


## Article

# The Assessment of the Quality and Quantity of Water Retained in Closed Granite Quarries with the View to Mitigate the Effects of Droughts in Agriculture

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**Abstract:** This paper presents the results of bathymetric measurements of quarry lakes located in inactive granite quarries (Poland, Lower Silesia, County Strzelin), which were used, among other reasons, to determine the surface area, depth, and volume of water retained in the analysed quarry lakes. The usability of water in quarry lakes for agricultural irrigation was also assessed, based on the FAO Guidelines and the PN-84/C-04635 standard. The average surface area of the analysed quarry lakes was 0.99 ha, the average depth was 6.0 m, and the maximum depth was 14.3 m. At the same time, the total volume of the retained water amounted to 307.8 thousand m<sup>3</sup>, which accounts for 10.6% of the retention capacity of water reservoirs situated in the catchment of the Oława River. The average values of water quality indicators were as follows: electrical conductivity—0.332 mS × cm<sup>-1</sup>; sodium adsorption ratio—0.56; total dissolved solids—212.4 mg/L; water pH—7.8; BOD<sub>5</sub>—2.4 mgO<sub>2</sub>/L. The mean concentrations of ions had the following values: nitrates—0.91 mgN-NO<sub>3</sub><sup>-</sup>/L; sulphates—176.3 mg SO<sub>4</sub><sup>2-</sup>/L; chlorides—36.56 mg Cl<sup>-</sup>/L; sodium ions—14.8 mg Na<sup>+</sup>/L; calcium—41.3 mg Ca<sup>2+</sup>/L; magnesium—7.48 mg Mg<sup>2+</sup>/L; manganese—0.1 mg Mn/L; and iron—0.01 mg Fe/L. The concentrations of water quality indicators that were recorded for the analysed Strzelin quarry lakes were similar to those observed in natural lakes and uncharged water bodies. Water from the analysed quarry lakes met (with some minor limitations) the requirements that enable them to be used for agricultural irrigation. The volume of the water retained in the analysed quarry lakes constitutes an important element of the total balance of water retained in all the reservoirs, ponds, and all Strzelin quarry lakes situated in the catchment of the Oława River, accounting for 10.6% of the total volume of retained water. The article presents the innovative concept of the possibility of using water from quarry lakes in agriculture, based on their quantity and quality and the requirements for the purpose for which they will be used, e.g., for agricultural irrigation.



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## 1. Introduction

At the beginning of the twenty-first century, the deficit of fresh water, including the water for agricultural and industrial needs was estimated at 230 km<sup>3</sup>/year; by 2025, this planetary deficit will increase to 1300–2000 km<sup>3</sup>/year [1]. According to estimations, by the year 2050, 3.9 billion people, i.e., over 40% of the world's population, will live in severely water-stressed river basins [2]. The total amount of freshwater resources in Europe is approximately 2270 km<sup>3</sup>/year [3], of which the freshwater resources in Poland are estimated to amount to 56.9 km<sup>3</sup>/year (average from the period 2000–2020) [4], with a decreasing trend noted in recent years [4–9]. According to estimations, European water resources amount, on average, to approx. 4.7–5.0 thousand m<sup>3</sup>/year per person and in Poland to 1.4–1.5 thousand m<sup>3</sup>/year per person [4,10,11].



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Shaping and protecting the water resources from periodical excessive amounts of water (snowmelt and rainfall in the spring and short but intensive rainfalls in the summer) or water deficit (at the end of spring and all summer), which is realised, among others, by water retention in reservoirs, is essential especially in areas/regions with low water resources [10,12]. The total capacity of 133 Polish retention reservoirs (existing ones and those still under construction) is approx. 3.5–3.6 km<sup>3</sup> [12]. Furthermore, approx. 32,000 small retention reservoirs may retain about 0.63–0.85 km<sup>3</sup> of water [4,12], which, in total, accounts for approximately 6% of Polish water resources. At the same time, about 7000 large reservoirs could be found across Europe, with a total capacity representing about 2.0% of the total freshwater resources [2].

In many cases the water is characterised as low quality [13]. Water deficits and poor water quality (e.g., for irrigation) require the solution of several problems—such as increasing the effectiveness of using water resources and reducing the influence of irrigation on the environment, by using various sources of water for irrigation [14,15]. This is why it may be important to use quarry lakes as sources of water for irrigation, in particular in areas with poor water resources [16–22].

The global extent of land area impacted by mining and quarrying is estimated at approx. 421 thousand km<sup>2</sup> in Europe, exclusive of Russia, while the estimated area impacted by active mining is about 40 thousand km<sup>2</sup> [23]. Their spatial distribution is rather varied, because it depends on the location of deposits of mineral resources [24]. In Poland, mining areas occupy approx. 422 km<sup>2</sup> out of which open-pit mines account for approx. 347 km<sup>2</sup> [8]. Some of the latter are open-pit basins. These are former excavations of clay, sand and gravel [18,25–27], stone quarries [20,26–30], open-cast coal [18,25–27,31–34] and lignite mines [26,27,31–37], as well as open-cast ore metal mines [18,25,27,34]. When the mining process, and thus the dewatering of the pit, is discontinued, they often fill with groundwater, rainfall and surface runoff, which results in the emergence of mine or quarry lakes [17,20,21,36,38–49].

Depending on the type of the excavated resources and the mining technology used, mine and quarry lakes may vary in depth, surface area, and volume, retaining even up to hundreds of millions of cubic meters of water [17,20,28,32,33,35,39,42,43,48,50–58]. Usually, the largest mine lakes emerge in former lignite mines [24,35,59,60], which even led to the creation of an Anthropogenic Lake District [60,61].

Most mine lakes are located in Australasia, Europe, and North America [16,25,27,62,63]. In particular, most pit lakes were formed in Canada [25,27,31,44,64], the USA [25,27,38,65,66], the Czech Republic [27,63], Australia [22,27,34,44] and Germany [22,27,34,35,39,42,44,67,68]. But in recent decades, hundreds of new mine or quarry lakes have been created, including in many other countries, e.g., China [24,69,70], Italy [19,48], Indonesia [63], Ireland [22], France [52], Poland [22,27,37,49,60,63], Sweden [51], the U.K. [31], South Africa [25], Greece [34] and Spain [27,59,63].

Mine or quarry lakes may be used for various purposes, among others: recreation and tourism [27,31,40,70–74], wildlife habitats [16,17,70–72], aquaculture and fish farming [17,19,27,71,75,76], water management [17,20,27,31,72,76], floating photovoltaic systems [77], as a source of low-cost thermal energy (i.e., for greenhouses, agribusiness factories) [48], water reservoirs in hydro storage power plants [78], greenhouse carbon fixation [27], potable and industrial water reservoirs or irrigation water storage for agriculture and horticulture [17,19,21,28,31,72,74,76,79], capturing flood waters, or improving the flow rate in water courses during droughts [29,35,80].

The potential use of mine and quarry lake water depends, however, on the water quantity and quality [16,17,21,32,35,39,44,46,50,52,67,72,79,81–84]. The volume of water retained in quarry lakes or small mine lakes varies and it may range from several thousand m<sup>3</sup> to several (or more than ten) million m<sup>3</sup> [20,22,27,34,40,47–49,59,78,80,85]. However, most of the publications on mine lakes in the subject literature discuss coal and lignite mines, where the volume of the retained water ranges from 30–60 million m<sup>3</sup>, sometimes exceeding 100 million m<sup>3</sup>, and often reaching even up to 330–350 million m<sup>3</sup> [27,32,36,44,63,67,81,86–90].

In many cases, the mine and quarry lakes contain fresh and clean water [19,21,28,37,40,46,58,60,79,91–94]. However, the risks related to water quality often apply to lignite mines or open-cast ore metal mines, and they are usually connected with increased salination, concentration of heavy metals, acidification that increases the mobility of heavy metals, as well as the oxidation of sulphide minerals, especially pyrite [16,18,25,27,32,33,59,60,84,95].

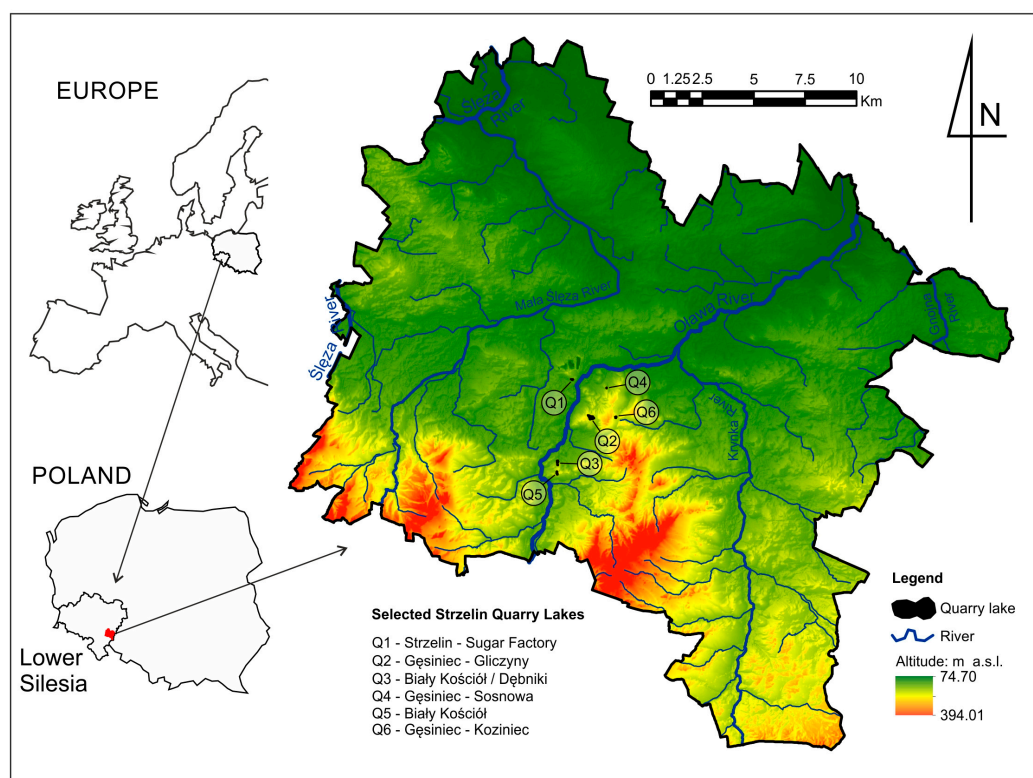
The reclamation of the closed mine pits in the water direction and creating mine or quarry lakes may be an element of the realisation of the tasks related to counteracting the effects of drought and reducing water deficits [12,96–98]. The creation of mine and quarry lakes may also be a partial answer to meeting the goals of the EU Water Framework Directive [22,96]. Furthermore, it may become an important activity for increasing water resources and their sustainable and reasonable management both in local and regional terms [10,20,22,47,49,75,99–106]. In this approach, mine and quarry lakes may be used, for among other purposes, to collect and retain water that is later used, for example, as a source of potable or industrial water supply, for aquaculture and fish farming and for irrigation in agriculture and horticulture [19,21,27–29,31,35,67,70,71,74,76,79].

One of the main problems in agricultural regions (including, among others, Strzelin County) is limited resources of surface waters. In many cases, the water retained in the analysed Strzelin quarry lakes was not included in the balance of reservoirs retention capacity in the catchment of the Oława River [20,49]. Therefore, it is not taken into consideration in the water management programmes that concern water retention and distribution, especially with the aim to mitigate the effects of droughts in agriculture. Currently, the availability of water retained in quarry lakes in Strzelin County for agriculture is poor and the water is used only to a limited extent, because of the lack of reasonable proposals concerning the use of the water retained in Strzelin quarry lakes. Officially, none of them is a source of water supply for agricultural irrigation. The new idea presented in this article is addressed first of all to water authorities, farmers and scientist, as well as teachers. It concerns the possibility of using the water retained in quarry lakes to improve the availability of surface waters for agricultural purposes. The possibility of using water from quarry lakes in agriculture will be determined by its quantity and quality. It is important that the water from quarry lakes should meet the quality requirements for the purpose for which it will be used, e.g., for agricultural irrigation.

The aim of this paper was to estimate the volume of water retained in selected Strzelin quarry lakes that formed in closed granite quarries, as well as to assess the quality of water in the analysed flooded quarries in terms of its usability for agricultural irrigation. The article is a continuation, extension, supplement and discussion of the earlier articles by its authors [20,21,47,49,79], concerning the subject of water resources retained in quarry lakes and the assessment of their suitability for agricultural irrigation. The research subject will be continued in the future.

## 2. Materials and Methods

The subject of the study are closed granite quarries flooded with water that are situated in Strzelin County (Figure 1) [20,21,46,47,49,79], Lower Silesian Voivodeship (Poland, Central Europe), in the area of the Strzelin Hills [107,108], and in the catchment of the Oława River, in the basin of the Oder River [109]. The description of Strzelin County and of the geological structure of the research area was published, among others, in articles [20,21,46,47,49,79].



**Figure 1.** Position of the analysed quarries (DTM created by B. Jawecki [49], modified by the author B.J.).

Samples of water for laboratory tests were collected from the superficial layer of water, at a depth of 0.5 m [110], approximately 5–7 m from the reservoir coast, at 8–10 h a.m., once every quarter (spring, summer, autumn, winter—with and without ice cover), in the period from December 2016 to March 2018 [21,46,79]. In total, 30 samples were collected. The collection of samples and the results of the chemical analysis of the water from the superficial layer of mine and quarry lakes are presented in contemporary publications [22,33,58,59]. The water was analysed at the laboratory [21,46,79], following reference test methodologies and/or Polish Reference Standards [111]. The content of nitrates ( $\text{NO}_3^-$ —spectrophotometric method), sulphates ( $\text{SO}_4^{2-}$ —gravimetric method), chlorides (titration method (Mohra method)), Na, Ca, Mg, Fe, and Mn (all: atomic absorption spectrometry (AAS) method) was determined, as well as the values of  $\text{BOD}_5$  (titration method), pH (potentiometric method), and  $EC_w$  (electrical conductivity of water (conductivity method)). The SAR index (sodium adsorption ratio—potential sodium hazard from irrigation water) and TDS (total dissolved solids) were also measured. The SAR and TDS were calculated with the use of Equations (1) and (2) [112–114]. The mean pH reaction was calculated from the average value of the concentration of  $[\text{H}^+]$  ions obtained from the conversion of the initial pH value. The obtained results were classified according to FAO Guidelines [114] and to the Polish Reference Standard PN-84/C-04635 [115,116]. The evaluation was based on the average values from the measurement period, while the value adopted for the overall evaluation was the worst of all the analysed indicators.

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{++} + \text{Mg}^{++}}{2}}} \quad (1)$$

( $\text{Na}^+, \text{Ca}^{++}, \text{Mg}^{++}$  in meq  $\times$  dm $^{-3}$ )

Source: FAO [114]

$$\text{TDS} = EC_w \times h \quad (2)$$

where:

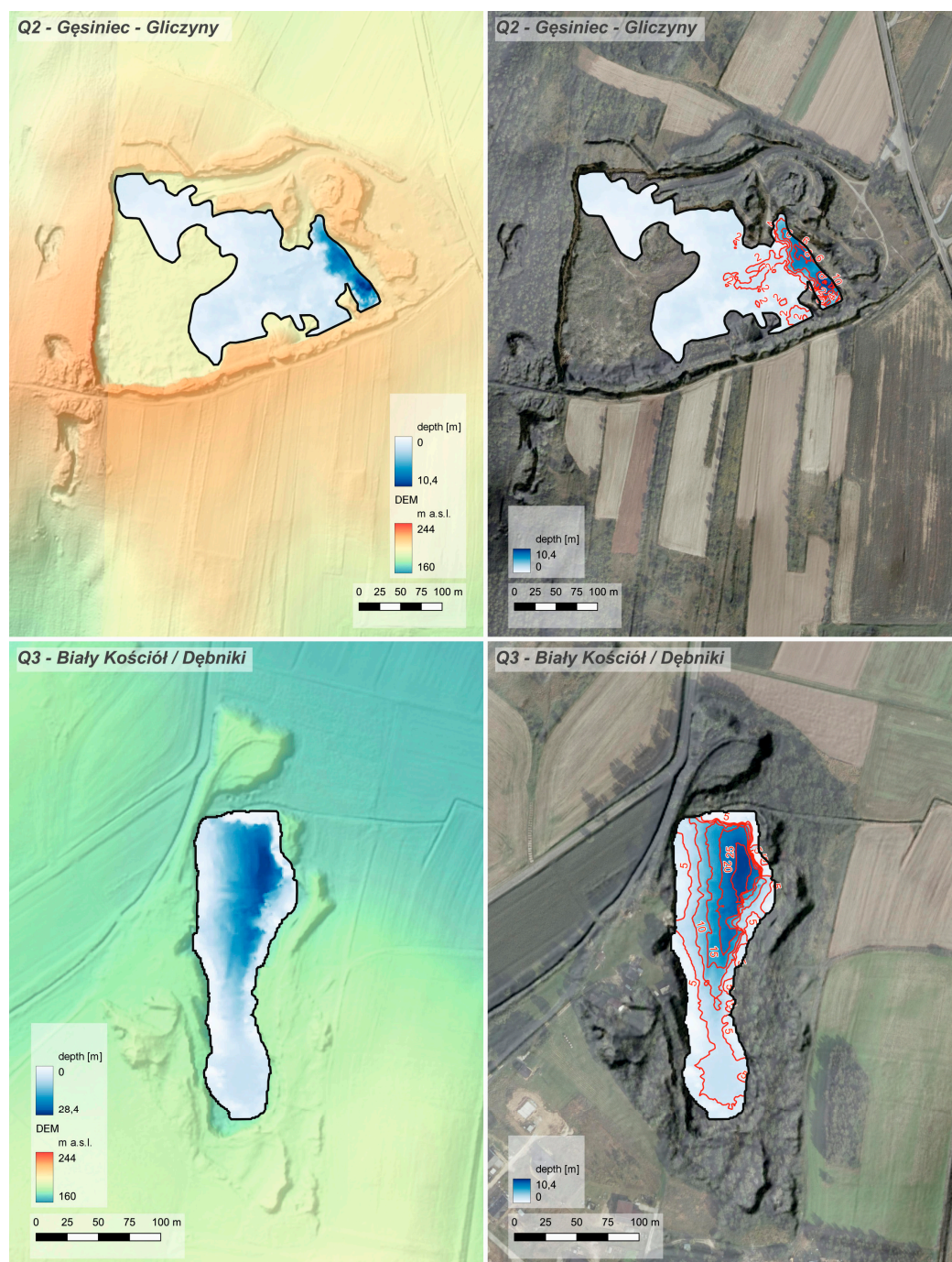
$$h = 640 \text{ for } EC_w < 5 \text{ mS} \times \text{cm}^{-1}$$

$$h = 800 \text{ for } EC_w > 5 \text{ mS} \times \text{cm}^{-1}$$

Source: Bauder et al. [112], Saha et al. [113]

Research on the morphological properties of mining and post-mining pits often uses GIS tools [20,47,117,118], where the output data are obtained with use of traditional geodesic methods (total station, GNSS) measurements that employ LiDAR techniques (TLS, ALS, MLS, UAV), or a combination of the GNSS and network real-time kinematic (NRTK) methods [20,47,119–127]. On the other hand, bathymetric surveys of flooded quarries are mostly carried out using single-beam sonar probes [57,60], including low-cost sonar systems [33,128], although LiDAR techniques may also be used for the purposes of such studies [129,130]. The authors used orthophotomaps (Figure 2) that are available free of charge according to art. 40a of the Act-Geodesic and Cartographic Law [131] from the Chief Land Surveyor of the Country, on the website <https://mapy.geoportal.gov.pl> (accessed on 1 October 2022). The digital terrain model (DTM) of Strzelin County (Figure 1) was created based on LiDAR ALS data (licence no. DIO.7211.160.2018\_PL\_N) by B. Jawecki [49]. The survey was conducted with use of a single-beam Deeper CHIRP+ sonar equipped with a GPS receiver (scanning depth: 0.15–100 m, three CHIRP frequencies: 675 kHz (cone angle 7°), 240 kHz (cone angle 20°), and 100 kHz (cone angle 47°), scanning rate: 15 refreshments per second). The analysed quarry lakes were scanned in July, September, and October 2021. The bottoms of the quarry lakes were scanned with use of a remotely controlled boat equipped with a sonar with a beam of the frequency of 240 kHz and an angle of the scanning cone of 20°. The obtained data were then analysed and processed with the use of GIS tools in order to create bathymetric maps of the surveyed quarry lakes and to estimate the water table surface area and the volume of water retained in the basins of the flooded quarries. The potential differences between the data concerning the surface of the quarry lakes and their depths obtained from field measurements and those read in the available orthophotomaps, NMT, etc., may result, among others, from: the presence of trees overgrowing the shores of the analysed water reservoirs that hinder the measurement of the coastline of the quarry lake, the presence of reed and bushes growing out of the water, sunken and dry trees protruding out of the water, waste floating on the surface of the water that created obstacles preventing the drone from moving freely across the reservoir and thus establishing the determination of its surface area and depth, and finally, the seasonal fluctuations in the water level in the reservoir.

The volume of the water retained in the analysed quarry lakes was estimated with use of the QGIS and Saga Gis open source software, based on the created spatial data base. The initial stage of processing measurement data consisted in their verification in order to identify any potential errors that may result, e.g., from the recording inaccuracy of the used GPS receiver, tilting of the boat and rippling of the water, etc. The visual assessment, based, among others, on the orthophotomap and the NMT, was the basis for eliminating outlier data on the depth and position. As a result, SHP layers were created that contained, depending on the surface area of the analysed reservoir, from 6118 to 65,528 points per object, which corresponds to a sampling density ranging from 0.96 to 2.23 points per 1 m<sup>2</sup>, on average 1.6 points per 1 m<sup>2</sup>. Then, based on the discrete layers: the point layer that contained depth layers obtained from direct measurements, continuous, raster layers were generated that reflected the variability of the position of the bottoms of specific pits in reference to the level of the water table. This was performed with use of the commonly used geostatistical method based on Kriging algorithms. Based on the results, spatial models of the bottom formation of a resolution of 1.0 m were created. This enabled us to calculate the capacity of individual quarry lakes as the average value of specific raster layers and to generate bathymetric maps.



**Figure 2.** Sample bathymetric maps created for quarry lakes Q2 Gęsiniec-Gliczyny and Q3 Biały Kościół Dębniaki (left side: DTM with a bathymetric map of the quarry lake, right side: orthophotomap with terrain formation and bathymetric map with isobates) (author T.K.).

Tests were conducted in six flooded quarries of granitoides, whose basic characteristics are presented in Table 1. Quarries Q1–2 and Q4–6 are non-runoff quarries, while part of the water from quarry Q3 is discharged gravitationally to the drainage ditch, whose bottom at the quarry lake is positioned on the ordinate of approx. 174.7 m a.s.l. In the long-term perspective, seasonal fluctuations in the water level of the analysed reservoirs range from approx. 0.3 m to approx. 1.0 m. Based on the criteria defined in the Ordinance of the Minister of Infrastructure [132] they were classified as artificial reservoirs and their types were defined as (Table 1): WSm\_a—a lake on calcareous substrate, with a low Schindler factor, stratified; WSd\_a—a lake on calcareous substrate, with a high Schindler

factor, stratified; Wsd\_b—a lake on calcareous substrate, with a high Schindler factor, polymictic; K\_a—siliceous lake, low alkaline, stratified. It should be borne in mind that the typology and classification of lakes and water reservoirs adopted in Poland do not take into consideration the specificity of such bodies as mines or quarry lakes. Due to this, it seems justified to urge for the introduction of another type of surface water, including artificial water reservoirs, to the draft amendment to the Water Management Plan in the Oder River Basin [133].

**Table 1.** Characteristics of the analysed quarry lakes (author B.J.).

Quarry Lake	Code on the Map (Figure 1)	Location Coordinates	Resources Mined	Catchment of JCWP <sup>1</sup>	Type of Reservoir <sup>2</sup>
Strzelin-Sugar Factory	Q1	N 5°46'18" S 17°3'05"	Granite		Wsd_a
Gęsiniec-Gliczyny	Q2	N 5°45'15" S 17°3'56"	Tonalite, Diorite, Granite	Oława from Podgródka to Krynka	Wsm_a
Biały Kościół/Dębniki	Q3	N 5°44'08" S 17°2'32"	Granite		Wsm_a
Gęsiniec-Sosnowa	Q4	N 5°46'07" S 17°4'29"	Granite	Code: PLRW6000191334199	Wsd_b
Biały Kościół	Q5	N 5°43'51" S 17°4'54"	Granite		Wsm_a
Gęsiniec-Koziniec	Q6	N 5°45'21" S 17°2'32"	Granite		K_a

Notes: <sup>1</sup> Surface Water Body; <sup>2</sup> Classified according to the Guidelines in the Ordinance of the Minister of Infrastructure [132].

### 3. Results and Discussion

#### 3.1. The Quantity of Water Retained in Closed Strzelin Granite Quarries

The results of sonar measurements became the basis for creating bathymetric maps of the analysed quarry lakes (Figure 2), which allowed for the determination of the length and width of quarry lakes, the surface area of the water reservoir, its depth and the volume of retained water (Table 2).

**Table 2.** Characteristics of the selected bathymetric and morphological parameters of the analysed quarry lakes (author B.J.).

Quarry Lake	Code on the Map	Reservoir Length [m]	Reservoir Width [m]	Surface of the Water Table [ha]	Maximum Depth [m]	Average Depth [m]	Water Volume [million m <sup>3</sup> ]
Strzelin-Sugar Factory	Q1	126	57	0.39	10.0	5.0	0.0194
Gęsiniec-Gliczyny	Q2	347	220	2.93	10.4	1.8	0.0527
Biały Kościół/Dębniki	Q3	242	77	1.23	28.4	10.0	0.1227
Gęsiniec-Sosnowa	Q4	44	42	0.10	4.3	1.7	0.0017
Biały Kościół	Q5	171	51	0.73	17.7	8.3	0.0604
Gęsiniec-Koziniec	Q6	110	81	0.55	15.0	9.4	0.0509
Average/Total		173.3	88.0	0.99	14.3	6.0	∑0.3078

The average surface area of the surveyed quarry lakes (Table 2) is 0.99 ha and falls in the range of 0.10–2.93 ha, while their average length is 173.3 m (ranging from 44–347 m), and width is 88.0 m (ranging from 42–220 m). The surface area of these quarry lakes is relatively small in comparison to that of mine and quarry lakes that emerge in the basins of lignite, coal or metal open pit mines and large quarries of cohesive rock material, which may reach even tens or hundreds of hectares [17,18,20,28,32,33,35,42,43,47,49,51,52,54,55,80,83–85].

Most of the analysed quarry lakes are also relatively shallow, with an average depth of approx. 6 m, ranging from 1.7 to 10.0 m, while the average maximum depth is approx. 14 m, ranging from 4.3 to 28.4 m (Table 2). These values are similar to the parameters of shallow quarry lakes that are formed in quarries of cohesive rock materials and lignite, coal or metal open pit mines whose depth reaches 10–15 m [21,28,33,55,80,83], but they differ significantly from the depth of mine lakes in lignite [35,42,43,54,85], coal [18,32,52] or metal open pit mines [18,46,51,85], and even of quarry lakes [20,21,47,49], whose depths may significantly exceed 30 m.

The total volume of water retained in the analysed quarry lakes, calculated based on bathymetric measurements, amounts to 0.3078 million m<sup>3</sup> and ranges from 0.0017–0.1227 million m<sup>3</sup> (Table 2). Due to their geomorphological parameters, quarry lakes that are formed as a result of anthropogenic activity determined by the geological structure and resource mining technology, the volume of water retained in the analysed quarry lakes is lower than that of water retained in lakes that emerge in quarries of cohesive rock materials [20,40,47,49,80,85], or in smaller mine lakes that emerged in the area of the Adamów Lignite Mine [90,134]. However, a majority of the mine lakes discussed in the literature are lakes formed in coal and lignite mines, where the average volume of retained water usually falls into the range of 30–60 million m<sup>3</sup> [32,36,44,54,81,88–90]. At the same time, the volume of water retained in the analysed quarry lakes will increase the total volume of water retained in the catchment of the Oława River and the balance catchment WR09 Nysa Kłodzka by 11.1% and 0.29%, respectively [20,47,49]. It accounts for 10.6% of all the water resources retained in the water reservoirs, ponds, and Strzelin quarry lakes in the catchment of the Oława River [49].

The calculated results of water volume presented here, which were based on field bathymetric analyses of the water retained in the surveyed quarry lakes, provide a verification of the algorithm/model that was proposed for the purposes of calculating the volume of water retained in quarry lakes, proportionally to the quarry lakes that are formed in inactive granite quarries [49].

The total volume of water retained in the analysed quarry lakes located in closed granite quarries, which was calculated with the use of the algorithm (Equations (1) and (2)) [49] amounted to 0.4279 million m<sup>3</sup> and it was 39% larger than the volume of water calculated based on bathymetric measurements. The differences between the values of water volume calculated with use of the algorithm and based on bathymetric surveys for individual quarry lakes fall into the range of 2.6–43.5% (on average 30.2%). In most of the cases, the values calculated with use of the algorithm were higher than those based on field bathymetric studies. Only in quarry lake Q2 was the value calculated based on the results of field measurements higher (by 32.9%) than that calculated with use of the algorithm. This may be explained by the fact that the older and deeper part of the flooded pit has a surface area of approx. 0.27 ha and a depth of approx. 10–11 m, while the newer, shallower part has a surface area of 2.66 ha and a depth of approx. 2 m, which was taken into account in calculating the volume of water based on the proposed algorithm [49]. The most similar values of the calculated volumes of water were noted in Q6 where the difference was only 2.6%.

In order to minimise the differences between the values of the volume of water retained in quarry lakes that are located in the granite quarry that has been closed for about 20 years, which were determined based on bathymetric measurements and the values calculated with use of the algorithm, the authors propose [49] to add a reduction coefficient for quarry lakes in inactive quarries (CQL) to Equation (1). This coefficient should have the value of 0.642 or to reduce the RF coefficient in Equation (2) [49] to 0.407. This action will result in decreasing the volume of water calculated with use of the algorithm by the average value (35.8%) of the absolute difference between the water volume calculated with the algorithm and the value based on bathymetric surveys, which will result in reducing the potential differences between these values to approx. 7%.

Taking into account the volume of water retained in the inactive Strzelin granite quarries, calculated based on bathymetric studies, will lead to a slight decrease in the total



volume of water (2.635 million m<sup>3</sup>) retained in the Strzelin quarry lakes [49] by 4.6% and a decrease in the volume of water retained in the reservoirs, ponds, and Strzelin quarry lakes in the catchment of the Oława River (5.297 million m<sup>3</sup>) and the balance catchment WR09 Nysa Kłodzka (107.595 million m<sup>3</sup>) [49], by 2.2% in the catchment of the Oława River and by 0.1% in the balance catchment WR09 Nysa Kłodzka. It should be emphasised that the major part of the total volume of water resources retained in the Strzelin quarry lakes is retained in quarry lakes that are situated in active quarries (Strzelin, Sobótka, Gębczyce, and Jegłowa), which account for about 70% of the retained water [49]. However, these lakes are characterised by high dynamics, due to the periodical discharges of the retained water [20,47,49].

### 3.2. The Quality of Water Retained in Closed Strzelin Granite Quarries

#### 3.2.1. The pH

The pH of the water from flooded quarries fell into the range 7.1–9.3 (Table 3). The average pH values fell into the range of 7.61–7.98 (Figure 3), where the highest values (pH 9.0 and 9.3) were noted in the eutrophic [46,135] granite quarries Q3 and Q5. Such pH values were noted in the spring and summer, which means that they are probably linked to strong photosynthesis in the summer season, where a rapid growth of phytoplankton and intensified photosynthesis may lead to alkalinisation and, thus, an increase in the pH of the water [136,137]. Similar results (pH 7.7–8.4 (max. 9.7)) were obtained by other authors in flooded marble, limestone, and quartzite quarries in Poland [21,30,40,46,79] and the USA [138]. The average values of pH in the analysed quarry lakes fell into the range that is characteristic for natural lakes (pH 6.5–8.5). However, in most of the analysed quarry lakes (with the exception of Q2) pH values exceeding 8.5 were noted at least once, and in quarries Q3 and Q5 these values reached or even exceeded pH 9.0. The average pH values fell into the range of pH 6.5–8.4, which is recommended by the FAO [114] for waters used for irrigation. However, in each of the analysed quarry lakes, the pH value reached or even exceeded the maximum acceptable level according to the FAO at least once. This happened most often in quarry lakes Q3 and Q5. The average reaction values were below the value of pH 8.0 that is recommended for irrigation in Poland (PL) [115,116]. However, in 60% of the analysed water samples (usually in the summer) pH values above 8.0 were noted, usually in quarry lakes Q2, Q3, Q5, and Q6.

**Table 3.** Average, minimum and maximum value of the analysed water quality indicators in selected Strzelin granitoid quarry lakes (author B.J.).

Parameter	Q1	Q2 <sup>1</sup>	Q3 <sup>1</sup>	Q4	Q5	Q6
	avg. ± standard error min.–max.					
pH (–)	7.61 7.1–8.8	7.98 7.6–8.4	7.73 7.2–9.0	7.75 7.3–8.7	7.81 7.2–9.3	7.88 7.4–8.7
EC <sub>w</sub> (mS/cm)	0.351 ± 0.024 0.310–0.444	0.288 ± 0.007 0.270–0.311	0.384 ± 0.008 0.369–0.407	0.318 ± 0.024 0.287–0.346	0.456 ± 0.009 0.433–0.481	0.194 ± 0.004 0.180–0.201
SAR (–)	0.39 ± 0.02 0.31–0.45	0.38 ± 0.03 0.30–0.49	0.69 ± 0.03 0.58–0.77	0.30 ± 0.02 0.22–0.35	1.08 ± 0.06 0.93–1.21	0.56 ± 0.03 0.44–0.62
TDS (mg/L)	224.9 ± 15.49 198.4–284.2	184.2 ± 4.64 172.8–199.0	245.9 ± 4.83 236.2–260.5	203.4 ± 6.11 183.6–221.4	291.8 ± 5.84 277.1–307.8	123.9 ± 2.33 115.2–128.6
BOD <sub>5</sub> (mg O <sub>2</sub> /L)	2.52 ± 0.35 1.60–3.40	1.54 ± 0.37 0.90–2.90	2.04 ± 0.55 1.00–4.10	3.38 ± 0.53 2.10–4.80	4.02 ± 0.83 2.00–5.80	1.10 ± 0.27 0.50–2.00

Table 3. Cont.

Parameter	Q1	Q2 <sup>1</sup>	Q3 <sup>1</sup>	Q4	Q5	Q6
	avg. ± standard error min.–max.					
Nitrates (mg NO <sub>3</sub> <sup>-</sup> /L)	2.25 ± 0.90 0.44–5.14	0.84 ± 0.16 0.49–1.33	0.43 ± 0.16 0.00–0.97	0.83 ± 0.24 0.22–1.42	0.58 ± 0.15 0.13–1.06	0.53–0.07 0.35–0.71
(mg N-NO <sub>3</sub> <sup>-</sup> /L)	0.51 ± 0.20 0.10–1.16	0.19 ± 0.04 0.11–0.3	0.10 ± 0.03 0.00–0.22	0.19 ± 0.05 0.05–0.32	0.13 ± 0.03 0.03–0.24	0.12–0.02 0.08–0.16
Sulphates (mg SO <sub>4</sub> <sup>2-</sup> /L)	175.24 ± 79.99 68.30–491.20	233.48 ± 69.27 83.10–496.10	168.82 ± 65.71 8.20–408.10	183.22 ± 111.92 50.50–626.60	153.70 ± 61.78 37.00–385.90	143.18 ± 76.72 5.80–433.60
Chlorides (mg Cl <sup>-</sup> /L)	34.76 ± 4.02 27.80–50.00	15.20 ± 0.52 13.40–16.60	56.92 ± 2.36 47.60–60.40	34.80 ± 7.63 24.60–65.00	53.32 ± 7.28 25.00–65.60	24.40 ± 0.77 21.60–26.20
Sodium (mg Na <sup>+</sup> /L)	11.04 ± 0.71 8.40–12.40	9.78 ± 0.84 7.50–12.60	19.74 ± 0.97 16.50–22.30	8.54 ± 0.73 5.90–10.00	29.20 ± 1.63 23.90–33.80	10.52 ± 0.65 8.20–11.90
Calcium (mg Ca <sup>2+</sup> /L)	46.36 ± 2.10 40.50–52.80	42.08 ± 1.81 38.40–49.00	48.32 ± 0.88 46.60–51.70	52.84 ± 1.90 47.30–58.60	34.64 ± 2.88 25.50–40.40	21.94 ± 0.33 21.00–22.60
Magnesium (mg Mg <sup>2+</sup> /L)	8.72 ± 0.27 8.00–9.60	5.34 ± 0.17 5.10–6.00	8.82 ± 0.28 8.10–9.80	6.32 ± 0.18 5.80–6.90	12.62 ± 0.33 11.90–13.70	3.08 ± 0.11 2.90–3.50
Manganese (mg Mn/L)	0.200 ± 0.088 0.000–0.51	0.024 ± 0.008 0.000–0.040	0.089 ± 0.071 0.000–0.370	0.062 ± 0.019 0.010–0.120	0.158 ± 0.071 0.030–0.390	0.046 ± 0.028 0.000–0.140
Iron (mg Fe/L)	0.255 ± 0.115 0.030–0.620	0.060 ± 0.038 0.000–0.210	0.002 ± 0.002 0.000–0.010	0.090 ± 0.022 0.020–0.160	0.060 ± 0.2 0.030–0.090	0.028 ± 0.019 0.000–0.100

Note: <sup>1</sup> source: Jawecki et al. [21].

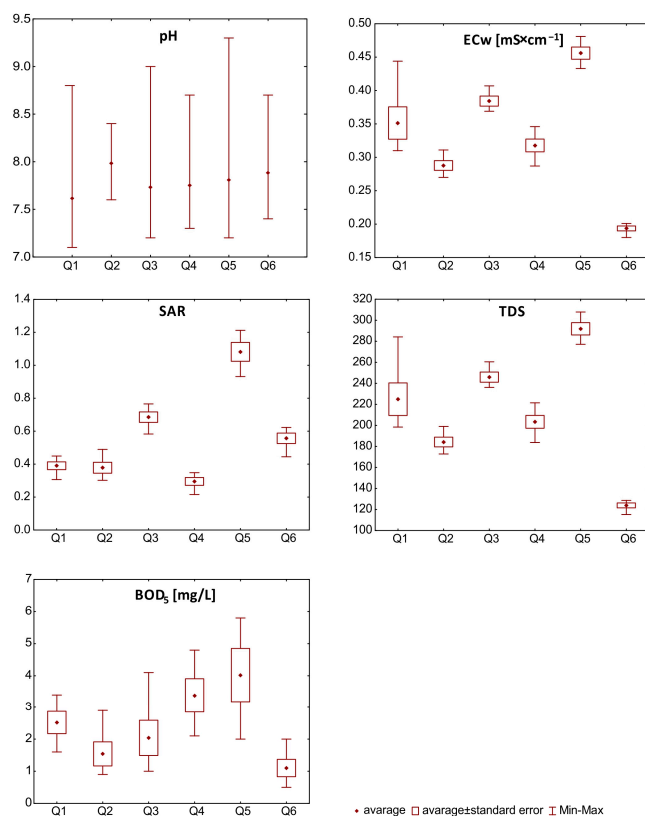


Figure 3. The average and range of variability values of the indicators that characterise the usability of water from selected quarry lakes in the Strzelin granitoids quarry lakes for agricultural irrigation (author B.J.).

### 3.2.2. The Electrical Conductivity of Water

The water in the analysed quarry lakes is characterised by low  $EC_w$ , below  $0.5 \text{ mS} \times \text{cm}^{-1}$  (Table 3), which is characteristic of 80% of lakes [139,140]. In the analysed quarry lakes, the average value of  $EC_w$  fell into the range  $0.194\text{--}0.456 \text{ mS} \times \text{cm}^{-1}$  (Figure 3). The maximum value of  $0.481 \text{ mS} \times \text{cm}^{-1}$  was noted for Q5 (Table 3). The selected Strzelin quarry lakes are characterised by  $EC_w$  values below  $0.7 \text{ mS} \times \text{cm}^{-1}$  [21,46]. Mine or quarry lakes are often salinized, with the consequence that the  $EC_w$  exceeds  $1 \text{ mS} \times \text{cm}^{-1}$ , reaching  $3 \text{ mS} \times \text{cm}^{-1}$ , and even exceeding  $20 \text{ mS} \times \text{cm}^{-1}$  [32,35,40,51,52]. For example, the  $EC_w$  in marble and limestone quarry lakes ranges from  $0.481\text{--}0.653 \text{ mS} \times \text{cm}^{-1}$  [21,30,46], while in a silica sand quarry lake it is  $1.2 \text{ mS} \times \text{cm}^{-1}$  [18], and in quartzites and quartzitic sandstones quarry lakes  $1.10\text{--}5.57 \text{ mS} \times \text{cm}^{-1}$  [141]. The selected Strzelin quarry lakes (Poland) are characterised by  $EC_w$  values below  $0.7 \text{ mS} \times \text{cm}^{-1}$  [21,46]. According to the guidelines on the suitability of water for irrigation [116], water in quarry lake Q6 had a low degree of salination ( $0\text{--}0.25 \text{ mS} \times \text{cm}^{-1}$ ), and the other flooded granite quarries are characterised by a medium degree of salination ( $0.25\text{--}0.75 \text{ mS} \times \text{cm}^{-1}$ ).

### 3.2.3. The Total Dissolved Solids and the Sodium Adsorption Ratio

The value of the TDS indicator fell into the range of  $115.2\text{--}307.8 \text{ mg/L}$ , with average values in the range of  $123.9\text{--}291.8 \text{ mg/L}$  (Figure 3). The highest values were noted (Table 3) in quarry lake Q5 (on average  $291.8 \text{ mg/L}$ ; range  $277.12\text{--}307.8 \text{ mg/L}$ ), while the lowest ones were found in Q6 (on average  $123.9 \text{ mg/L}$ ; range  $115.2\text{--}128.6 \text{ mg/L}$ ). The SAR index of the waters in the analysed quarries fell into the range of  $0.22\text{--}1.21$  (Table 3), with the average values ranging from  $0.30\text{--}1.08$  (Figure 3). The water in all analysed quarry lakes does not exceed the value of  $EC_w$   $0.7 \text{ mS} \times \text{cm}^{-1}$  and TDS  $450 \text{ mg/L}$ , which means that it may be used for irrigation without any restrictions [112,113,116]. However assessment of the sodium hazard of irrigation water based on SAR and  $EC_w$ , evaluated using  $EC_w$  and SAR together [112–114], demonstrates that, in spite of a low SAR index ( $<3$ ) of the analysed water reservoirs and low  $EC_w$  values ( $0.2\text{--}0.7 \text{ mS} \times \text{cm}^{-1}$ ), the waters from quarry lakes Q1–Q5 may be subject to slight to moderate restrictions, and from quarry lake Q6 ( $<0.2 \text{ mS} \times \text{cm}^{-1}$ ) even severe restrictions in using water for irrigation, in particular for specific types of crops and soils, e.g., if applied to soils containing more than 30% smectite clay [112].

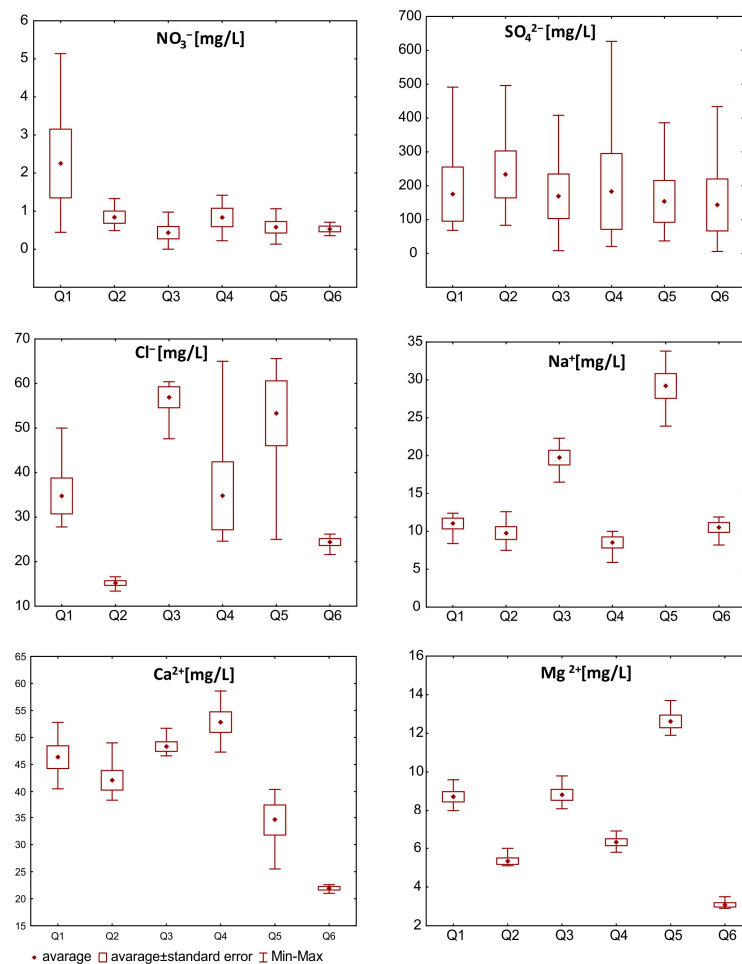
### 3.2.4. The Biological Oxygen Demand Index (BOD<sub>5</sub>)

The average value of the BOD<sub>5</sub> index fell into the range of  $1.10\text{--}4.02 \text{ mgO}_2/\text{L}$  (Figure 3, Table 3), and the highest concentrations were noted in the flooded closed quarry Q5 (average  $4.02 \text{ mgO}_2/\text{L}$ , max  $5.80 \text{ mgO}_2/\text{L}$ ). The higher values of BOD<sub>5</sub> were noted in the spring and summer, which means that they are probably linked to the surface runoff, because in the spring and summer snowmelt and more intensive rainfall usually occur. These values were similar to those noted in natural lakes or artificial water reservoirs in Poland [46,142,143] and demonstrated that contamination with organic substances was low. Significant fluctuations and the highest values of BOD<sub>5</sub> that were found in quarry lakes Q1, Q3–Q5 may point to high productivity and eutrophication of their waters [46,142]. As the BOD<sub>5</sub> value in the analysed quarry lakes was below  $12.0 \text{ mgO}_2/\text{L}$ , their waters may be used for irrigation [115].

### 3.2.5. Nitrates

In the analysed quarry lakes, the average nitrate content in the water fell into the range of  $0.43\text{--}2.25 \text{ mgNO}_3^-/\text{L}$  (Figure 4), where in Q3 no nitrates at all were found in the spring of 2017 (Table 3), and the highest value of  $5.14 \text{ mg NO}_3^-/\text{L}$  was noted in Q1 (Table 3). In the different analysed quarries, higher contents of nitrates were noted in different seasons of the year: in Q1 and Q4 in the summer and autumn, in Q2, Q3, Q5 in the spring and summer, and in Q6 in the summer and winter. The obtained results show that the higher content of nitrates in quarries was observed in summer, but high

concentrations of nitrates were also noted in other seasons of the year. This subject requires further research. In most cases (Q2–Q6), the content of nitrates in the waters of the analysed quarry lakes was similar to the concentrations that were found in other Strzelin quarry lakes (Poland)—0.30–0.58 mg NO<sub>3</sub><sup>-</sup>/L [21,46] and lower than the values noted in post-mining lakes—0.824–1.771 mg NO<sub>3</sub><sup>-</sup>/L [21,35,40,46]. Moreover, it was several times lower than in artificial water reservoirs (1.7–26.0 mg NO<sub>3</sub><sup>-</sup>/L) [110,144] or natural lakes (0.44–32.27 mg NO<sub>3</sub><sup>-</sup>/L) [140,142]. The concentration of nitrates in the waters of quarry lake Q-1 (average 2.25 mgNO<sub>3</sub><sup>-</sup>/L) diverged from the nitrate content values found in the other quarry lakes analysed here, and from some of the analysis results noted for other Strzelin quarry lakes (Poland) [21,46]. The flooded Q1 quarry is situated in an urban area, in the vicinity of an active mine (where excavations are conducted with use of explosives) and a sugar factory (remnants of deposit tanks) as well as intensively cultivated fields. The higher concentration of nitrates in the water is likely to result from washing out the residue of explosive materials to the water reservoir, as well as superficial and underground supply from the surrounding area [21,46,51]. However, the content of nitrates in the waters of the analysed quarry lakes (Table 3) does not exceed 5 mgN-NO<sub>3</sub><sup>-</sup>/L. and thus, according to the guidelines concerning the influence of nitrate content on the usability of water for irrigation [113,114,116], the water may be used without any limitations.



**Figure 4.** The average and range of variability concentration of selected ions in the water of the analysed Strzelin granitoids quarry lakes (author B.J.).

### 3.2.6. Sulphates

The average sulphate content in the waters of the analysed quarry lakes fluctuated in the range 143.18–233.48 mgSO<sub>4</sub><sup>2-</sup>/L (Figure 4). The lowest measured value (5.80 mgSO<sub>4</sub><sup>2-</sup>/L) was found in quarry Q6 (Table 3), while the highest one (626.60 mgSO<sub>4</sub><sup>2-</sup>/L) in quarry Q4

(Table 3). Higher values of sulphates were noted in the winter and spring. This is probably linked to snow fall and rainfall, because acid rains occurred in Strzelin County in the winter and spring season [145]. These values are similar to the concentrations of sulphates that are found in natural lakes: 0.7–186.4 mgSO<sub>4</sub><sup>2-</sup>/L [51,142,146] and in the waters of flooded mines (quarries) of rock materials, the concentration values fluctuated in the range of 236–503 mgSO<sub>4</sub><sup>2-</sup>/L [18,21,40]. The content of sulphates in the analysed quarry lakes was lower than the values noted in mine lakes in metal ore excavation pits, where it fell into the range of approx. 400–25,000 mgSO<sub>4</sub><sup>2-</sup>/L [18,51]. On the other hand, the concentration of sulphates in mine lakes in open-cast lignite and coal mines varied significantly within the range of approx. 30–100 mgSO<sub>4</sub><sup>2-</sup>/L [18,35], 230–770 (900) mgSO<sub>4</sub><sup>2-</sup>/L [32,35,42,52], 1800–2600 mgSO<sub>4</sub><sup>2-</sup>/L [42,44], reaching even up to 25,000 mgSO<sub>4</sub><sup>2-</sup>/L [18]. The concentration of sulphates in the analysed Strzelin quarry lakes is significantly lower than the values in the waters of acidic lakes that emerged in coal mining pits, especially lignite mines. The average concentration of sulphates in the waters of the analysed quarry lakes allows us to consider that they meet the requirements for being used in irrigation. However, the maximum values that were noted in April 2017 exceeded the maximum acceptable limit of 400 mgSO<sub>4</sub><sup>2-</sup>/L [115].

### 3.2.7. Chlorides

The average content of chlorides in the analysed quarry lakes fell into the range from 15.20 to 56.92 mgCl<sup>-</sup>/L (Figure 4). Higher concentrations of chlorides were noted in the summer and spring. The lowest values, in the range of 13.40–16.60 mgCl<sup>-</sup>/L, were noted in quarry Q2 (Table 3), and the highest ones, ranging from 47.60 to 60.40 mgCl<sup>-</sup>/L, in quarry Q3 (Table 3). At the same time, the content of chlorides in natural lakes fell into the range of 70–100 mgCl<sup>-</sup>/L [142,146], while in quartzite schist, marble and limestone quarry lakes this content was, respectively, 22.04 mgCl<sup>-</sup>/L–39.44 mgCl<sup>-</sup>/L [21] and 175 mgCl<sup>-</sup>/L [40], and in mine lakes in metal ore excavation pits it ranged, approximately, from 2.2 to 2.8 mgCl<sup>-</sup>/L [51], while in lignite mine lakes from 0 to 100 mgCl<sup>-</sup>/L [35]. In coal mine lakes, the values fell into the range of 780–880 mgCl<sup>-</sup>/L [32]. The concentration of chlorides in the analysed Strzelin quarry lakes was below the threshold value (400 (300 for greenhouses) mgCl<sup>-</sup>/L) defined in the Polish Norm [115,116] and did not exceed the threshold value of (140 (100 for sprinkler irrigation) mgCl<sup>-</sup>/L) as provided in the FAO Guidelines [113,114]. This means that no restrictions apply for the use in irrigation and the water met the requirements that enable it to be used in irrigation in terms of chloride content.

### 3.2.8. Sodium

The average sodium content in the analysed quarry lakes fluctuated in the range of 8.54–29.20 mgNa<sup>+</sup>/L (Figure 4). The higher concentrations of sodium were noted in the spring and summer. The highest values, ranging from 23.90 to 33.80 mgNa<sup>+</sup>/L, were noted in quarry Q5 (Table 3), and the lowest ones, between 5.90 and 10.00 mgNa<sup>+</sup>/L, in quarry Q4 (Table 3). In quarry lakes Q1, Q2, Q4, and Q6, the content of sodium ions was similar to the average concentration (10–11 mgNa<sup>+</sup>/L) in natural Polish lakes [147], whereas in Q3 and Q5 it fell into the lower ranges of threshold sodium concentrations (~21.0–60.0 mgNa<sup>+</sup>/L) noted in quarry lakes and quarry ponds [148]. In the analysed quarry lakes, the concentration of sodium ions was decidedly lower than that noted for coal mine lakes ~450 mgNa<sup>+</sup>/L [32]. At the same time, it was lower than the content of sodium ions found in retention reservoirs (~45–55 mgNa<sup>+</sup>/L) that are used for irrigation [149] and significantly lower than the concentration of sodium ions in certain lakes (~138–178 mgNa<sup>+</sup>/L) that are the source of water for irrigation [149]. Although the concentration of sodium in the waters of the analysed quarry lakes is relatively low, the application of these waters in surface irrigation will be subject to severe restrictions on use for Q1–Q3, Q5–Q6 and for Q4 to slight to moderate restrictions, due to their toxicity for certain types of crops [113,114]. However, the water from the analysed quarry lakes may be used for sprinkler irrigation without any limitations [113,114]. The water from the analysed quarry

lakes contained less than  $140 \text{ mgNa}^+/\text{L}$ , which means that it meets the requirements provided in the Polish Norm [115], and the requirements for usability in irrigation defined in the study by Kaniszewski and Treder [116]. The concentration of sodium ions was the basis for the determination of the SAR index which was discussed above.

### 3.2.9. Calcium

In the waters of the analysed quarry lakes, the mean calcium content fell into the range of  $21.44\text{--}52.84 \text{ mgCa}^{2+}/\text{L}$  (Figure 4). The highest concentrations ( $47.30\text{--}58.60 \text{ mgCa}^{2+}/\text{L}$ ) of calcium were found in Q4 (Table 3), and the lowest ones ( $21.00\text{--}22.60 \text{ mgCa}^{2+}/\text{L}$ ) in Q6 (Table 3). The higher content of calcium was noted in the spring. The other Strzelin quarry lakes have rather poor calcium content [21,46]. In most of the discussed cases (quarry lakes Q1–Q4), the observed values of calcium content were similar to the lowest values noted in natural lakes ( $\sim 50.0\text{--}124.0 \text{ mgCa}^{2+}/\text{L}$ ) or even lower (Q5–Q6) [142,147,150]. They were also below the bottom threshold of calcium content ( $\sim 50\text{--}180 \text{ mgCa}^{2+}/\text{L}$ ) that was noted in other quarry lakes or quarry ponds in [21,32,40,148]. Additionally, the concentrations of calcium that were noted in the analysed quarry lakes were similar to the values found in a retention reservoir that is used for irrigation ( $\sim 15\text{--}37 \text{ mgCa}^{2+}/\text{L}$ ), and, at the same time, lower than the concentrations ( $\sim 132\text{--}161 \text{ mgCa}^{2+}/\text{L}$ ) noted in a natural lake that is also used for irrigation [149]. The calcium content in the analysed quarry lakes (Q1–Q6) was higher than in some of the coal mine lakes  $\sim 6.0\text{--}35.0 \text{ mgCa}^{2+}/\text{L}$  [18,32]. However, some coal and lignite mine lakes were characterised by higher concentrations of  $\sim 100\text{--}500 \text{ mgCa}^{2+}/\text{L}$  [18,35]. On the other hand, in mine lakes that emerged in metal ore excavation pits, the calcium load fell into the range of approx.  $\sim 330\text{--}1120 \text{ mgCa}^{2+}/\text{L}$  [18], which was decidedly higher than in the analysed Strzelin granite quarry lakes. The calcium ion content was also used to determine the SAR index discussed in another section of this article.

### 3.2.10. Magnesium

The average magnesium content in the analysed quarry lake waters fell into the range of  $3.08\text{--}12.62 \text{ mgMg}^{2+}/\text{L}$  (Figure 4). In the analysed quarries, the concentrations of magnesium were similar in all seasons of the year. The highest average loads ( $11.90\text{--}13.70 \text{ mgMg}^{2+}/\text{L}$ ) were noted in Q5 (Table 3), and the lowest ones ( $2.90\text{--}3.50 \text{ mgMg}^{2+}/\text{L}$ ) in Q6 (Table 3). The magnesium concentrations noted in selected natural lakes in Poland fell into the range of  $\sim 9.5\text{--}40.0 \text{ mgMg}^{2+}/\text{L}$  [142,147,150], which allows us to state that the magnesium load in Strzelin quarry lakes was similar to the lower and medium values found in these lakes, and in the lower ranges of calcium load ( $\sim 4\text{--}58 \text{ mgMg}^{2+}/\text{L}$ ) that were observed in other quarry lakes or quarry ponds [21,40,148]. Additionally, they were lower than or similar to the concentrations of magnesium ( $\sim 14\text{--}20 \text{ mgMg}^{2+}/\text{L}$ ) noted in the retention reservoir and lower than the concentration ( $\sim 24\text{--}45 \text{ mgMg}^{2+}/\text{L}$ ) found in a natural lake, where both the reservoir and the lake were used for irrigation [149]. The magnesium load in quarry lakes Q1–Q6 was lower than or similar to the lower values observed in certain coal and lignite mine lakes ( $\sim 10\text{--}200$  (2240)  $\text{mgMg}^{2+}/\text{L}$ ) and significantly lower than the high and maximum values [18,32,35]. The magnesium load that was found in mine lakes that emerged in metal ore excavation pits ( $\sim 860\text{--}1240$  (3150)  $\text{mgMg}^{2+}/\text{L}$ ) was even several hundred times higher [18] than the concentrations observed in the analysed Strzelin quarry lakes. The magnesium ion content was also used to determine the SAR index discussed above.

### 3.2.11. Iron

The average iron content in the analysed quarry lakes fell into the range of  $0.002\text{--}0.255 \text{ mg Fe}/\text{L}$  (Table 3). The higher content of iron was noted in the winter. The highest value ( $0.620 \text{ mg Fe}/\text{L}$ ) was noted in quarry lake Q1. In 33% of the analysed samples, no presence of iron was detected at all, while in four analysed samples from Q3 iron was not found, and in Q1 and Q4 the presence of iron was detected in all the analysed samples. Similar loads of iron ( $0.016\text{--}0.5 \text{ mg Fe}/\text{L}$ ) were noted in natural lakes [142,151]. However, in some cases, the concentration of iron ( $3.93\text{--}49.0 \text{ mg Fe}/\text{L}$ )

in lake waters was higher than that in the analysed quarry lakes [42,152], similar to the concentrations of iron (0.062–12.0 mg Fe/L) that were noted in artificial water reservoirs [153,154]. Research on the iron load in the waters of a silica sand quarry lake in Poland revealed a concentration of 0.14 mg Fe/L [18], while in quartzites and quartzitic sandstone quarry lakes the value fell into the range of 5.2–23.3 (860) mg Fe/L [141], which was significantly higher than in the analysed quarry lakes (Q1–Q6). However, in the other analysed Strzelin quarry lakes: quartzite schist (average 0.078 mg Fe/L), granite (average 0.016 mg Fe/L) marble (average 0.040 mg Fe/L) [21], the concentration of iron in the water was usually similar. The iron loads in flooded inactive metal ore excavation pits quite often reached 2.5–3.23 mg Fe/L or even up to 248 mg Fe/L [18,51], with the lower values in the range of 0.05–0.575 mg Fe/L [18], i.e., similar to the values noted in the analysed Strzelin quarry lakes. On the other hand, the iron loads measured in coal and lignite mine lakes ranged from 14.2–206.0 mg Fe/L to 690.0–2463.248 mg Fe/L [18,42,44], although in certain objects the values were decidedly lower, ranging from 0.003–1.1 mg mg Fe/L [18,32,35,42,45]. Values similar to these lower ranges were obtained in the Strzelin quarry lakes. The water from the analysed quarry lakes met the requirements of the FAO (<5.0 mg Fe/L [114]) as well as those provided in the Polish Norm (<10.0 mg Fe/L [115]) in terms of iron content, which means that the water may be used for irrigation. Occasionally, in quarry lakes Q1, Q2, and Q3, iron loads in the range of 0.1–1.5 mg Fe/L were noted. This implies slight to moderate restrictions to use in drip irrigation due to the possibility of clogging the drip nozzle [113,116]. However, in most of the cases, the water in the analysed quarry lakes was characterised by concentrations below <0.1 mg Fe/L, which means that it is less likely to clog the drip nozzle and that drip irrigation may be applied without any restrictions [113,116].

### 3.2.12. Manganese

The average manganese content in the analysed quarry lakes in the Strzelin area fell into the range of 0.024–0.200 mgMn/L (Table 3). A higher content of manganese was noted in the winter. The highest values were noted in quarry lake Q1: 0.51 mgMn/L (Table 3). In the summer of 2017, the presence of manganese was not detected in quarry lakes Q1–Q3 and Q6. The concentration of manganese in the analysed waters (Table 3) was similar to the content (0.007–0.200 (1.32) mgMn/L) noted in natural lakes [151,152]. Higher manganese loads than in the analysed quarry lakes (~4.5–81 mgMn/L) were found in the waters of quarry lakes that emerged in metal ore mines [18,51]. The concentration of manganese in mine lakes that were formed in coal and lignite mines fell into the range of 0.0002–1.8 mgMn/L, reaching up to 11.8–13.0 mgMn/L or even 150.0 mgMn/L [18,35,45,155], where the values above 0.55 mgMn/L significantly exceed those noted in the analysed Strzelin quarry lakes. In other Strzelin quarry lakes: quartzite schist (average 0.030 mgMn/L), granite (average 0.008 mgMn/L), and marble (average 0.090 mgMn/L) [21], the values of manganese load in the water were mostly similar to or lower than the results obtained in the analysed quarry lakes. On the other hand, in quartzite and quartzitic sandstone quarry lakes it fell into the range of 1.062–6.317 mgMn/L [141], which was higher than in the analysed quarry lakes. In the silica sand quarry lake, the manganese load was <0.01 mgMn/L [18] and was similar to most of the results from individual samples, although it was lower than the average values in the analysed Strzelin quarry lakes. The water from the analysed quarry lakes met the requirements of the Polish Norm (<0.08 mgMn/L) [115] in terms of manganese load, which means that it may be used for irrigation. As far as the FAO requirements are concerned (<0.2 mgMn/L [114]), the water in quarry lake Q1 (in terms of the average (0.200 mgMn/L) and maximum value (0.510 mgMn/L)) did not meet the requirements that would enable its use for irrigation. Some individual samples from quarry lakes Q3–Q5 (maximum values of 0.370 mgMn/L, 0.120 mgMn/L, and 0.390 mgMn/L, respectively) did not meet the requirements provided in the FAO Guidelines for water to be used in irrigation, either. Moreover, in quarry lakes Q1 and, occasionally, in Q3, manganese loads in the range of 0.1–1.5 mgMn/L were noted. This implies slight to moderate restrictions to use in drip irrigation due to the possibility of

clogging the drip nozzle [113,116]. On the other hand, in quarry lake Q2 and in most cases, in Q3–Q6, the manganese load in the water from the analysed quarry lakes was <0.1 mgMn/L, which means that it was less likely to clog the drip nozzle and that water may be used for drip irrigation without any limitations [113,116].

3.3. The Comparison of Selected Water Indicators of the Strzelin Quarry Lakes vs. Other Mine Lakes and Quarry Lakes and Ponds

The water quality indicators of the analysed quarry lakes were decidedly lower in comparison to those in quarry lakes and quarry ponds, pit lakes and mine lakes, in particular acidic mining lakes, in Poland [21,30,40,46,79,141,148] and other countries, for example: Germany [35,42,155], Australia [18,32,45], Sweden [51], France [52] and the USA [138]. The range of the averages values and concentrations of water indicators in selected Strzelin quarry lakes—closed granite quarries (gSQLs) vs. other mines lakes, and quarry lakes and ponds, was presented in Table 4.

**Table 4.** The comparison of the range of averages values and concentrations of selected water indicators in the analysed Strzelin quarry lakes (gSQL) vs. other mines lakes, and quarry lakes and ponds. (author B.J.).

Parameter	gSQL <sup>1</sup> Q1–Q6	Mines and Quarry Lakes in Different Countries							
		Poland [21,30,40, 46,79,141, 148]	Germany [35,42,155]	Australia [18,32,45]	Sweden [51]	France [52]	USA [138]		
Ore Type	Rock Raw Materials	Rock Raw Materials	Lignite	Coal	Metal	Sand	Metal	Coal	Rock Raw Materials
pH (–)	7.61–7.98	2.2–3.4 6.9–9.0	~2.8–4.4 ~6.2–9.4	1.5–5.5 6.8–8.8	2.8–8.6	8.5	2.7–5.9	6.8–9.3	7.37–9.74
EC <sub>w</sub> (mS × cm <sup>-1</sup> )	0.194–0.456	0.163–5.57	~0.200– 6.400	0.42–28.0	0.89–11.0	1.2	0.295–1.84	~1.3–2.4	0.409–1.929
(mg N- NO <sub>3</sub> <sup>-</sup> /L)	0.10–0.51	0.00–7.79	~0.1–4.8	–	–	–	–	–	–
Sulphates (mg SO <sub>4</sub> <sup>2-</sup> /L)	143.18– 233.48	7.40–606.40	~200.0– 2700	31–25,000	782–12,000	296	148–1270	500–1200	–
Chlorides (mg Cl <sup>-</sup> /L)	15.20–56.92	16.60– 1099.0	~0.5–250 (1250)	300–8000	–	–	~2.2–3.0	–	–
Sodium (mg Na <sup>+</sup> /L)	8.20–23.90	5.80–55.90	–	~440–460	–	–	–	–	–
Calcium (mg Ca <sup>2+</sup> /L)	21.94–52.84	19.60–189.0	~0.20– 500.0	2.3–800	0.02–1120	67	–	–	10.15–29.23
Magnesium (mg Mg <sup>2+</sup> /L)	3.08–12.62	3.60–37.0	~5.0–160.0	0.077–120	115–3150	58	~4.2–5.8	–	13.82–53.33
Manganese (mg Mn/L)	0.024–0.200	0.000–0.310 1.064–6.317	~0.2–11.5	0.0002–150	0.041–81	–	~2.5	~0.001–0.37 (4.5)	0.0076–0.00961
Iron (mg Fe/L)	0.002–0.255	0.000–860	~0.2–195	0.0003– 2463	0.05–248	0.14	–	~0.001–0.30	0.138–0.502

Note: <sup>1</sup> range of average values.

3.4. The Evaluation of the Usability of Quarry Lake Water for Irrigation

The average pH of the water in the analysed quarry lakes did not exceed pH 8.0. However, periodically (typically in the summer) it exceeded pH 8.5, usually in the eutrophic quarry lakes Q3 and Q5. The average pH values met the requirements of the recommended Polish standards of the quality of water used in irrigation and were in the pH range recommended by the FAO (Table 5). However, the average pH value indicates medium restrictions in using water for drip irrigation due to the probability of clogging the nozzles



(Table 5). It should be noted that in 60% of the analysed water samples (usually in the summer), pH values above 8.0 were noted, mainly in quarry lakes Q2, Q3, Q5, and Q6. The water in the analysed quarry lakes is characterised by low and medium salination ( $EC_w < 0.5 \text{ mS} \times \text{cm}^{-1}$ ), and therefore does not require any restrictions in use connected with salination. Thus, it meets the requirements for usability in irrigation according to the FAO Guidelines and the standards that are applicable in Poland (Table 5). The value of the TDS index in the analysed quarry lakes does not exceed 450 mg/L, and therefore does not indicate the need to apply any restrictions connected with the risk of salination or restrictions in the use of water for drip irrigation resulting from the risk of clogging the nozzles (Table 5). The assessment of the usability of water for irrigation revealed a low sodium hazard in irrigation water based on SAR. However, the assessment of sodium hazard in irrigation water based on SAR and  $EC_w$  suggests severe restrictions in using water from Q6 for irrigation and slight to moderate restrictions in using the water from quarry lakes Q1–Q5 for irrigation. According to the FAO Guidelines, the sodium content points to severe restrictions on using the water from quarry lakes Q1–Q3 and Q5–Q6 for surface irrigation and slight to moderate restrictions on using the water from quarry lake Q4 for surface irrigation (Table 5) due to its potential toxicity for certain types of crops. However, neither restrictions are required for the use of water in sprinkler irrigation. The average concentrations of water quality parameters: BOD<sub>5</sub>, nitrates, sulphates, manganese, and iron meet the requirements and recommendations provided in the applicable Polish standards and the FAO Guidelines (Table 5). On the other hand, the concentration of iron and manganese in quarry lake Q1 and of manganese in quarry lake Q5 points to medium restrictions in using the water in drip irrigation due to the likelihood of clogging the drip nozzles (Table 5).

**Table 5.** Evaluation of the usability of quarry lake water for irrigation purposes (author B.J.).

Parameter	Q1		Q2		Q3		Q4		Q5		Q6	
	PL	FAO	PL	FAO	PL	FAO	PL	FAO	PL	FAO	PL	FAO
pH <sup>2,3</sup>	DM	DM	DM	DM	DM	DM	DM	DM	DM	DM	DM	DM
$EC_w$ <sup>1,3,4</sup>	[Green bar]											
SAR <sup>4</sup>	SH-L		SH-L		SH-L		SH-L		SH-L		SH-L	
$SAR/EC_w$ <sup>3,4</sup>	[Blue bar]		[Blue bar]		[Blue bar]		[Blue bar]		[Blue bar]		[Red bar]	
TDS <sup>1,3,4</sup>	DL	DL	DL	DL	DL	DL	DL	DL	DL	DL	DL	DL
BOD <sub>5</sub> <sup>2</sup>	[Green bar]											
Nitrates <sup>1,3,4</sup>	[Green bar]											
Sulphates <sup>2</sup>	[Green bar]											
Chlorides <sup>1,2,3,4</sup>	[Green bar]											
Sodium SU.I <sup>1,2,3,4</sup>	[Red bar]		[Red bar]		[Red bar]		[Blue bar]		[Red bar]		[Red bar]	
SPI	[Green bar]											
Manganese <sup>1,4</sup>	DM	DM	DL	DL	DL	DL	DL	DL	DM	DM	DL	DL
Iron <sup>1,4</sup>	DM	DM	DL	DL	DL	DL	DL	DL	DL	DL	DL	DL
Requirements of the standard PN-84/C-04635					Met				Failed		No guidelines available	
Degree of restriction on use water to irrigation			None		Slight to moderate				Severe		No guidelines available	

SU.I—Surface irrigation, SPI—Sprinkler irrigation

SH-L—low, SH-M—medium, SH-H—high, SH-VH—very high—the sodium hazard of irrigation water based on SAR [113].

Notes: PL—<sup>1</sup> Kaniszewski and Treder [116] or <sup>2</sup> PN-84/C-04635 [115]. FAO—<sup>3</sup> Ayers and Westcott [114] or <sup>4</sup> Saha et al. [113].

#### 4. Summary and Conclusions

The analysed quarry lakes were formed in inactive granite quarries, as a result of flooding, mainly with rainwater, surface runoff and underground discharge from the direct catchment of the quarries. They are characterised by relatively low surface areas (0.1–2.93 ha) and varied depth, although, considering the maximum depths of 4.3–28.4 m, they may be considered as relatively deep. The volume of water in the analysed reservoirs, determined based on bathymetric measurements, indicates that the volume of water retained in specific pits of inactive quarries is relatively low and falls into the range from 1.7 thousand m<sup>3</sup> to 122.7 thousand m<sup>3</sup>. The total volume of water retained in the analysed quarry lakes amounts to 307.8 thousand m<sup>3</sup>, which constitutes a significant element in the retention capacity balance of the water reservoirs, ponds, and Strzelin quarry lakes, particularly in those objects that are located in the catchment of the Oława River (10.6%).

The performed calculations of the volume of water retained in the quarry lake based on field bathymetric studies and geospatial analysis allowed for the verification of the volume of water determined with use of the algorithm [49]. For the Strzelin quarry lakes that are located in granite quarries which were closed about 20 years ago, it was proposed to reduce the volume of water calculated with use of the algorithm by 35.8%. As a result, the differences between the water volume calculated in this way and that obtained in field bathymetric measurements will decrease to approximately 7%.

Most of the analysed quarry lakes are located in agricultural or forest areas, but none of them are a source of water supply for agricultural irrigation. Taking the quarry lakes into account in the balance of reservoir water retention that is prepared by water authorities will enable us to include them in the water management programmes, the actions related to the development and renovation of the infrastructure for distributing water from quarry lakes to potential places of use. However, due to their location, the potential use of the analysed quarry lakes in water management will be mainly of local importance. The cost of building infrastructure to transport the water over longer distances, e.g., outside Strzelin County, may be too high and economically unjustified. The focus on the potential of the water retention possibilities offered by quarries and the good quality of water retained in quarry lakes should translate into the appropriate water management of quarries that are being shut down. This may be quite important, not only from the local aspect but also from the regional point of view, as, for example, Lower Silesia is home to dozens of active quarries as well as hundreds of inactive ones, some of which are flooded.

The quality of water in the analysed quarry lakes was similar to the parameters of natural lakes and unloaded artificial water reservoirs. At the same time, the water quality indicators were decidedly lower in comparison to those in most mine lakes, in particular acidic mining lakes. Most of the quality parameters in the analysed quarry lakes met the Polish and international requirements provided in the guidelines on the usability of water for irrigation.

The conducted research allowed the authors to formulate the following conclusions:

1. The total volume of water retained in the analysed quarry lakes (307.8 thousand m<sup>3</sup>), constitutes a significant element in the retention capacity balance of the water reservoirs, ponds, and Strzelin quarry lakes that are located in the catchment of the Oława River (10.6% of the total capacity).
2. The quarry lakes discussed in this study were characterised by values of water quality parameters that are similar to those of natural lakes. A major part of the quality parameters in the analysed quarry lakes met most of the Polish and international requirements provided in the guidelines on the usability of water for irrigation.
3. All quarry lakes were characterised by low sodium hazard of irrigation water based on SAR. However, quarry lakes show the assessment of sodium hazard of irrigation water based on SAR and  $EC_w$ , where water from quarry lakes Q1–Q5 should be subject to slight to moderate restrictions in the use for irrigation, and water from Q6 to severe restrictions in such use.

4. In terms of the assessment of potential toxicity, the noted sodium content points to no need to apply any restrictions in the use of the water from the analysed quarry lakes for sprinkler irrigation, and severe restriction on the use of water from quarry lakes Q1–Q3 and Q5–Q6 for surface irrigation, as well as slight to moderate restriction on the use of water from quarry lake Q4 for surface irrigation.
5. The concentrations of manganese and iron in lake Q1, manganese in Q5, and the pH values in Q1–Q6 point to medium restrictions in the use of water for drip irrigation, connected with the risk of clogging the drip nozzles.

## 5. Limitations

The conducted research allowed us to estimate the static water resources retained in the analysed open-mine pits. In order to determine their actual usability for agricultural irrigation, complete balance analyses are required that will allow the determination of the potential capacity and the principles of usage taking into consideration the rate of recreation of the retained water resources. A precise quantitative estimation will be possible if top-class measuring equipment is used, which will allow for the creation of 3D models of a higher level of precision and detail. The assessment of the hydrological and chemical parameters should be extended to include samples collected at various depths.

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