Estimating Water Retention in Post-mining Excavations Using LiDAR ALS Data for the Strzelin Quarry, in Lower Silesia

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Received: 12 April 2017 / Accepted: 26 February 2018 / Published online: 3 March 2018
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Abstract

A digital terrain model of the Strzelin granite quarry was created from ISOK project data obtained from airborne laser scanning (ALS). Based on 2009, 2012, and 2014 data, the volume of water in the Strzelin quarry's two excavations were determined. Additionally, the predicted volume of retained water after mining ceases was calculated, assuming a water level of 150.0 m a.s.l. In 2014, the two reservoirs retained, respectively, ≈ 0.14 and 0.01 million m^3 of water. If the two pits are eventually connected, ≈ 6.6 million m^3 of water could be retained. Including the 2014 water volume as a small-scale retention basin would increase the volume of retained water in the Ślęza catchment and Strzelin County by 19.0%, and 34.2%, respectively. The hypothetical reservoir created after mining ends would increase small-scale (reservoir and pond) retention ≈ 8 times in the Ślęza catchment and ≈ 15 times in the County, constituting a significant improvement.

Keywords Water reclamation · Small-scale water retention · GIS · Digital terrain model (DTM) · ISOK project

Introduction

Poland's domestic water resources are relatively low, for a European country, with a mean annual surface water discharge of $\approx 61.2 \text{ km}^3$ (GUS 2015). The water resource index

averages 1590 m^3 per year per person, but in dry years this index falls to 1100 m^3 per year per person (Walczykiewicz 2014). In many cases, the water is of poor quality. It is estimated that the water resources in Europe amount, on average, to $\approx 4750 \text{ m}^3$ per year per person. So it is important to control and protect Poland's water resources, which is done, in part, by water retention in reservoirs (Łabędzki 2016). Still, Poland's ≈ 100 reservoirs constitute less than 6.0% of the area's annual discharge. This situation does not provide sufficient protection against periodic water surpluses or deficits (GUS 2015). In comparison, about 7000 large reservoirs exist across Europe, with a total capacity representing about 20.0% of Europe's freshwater resources (EEA 2009).

In Poland, there are also $\approx 31,300$ small-scale retention reservoirs, with a total volume of ≈ 0.8 billion m^3 (GUS 2015). Reservoirs with a volume of up to 5 million m^3 are considered small-scale retention reservoirs (Drabiński et al. 2006; Mosiej 2014; Mosiej and Bus 2015). Natural ways to improve small-scale retention include: changes in land use (e.g. forestation, proper spatial arrangement and types of development); increasing soil retention and reducing soil erosion; and preservation and revitalization of wetlands. The technical forms of water retention include: water reservoirs of different sizes and purposes (ponds, field agricultural reservoirs, fire water reservoirs, oxbow lakes, moats, mine/quarry pits) and installations that enable water level

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adjustment (weirs, gates, barrages) as well as flood polders, inter-dike areas, and properly functioning drainage systems (EC 2012; Gomez et al. 2013; Mioduszewski et al. 2014).

The objectives of small-scale water retention may differ, but they generally benefit the environment and influence the water balance of a catchment, increase its water resources, decrease flood-stages, increase low flows, contribute to water quality improvement, and enrich a landscape's natural value (Jawecki 2004; Łabędzki 2016; Mioduszewski et al. 2014; Wiatkowski et al. 2013).

In Poland, $\approx 26,500$ ha of land are used for opencast mining (Kaszelewicz and Kaczorowski 2009). After mining ceases, the potential creation of pit or quarry lakes is particularly important to water management. Many artificial lakes have formed in former clay, sand, and gravel pits, quarries, and opencast lignite mines when mining ceased (Jawecki 2012; Jawecki et al. 2014; Schultze et al. 2010). In recent decades, hundreds of such lakes have been created in many countries around the world (Doupé and Lymbery 2005; Duval et al. 2009; McCullough 2008; Schultze et al. 2010; Soni et al. 2014; Townsend et al. 2009). According to estimates, $\approx 10.0\%$ of formerly mined land is used in this way (Kaszelewicz et al. 2010).

Such lakes develop when dewatering efforts stop and the excavated areas slowly fill with groundwater, rainfall, and surface runoff (Hinwood et al. 2012; Kleeberg and Grüneberg 2005; McCullough 2008). This process may last for months, years, or even decades and its pace depends on the size of the excavation, the hydrogeological conditions, and the geological structure of the mine and its surroundings (Kumar et al. 2016; Schultze et al. 2010). Sometimes, water from rivers or streams is used to quickly flood the mine (Schultze et al. 2010; Singleton et al. 2013).

The lakes thus created can have different depths, surface areas and volume, depending on the excavated raw material and the mining technology (Clews et al. 2014; Kumar et al. 2016; McCullough and Lund 2006; Molenda 2006; Schultze et al. 2010; Singleton et al. 2013). The methods of determining the geomorphological parameters of the excavation depend on its accessibility and on the depth of the water reservoir (if it exists). The volume of the excavation at a given moment can be calculated using traditional geodesic methods or modern techniques, such as the GNSS technology and RTK method (Labant et al. 2013; Polak et al. 2014). If LiDAR data are available or possible to obtain, the geomorphological parameters of the excavation can be determined by terrestrial (TLS) or airborne laser scanning (ALS) or other photogrammetric measurement (Wajs 2015; Witt 2016). The bathymetric measurements are required to determine the parameters of the submerged terrain (Deus et al. 2013).

Water in flooded mines can be used for various purposes, including: recreation and tourism (bathing, swimming,

diving, fishing, surfing, boating, canoeing, water skiing), wildlife habitat, aquaculture and fish farming, water management (water storage, storage of high flood, addition to low-water), drinking and industrial water reservoirs, or storage of irrigation water for agriculture and horticulture (Axler et al. 1996; Ceppi et al. 2014; Doupé and Lymbery 2005; Jawecki 2012; McCullough 2008; McCullough and Lund 2006; Ravazzani et al. 2011; Schultze et al. 2010). The potential use of mine and quarry lake water depends on both water quantity and quality (Axler et al. 1996; Clews et al. 2014; Doupé and Lymbery 2005; Kumar et al. 2016; McCullough 2008; McCullough and Lund 2006; Schultze et al. 2010).

Adapting to climate changes, including counteracting the effects of floods and droughts (especially in the agriculture and water management sectors) and decreasing the water deficit are important elements of Poland's water management policy. Increasing the volume of retained water by creating various forms of small-scale retention can increase water resources and improve the rational management of such resources, especially from a local and regional perspective (Łabędzki 2016; Linnerooth-Bayer et al. 2015; Ministry of the Environment 2013; Mioduszewski et al. 2014; Szwed 2015). This is particularly important in areas with limited water resources (Ceppi et al. 2014; Kumar et al. 2009; Ravazzani et al. 2011).

The aim of this study was to determine the volume of water retained in the Strzelin quarry in the years 2009, 2012, and 2014, assuming that both of its excavations were filled with water up to 150.0 m a.s.l. (above sea level). We also estimated the volume of water that could be hypothetically retained if the pillar separating the pits were removed and the combined pit was filled with water to the assumed same level. We also evaluated the potential of applying LiDAR ALS data to estimate water retention. The results were used to determine the influence of water retention in the Strzelin quarry on the small-scale reservoir retention resources of the area.

Material and Methodology

The Strzelin granite quarry is located in the Lower Silesian Voivodeship, Poland, in the western part of the town of Strzelin. Granite and gneiss from the Strzelin deposit are excavated in two (Strzelin I and Strzelin II) pits (Fig. 1). The surface area of the deposit is 31.83 ha and the excavation area is 47.93 ha, with a mining area of ≈ 129.7 ha. The planned direction of excavation reclamation was forestation (MIDAS 2012). The Strzelin I pit has a surface area of ≈ 10.0 ha, a depth of ≈ 113.9 m (to the water level, which in 2009 was stabilized at 66.0 m a.s.l.) and a volume of ≈ 5.1 million m^3 , while Strzelin II has, respectively, ≈ 12.3 ha, ≈ 56.6 m

part 1

part 2

part 3

part 4

Fig. 1 The location and photographic documentation of the Strzelin Granite Quarry (photos: B. Jawecki, map source on license, coordinate system PUWG-92, figure—own compilation)

(to the water level, which in 2014 was stabilized at 130.0 m a.s.l.), and ≈ 2.4 million m^3 (Table 1). The quarries are open pits and mining is conducted using the longwall system. The industrial resources estimated at the end of 2015 amounted to 59.8 million tonnes (t), with annual excavation amounting to ≈ 1.1 million t (Szuflicki et al. 2016). The excavated rock

is used to manufacture blocks, crushed stone and crushed-stone aggregate for use in constructing roadworks, buildings, and railways. The excavated volume is increased by 0.375 million m^3 annually based on the excavated amount and the bulk density of the rock (granite – 2.64 g/cm^3 , gneiss – 2.67 g/cm^3 ; MIDAS 2012).

Table 1 Characteristics of the Strzelin I and II quarries and their potential characteristics if they were connected

	Unit	Strzelin I	Strzelin II	Potential pit
Ordinate of excavation edge				
Adopted for calculations	m a.s.l	170.0	170.0	170.0
Highest	m a.s.l	179.9	186.6	186.6
Lowest	m a.s.l	169.3	169.4	169.3
Ordinate of the excavation bottom				
Lowest (water level in the sump)	m a.s.l	66.0	130.0	66.0
Depth of the excavation				
To 170.0 m a.s.l	m	103.4	40.0	103.4
To the highest ordinate of the edge	m	113.9	56.6	120.6
To the lowest ordinate of the edge	m	103.3	39.4	103.3
Surface area of the excavation (at 170.0 m a.s.l.)	ha	9.71	12.56	27.45
Volume of the excavation ^a (at 170.0 m a.s.l.)	million m ³	5.097	2.364	11.588

^aVolume calculated to the bottom and to the water level in the sump in the excavation

The geological documentation of the Strzelin deposit (Balawajder 1988) states that no inflow of water was noted during exploratory drilling, although the western part of the lode (where the Strzelin II pit is located) contained three water reservoirs with a total volume of $\approx 270,000 \text{ m}^3$ (including one with a volume of $\approx 253,000 \text{ m}^3$). Strzelin I contains a bailed sump (a reservoir of mine water, which is drained by suction pumps; Głapa and Korzeniowski 2005), with a volume of $\approx 100 \text{ m}^3$. The water levels in the reservoirs fluctuated $\approx 1.5 \text{ m}$, depending on the amount of precipitation and evaporation, but was not recorded.

Water flows into the Strzelin I and II pits from rainfall, surface and sub-surface runoff and water transfer between the pits. The water level in the Strzelin II excavation, based on a map from 1983, reached 150.0 m a.s.l. This ordinate was assumed to be the target water level in the quarry after the end of mining. Currently, a water reservoir has developed in the Strzelin I pit, while in Strzelin II, the sump is periodically drained.

According to the hydrographical map of Poland (NWMA 2010), the Strzelin quarry is located in the catchment of the Ślęza River (located in WR08 Bystrzyca water balance catchment), in the Oder River basin. According to the small-scale water retention programme of the Lower Silesian Voivodeship (Drabiński et al. 2006; RWMA 2016), the total volume of reservoir and pond retention in the Ślęza catchment is 0.809 million m^3 (0.552 million m^3 in reservoirs and 0.257 million m^3 in ponds). The quarry is situated in the WR08 Bystrzyca water balance catchment (balance region W-VIII Bystrzyca Ślęza; PIG 2007; RWMA 2016), which includes 7 reservoirs with a total retention volume of 16.19 million m^3 . In administrative terms, the quarry is located in Strzelin County, where reservoir and pond retention amounted to 449,800 m^3 (as of Dec. 31st, 2004; Drabiński et al. 2006), based on reservoirs of at least 1 ha in area. According to the County's

water law permits for the years 2005–2015, as of Dec. 31st, 2015, the County now contains a total of 46 reservoirs and ponds with a total volume of 1.64 million m^3 ; this total now includes facilities with a surface area less than 1 ha.

The study was based on LiDAR data obtained under the ISOK project (Informatics System for the Protection of the Country from extraordinary dangers), with the use of airborne laser scanning. The ISOK project was created in response to the high risk of flooding in Poland, especially following the flood damages in the Oder River basin in 1997 and along the Vistula River in 2010. ALS data were gathered from 2010 to 2013. First, measurements were obtained for areas with a risk of flooding (Wężyk et al. 2015). The density of the data (in the form of a point cloud) corresponded to 4 points per m^2 for non-urban areas and 12 points per m^2 for urban areas. The ALS data point clouds were then subjected to a classification process and finally, a digital terrain model (DTM) and digital surface model (DSM) were generated from the respective classes. The classification was performed in compliance with Standard 1.2 of the LAS file format issued in 2008 by the American Society for Photogrammetry and Remote Sensing (APSRs). Data in the format of LAS files contain information about the class of the given object (8 classification classes) and geographical coordinates of each point. The accuracy of point classification is at least 95.0% and the height means error falls within a range of up to 0.2 m. All height data were prepared in the flat rectangular coordinate system “PUWG-92” (EPSG: 2180); the heights refer to the “Kronsztadt 86” normal height system.

The LiDAR ALS data from the ISOK project are available free of charge for research and teaching purposes from the Head Office of Land Surveying and Cartography resources. The LiDAR flight was made on the 27–28.04.2012, from a height of 715 m above terrain surface in an E-W direction. The obtained density of the points cloud, after equalization

and classification, is 4 points per m^2 while the height accuracy is ≤ 0.15 m.

By interpolation of the point cloud in the ArcGIS 10.3 software, a digital terrain model (DTM) was created for the Strzelin I and II excavations in a ESRI GRID format model with a regular square grid and a spatial resolution of 0.5 m. Due to the ALS technology, the prepared DTM presents only the terrain above the water level, which was situated at 75.00 and 134.00 m a.s.l., respectively, in the Strzelin I and II pits in 2012, when the data were obtained. The information of the Strzelin I excavation terrain relief to 66.0 m a.s.l. was supplemented based on the analogue geodesic map from 2009. The water level was assumed on 66.0 m a.s.l. For 2014, the water level in the pits were assumed based on orthophotomaps created during that period, assuming a water level of 85.0 m a.s.l. for Strzelin I and 130.00 m a.s.l. for Strzelin II (the excavation between 134.0 and 130.0 m a.s.l. was based on the analogue map). A terrain level of 170.0 m a.s.l. was assumed as the upper edge of the excavation, pursuant to contours generated from the DTM. This height corresponds to the visual edge of the excavation area in the orthophotomap. Further analyses were conducted with use of Surfer10 software, where the DTM was imported in GRID format from the ArcGIS environment.

Results

In addition to atmospheric precipitation and surface and sub-surface runoff, the quarry workers indicate that the Strzelin II excavation is also supplied with water that flows through cracked rock from the Mikoszków excavation that is adjacent to the west (Fig. 1). Additionally, water flows from Strzelin

II to Strzelin I. As a result, and due to the fact that the pumping of water was periodically neglected, the sump in the Strzelin I pit increased its size, becoming a reservoir. By 2009, the estimated volume of retained water was 0.005 million m^3 (Fig. 2) and the area covered by water in this reservoir (at 66.0 m a.s.l., Fig. 3) was 0.12 ha. In 2012, the area of the water (75.0 m a.s.l., Fig. 3) was 0.58 ha, while the volume of retained water had increased to 0.033 million m^3 (Fig. 2). Thus, in 3 years, its area had increased fivefold and the volume of retained water had increased sevenfold. In 2014, the area of the reservoir (85.0 m a.s.l., Fig. 3) was 1.48 ha, and the volume of retained water was 0.141 million m^3 (Fig. 2), a 13- and 30-fold increase, respectively, compared to 2009. Basing on the DTM calculations with a spatial resolution of 0.5 m obtained from the ISOK project data, if the excavation was filled with water to its 1983 level (150.0 m a.s.l.), the area would be 7.93 ha, and the volume of retained water would be 3.344 million m^3 (Fig. 2), a 68-fold increase in area and a 714-fold increase in volume of retained water, compared to 2009.

The volume of water retained in the reservoir in the Strzelin I excavation in 2014 (at a water level of 85.0 m a.s.l.) increases the volume of small-scale pond and reservoir retention in Strzelin County by 31.2% (according to data from the Small-scale Retention Programme that covers facilities with an area > 1 ha; Drabiński et al. 2006) and by 8.6% if one also includes those < 1 ha. In hydrological terms, the volume of water in these excavations as of 2014 increases the water resources in the Ślęza catchment by 17.4% and in the WR08 Bystrzyca balance catchment by 0.9%. Moreover, the potential water reservoir that would develop in the Strzelin I excavation if the water level reached 150.0 m a.s.l. would increase the small-scale reservoir and pond retention volume

Fig. 2 Current and planned water retention volume in the Strzelin quarry in the context of reservoir and pond retention in terms of the county and the catchment

Fig. 3 DTM and cross-sections of the Strzelin I quarry with the ordinate of water level in the excavation (coordinate system PUWG-92, figure—own compilation)

in Strzelin County by sevenfold (based on the amount of water in reservoirs > 1 ha) or twofold (based on the water law permit data). At the same time, it would increase the water resources in the Ślęza catchment fourfold and in the WR08 Bystrzyca balance catchment by 20.7%.

In the Strzelin II excavation there is a sump from which the water is pumped and discharged (to the Pluskawa water course or to the Strzelin I excavation). In 2009 and 2012, the inundated area (134.0 m a.s.l., Fig. 4) was 1.19 ha, and the estimated volume of retained water was 0.046 million m³ (Fig. 2). In 2014, the area of the reservoir (130.0 m a.s.l., Fig. 4) was 0.26 ha, and the volume of retained water was 0.013 million m³ (Fig. 2). Due to the fact that water was pumped out of the excavation, the water level area decreased by ≈ 78.0% and the volume of the retained water fell by

≈ 70.0% compared to the year 2012. Basing on the DTM of the excavation, if the water level was maintained at the assumed target ordinate (150.0 m a.s.l., Fig. 4), the area of the reservoir would reach 5.65 ha, while the volume of retained water would total 0.586 million m³ (Fig. 2). Thus, the area of water would increase fivefold and the volume of the retained water 13-fold.

The volume of water retained in the Strzelin II reservoir in 2014 (at 130.0 m a.s.l.) increases the volume of small-scale pond and reservoir retention in Strzelin County by 3.0% (considering reservoirs > 1 ha) and by 0.8% (based on the water law permit data), in the Ślęza catchment by 1.7% and in the WR08 Bystrzyca balance catchment by 0.1%. Moreover, the potential reservoir that would develop in Strzelin II if the water level reached 150.0 m a.s.l. would increase the volume of small-scale reservoir and pond retention in the Strzelin County by 130.2% (considering reservoirs of an area > 1 ha) and by 35.7% (with respect to the water law permit data), in the Ślęza catchment by 72.4%, and in the WR08 Bystrzyca balance catchment by 3.6%.

The potential joining of Strzelin I and II, (by mining the granite pillar separating the two) and excavating Strzelin II up to the 130.0 m a.s.l. would create a single excavation with an area of 27.5 ha (Fig. 5) and a capacity of 11.6 million m³ (Table 1). Below 130.0 m a.s.l., the Strzelin I excavation would remain unchanged. A water reservoir with an area of 23.97 ha and a volume of 6.576 million m³ (Fig. 2) would emerge after the potential excavation had been filled with water up to 150.0 m a.s.l. (Fig. 5), increasing the pond and reservoir retention resources in Strzelin County 15-fold (considering the water retained in reservoirs > 1 ha) and fourfold with respect to the water law permit data. However, it should be noted that, due to its volume, such a reservoir would no longer be a small-scale retention reservoir, as its capacity will exceed 5 million m³. The resources of retained water in the Ślęza catchment would increase eightfold, while the water retention resources in the WR08 Bystrzyca balance catchment would increase by 40.6%.

Discussion and Conclusions

Including the volume of water retained in Strzelin I and II in the water retention balance would increase the volume of water retained in the WR08 Bystrzyca balance catchment by 0.9%, in the Ślęza catchment by 19.0 and 34.2% in Strzelin County (considering reservoirs of an area > 1 ha) and by 9.4% (according to data from water law permits). The reservoir that would be created by joining the two pits and filling them with water up to 150.0 m a.s.l. would retain 6.576 million m³ of water, increasing small-scale retention in administrative and water balance regions. This might contribute to the improvement of the water balance (Kowalewski 2008;

Fig. 4 DTM and cross-sections of the Strzelin II quarry with the ordinate of water level in the excavation (coordinate system PUWG-92, figure—own compilation)

Łabędzki 2016; Mosiej 2014) and mitigate the consequences of water deficits. Depending on the quality of the retained water, it may be used, among others, for irrigation purposes (the Strzelin County is an agricultural area), supplying rivers and streams in times of low water level, providing water to residents and to the industry and water recreation (Ceppi et al. 2014; Doupé and Lymbery 2005; Hinwood et al. 2012; Kumar et al. 2009; McCullough and Lund 2006; Ravazzani et al. 2011; Schultze et al. 2010; Singleton et al. 2013; Soni et al. 2014).

There are ≈ 80 closed quarries and ≈ 270 sand mines, gravel pits, and clay pits in Strzelin County. Some of them have become reservoirs, ranging from small, shallow, mid-field or mid-forest ponds to medium-size reservoirs that are over ten and even up to several tens of meters deep. These may constitute an important element of the surface water

balance of Strzelin County and of the Oława and Ślęza catchments in the Lower Silesian Voivodeship in the upper- and mid-Oder water region. The contribution of water reservoirs created in post-mining excavations requires further studies in local, regional, national, and continental terms. In Poland, there are $\approx 40,054$ ha of land that was devastated and degraded by mining and quarrying (0.13% of the surface area of Poland) (GUS 2015), of which $\approx 10.0\%$ is being reclaimed as reservoirs (Kasztelewicz et al. 2010). The purpose of such activities includes limiting water deficits and the negative effects of droughts and floods, which is particularly important in areas characterized by low water resources (Ceppi et al. 2014; Doupé and Lymbery 2005; Kumar et al. 2009; Łabędzki 2016; Linnerooth-Bayer et al. 2015; McCullough and Lund 2006; Ministry of the Environment

Fig. 5 DTM and cross-sections of the potential Strzelin quarry excavation that would emerge after joining both excavations, with the ordinate of water level in the excavation (coordinate system PUWG-92, figure—own compilation)

2013; Mosiej 2014; Ravazzani et al. 2011; Szwed 2015; Walczykiewicz 2014).

Following analysis of the ALS data obtained from the ISOK project in the form of a DTM in the Strzelin quarry area, we conclude the following:

1. The volume of water retained (as of 2014) in the Strzelin I and II pits (0.154 million m³) is an important element of the reservoir retention balance, in terms of the Ślęza catchment, the WR08 Bystrzyca balance catchment, and Strzelin County. It had not previously been accounted for and significantly increases reservoir retention in the Strzelin County area.
2. Removing the pillar that separates the Strzelin I and II pits, and thus creating a single excavation after mining ceases, will create a water reservoir with an estimated volume of 6.576 million m³, which would increase water retention in the Ślęza catchment eightfold, in the WR08

Bystrzyca balance catchment by ≈40.0%, and in Strzelin County fourfold.

3. Under favorable hydrogeological and geomorphological conditions, reclamation of excavations as reservoirs will increase the retention capacity of a catchment, while at the same time helping an area adapt to climate changes by counteracting the effects of droughts and floods.
4. As a large number of closed excavations of various sizes have been inundated in Strzelin County, i.e. water reclaimed, they may constitute an important element of the small-scale retention balance. However, determining the scale of such activities and their results requires further research and analysis.
5. The issue of using closed excavations as water retention reservoirs may also be important on the regional, national, and continental scale, since hydrographic divisions reach beyond administrative borders and because

open-cast mines exist throughout much of and in many other locations.

6. The use of a high-resolution digital terrain model in connection with hydrogeological data is an efficient way to predict the volume of water that may be retained in excavations after the end of mining based on the assumption that the area will be water reclaimed.

Acknowledgements The study was based on: LiDAR ALS data (available free of charge for research and teaching purposes) from the Head Office of Land Surveying and Cartography resources on license No. DIO.7211.197.2016_PL_N (Paweł B. Dąbek, Wrocław University of Environmental and Life Sciences, Institute of Environmental Protection and Development) and on map from the Marshal of Lower Silesia Voivodeship resources on license No. MGW.I.7522.524.2016_02_N and MGW-I.7522.129.2017_02_CL0 (Bartosz Jawecki, Wrocław University of Environmental and Life Sciences, Institute of Landscape Architecture).

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