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The Use of Digital Terrain Models to Estimate the Pace of Filling the Pit of a Central European Granite Quarry with Water

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Abstract: This paper presents the results of an analysis of the pace of filling one of the deepest European granite quarries with water. A DTM (digital terrain model) based on data from LiDAR ALS (light detection and ranging airborne laser scanning) was used to create a model of the pit of the Strzelin I granite quarry and to determine the reach and surface area of the direct catchment of the excavation pit. The increase in the volume of water in the excavation pit was determined. Analogue maps and DTM were used to calculate the maximum depth of the pit (113.3 m), its surface area (9.71 ha), and its capacity (5.1 million m^3). The volume of water collected in the excavation pit during the years 2011–2018 was determined based on the analogue base map and the DTM. The result was 0.335 million m^3. Based on the data made available by the mining company, the correlation of the DTM with the orthophotomap of the mining area and additional field measurements, the ordinates of the water level in the years 2011–2018 were determined. Initially, the water surface level in the quarry was located on the ordinate of 66.6 m a.s.l. (July 20, 2011). After the pumping of water was discontinued, the level rose to 96.1 m a.s.l. (January 28, 2018). The increase in the water volume in the quarry pit during specific periods was determined (actual retention increase). The obtained data on the volume of the retained water referred to the period during which it accumulated in the quarry. On average, the net increase in water retention in the excavation pit was 138.537 $m^3 \cdot d^{-1}$, and the calculated net supply from the direct catchment (16.04 ha) was 101.758 $m^3 \cdot d^{-1}$. The use of DTM and measurements of the water level in the excavation pit seem to be an efficient means of estimating the pace of spontaneous filling of the quarry with water supplied from the direct physiographic catchment.

Keywords: quarry lake; quarry; water reclamation; LiDAR ALS; DTM; GIS; hydrology

1. Introduction

According to estimates, the global extent of the land area impacted by mining and quarrying is approximately 421 thousand km^2 in Europe, excluding Russia, while the estimated area impacted by active mining is about 40 thousand km^2 [1]. Most of these areas are open-cast mines. In Poland, the mining areas occupy approximately 41,000 hectares, of which open-cast mines account for approximately 335 km^2 [2]. After closing down, these areas will be subject to reclamation. The main areas of such reclamation and land management of post-mining areas include: agriculture (e.g., cropping, breeding and fish farming) [3–8], forestry (e.g., forestry, protection and recreation) [4,6–10]; nature (e.g., nature reserve, landscape parks, natural monuments, ecological areas, Natura 2000 areas, natural successions and wildlife habitats) [4–16]; economic (e.g., housing, industry, commercial services, and municipal operations) [3,6–9,11,12,17,18]; aquatic (e.g., water management, recreation, mine ore quarry lakes) [3,4,6–8,10–13,15,16,19,20]; and leisure and tourism (e.g., recreation, education, cultural) [3,5–12,14–18,21]. Considering the problem of fresh water deficits in the world [22], water reclamation that leads to the creation of pit lakes or quarry lakes may be important from the point of view of water management [23], particularly in areas with low water resources [12,24–26].

In many countries (e.g., in Australia, Canada, China, Czech Republic, Germany, Italy, France, Poland, Sweden, the U.K. and the USA), hundreds of new pit or quarry lakes have been created [3,12,13,16,19,20,23,27–37] in former excavations of clay, sand and gravel, in former stone quarries, and in former open-cast coal and lignite mines when their respective operations ceased [10,15,23,36,38–41]. Pit lakes or quarry lakes may be used for various purposes, including, among others: recreation and tourism [3,5,9–12,16,17,21,26,42–44], wildlife habitats [5,9–12,16,24], aquaculture and fish farming [3,5,24,26,36,45–48], water management [3,5,10–13,16,23,24,36,42,48], floating photovoltaic systems [49], potable and industrial water reservoirs or irrigation water storage for agriculture and horticulture [3,10–12,16,19,20,24,26,36,44,48,50,51], capturing flood waters, or improving the flow rate in water courses during droughts [36,52–54].

The potential use of water from pit lakes or quarry lakes depends on its quality and amount [11,19,23,36,37,47,54–57]. These values are influenced by the size of the excavation pit, hydrogeological conditions, the geological structure of the mine and its surroundings, as well as the size and management of its own (direct) catchment [3,23,25,36,37,40,44,54,58–61].

After discontinuation of dewatering, the pits fill with groundwater, rainfall, and surface runoff to form emerging pit lakes or quarry lakes [3,23,24,27,31,32,37,41,42,62,63], which may have different depths [3,23,24,30,31,36,50,57,58,61,64–67], surface area [3,23,24,32,36,37,50,57,58,66,67] and cubic capacities [23,36,50,67,68], depending on the type of the excavated material and mining technology used [23,30,36,37,56,61,65]. Depending on the geomorphological parameters of an open-excavation pit, hydrogeological conditions, the geological structure of the mine and its surroundings, as well as the possibility to use water from rivers and streams to flood the pit, the process of flooding the pit bowl may last from several months to several decades [3,25,31,36,50,54,59,61,69–71].

The monitoring of mining and post-mining areas may be carried out with use of LiDAR and GIS technology [23,72,73]. The geomorphological parameters of the pit (in particular the cubic capacity of excavation) indicate the potential amount of water required to fill the excavation pit, which will become the bowl of the new pit lake or quarry lake. The geomorphological parameters of the pit (including its cubic capacity, surface area and depth) may be determined with the use of traditional geodetic methods (levelling) or modern ones, such as GNSS technology and the RTK method [74,75]. If LiDAR data are available or may be obtained, the geomorphological parameters may be determined based on data from terrestrial laser scanning (TLS), airborne laser scanning (ALS), mobile laser scanning (MLS) techniques, or other photogrammetric measurements (e.g., with use of unmanned aerial vehicles (UAVs)) [23,75–81]. These methods can also be used to determine the parameters of their own catchments (direct catchments of the pit) that are necessary for hydrological calculations. LiDAR data, digital terrain model (DTM) data, or digital elevation model (DEM) data, as well as aerial photographs (orthophotomaps), may also be used, among others, in predicting the retention capacity of reservoirs and polders [23,82], in constructing decision support systems for the purposes of stormwater management [83–85], or to model the risk of occurrence and range of floods [86–88].

The methods of calculating the amount of water supplied to the excavation pit includes a method for reservoir water balance, which takes into account (depending on local conditions and the adopted assumptions) the surface runoff from the direct catchment, underground supply, rainfall onto the surface of the reservoir, evaporation of water from the surface and retention [41,58–60,89–91]. The literature also discusses the use of the method of unit runoff from the direct catchment of the pit (where the reliable rain intensity was determined with the Błaszczyk and Reinhold method and the Bogdanowicz and Stachy model), the volume of rainwater falling directly onto the pit and underground supply [92], and the inflow of groundwater to the mine may be modelled based on the finite difference method and the finite element method (in Poland usually with use of the MODFLOW and FEFLOW programs) [41]. Rapantova et al. [93] presented the current state of groundwater flow modelling applications in mining hydrogeology. Among the methods used in hydrological modelling and calculations, the literature often lists methods based on parametric, statistical, and determinist (physical) models, including HEC, ANSWERS, SWRRBWQ, BASINS, SWAT, MIKE SHE, Xin'anjiang, WASH123D, BAYMOD and CASC2D, which are commonly used worldwide [94–97]. A description of selected methods used in Poland was provided, among others, in the work by Banasik et al. [98].

In Polish quarries (especially quarries of sand, gravel, clay, stone/solid rocks), the geomorphological parameters of the pit are usually determined with the use of traditional geodetic methods. Thus, it is important to show the owners of quarries that modern methods, such as LiDAR methods, are more precise and superior (e.g., for calculating the amount of extraction and calculating the fee of extraction natural resources, or the real rate of filling the excavation with water). Poland has poor water resources, so creating new water reservoirs is important. The aquatic reclamation of quarrying could be an alternative to constructing new water reservoirs. The aquatic reclamation of quarries could be an alternative method for increasing the volume of retention in water reservoirs. In Poland, there are many old quarries, which are backfilled with different kinds of waste (especially industrial waste). Research on aquatic reclamation of quarries could offer alternatives to backfilling them with waste. Moreover, the creation of water reservoirs in abandoned quarries could be an important element of adaptation to climate change (water retention in post-mining reservoirs), especially at the local scale—not only in Poland, but also in other countries with poor water resources.

This work is dedicated to the use of DTM to calculate the rate of retention increase in the quarry and to calculate the time necessary to fill the quarry to the assumed elevation. This study is a continuation of the topic developed in the work of Jawecki and others [23], in which the use of LiDAR ALS data to estimate the retention volume of the quarry and the impact of the retention capacity of the quarry lake on the volume of reservoir retention in the balance catchments was presented.

2. Materials and Methods

The subject of this study was the Strzelin I granite quarry located in Central Europe. This quarry is part of the Strzelin granite quarry (SGQ), which is situated in Southwestern Poland, in the Lower Silesian Voivodeship, in the western part of the town of Strzelin (Figure 1).

In the quarry, granite (mainly) and gneiss from the Strzelin deposit (surface area of 31.83 ha) are quarried in the longwall system. As of December 31, 2017, the geological resources are 72,564 thousand tonnes of industrial resources; 57,735 thousand tonnes, and 1079 thousand tonnes were mined in 2017 [99]. The average output in the years 2013–2017 was 1033.6 thousand tonnes [100]. The SGQ quarry operates as part of the Strzelin II mining region, with a surface area of 129.66 ha, where quarrying is conducted in the Strzelin II mining area with a surface area of 44.93 ha [100,101]. The Strzelin I quarry operates in a pit excavation system. It has a surface area of approximately 9.7 ha, a depth of approximately 113.9 m (measured between the water level in the sump in 2009 and the highest ordinate of the pit edge) and a cubic capacity of approximately 5.1 million m^3 (calculated to the ordinate of 170.0 m a.s.l.) [23]. It is one of the deepest granite excavation sites in Europe. With an annual output in the range of 1 million tonnes, the cubic capacity of the SGQ quarrying pits increases by approximately 0.375 million $m^3 \cdot year^{-1}$ [23], mainly in the Strzelin II quarry and in part of the Strzelin I quarry.

The rock in the Strzelin I and II quarries includes medium- and fine-grained granite, light grey biotitic granite and white biotitic-muscovite granite (crossed by veins of aplite), as well as xenoliths of the covering rock (dark Stachow gneiss) [102–104]. The estimated age of the medium-grained biotitic granite is 303 ± 2 million years (and 283 ± 8 million years for fine-grained biotitic granite) [105,106], but older articles indicate the age of the Strzelin granites from 282 ± 5 to 347 ± 12 million years [107–109] and 500 million years for the gneiss [110,111]. The pillar that separates the excavation pits Strzelin I and II was covered by weakly clayey sands, which are currently piled in the southwestern part of the mining area. According to the geological documentation of the Strzelin deposit [112], no inflow of water was noted in the drilling holes, although in the western part of the pit, there are three water reservoirs with a total volume of approximately 270 thousand m^3 (including one with a volume of approximately 253 thousand $m^{3,}$ with the ordinate of the water level at 150.0 m a.s.l. (according to the base map of 1983)), and the Strzelin I pit contains a drained sump with a capacity of approximately 100 m^3. Currently, as a result of the discontinuation of drainage, a water reservoir has emerged in the Strzelin I pit. This reservoir is supplied by rainwater, surface runoff, and groundwater from the direct catchment, as well as a periodical, unmeasured, discharge of part of the water from the sump located in the Strzelin II quarry. Due to the fact that the access is difficult, the water level in the Strzelin I quarry lake is not recorded, and the changes in its water level depend on rainfall intensity, surface runoff from the direct catchment, and evaporation.

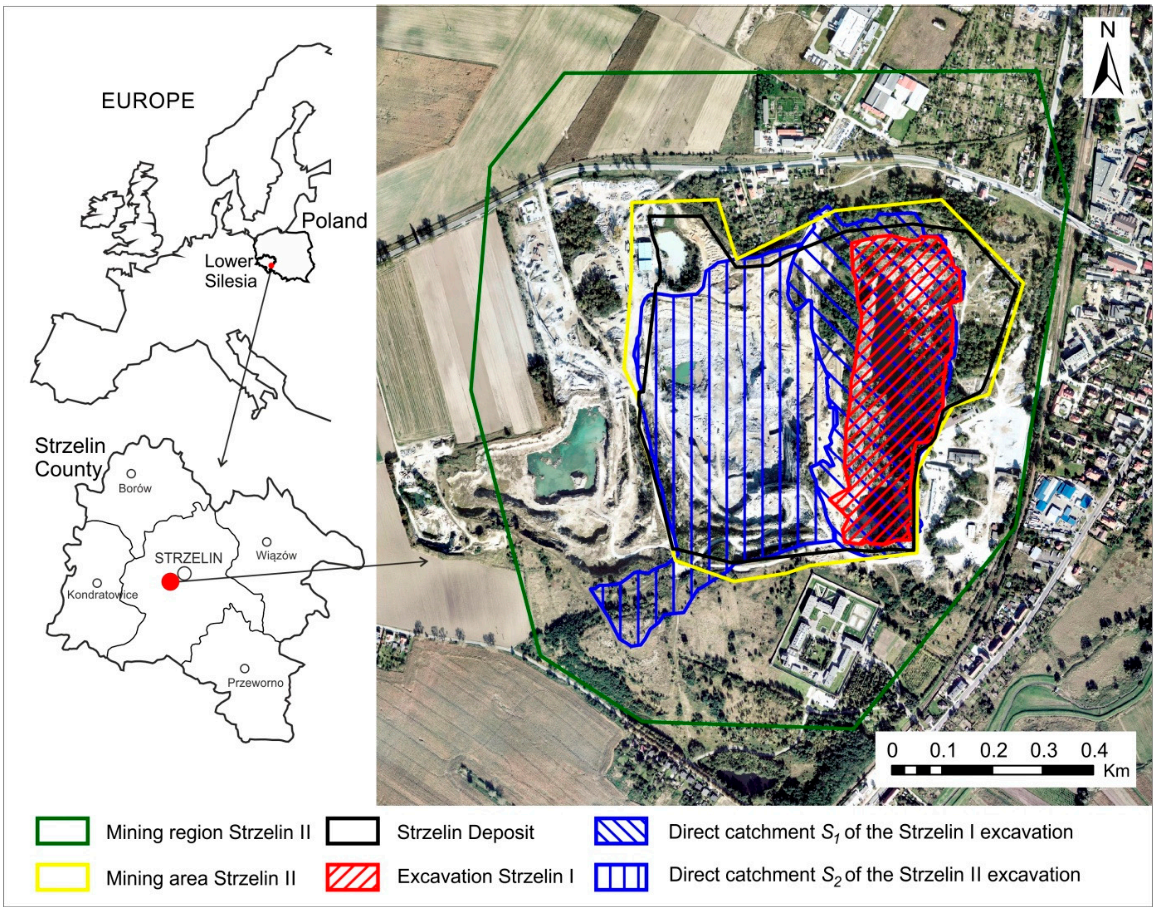

Figure 1. Location of the Strzelin granite quarry a scheme map of Europe, Poland, and the Strzelin County, as well as the reach of the Strzelin I pit and the direct catchments S_1 and S_2 (orthophotomap from 3 October 2013 (licence no. DIO.7211.195.2017_PL_N for Institute of Landscape Architecture, Wroclaw University of Environmental and Life Sciences)).

This paper is based on LiDAR data (licence no. DIO.7211.160.2018_PL_N for Institute of Landscape Architecture, Wroclaw University of Environmental and Life Sciences (Chief Land Surveyor of Country, Warsaw, Masovian Voivodeship, Poland)), obtained with use of airborne laser scanning (ALS), orthophotomaps (licence no. DIO.7211.195.2017_PL_N for Institute of Landscape Architecture, Wroclaw University of Environmental and Life Sciences, DIO.7211.204.2019_PL_N for Wroclaw University of Environmental and Life Sciences (Chief Land Surveyor of Country, Warsaw, Masovian Voivodeship, Poland)), and an analogue geodetic master map of the object of the year 2009 [113] ("GEOMETR", Szczawno Zdrój, Lower Silesian Voivodeship, Poland), made available by MINERAL Polska (MINERAL Polska LLC, Czarny Bór, Lower Silesia Voivodeship, Poland). The LiDAR flight was performed on 26–27 April 2012, from a height of 715 m above the terrain's surface, in the E–W direction. The obtained density of the point cloud, after equalisation and classification, is 4 points·m^{-2}, while the height accuracy is mh ≤ 0.15 m, and the situation accuracy is mh ≤ 0.50 m. The cloud of points was subject to interpolation in the ArcGis 10.6 (Esri: Redlands, CA, USA) software to create a digital terrain model (DTM) for the Strzelin excavation pit in the GRID format [23].

The DTM shows the formation of the land surface of the excavation pit on the days of the flights (26–27 April 2012), where the bottom is the water level in the sump. The characteristics of the geomorphological parameters of the pit before the LiDAR flights were based on the analogue geodetic master map. The ordinates of the water level in the water reservoir that emerged in the pit were read from the master map, assuming that until the day when drainage was discontinued (20 July 2011), the water level remained on a relatively stable ordinate of the terrain. The ordinate of the water level in subsequent years was determined directly based on the DTM (created on the 27 April 2012) and by correlating the contours obtained from the DTM with the orthophotomaps (created on 10 April 2013 and 23 May 2016), as well as by conducting field measurements of the height of the pit wall from the edge (ordinate determined based on the DTM) to the water level with the use of TruPulse 360° B rangemeter (Laser Technology Inc., Centennial, CA, USA) (date of measurement: 28 January 2018).

The problem of determining the volume of water retained in the quarry was solved by determining the water balance of the quarry catchment, from which all the water is directly supplied to the pit [58–60,89–91]. The general equation of the water balance for the catchment takes the form of Equation (1):

$$\mathrm{P} = \mathrm{E} + \mathrm{R} + \mathrm{G} + \mathrm{U} + \Delta\mathrm{S} \tag{1}$$

where P is the precipitation (mm), E is the evaporation (mm), R is the surface runoff (mm), G is the subsurface runoff (mm), U is the groundwater runoff (mm) and ΔS is the change in storage over time (mm).

For closed catchments of a drainless basin area, such as the quarry, one may assume that the non-permeable material of the bottom and walls of the bowl prevents drainage and effectively eliminates in-depth water drainage, so only the surface runoff factor is used here. Due to the above, the equation takes the simplified form presented in Equation (2):

$$\mathrm{P} = \mathrm{E} + \mathrm{R} + \Delta\mathrm{S} \tag{2}$$

The total annual precipitation of 604.7 mm was obtained from the data resources of the Institute of Meteorology and Water Management, National Research Institute (IMGW–PIB) [114]. This value refers to the measurements taken at the Strzelin station in the period 1951–2014.

The value of the surface runoff was determined with the use of the runoff coefficient α (Equation (3)), according to Iszkowski's formula, which equals 0.50 for land with large denivelation and negligible permeability of the substrate [115]. After transforming the formula to determine the runoff coefficient (Equation (3)), the total annual surface runoff was calculated: 328.5 mm. The transformation of the formula for calculating the surface runoff (Equation (4)) allowed us to determine the total annual volume of the runoff (V), which was V_{1+2} = 121.545 thousand m^3 for catchments S_1 + S_2 and V_1 = 52.560 thousand m^3 for catchment S_1, respectively. The daily calculation runoff was determined from the main formula presented in Equation (5):

$$\alpha = \frac{R}{P} \tag{3}$$

where α is the runoff coefficient (-), R is the surface runoff (mm) and P is the precipitation (mm).

$$R = \frac{V}{A} \times 0.001 \quad (4)$$

where R is the surface runoff (m^3), V is the total annual runoff (m^3) and A is the surface (km^2).

$$Q = \frac{V}{365} \quad (5)$$

where Q is the daily calculated runoff ($m^3 \cdot d^{-1}$), V is the total annual runoff volume (m^3) and 365 is the number of days in a year.

Based on the DTM, the geomorphological parameters of the pit (cubic capacity, water surface level in the pit, and depth of the reservoir to specific ordinates) were determined in the ArcGIS 10.6 environment, and the course of the topographic borders of the (direct) catchment of the pit was tracked. The direct catchments (Figure 1) were determined for Strzelin I (catchment S_1) and Strzelin II (catchment S_1), because some of the water flowing into the Strzelin II pit is then pumped to the Strzelin I pit. The area of SGQ is located on the watershed of the catchments of the Ślęza and Oława Rivers. However, the Strzelin I excavation pit is a drainless basin, and a major part of the pit is situated in the catchment of the Ślęza River [116]. The increase in the volume of water retained in the pit in the period between subsequent measurements of the water level ordinate formed the basis for calculating the pace of retention in the pit (Equation (6)):

$$S_r = \frac{V_r}{D} \quad (6)$$

where S_r is the average actual increase of retention in the reservoir ($m^3 \cdot d^{-1}$), V_r is the volume of water accumulating in a given time between specific ordinates (m^3), and D is the number of days of the accumulation of the given volume of water (d).

The authors used the general water balance equation (Equation (1)) to determine the average daily calculated water supply (Equation (5)) to the Strzelin I pit from catchment S_1 and catchment $S_1 + S_2$. Then, the value of evaporation from the surface of the water reservoir was deducted (it was calculated based on the average annual value of evaporation for the Ślęza River catchment (577 mm) [116]) in order to estimate the potential volume of water that may be retained in the pit. The adopted target ordinate of the water level of the emerging quarry lake was 150.0 m a.s.l. [23]. The obtained values of the increase in retention in the Strzelin I pit and the calculated net supply were then used to determine the time (Equation (7)) required to fill the bowl of the pit up to the adopted target ordinate. For the purposes of the study, the average net calculated inflow from catchment S_1 and catchment $S_1 + S_2$ were used (Q_{S_1}, $Q_{S_1+S_2}$), as well as the average actual increase in retention in the pit from the years 2011–2018 ($S_{2011-2018} = Q_{2078}$):

$$T = \left(\frac{V_t}{C}\right) \div 365 \quad (7)$$

where T is the prognosed time required to fill a specific cubic capacity of the pit (years), V_q is the prognosed cubic capacity of the Strzelin I pit from the ordinate 96.1 to 150.0 m a.s.l. (m^3) and C is the average increase in the retention (S_r) or water supply to the pit (Q) ($m^3 \cdot d^{-1}$).

The analyses of the pace of filling the Strzelin I pit with water considered the calculation variants (the supply from catchment S_1 and the combined supply from catchments $S_1 + S_2$), as well as the variant based on the actual filling of the pit bowl, based on the increase in the volume of the water accumulated in a specific time. The time in which the pit would fill up to the target ordinate of 150.00 m a.s.l. was estimated.

On the 20 July 2011, the drainage of the Strzelin I pit was discontinued, which resulted in the eventual flooding of the quarry with rainwater, as well as surface runoff, supported by a periodical discharge of part of the water from the sump in the Strzelin II excavation pit. The SGQ is located on the so-called Gallows Hill (Szubieniczne Wzgórze) on the watershed separating the catchments of the Oława and Ślęza Rivers. However, the main part of the Strzelin I pit is located in the catchment of the Ślęza River. The Strzelin I quarry is a drainless basin that is supplied with waters from its own (direct) physiographic catchment of a surface area of 16.04 ha (Figure 2), and the surface area of the Strzelin II pit (from which part of the water is regularly discharged into the Strzelin I pit) is 21.30 ha.

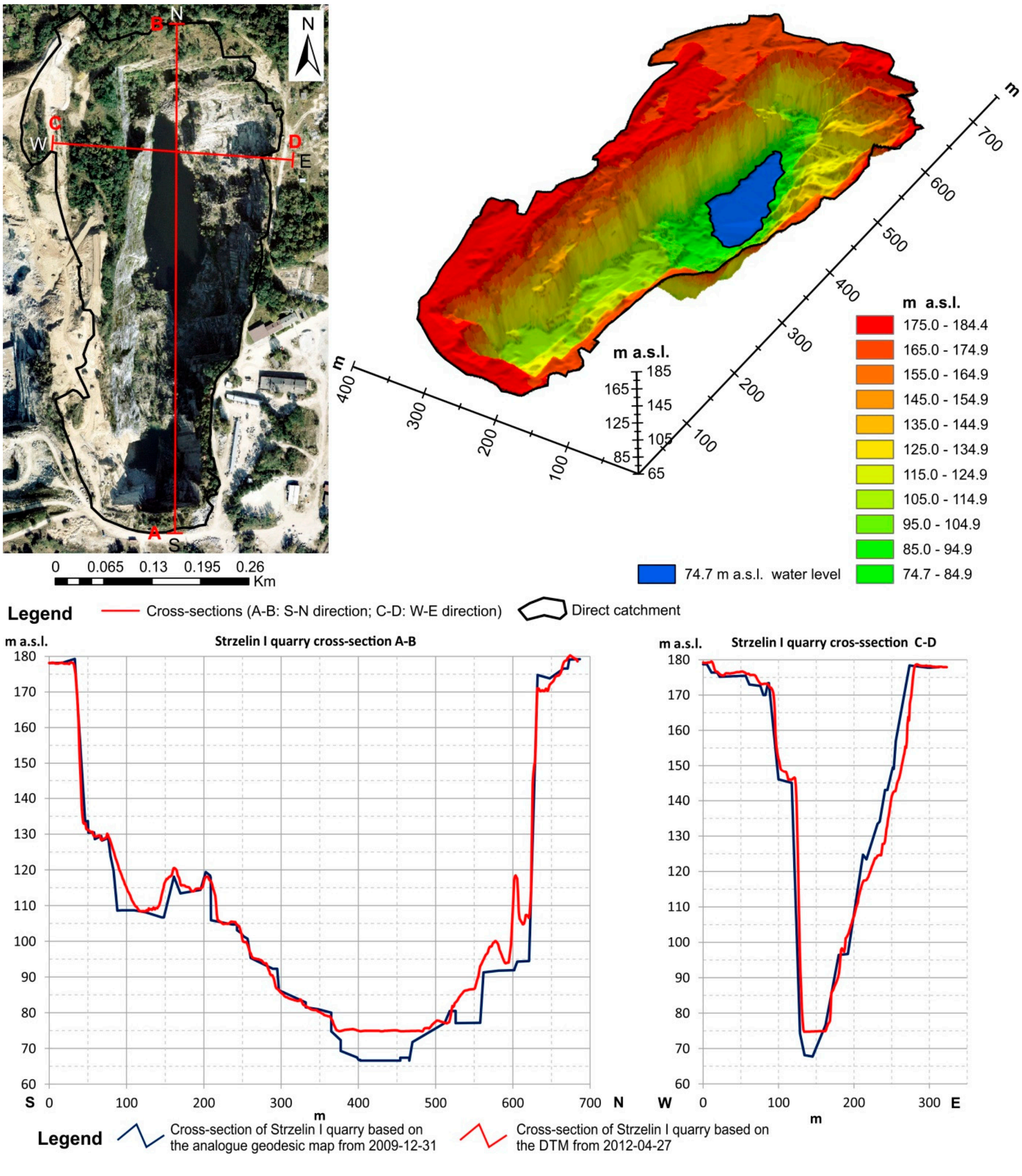

Figure 2. General view of the hypsometric 3D model and cross-sections of the Strzelin I pit.

3. Results and Discussion

The calculated annual water supply reduced by losses caused by evaporation from the surface of the reservoir that emerged in the pit was V_{S_1} = 37.2 thousand m^3 from catchment S_1 and $V_{S_1+S_2}$ = 106.1 thousand m^3 from catchment $S_1 + S_2$.

Initially (on 20 July 2011), the water level in the quarry lake was located at the ordinate of 66.6 m a.s.l., the surface area of the reservoir was ~0.18 ha, and the estimated depth was approximately 2.5 m (Table 1). By 28 January 2018, the surface area of the reservoir increased to 2.67 ha, the depth to 29.5 m, and the water level of the quarry lake was located at the ordinate of 96.1 m a.s.l. In the analysed period, the volume of water retained in the quarry increased from 0.005 million m^3 to 0.335 million m^3 (Table 1, Figure 3A), so in the period from the 20 July 2011 to 28 January 2018, 0.330 million m^3 of water accumulated between the ordinates of 66.6 and 96.1 m a.s.l. (Table 1, Figure 3B).

Table 1. Characteristics of the quarry lake in the Strzelin I quarry, based on the DTM created with use of LiDAR ALS data of 26–27 April 2012.

Measurement Date	Ordinate of the Water Level	Maximum Depth of the Reservoir	Increase in Reservoir Depth	Surface Area of the Reservoir	Increase in the Surface Area	Volume of Water Retained	Increase in the Volume of Retained Water
	m a.s.l.	m	m	ha	ha	m^3	m^3
2011-07-20	66.6	~2.5 *		0.1849		4623 *	
2012-04-23	74.7	8.1	8.1	0.4813	0.2964	37,525	32,902.7
2013-10-04	84.9	18.3	10.2	1.4855	1.0042	109,654	72,128.8
2016-05-23	89.9	23.3	5	1.9204	0.4349	194,918	85,263.9
2018-01-28	96.1	29.5	6.2	2.6704	0.7501	334,895	139,976.9
Prognosed	150.0	83.4	53.9	7.9270	5.2566	3,348,981	3,014,086.1

* estimated value.

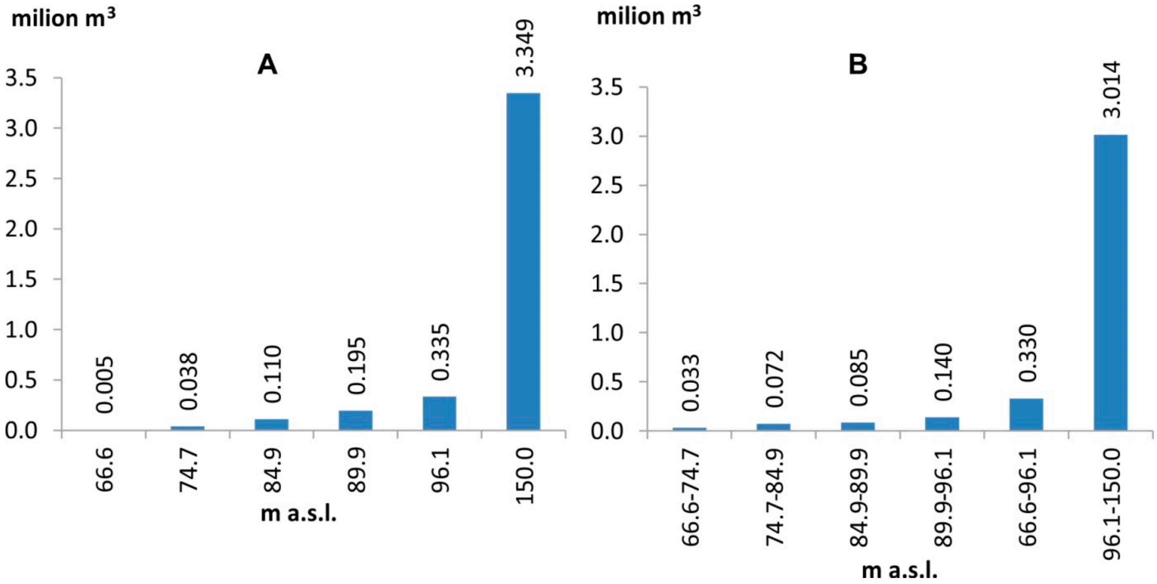

Figure 3. Volume of water in the quarry lake at a specific water level ordinate (**A**) and between water level ordinates (**B**).

If the prognosed water level reaches the ordinate of 150.0 m a.s.l., the resulting quarry lake will have a surface area of 7.92 ha, a depth of 83.4 m, and will retain 3.349 million m^3 of water (Table 1, Figure 3A). Thus, compared to the current geomorphological parameters, the surface area will increase by 5.26 ha, the depth by 53.9 m, and the volume of retained water by 3.014 million m^3 (Table 1, Figure 3B).

Comparing the volume of retained water to the time in which it accumulated, the net values of retention increase in the emerging quarry lake in the Strzelin I pit were obtained (Figure 4A). In the analysed period, the highest actual retention increase was noted in the years 2016–2018 (227.6 $m^3 \cdot d^{-1}$) and the lowest in the years 2013–2016 (88.6 $m^3 \cdot d^{-1}$). The average retention increase in the 2011–2018 period was 138.5 $m^3 \cdot d^{-1}$ (Table 2, Figure 4A). At the same time, the supply from catchment S_1, calculated empirically, was Q_{S_1} = 101.8 $m^3 \cdot d^{-1}$, and from both catchments, S_1+S_2 − $Q_{S_1+S_2}$ = 290.7 $m^3 \cdot d^{-1}$ (Table 2, Figure 4A). The analysis of the curves of the sums of the actual retention increase and the calculated supply (Figure 4B) demonstrate that the increase in retention (Table 2: S_{2012}, S_{2013}, S_{2016}, S_{2018}, $S_{2011–2018}$) in the Strzelin I pit was higher than the calculated (Table 2: Q_{S_1}) supply from catchment S_1, but lower than the total supply (Table 2: $Q_{S_1+S_1}$) from catchments S_1+S_2. This may indicate that the reservoir is additionally supplied with water from sources other than the direct catchment S_1. Due to the lack of potential aquifers in the deposit (the drillings conducted for geological documentation did not reveal any inflow of water [112]), one may assume that the highest actual retention increase in the Strzelin I pit results from the discharge of water from the Strzelin II quarry. However, the significant difference between the actual retention and the calculated supply from catchments S_1 + S_2 might suggest that not all the water available in the Strzelin II quarry was discharged to the Strzelin I pit (Figure 4B). This has been confirmed in field observations that revealed that the water from thee sump in the Strzelin II quarry was used for sprinkling roads and other technological processes in the quarry in order to limit dust emissions.

Table 2. Estimation results for the pace of filling the pit of the Strzelin I quarry with water.

Analysed Period of Increase in the Volume of Water Retained	Range of Ordinates for the Water Level	Depth between Ordinates	Volume (V) of Water between Ordinates	Average Retention Increase (S) and Water Supply (Q) to the Quarry	Calculated and Prognosed Number of Days of Filing with the Given V at a Given S and Q	Time of Filling of the Pit Bowl
	m a.s.l.	**m**	**m^3**	**$m^3 \cdot d^{-1}$**	**d**	**years**
Actual						
2011–2012 (S_{2012})	66.6–74.7	8.1	32,903	118.355	278	0.8
2012–2013 (S_{2013})	74.7–84.9	10.2	72,129	136.349	529	1.4
2013–2016 (S_{2016})	84.9–89.9	5.0	85,264	88.632	962	2.6
2016–2018 (S_{2018})	89.9–96.1	6.2	139,977	227.605	615	1.7
2011–2018 ($S_{2011–2018}$)	66.6–96.1	29.5	330,272	138.537	2384	6.5
Prognosed						
2018–2078 ($Q_{2078} = S_{2011–2018}$)	96.1–150.0	53.9	3,014,086	138.537	21,757	59.6
Calculated supply from catchment S_1 (Q_{S_1})	96.1–150.0	53.9	3,014,086	101.785	29,612	81.1
Calculated supply from catchment $S_1 + S_2$ ($Q_{S_1+S_2}$)	96.1–150.0	53.9	3,014,086	290.662	10,370	28.4

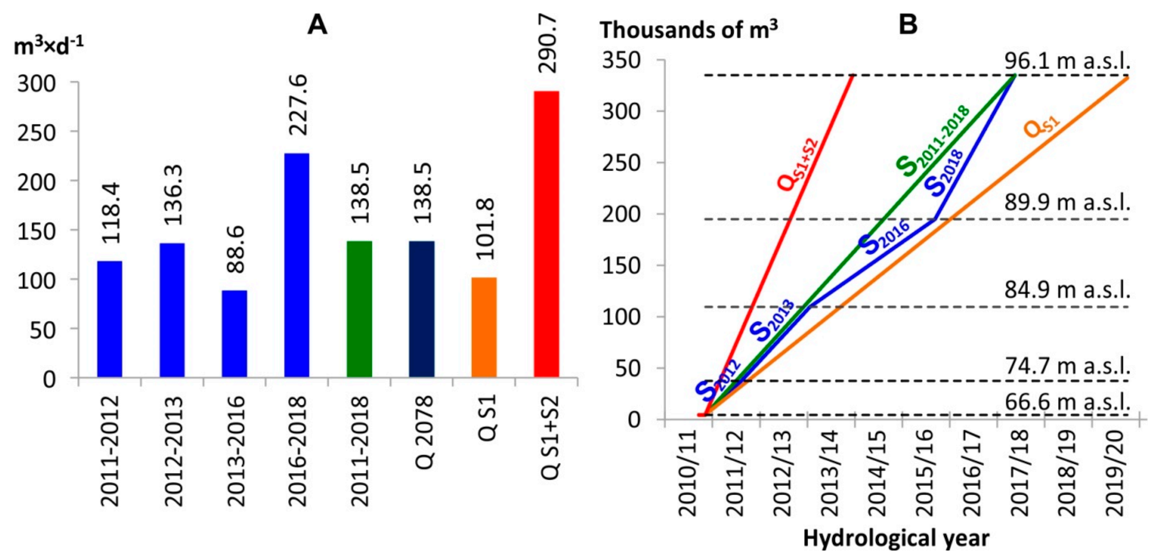

Figure 4. (**A**) is the average actual increase in retention in Strzelin I quarry lake in specific years (Table 2) and the calculated water supply (Q_{S_1}, $Q_{S_1+S_2}$). (**B**) is the sum curve of the actual retention increase (S) in the Strzelin I quarry lake during the period from 20 July 2011 to 20 January 2018 and the net calculated supply of Q_{S_1} and $Q_{S_1+S_2}$.

Filling the water reservoir to the current ordinate (96.1 m a.s.l.) with water flowing in from catchment S_1 would take approximately 9.0 years (Figure 4B), and from both catchments S_1 + S_2, approximately 3.1 years (Figure 4B). However, the reservoir was actually filled to the current ordinate (96.1 m a.s.l.; 0.330 million m^3) in about 6.5 years (Table 2, Figure 4B, Figure 5), and the filling of the bowl to the specific measured ordinates took from 0.8 to 2.6 years (Table 2, Figure 5). In order to fill the pit with water to the ordinate of 150.0 m a.s.l., a supply of 3.014 million m^3 of water is required (Table 1, Figure 3B). Assuming that this water is supplied only from the direct catchment, this process would last approximately 81.1 years (Table 2, Figure 5), whereas supplying the emerging quarry lake with water from the combined catchments S_1 + S_2 would shorten the filling time to 28.4 years (Table 2, Figure 5). However, the actual average increase in retention in the Strzelin I pit indicates that the filling would take 59.6 years (Table 2, Figure 5), i.e., twice as fast than with the supply calculated for catchment S_1, but roughly 0.4 times longer than for the water supply from the combined catchments S_1 + S_2. The obtained results demonstrate that the actual water supply to the Strzelin I quarry is different in the specifically analysed periods and higher than the average calculated supply from catchment S_1. This is influenced by rainfall conditions and by the periodical discharge of part of the water from the Strzelin II quarry.

Thus, a discussion of the results may be difficult due to specific properties of the mines, such as their locations, geological structures, topography, and land management in the catchment, as well as the climate and meteorological conditions of the analysed facilities.

The prognosed retention capacity of the Strzelin I granite quarry (~3.3 million m^3), as well as the capacity of the potential Strzelin quarry lake that would emerge as a result of connecting the Strzelin I and II pits (~6.6 million m^3) [23], correspond with the capacity of the water reservoirs that emerged in mines of solid rock materials [42,53,60] or pit lakes created in the Adamów lignite mine (i.e., smaller reservoirs created in the area) [71,117]. It should be noted that a major part of the pit lakes presented in the literature refers to coal and lignite mines, and the capacity of water retained in such lakes reaches 30–60 million m^3 [20,89], quite often exceeding 100 million m^3 [20,41,57,91,117], even up to 330–350 million m^3 [55,61]. The prognosed capacity of the water reservoirs that are planned to be created in the lignite mine "Bełchatów" after discontinuation of its operations is expected to reach 1.3 and 1.7 billion m^3, and in the "Turów" lignite mine, 1.2 billion m^3 [70,71]. In comparison to the pit lakes created in lignite mines, the quarry lake that will emerge in the Strzelin granite quarry will be decidedly smaller, but it will still be relatively large compared to other quarries (e.g., Zakrzówek, Tarnów Opolski, Świerki) [42,53,60].

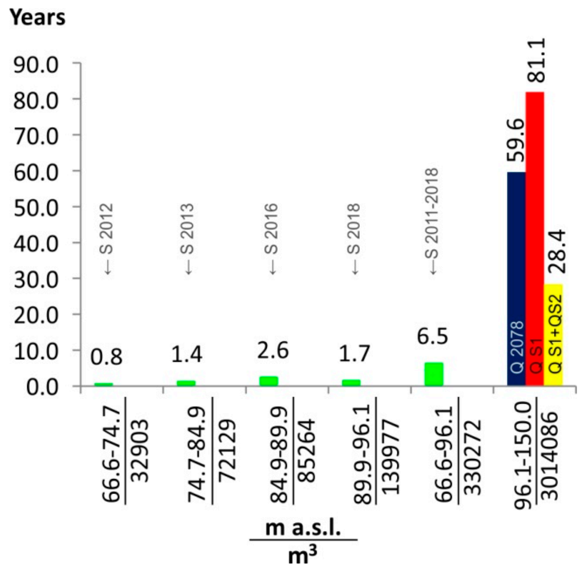

Figure 5. Time of the increase in volume of water retained between specific ordinates' water levels in the Strzelin I quarry lake (the green columns represent the measured values, while the blue, red and yellow columns represent the prognosed values for supplies Q_{2078}, Q_{S_1} and $Q_{S_1+S_2}$).

In some open-cast mines, groundwater supply plays a significant role in filling the pit [41,58,117]. However, based on the geological documentation of the Strzelin deposit, no inflow of water to the drilling holes was found [112], as the water in the pit originated mainly from precipitation and surface runoff in the direct catchment of the pit [23]. The surface area of the direct catchment of the Strzelin I pit is relatively small (16.04 ha), which is characteristic of mines made of dense rock material and has also been noted in other, similar mines [92]. This result has been confirmed by related publications, which reveal that the volume of the surface supply to the quarries results from the volume of the precipitation falling directly onto the pit and the intensity of the surface runoff from the topographic catchment [92].

The prognosed duration of flooding the Strzelin I pit to the ordinate of 150.00 m a.s.l. (approximately 60 years (Table 2, Figure 5) with an average net supply of 138.5 $m^3 \cdot d^{-1}$ (Table 2, Figure 4A), only slightly higher than the average calculated supply (101.8 $m^3 \cdot d^{-1}$ (Table 2, Figure 4A) from the physiographic direct catchment) points to difficult hydrogeological conditions (which are confirmed in the geological documentation of the deposit [112]) and the fact that the quarry is supplied with rainwater from a direct catchment with a non-existent groundwater supply. Considering the cubic capacity of the pit (~5.1 million m^3, potentially ~3.34 million m^3 of retained water), this confirms the cases featuring the spontaneous filling of an open excavation pit with water over several years to several decades, as discussed in the literature [3,25,36,54,59,70,91,117]. For example, it is prognosed that the natural filling of the water reservoirs in the Bełchatów mine may take about 60 years, and if additional water is supplied from outside the depression bowl, it may take 18 years [71]. The calculations performed for the purposes of this study demonstrate that the discharge of some of the water from the sump in the Strzelin II pit would shorten the potential duration of filling the Strzelin I pit by approximately 20 years. The literature states that supplementing the supply of water to the reservoir in an excavation pit with the discharge of water from other active pits may significantly shorten the time needed to flood the pit by as much as approximately 9–11 years [71,89,91]. Discharging the entire water flow into the Strzelin II pit would shorten the time to fill the Strzelin pit by about 31.2 years.

It should be noted, however, that the filling of Strzelin I pit may take longer than 59.6 years, because excavation works are still being conducted in the Strzelin granite quarry, increasing the total cubic capacity of the Strzelin I and Strzelin II pits by approximately 0.375 million $m^3 \cdot year^{-1}$ [23]. It is estimated that, after the pillar separating the pits is eliminated, the target cubic capacity of the whole pit will reach approximately ~11.6 million m^3 and may retain up to ~6.6 million m^3 of water [23], which will potentially double the time required to fill the pit with water. Optionally, the pit may additionally be flooded with water from rivers (the literature presents such cases [3,31,36,50,59,71,117]) (e.g., from the Oława River). However, this possibility seems unlikely, as the pit is situated on the so-called Gallows Hill (the watershed between the catchments of the Oława and Ślęza Rivers [118]), which is situated 420 m from the riverbed and 10–20 m above the bed of the Oława River. Thus, filling the pit with river water would not be viable, as the water would have to be pumped to the pit. Moreover, the Oława River is a source of potable water for Wrocław [119], so the use of its waters for other purposes is limited [120], and the poor chemical quality of the river water [121,122] might lead to a deterioration of the water quality in the potential Quarry Lake Strzelin I and limit its use [3,11,12,19,20,24,36,37,44,47,54–57,64–66].

The use of a 3D model of an open-cast mine (DTM, DSM, DEM), based on data obtained from LiDAR ALS, TLS MLS, or other photogrammetric measurements, including those from a UAV, allows for the analysis of changes in the deformations of the mine area, thereby determining the cubic capacity of the excavation pit and mining heaps, the course of the deposit of the excavated material and the ongoing determination of the exploitative volumes in quarries and other open-cast mines [75,78,80,81,123]. It may also be an efficient tool for calculating the potential retention capacity of the pit [23] and for estimating the pace of filling the pit with water, as has been presented in this article.

The role that flooded pits play in retention is particularly significant in areas with low water resources [12,23–26], including Poland [124,125], and the use of closed down pits for water retention may increase the reservoir retention capacity of a catchment by several tens of times, especially in terms of small reservoir retention [23,117]. Additionally, closed mines and quarries may become an important element of the green [111,126] and blue infrastructure of urban areas [23,48], such as the InterContinental Shanghai Wonderland Hotel, located inside an old quarry, with a water reservoir, living walls on the quarry walls, green roofs in the hotel, and parks around the old quarry and hotel.

4. Summary and Conclusions

LiDAR ALS data were used to create a digital terrain model (DTM) of the Strzelin I quarry. This model was then combined with the analogue geodesic master map, which enabled the characterisation (Table 1) of the basic morphological parameters of the pit (a surface area of ~9.7 ha, a depth of ~113.9 m and a cubic capacity of ~5.1 million m^3) and of the quarry lake that emerged in the pit bowl (Table 1, Figure 3) (starting from the ordinate of 66.6 m a.s.l. with a depth of 8.1 m, a water surface area of 0.48 ha, and water volume of 0.033 million m^3). However, progress in mining operations requires regular updates of the data that are used as the basis for creating the DTM. The cross-sections of the pit (Figure 2), created based on the DTM and analogue map, show the change in the water level in the pit (in both cases, this is the bottom of the pit) and confirm the fact that the DTM is more accurate than analogue geodesic master maps; this difference results from the fact that it is difficult for surveyors to access certain parts of the Strzelin I pit. The DTM of the Strzelin I quarry, combined with orthophotomaps of the area created at different times, enabled the determination of the ordinate of the water level in the Strzelin quarry lake and of the increase in the volume of the retained water (Table 2, Figure 4). In the years 2011–2018 (6.5 years), the water level in the quarry lake increased from an ordinate of 66.6 m a.s.l. to 96.1 m a.s.l., which corresponds to 0.330 million m^3 of retained water. The average increase in the retention in the pit was 138.5 $m^3 \cdot d^{-1}$, i.e., approximately 36.7 $m^3 \cdot d^{-1}$ more than that which resulted from the calculated supply from the direct catchment S_1. The higher volume of water supplied to the pit was likely caused by a periodical discharge of the water from the Strzelin II pit. The average actual increase in retention in the pit was determined based on the volume of retained water, and the time in which it accumulated was the basis for estimating the remaining time until the pit was filled (Table 2, Figure 5) up to the adopted ordinate of 150.0 m a.s.l. (3.014 million m^3).

The estimated time was 59.6 years, which is shorter than for the calculated supply from the direct catchment S_1 (81.1 years). However, it should be noted that the Strzelin granite quarry is an operating mining facility, where rock material is excavated. This leads to changes in the morphological parameters of the pits, so the DTM of SGQ should be updated regularly. In the analysed period (2011–2018), mining works were conducted in the Strzelin II quarry and in the pillar that separates the Strzelin I and II pits. The excavation activities in the Strzelin I quarry were suspended as late as 2017.

The conducted analyses presented herein allowed us to draw the following conclusions:

1. The use of DTM allowed the authors to determine the morphological parameters of the quarry lake in the Strzelin I pit with satisfactory precision, as of the date of the LiDAR ALS flights: a depth of 8.1 m, a water surface area of 0.48 ha, a water volume of 0.033 million m^3 (existing now at a depth of 29.5 m), a water surface area of 2.67 ha, a water volume of 0.335 million m^3. The parameters of the prognosed lake that will emerge after discontinuing mining operations are as follows: depth, 83.4 m, water surface area, 7.93 ha, volume of water, 3.335 million m^3.
2. According to the prognosis, filling the Strzelin I quarry lake to the adopted ordinate of 150.0 m a.s.l. (3.014 million m^3) will take 59.6 years based on the average actual retention increase ($S_{2011–2018} = Q_{2078}$ = 138.537 $m^3 \cdot d^{-1}$), 81.1 years based on the calculated supply from the direct catchment S_1 (Q_{S_1} = 101.785 $m^3 \cdot d^{-1}$), and 28.4 years if the total volume of water supplied to Strzelin II is discharged into the pit ($Q_{S_1+S_2}$=290.662 $m^3 \cdot d^{-1}$).
3. If the water direction of reclamation is chosen for the Strzelin I quarry, a high-resolution digital terrain model may be an effective tool for estimating the potential volume of water that may be retained in the bowl of the pit after discontinuing mining operations.
4. The use of DTM combined with measurements of the water's surface level in the bowl of the pit, based on orthophotomaps created at different times, allows one to estimate the actual pace of flooding in the quarry.

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