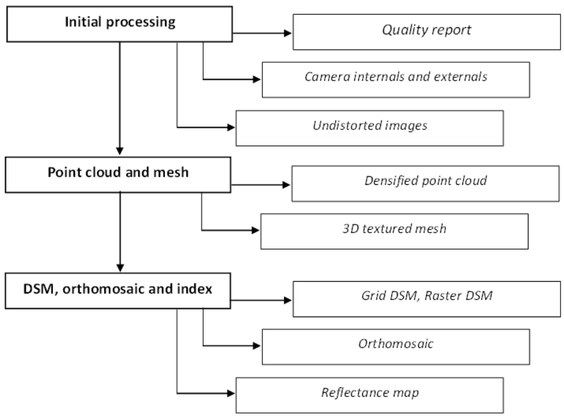

Figure 5. Technological scheme of creating an orthomosaic in Pix4D.

2.3 Estimating the accuracy of the orthomosaic and DTM

For an independent assessment of the accuracy, 22 control points were used (Table 3). According to Bessel formula. the MSE of plan and height coordinates was calculated. Its values are given in Table 4. The obtained values fully satisfy the accuracy of the topographic survey.

3 Calculation of plane-volume characteristics of karst formations in Solotvyno

After processing the survey materials and receiving an orthomosaic, a digital terrain model and a 3D model of the survey area, it became a question of assessing the scale of karst phenomena within the Solotvyno village of the Transcarpathian region. Until now, quite a few works have been carried out on the dynamics of karst processes in the studied area using GIS techniques.

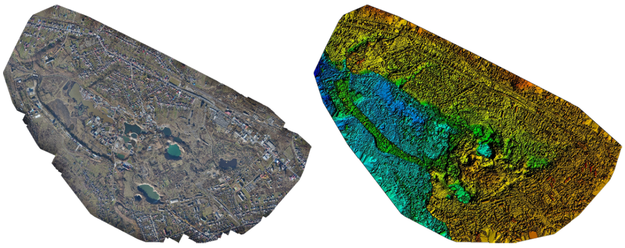

Figure 6. Orthomosaic and DTM created in the Pix4D software package.

Table 3. Checkpoint Accuracy Assessment

No.	ΔX [m]	ΔY [m]	ΔZ [m]
2	-0.066	-0.134	-0.186
3	0.065	0.093	0.173
4	0.056	0.046	-0.222
5	0.067	-0.091	-0.185
7	0.049	-0.027	0.239
10	0.157	-0.036	-0.086
11	0.025	-0.018	-0.224
20	-0.055	0.020	-0.039
21	-0.082	-0.040	-0.027
23	0.064	0.026	-0.095
25	0.018	-0.101	-0.512
27	-0.087	0.031	0.306
29	-0.144	0.097	-0.113
32	-0.072	-0.014	-0.253
33	-0.131	-0.211	0.388
37	-0.055	-0.107	-0.108
39	-0.031	-0.056	0.122
42	0.000	0.093	-0.207
48	0.036	0.040	-0.001
49	-0.043	-0.061	-0.019
58	0.047	0.079	0.022
59	0.047	-0.009	0.167

Table 4. MSE of plan and height coordinates

	MSE Pix4dmapper	Independent control
X [m]	0.07	0.08
Y [m]	0.07	0.08
Z [m]	0.11	0.21
Altitude [m]	0.15	0.24

The basis for calculating volumetric characteristics is a digital terrain model.

To work with raster data in the Pix4Dmapper software, a panel with a group of tools was used and an item for calculation was selected in the context menu.

First, for each of the studied objects, the areas were calculated using the polygon creation tool. Examples of boundary identification are shown in Figure 7 and Figure 8.

For a qualitative determination of the parameters of objects, a repeated stage of creating a 3D model with a greater density of points and an identification parameter was performed. In the Volumes menu, separate calculation elements were created for mines No. 7 and No. 8 and nearby funnels of a smaller diameter. With the help of vertices and polylines, the corresponding edges of the funnels are marked (Figure 9).

Similar actions were carried out for each object; a data set consisting of area and volume parameters was obtained.

Based on the measurement results, a table was drawn up and the values were compared with the indicators obtained by the authors of the work Kalynych et al. (2017). The results are shown in Table 5

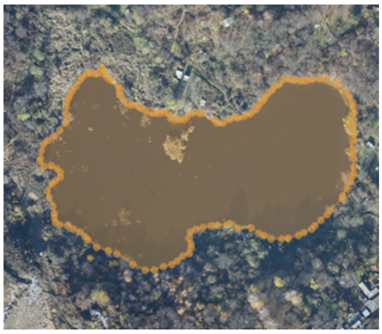

Figure 7. Chornyy Mochar Tract

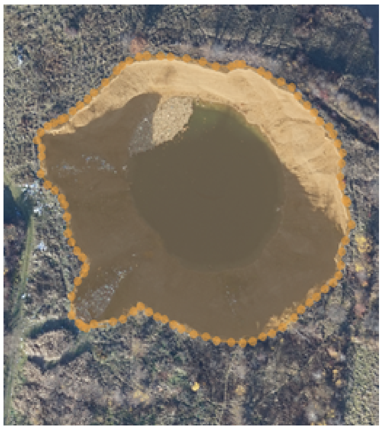

Figure 8. Karst funnel near mine No. 8

and in Figure 10.

From Figure 10 we can see that changes in the areas of karst formations do not develop linearly, which means that they are far from complete. The formation above mine No. 8 has somewhat slowed down its development over the last observation period (2020-2021). The karst formations of mine No. 7 and Chornyy Mochar, on the contrary, are accelerating. This certainly indicates the further deterioration of the situation. Table 6 shows the numerical values of the area change rates for the corresponding period. The table shows values from the following sources: 2010 aerial photography, 2016 satellite images, 2018 topographic survey materials, 2020 UAV aerial survey data, 2021 UAV aerial survey data.

The volume characteristics of the funnels were calculated and presented in the Table 7.

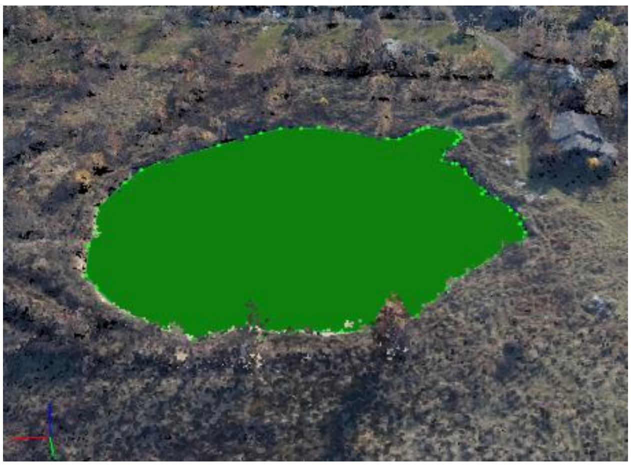

Figure 9. Setting the contour of a 3D object for mine No. 8

Table 5. Changes in the area of karst formations by years

Years	Mine No. 8 [ha]	Mine No. 7 [ha]	Chornyy Mochar [ha]	Karst funnel near mine No. 8 [ha]
2010	1.1704	1.2383	0.9035	—
2016	3.2054	3.7896	0.9857	—
2018	4.2457	3.8429	1.1277	—
2020	4.3460	3.9604	2.0255	0.6302
2021	4.3711	4.5518	2.1487	0.6431

Table 6. The rate of change of karst formations

Time period	The rate of change of karst formations			
	Mine No. 8	Mine No. 7	Chornyy Mochar	Karst funnel near mine No. 8
2010 – 2016	0.339	0.425	0.014	-
2016 – 2018	0.520	0.027	0.071	-
2018 – 2020	0.050	0.059	0.449	-
2020 – 2021	0.025	0.591	0.123	0.013

Table 7. The results of measuring the volumes of funnels

Years	Mine No. 8 [m^3]	Mine No. 7 [m^3]	Chornyy Mochar [m^3]	Karst funnel near mine No. 8 [m^3]
2021	552891.52	564378.67	there is no funnel	89987.71
April, 2020	784452.3	713268.1	there is no funnel	84668.5
October, 2021	823518.3	752493.6	there is no funnel	89032.3

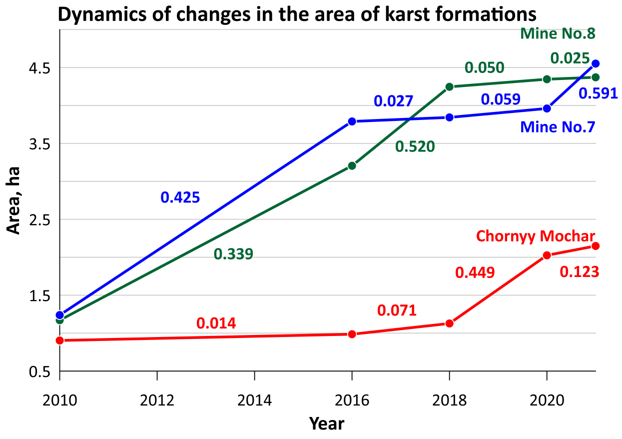

Figure 10. Dynamics of changes in the area of karst formations

Thus, it can be noted that the destructive processes have not stopped and continue to have a negative impact on the relief of Solotvyno. As for the calculated volumes of funnels, for a full-fledged analysis, additional studies are needed to compare the results.

4 Conclusions

The use of UAVs for the purposes of aerial photography is a reliable andmore economically justified alternative to traditional manned aerial surveyfrom UAVs when involved in large-scale survey tasks. Moreover, in recent years, as a result of the development of technologies and methods of surveying, materials obtained with the help of UAVs have almost completely replaced traditional methods of collecting information. The availability of the latest software products allows you to quickly and efficiently process large amounts of data, which in turn increases labor productivity.

With regard to the use of UAVs for monitoring purposes, the following specific advantages can be distinguished: high maneuverability, the possibility of filming from a low altitude, the availability of filming in difficult inaccessible areas, attracting a small number of people and cost. The production of new domestic models of devices is gradually increasing its volume and helps to perform a number of tasks in various fields.

For the monitoring phase of 2021, aerial photography was carried out with the FLIRT "Arrow" UAV; as a result, 503 digital images with a resolution of 8.4 cm were obtained. Reference and control points were determined in the amount of 60 pieces in the RTK mode from the Geoterrase network. For the created orthomosaic and DTM in the "Pix4Dmapper" software, the quality by internal convergence is 15 cm. The accuracy assessment for control points are 11 cm in plan and 24 cm in height.

From the results of the calculation of errors we can conclude that on the basis of the images obtained from the UAV it is possible to create high-quality and accurate cartographic materials that meet the current regulatory document standards.

On the basis of the created cartographic materials, a study of karst manifestations on the territory of Solotvyno was carried out with a comparison of the impact of destructive processes for 2010-2021. Summarizing the performed calculations, it can be noted that the processes of increase in the size of karst funnels are not linear in nature. The pace decreased in the period 2018 – 2020, but did not stop. The areas of the funnels at the site of mines No. 7 and No. 8 for 2021 are 4.5518 hectares and 4.3711 hectares, respectively. The area of the funnel formed next to the flooded mine No. 8 is 0.6431 ha. The formed Chornyy Mochar Lake has an area of 2.1487 ha. This indicates the continued influence of groundwater on salt deposits.

On the basis of the materials obtained in this work, it is advisable to conduct additional studies that will help to investigate in more detail the processes of karst formation in time. First of all, in our opinion, it is necessary to reduce the survey interval: this will make it possible to more accurately determine changes in karst formations and will make it possible to foresee possible operational formations of sinkholes and provide for more details changes in these processes.

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