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Case Report

Concept and Implementation of Solutions Improving Water Relations in the Area of the Flooded Opencast Lignite Mine Kazimierz Północ in the East Wielkopolska Region (Central-West Poland)

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Abstract: Over a period of 30 years, the surface water level in the north-west of Konin, in the east of the Wielkopolska region, decreased by almost 6 m, resulting in a reduction of the surface area of the majority of nearby lakes, the disappearance of smaller water bodies and wetlands, and the drying out of streams draining the area. The causes of the decrease in the surface and groundwater level in the region are complex. They include both natural and anthropogenic factors, among others broad-scale mining activity. Based on knowledge of the hydrostructural composition of the analysed region and the functioning drainage system of opencast lignite mines, a concept was developed of a change in water supply to the flooded opencast lignite mine, Kazimierz Północ. The task of redirecting waters from the drainage of a nearby opencast mine, Józwin IIB, was implemented in 2020. Current observations and forecasts suggest that, owing to the applied solutions, the analysed opencast mine will be flooded in 2023, and not, as previously assumed, at the end of 2021. As a result, groundwater levels in the vicinity of the opencast mine as well as in lakes and rivers within the range of impact of the related depression cone will be restored faster, particularly in the Lake Powidzkie catchment. The objective of the study is to present stages of flooding of the former opencast lignite mine Kazimierz Północ, identify factors determining the process, and describe solutions accelerating it, with a simultaneous environmental impact assessment of the undertaken activities.

Keywords: post-mining water reservoir; mine drainage; water reclamation; management of water resources; water retention

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1. Introduction

The Powidzki Landscape Park in the subregion of the Gnieźnieńskie Lake District is not only known for its picturesque lakes [1,2]. It is also associated with the problem of the loss of surface water and groundwater [3,4], resulting from negative climate transformations (increase in evaporation, increasingly frequent periods with a small precipitation amount, snowless winters, prolongation of the growing season) [5], and human activity (excessive groundwater extraction in the region [6–9], reclamations accelerating water outflow, poor decisions in the scope of water management [10,11] or, finally, mining drainage conducted around the nearby opencast lignite mines) [12–14].

The phenomenon has long been observed in the area, as well as in the remaining parts of Wielkopolska and Kujawy, although it has particularly intensified over the last 30 years [15,16]. During that period, the water level in the surrounding lakes decreased by as much as several metres, and many smaller water bodies disappeared [2,3,16–18]. The loss of water resources in the region resulted in the disappearance of wetlands and the transformation of rivers into periodical streams. Groundwater levels were also considerably decreased. The loss of water resources is particularly evident in the eastern part of the Park, located in the zone of impact of the depression cone related to the nearby opencast lignite mine of Konin Brown Coal Mine (PAK KWB Konin) (flooded opencast mine Kazimierz Północ and operating opencast mine Jóźwin IIB). This region showed the greatest decrease in lake water level, reaching 6 metres in comparison to that in the 1980s [17,18]. As a result, most water bodies in the area became closed-drainage lakes, and an area of more than 250 km^2 defined as the catchment of the Ostrowo-Gopło Canal has been devoid of unitary outflow for more than 20 years [9]. In the zone of impact of the aforementioned depression cone, the level of the drained Miocene horizon and the connected horizon of the Wielkopolska fossil valley decreased within the Park by up to a dozen metres. The levels of the overlying interclay water horizons and the groundwater horizon also substantially decreased, particularly in the zone of privileged hydraulic contact, namely lake channels. The negative effect of the depression cone of the aforementioned post-mining water reservoirs also covered Lakes Powidzkie and Kosewskie, located to the west together with their catchments [3,16,18,19], as well as the western parts of Biskupia Struga, south of the post-mining water reservoirs. Such transformations also negatively affect tourist development in the region, which serves as one of the primary sources of income for the nearby communities.

Considering the natural resources of the study area as well as the interest of the local community and tourists visiting the region, activities were undertaken to counteract further water loss from the lakes of interest [1,12]. In a further perspective, the activities aimed at restoring their original water level [20,21]. The first stage involved a change of the system of water drainage from the opencast lignite mine Jóźwin IIB. Actually, most of the water was directed through canals to Struga Kleczewska and Rów Główny, supplying Biskupia Struga, and further to Lake Gosławskie. Some of the mining water was drained to the former opencast mine Kazimierz Północ, simultaneously supplied with groundwater from drained aquifers and precipitation.

The opencast mine commenced activity on 26 August 1992, when overburden removal began. Lignite was first excavated there on 25 October 1995. Before excavation, in October 1991, a drainage barrier was built around the mine. Excavation in the opencast mine was discontinued on 24 June 2011. A total of 48.45 Mt of lignite was removed from the mine during that time, and 348×10^6 m^3 of overburden was removed. From the moment of discontinuation of excavation, for a period of approximately two years, a dewatering pumping station operated until 11 March 2013. The drainage barrier around the opencast mine discontinued operation much earlier. Most of the barrier was liquidated in December 2005, i.e., when the opencast mine was still under exploitation. This was possible due to the direct vicinity of the opencast Jóźwin mine, the barrier of which functioned at the time; its range of operation covered the area of exploitation of the opencast mine Kazimierz Północ. The barrier north of the reservoir was liquidated last. The last two wells were liquidated in September 2007. From the moment of discontinuation of exploitation until the switching off of the floor pumping station, a technical reclamation of the opencast mine was conducted, and scarps and slopes of the post-mining water reservoir were formed with a gradient guaranteeing the preservation of their stability. Reclamation is currently under way with a view to flooding the excavation pit, primarily with waters from the drainage of the nearby opencast mine Jóźwin IIB, but also with groundwaters from drained aquifers, atmospheric precipitation, and waters supplied from the catchment area of the reservoir.

The method of water drainage and the approved volume of water from opencast mine Jóźwin II B that could be directed to the post-mining reservoir of Kazimierz Północ was regulated by a water law permit—by the authority of the Marshal of the Wielkopolska Voivodeship as of 27 April 2016 ref. DSR-II-1.7322.76.2015 [22].

In consideration of the fact that drainage of the opencast mine Jóźwin IIB will discontinue in a few years, at the end of 2019 a decision was made on a change of direction of water transport for the purpose of the faster filling of the excavation pit of the opencast mine Kazimierz Północ. In the middle of 2020, the pipeline transporting water to the new reservoir was redeveloped, allowing for the redirection of a major part of the mining water towards it. At the end of the same year, another pumping pipeline was added, permitting the redirection of twice as much water towards the developing reservoir. In May 2021, the water law permit was amended to allow for the redirecting of a greater part of water to the new post-mining reservoir Kazimierz Północ, by the authority of the Director of the Regional Water Management Authority in Poznań as of 25 May 2021 ref. PO.RUZ.4210.8.2021.OB.8 [23].

Considering the forecasted period of operation of the opencast mine Jóźwin IIB and limited groundwater supply to the new reservoir resulting from a decrease in pressure gradient, the complete filling of the reservoir is estimated for 2023 and not, as originally assumed, within a decade. This will result in the faster replenishment of groundwater in the vicinity of the new reservoir. Consequently, in a perspective of several years, this will contribute to the improvement of water relations in the catchments of Lakes Powidzkie and Kosewskie, and in the Biskupia Struga catchment [24,25]. In the future, it will permit the faster filling of the post-mining water reservoir in the opencast mine Jóźwin IIB.

The study objective was to present a change in the method of flooding of the Kazimierz Północ opencast lignite mine, and to determine the impact of faster filling of the emerging reservoir on the surrounding aquifer systems.

2. Materials and Methods

The study area is located in the eastern part of the Wielkopolska Voivodeship in the Kleczew Commune, Koniński poviat, approximately 90 km east of Poznań. According to the physico-geographical division of Poland by Kondracki [26], the area is located within the Gnieźnieńskie Lake District. Hydrographically, the area related to the opencast mine and its direct vicinity belongs to the catchment of Biskupia Struga and its two main tributaries: Struga Kleczewska and Rów Główny (Figure 1). Biskupia Struga drains the area eastwards, flowing into Lake Gosławskie, connected with other water bodies belonging to the summit level of the Ślesiński Canal that is connected to Warta, the largest tributary of the Oder River. A third order watershed runs north and west of the excavation pit. The areas on the western side are within the catchment of Lake Powidzkie, constituting the origin of Meszna, a right-bank tributary of Warta, and the area to the north-west is drained by tributaries of lakes located in the catchment of the Ostrowo-Gopło Canal (Figure 1), constituting a tributary of Lake Gopło. The study area is characterised by some of the lowest precipitation totals in Poland, and a very high evapotranspiration index. The analysis of nearby precipitation stations shows that the average precipitation from a multiannual period in the area oscillates around 500 mm year^{-1}, and in dry years it does not reach 300 mm/year (Figure 2, Table 1). Evaporation from free water surface over the last two decades has regularly exceeded 800 mm in the annual scale [16,18,27–29]. According to historical data [30] the snow cover usually persists for approximately 40 days, with an average thickness of 5–6 cm. In recent years, however, snow cover duration has not exceeded 20 days per year (data of the Institute of Meteorology and Water Management—National Research Institute—IMGW-PIB).

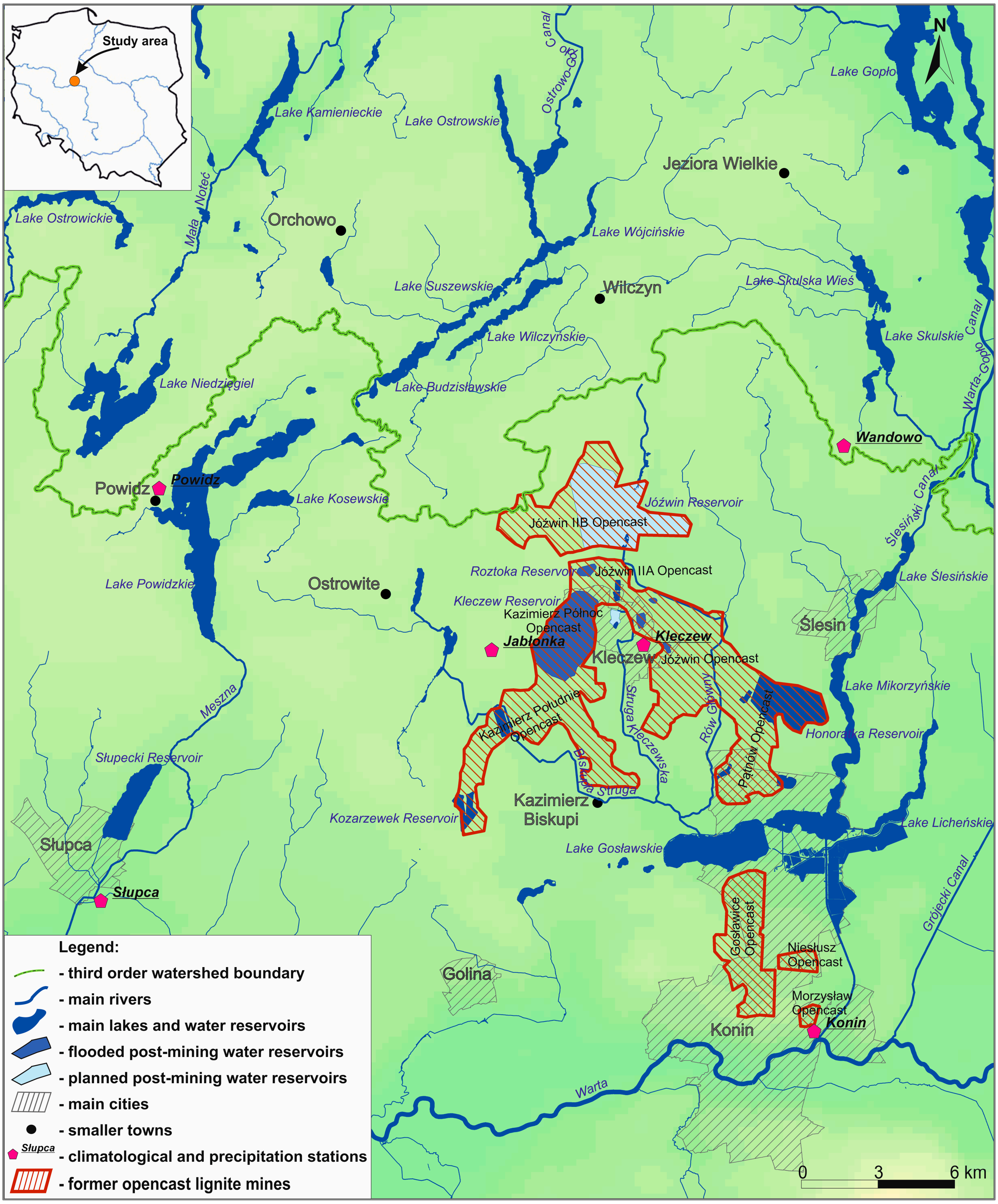

Figure 1. Location of the study area.

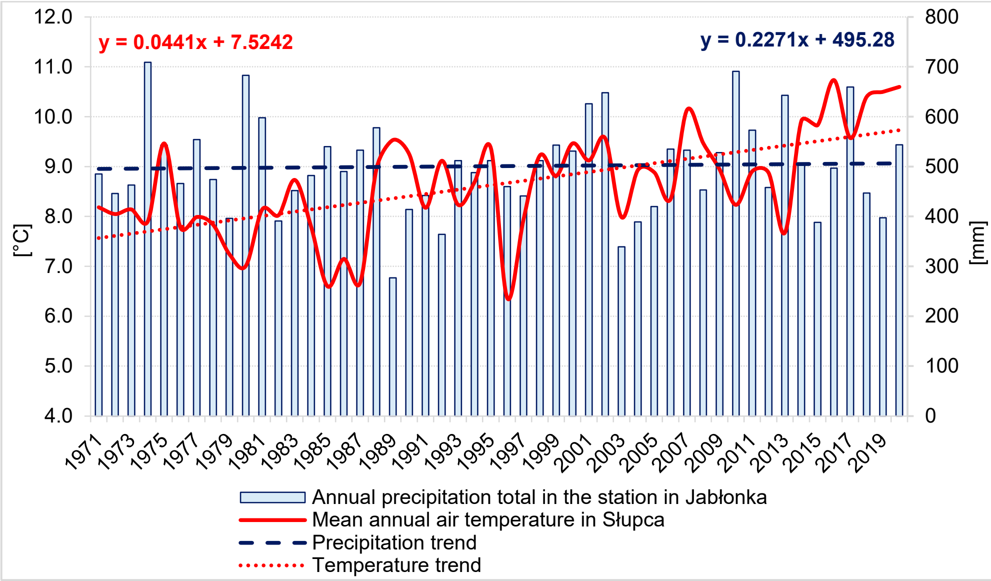

Figure 2. Climatograph illustrating changes in mean annual temperature and precipitation amount in the study area in the period 1971–2020 (based on the data of Institute of Meteorology and Water Management—National Research Institute—IMGW-PIB).

Table 1. Characteristic precipitation amounts in the study area for the years 1971–2020 (based on data of IMGW-PIB).

Precipitation Station	Jabłonka	Wandowo	Konin	Słupca	Powidz
Normal precipitation	501 mm	474 mm	545 mm	496 mm	532 mm
Minimum precipitation	277 mm	280 mm	329 mm	275 mm	302 mm
Maximum precipitation	709 mm	666 mm	901 mm	665 mm	745 mm
Trend	(+)	(+)	(+)	(+)	(+)

Note(s): (+) positive trend not statistically significant.

Broad-scale exploitation of lignite has been conducted in the study area since the 1950s. The initial works related to the exploitation of the local Pątnów deposit have shifted from the south-east towards the north-west, initially covering the opencast mine Gosławice neighbouring on Lake Gosławskie. In the following years, several opencast mines were launched and closed, namely Pątnów, Kazimierz Południe, Jóźwin I, Kazimierz Północ, Jóźwin IIAm, and Jóźwin IIB, that still functions today (however, not for longer than until the end of the first quarter of 2023). Such a direction of mining works determined the manner of draining mining waters used by drainage systems developed in earlier years. Mine waters were drained from the beginning of the functioning of the mine towards Lake Gosławskie, through canals, and by means of natural streams from the functioning excavation pits they were redirected to the largest western tributary of Lake Gosławskie, namely Biskupia Struga, and its two tributaries: Struga Kleczewska and Rów Główny (Figure 3). As a result, areas west of the opencast mines that remained within the range of the related depression cone were subject to deep drainage, and catchments on the east and south side were supplied by water from outside their natural alimentation zone. This led to drying in areas to the west, and contributed to the worsening of the possibilities of water supply to former opencast mines.

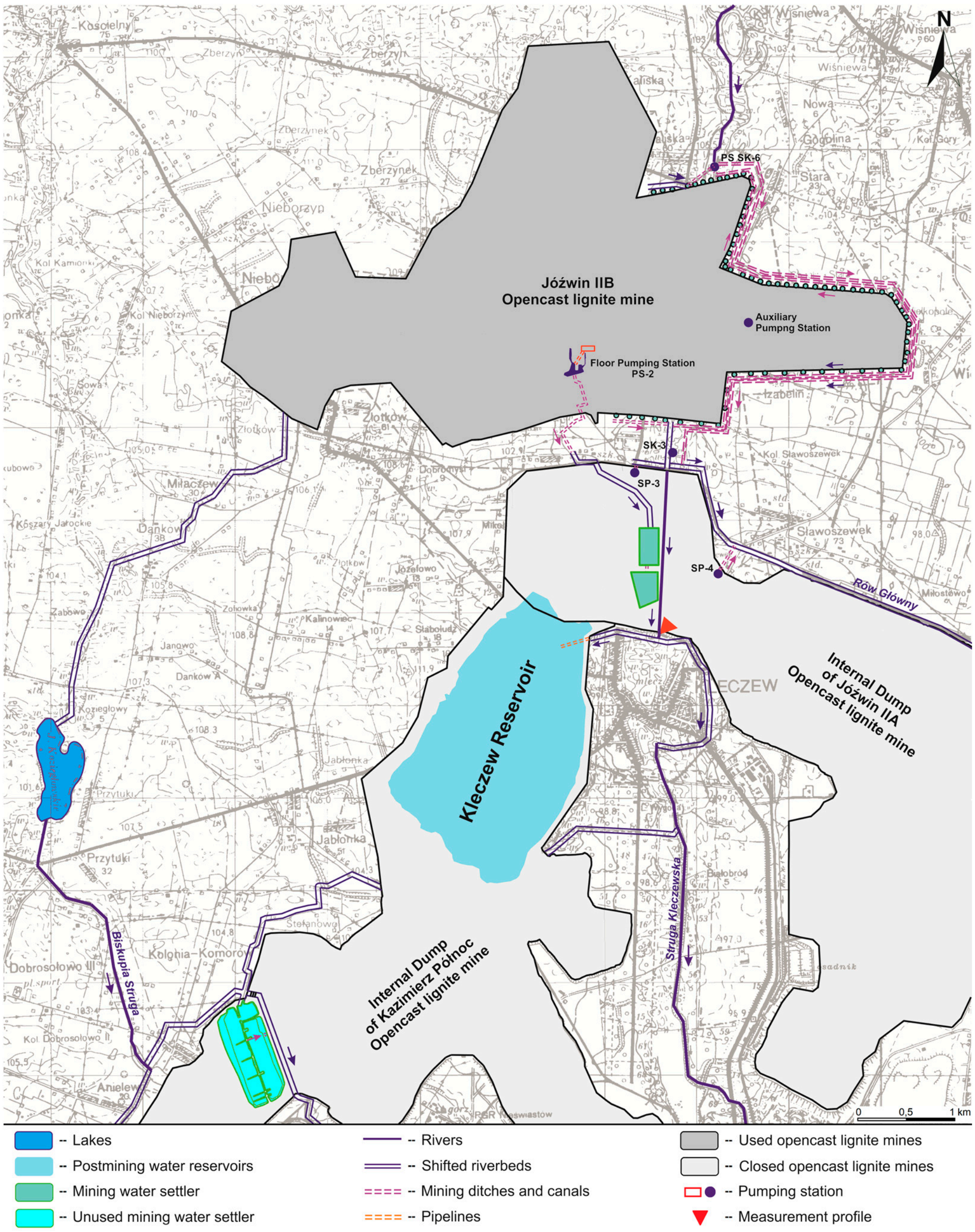

Figure 3. Diagram of drainage of opencast lignite mine Jóźwin IIB and supply to the former opencast mine Kazimierz Północ.

The article employed hydrological and meteorological data from the resource of the IMGW-PIB (Słupca station, Jabłonka station, Wandowo station, Konin station, Powidz station) and from PAK KWB Konin (Kleczew station). Data regarding the amount of water discharged from the drainage of opencast mine Jóźwin IIB were processed based on information included in Hydrological and Meteorological Yearbooks of PAK KWB Konin [31]. Hydrological and climatic comparisons and characteristics were presented in the scale of hydrological years, i.e., from 1 November of the preceding year to 31 October of the analysed year. Ordinates of the water surface provided in the paper referred to the Kronsztad ’86 system. The basic cartographic materials used in the paper included situational-height maps at a scale of 1:5000, raster topographic maps at a scale of 1:10,000, hydrographic maps at a scale of 1:50,000, and the digital Map of Hydrographic Division of Poland at a scale of 1:10,000. Satellite images used in the paper were obtained from websites Geoportal and GoogleEarthPro.

Desk studies involved analyses of the available data, used among other purposes for the hydrological–meteorological characteristics of the study area, and the assessment of the discharge of mine waters from the drainage of opencast mine Jóźwin IIB. Based on the available hydrological and meteorological data, situational-height maps, and analysis of historical and modern satellite images, the water balance of the flooded former opencast mine Kazimierz Północ was prepared. The water balance of the reservoir was based on a modified Penck–Oppokow equation [32], expressed in units of volume, usually in cubic metres or units of water column per reservoir surface area, usually in centimetres or millimetres. The equation is primarily used for lakes, and in its most developed form it is as follows [33,34]:

$$(P_r + I_r + I_s + I_{gr} + I_{gd}) - (E_r + O_r + O_{gr} + O_{gd}) = \Delta R_r \quad (1)$$

where:

P_r—precipitation on reservoir surface [mm; m^3],
I_r—river inflow [mm; m^3],
I_s—surface inflow [mm; m^3],
I_{gr}—groundwater inflow [mm; m^3],
I_{gd}—groundwater inflow from deeper aquifers [mm; m^3],
E_r—evaporation from reservoir surface [mm; m^3],
O_r—river outflow [mm; m^3],
O_{gr}—groundwater outflow [mm; m^3],
O_{gd}—groundwater outflow towards deeper aquifers [mm; m^3],
ΔR_r—reservoir retention during the balance period [mm; m^3].

In reality, studies only use an abbreviated version of the equation that omits groundwater elements which are difficult to estimate [33–36]. In its most common form, the equation treats groundwater components as a resultant of incoming and outgoing elements and water body retention, and they are presented as a value calculated from the remaining known elements.

Due to the character of the analysed reservoir, currently devoid of a natural river inflow and outflow, its surface supply primarily occurs through the discharge of mine water. The equation used in the calculations would, therefore, be as follows:

$$(P_r - E_r) + D_m + \Delta G = \Delta R_r \quad (2)$$

where:

P_r—precipitation on reservoir surface [mm; m^3],
E_r—evaporation from reservoir surface [mm; m^3],
D_m—discharge of mine waters [mm; m^3],
ΔG—resultant of groundwater inflow and outflow [mm; m^3],
ΔR_r—retention of the reservoir during the balance period [mm; m^3].

In the presented Equation (2), elements supplying the reservoir include precipitation on the reservoir surface and inflow of mine water. The outgoing element is evaporation from the reservoir surface. Another known parameter is retention of the reservoir determined based on the conducted geodesic measurements. Groundwater inflow and outflow are determined as the resultant of the remaining known parameters from the aforementioned equation.

The calculations were conducted on the scale of hydrological years, i.e., from 1 November of the preceding year to 31 October of the analysed year. The balance was expressed in units of height of water column [mm] per average surface of the reservoir in a given month, determined based on the available situational-height maps of the post-mining reservoir prepared before the commencement of its flooding and the average water level characteristic of a given month. The values were additionally converted to volume units [m^3].

Precipitation values were adopted based on meteorological data obtained from precipitation stations of IMGW-PIB and PAK KWB Konin in the study area, whereas the calculations considered corrected values. This approach appears justified, because each measurement instrument carries measurement error resulting from many factors, specified in detail by Byczkowski [37]. These include water losses in wetting the tank and internal part of the rain gauge receiver; precipitation water losses to evaporation; raindrops or snowflakes missing the rain gauge as a result of the disturbance of the wind field by the rain gauge, the so-called Jevons effect [38]; blowing snow in or out of the cylinder of the rain gauge, or finally the splashing of rain drops on the ring of the rain gauge. The application of the appropriate formulas permits minimising such errors, and approximating the measured values to the actual ones. This problem has been discussed by many authors [27,28,39–46]. It was, however, best presented in papers by employees of the Hydrological Station in Radzyń, who repeatedly compared differed methods of correction of precipitation measured at a height of 1 m in a Hellmann rain gauge, constituting the basic tool for the measurement of the precipitation amount in the observation network of IMGW-PIB and many other institutions. Their papers [41] permit the tracing the values of correction applied by other authors for different years and for different areas of Poland. The values change in a range of 18–55% in the winter half-year and 8–22% in the summer half-year. They evidently show high variability. Considering the relative proximity of location of the study area to that of the Hydrological Station in Radzyń, results of works conducted there were used. The calculations of corrected precipitation employed the following adjustments: 20% for winter months (XII–II), 15% for spring (III–V) and autumn months (IX–XI), and 10% for summer months (VI–VIII). The distribution of precipitation within the lake was calculated for fields with dimensions 100 × 100 m, interpolating the corrected results from precipitation stations located the nearest to the given water body.

Based on data from the synoptic station of IMGW-PIB in Koło and climatological stations in Słupca and Kleczew, values of evaporation from the water surface were calculated by means of the Iwanow [47] and Jaworski equations [42]. The equations are as follows:

Iwanow

$$E = 0.0018\ (25 + t)^2 \times (100 - f) \tag{3}$$

where:

E—monthly evaporation amount [mm],
t—mean monthly air temperature in a meteorological cage at a height of 2 m above ground level [°C],
f—mean monthly relative air humidity [%]

Jaworski

$$E_0 = 0.225\ (u_2 + 1)0.5 \times (e_{0j} - e) \tag{4}$$

where:

E_0—daily evaporation amount [mm],
u_2—mean daily wind speed at a height of 2 m above ground level [m/s],
e_{0j}—mean daily saturated water vapour pressure at surface temperature in the reservoir [hPa],
e—mean daily water vapour pressure in the air in a meteorological cage at a height of 2 m above ground level [hPa].

Based on papers by Kędziora [27,28], Rösler et al. [45,48], Nowak [29], and Nowak and Ptak [16], the paper employed the formula by Iwanow (3) and Jaworski (4). The calculations for the summer half-year used the formula by Jaworski and data on actual evaporation, measured on an evaporometer on Lake Sławskie at a distance of 155 km south-west of the study area, and Lake Sławianowskie 120 km north-west, belonging to the measurement network of IMGW-PIB. For the cold half-year, both formulas were applied, with a determination of the average from results obtained from both methods, multiplied by the correction factor for both formulas developed based on the comparison with data on actual evaporation from the nearest evaporometers. The temperature of the reservoir was determined based on randomly conducted measurements, and based on daily observations on deep Lake Powidzkie 15 km to the west, with morphometric parameters approximate to those of the analysed reservoir [49].

The inflow of mine water to the reservoir was calculated based on data presented in Hydrological and Meteorological Yearbooks of PAK KWB Konin with consideration of monthly hydrometric measurements conducted at the inlet of the canal supplying waters to pipelines and providing water supply to the Kleczew reservoir.

The water quality of the created reservoir was measured every two months in 2021, and in April and June 2022 by the Quality Research Centre, Water and Sewage Testing Laboratory in Konin. Two water samples were collected from the surface, from different parts of the reservoir, for the measurement of pH, oxygen concentration, BOD5, chlorite, sulphur, iron, total nitrogen and phosphorus, ammonium, conductivity, nitrite, organic nitrogen, ortophosphate, and manganese, by means of standard methods recommended by Polish regulations [50]. Physicochemical parameters of water quality are based on data of the PAK KWB Konin.

3. Results

The process of flooding of the opencast mine Kazimierz Północ commenced on 11 March 2013 at the moment of switching off the floor pumping station. At the first stage of flooding, the reservoir was filled with groundwater from drained aquifers and atmospheric precipitation. Water from the draining of opencast mine Jóźwin IIB in the period were discharged to Struga Kleczewska and Rów Główny, and their total amount reached approximately 9.04×10^7 m^3. The average monthly discharge of mine water during the time oscillated around 1.1–1.4 m^3 s^{-1}. This stage lasted until July 2016. In that period, the water level in the reservoir increased more than 20.0 m (from 35.08 m a.s.l. to 55.63 m a.s.l.) (Figure 4), i.e., by 20.55 m over a period of three years and four months. The average monthly value of the water level increase in the reservoir reached 0.51 m. It should be remembered that an increase in the water level in the new reservoir was accompanied by a decrease in the dynamics of that increase. This was determined by limited groundwater supply resulting from a decrease in the pressure gradient between the water level in the reservoir and the piezometric level of groundwater in the surrounding aquifers, as well as the increasing cubature of the reservoir with slopes shaped as terraces.

Considering a decrease in the inflow of groundwater, a decision was made on launching an additional water discharge from the drainage of the opencast mine Jóźwin IIB to the former opencast mine Kazimierz Północ that started operation in July 2016. Waters from deep drainage were still directed to the reconstructed Struga Kleczewska, where they were separated into the old channel of Struga Kleczewska and the new mining ditch, transitioning into a pipeline Φ = 1000 mm (over a section of 25 m), and further into a pipeline Φ = 500 mm (over a section of 500 m) until the water surface of the post-mining reservoir Kazimierz Północ. Waters from the surface drainage of the opencast mine Jóźwin IIB were directed to the post-mining reservoir Kazimierz Północ via the following route, ditch JZ10, mine water settlers, and further along the same route as waters from deep drainage, i.e., through a mining ditch transitioning into the aforementioned pipeline (Figures 3 and 5A,B). Such a supply system has been functioning since May 2020, i.e., for a period of three years and ten months. In that period, the ordinate of the water surface in the reservoir increased from a level of 55.63 m a.s.l. to 71.36 m a.s.l., i.e., by 15.73 m. The average monthly increase in water level reached 0.34 m, whereas during the last two years the value was equal to 0.20 m. The amount of water reaching the reservoir from the opencast mine Jóźwin IIB was 22.4 Mm^3 during that time, with total discharge from the opencast mine at a level of 155 Mm^3.

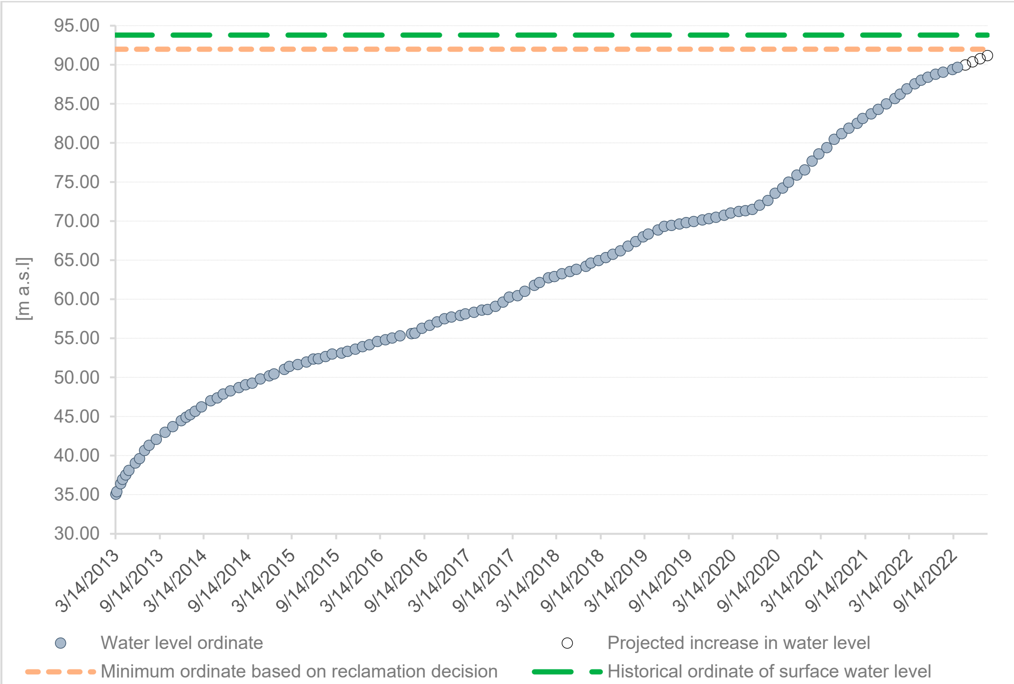

Figure 4. Changes in the location of the water level in the former opencast mine Kazimierz Północ (based on data of KWB Konin).

Figure 5. System supplying the post-mining reservoir Kleczew with mine waters from drainage of the opencast mine Jóźwin IIB: (**A**)—ditch supplying water, (**B**)—pipe supplying water in the period VII.2016-VI.2020 (Φ = 500 mm), (**C**)—pipe supplying water in the period VI.2020-XII.2020 (Φ = 1000 mm), (**D**)—pipes supplying water since XII.2020 (2 × Φ = 1000 mm).

Considering the fact that the rate of increase in the water level in the reservoir is declining, and drainage of the opencast mine Jóźwin IIB will be discontinued in several years, at the end of 2019 a decision was made to increase the amount of water to be directed to the developing post-mining reservoir. In May 2020, the first remodelling of the existing system supplying water from opencast mine Jóźwin IIB was performed. The remodelling involved the replacement of pipeline Φ = 500 mm with pipeline Φ = 900 mm over approximately half of the length of the pipeline, i.e., approximately 250 m (Figure 5C). Water discharge was launched again on 14 May 2020. To ensure the stability of the pipeline, the amount of discharged water was gradually increased—stoplogs were removed on the culvert gate valve under Toruńska Street that permits control of the volume of water inflowing from Struga Kleczewska towards the ditch supplying water to the post-mining reservoir Kazimierz Północ. At the end of June 2020, further measures were undertaken for the purpose of increasing the volume of water flow to the post-mining reservoir Kazimierz Północ. "Open work" was performed on the discharge pipe, and a valve was built on the culvert at the Kamińskiego Street that dammed water in Struga Kleczewska, forcing its faster flow towards the ditch supplying water to the developing reservoir. The implementation of the aforementioned works resulted in an increase in the water level in the ditch draining waters to the Kleczew reservoir, and increased filling of the discharge pipe to approximately 3/4 of its cross-section. This permitted supply to the reservoir of mine waters in a maximum amount of Q = 0.8 m^3/s, i.e., twice as high as in earlier years. As a result of these measures, water flow in the reservoir considerably accelerated and until December 2020 the water level ordinate in the reservoir increased from 71.36 m a.s.l. to 75.91 m a.s.l., i.e., by 4.55 m over a period of eight months. The average increase in water level reached 0.57 m. During the time, PAK KWB Konin applied for a change in the conditions of the current water law permit in the scope of increase in the acceptable amount of discharged waters from Struga Kleczewska through the mining ditch to the new post-mining water reservoir Kazimierz Północ to the amount of Q_s = 1.66 m^3/s, Q_h = 5 976 m^3/h, $Q_{śrd}$ = 143,424 m^3/d, O_r = 52,349,760 m^3/year (the decision was issued on 25 May 2021).

In December 2020, the supply system of the reservoir was remodelled again. The investment covered a change of parameters of the existing pipeline and the adding of a new pipeline. After remodelling, water is discharged to the post-mining reservoir Kazimierz Północ through two pipelines (Figure 5D) with the following parameters:

1. Φ = 1000 mm over a section of 25 m, further transitioning into pipeline Φ = 900 mm until the water surface of the reservoir,
2. Φ = 900 mm until the water level in the reservoir.

From the launch of the remodelled system until December 2021, i.e., over a period of one year, the water level ordinate in the reservoir increased from 75.91 m a.s.l. to 85.02 m a.s.l., i.e., by 9.11 m. The average monthly increase in water level during the period reached 0.76 m. Due to the rapidly increasing surface area of the post-mining reservoir, the pipelines supplying water are systematically shortened, and as of 17 October 2022 the length of each of them is 60 m. Over a period of 12 months from obtaining full efficiency, the system supplying mine waters to the post-mining reservoir Kazimierz Północ reached efficiency at a level of Q = 0.95 $m^3 s^{-1}$ (~30 Mm^3), with the total amount of water discharged in a given time from the opencast mine Jóźwin IIB averaging Q = 1.11 $m^3 s^{-1}$ (~35 Mm^3).

Analysis of the diagram of water level increase in the post-mining water reservoir Kazimierz Północ (Figure 4) shows that from the moment of launching the additional discharge of mine water from draining the opencast mine Jóźwin IIB, the process of filling the reservoir evidently accelerated. The substantial share of mine water in filling the new reservoir is visible in the analysis of its water balance for the last two years (Figure 6), during which the aforementioned remodels were implemented. It clearly shows that the inflow of mine water from the opencast mine Jóźwin IIB is dominant in comparison to other supply components. It accounts for a large majority of the increase in water level; however, only since May 2020, i.e., after increasing the pipeline capacity and reorganising the system supplying water to the reservoir. In 2021, after adding a second pipeline, the share became even larger, also translating into the faster filling of the reservoir despite its increasing surface area. Together with an increase in water level, a process not observed in earlier years occurs; namely, water outflow towards aquifers. The situation results from a fast increase in the water level in the reservoir in reference to the level of groundwater, particularly that drained by the drainage system of the opencast mine Jóźwin IIB. The situation particularly intensifies in periods with low precipitation, when the drained aquifers are not supplemented with infiltration waters (Figure 6).

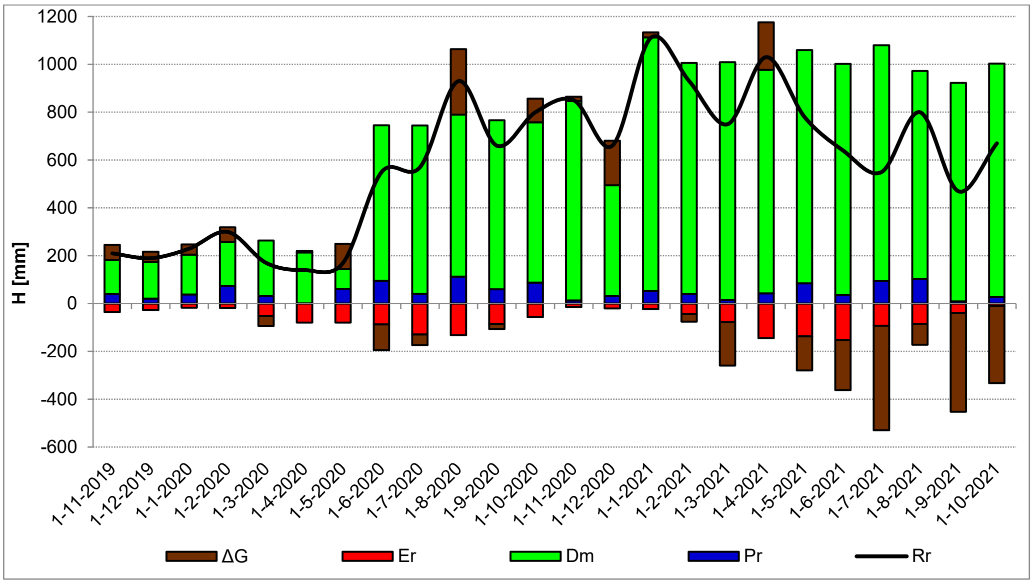

Figure 6. Water balance of the Kleczew reservoir at a monthly scale for the period 2020–2021 (ΔG—resultant of groundwater inflow and outflow, Er—evaporation from reservoir surface, D_m—discharge of mine waters, Pr—precipitation on reservoir surface, Rr—retention of the reservoir).

Water quality

Water quality in the Kleczew Reservoir was characterised by elevated concentrations of nutrients, particularly concentration of total nitrogen and total phosphorus, as well as high phosphates concentrations (Table 2), indicating eutrophic water quality. In the context of Polish regulations [50], concentrations of total phosphorus were four times higher than 0.05 mg P L^{1-}, i.e., the limit value characteristic of second classes (good ecological state) [50]. Total nitrogen was also higher than the limit value characteristic of the good ecological state of lakes (1.3 mg N L^{1-}). Water conductivity was typical of eutrophic lakes in the Wielkopolska region, with an average of 656 µS/cm. Water salinity based on chlorites and sulphur concentrations was low. Because this is the second year of the existence of the lake, its water quality is still under a strong impact of, among other factors, groundwater supply, the leaching of elements from the soil, and a turbulent type of water supply.

Table 2. Water quality in the Kleczew Reservoir (based on data of Konin Brown Coal Mine—PAK KWB Konin).

Parameter	Units	Mean	Min.	Max.
pH	-	8.3	8.2	8.4
temperature	°C	12.3	2.3	24.5
oxygen	mg O_2 L^-	11.4	8.7	13.5
total suspension	mg L^-	9.8	3.1	17.0
chlorides	mg Cl L^-	9.6	7.5	17.0
sulphur	mg S L^-	115	96	140
iron	Mg Fe L^-	0.150	0.021	0.358
BOD_5	mg O_2 L^-	1.72	1.76	1.77
COD-Cr	mg O_2 L^-	10.3	8.4	13.6
total nitrogen	mg N L^-	1.84	0.54	3.60
total phosphorus	mg P L^-	0.223	0.099	0.358
ammonium	mg N-NH_4^+ L^-	0.16	0.06	0.22
permanganate index	mg O_2 L^-	3.42	2.81	3.91
electrical conductivity	µS cm^-	656	579	756
solute concentration	mg L^-	421	374	456
nitrates	mg N-NO_3 L^-	0.20	0.08	0.30
nitrite	mg N-NO_2 L^-	0.008	0.000	0.015
phosphates	mg P-PO_4^{3-} L^-	0.225	0.02	0.84
Kjeldahl nitrogen	mg N L^-	1.16	0.50	2.04
manganese	mg Mg L^-	0.25	0.02	0.70
alkalinity	mg L^-	224.75	207	242.5

4. Discussion

The flooding of the post-mining water reservoir Kazimierz Północ commenced in March 2013 with the switching off of the floor pumping station draining the opencast mine. From then until the end of 2021, the water level in the reservoir increased by 50 m (Figure 4) and its surface area increased to ~407 ha (Figure 7). Over less than nine years, the reservoir was filled by 2/3 of its volume, reaching a volume of approximately 100 Mm^3. During this period, the reservoir was supplied with water from the drainage of the opencast mine Jóźwin IIB with a volume of approximately 59 Mm^3, primarily in 2020 and 2021 (Figure 8), when the remodelled system of supply of the reservoir already functioned. The measures undertaken in 2020 met the objective of accelerating the flooding of the post-mining water reservoir Kazimierz Północ.

The observation of the current rate of increase in the water level in the post-mining water reservoir Kazimierz Północ shows that the ordinate from the reclamation decision, namely 92.00 m a.s.l., treated as the minimum level of filling the reservoir, will be obtained under normal meteorological conditions in the first quarter of 2023 and not, as originally assumed, by 2030. The ordinate corresponding to the historical level of surface waters in the study area, namely 93.8 m a.s.l. (Figure 9), should be recorded in the reservoir in the third or fourth quarter of 2023. As a result, a water body will soon be developed with a surface area of approximately 530 ha, a volume of 145 Mm^3, and a maximum depth of 65.5 m.

With such parameters, this will be a water body second in terms of volume to the Jeziorsko reservoir in the Warta catchment, and the largest hydrological object of its type in Wielkopolska. It will also be the deepest water body in the area. In Wielkopolska Region, facing the greatest water deficits in the country [1,8,11,13–15,17,50–53], a new large water body will, therefore, be developed that will constitute a reservoir of easily available water for the surrounding industry and agriculture. The incorporation of the reservoir in the existing natural hydrographic network of the Gnieźnieńskie Lake District, combined with the system of regulation of water from the reservoir, will permit the capturing of water in the periods of its excess and its maintenance at a high level during hydrological lows. Most importantly, however, the fast filling of the post-mining reservoir Kazimierz Północ with water will allow for the reconstruction of the groundwater resources in the aquifers within the depression cone of that opencast mine. In combination with other works implemented in the area by national authorities in charge of water management [20], it offers a chance for the improvement of the hydrological conditions on neighbouring land of the area in a perspective of several years, particularly the restoration of wetlands and the recreation of the historical water levels in lakes in the Meszna catchment and in the wellhead zone of Biskupia Struga (Figure 1). It should also be remembered that the filled reservoir in the direct vicinity of the opencast mine Jóźwin IIB will also accelerate its flooding. In the context of this process, the continuous supply of the entire system will be required. The system will be prone to constant water deficit for years. We also hope that water quality in the reservoir shows values characteristic of mesotrophy, although the water contains elevated nutrient concentrations. Moreover, no negative effects of acid mine drainage are observed, which can be problematic in the case of the pollution of water under mine exploration [54,55].

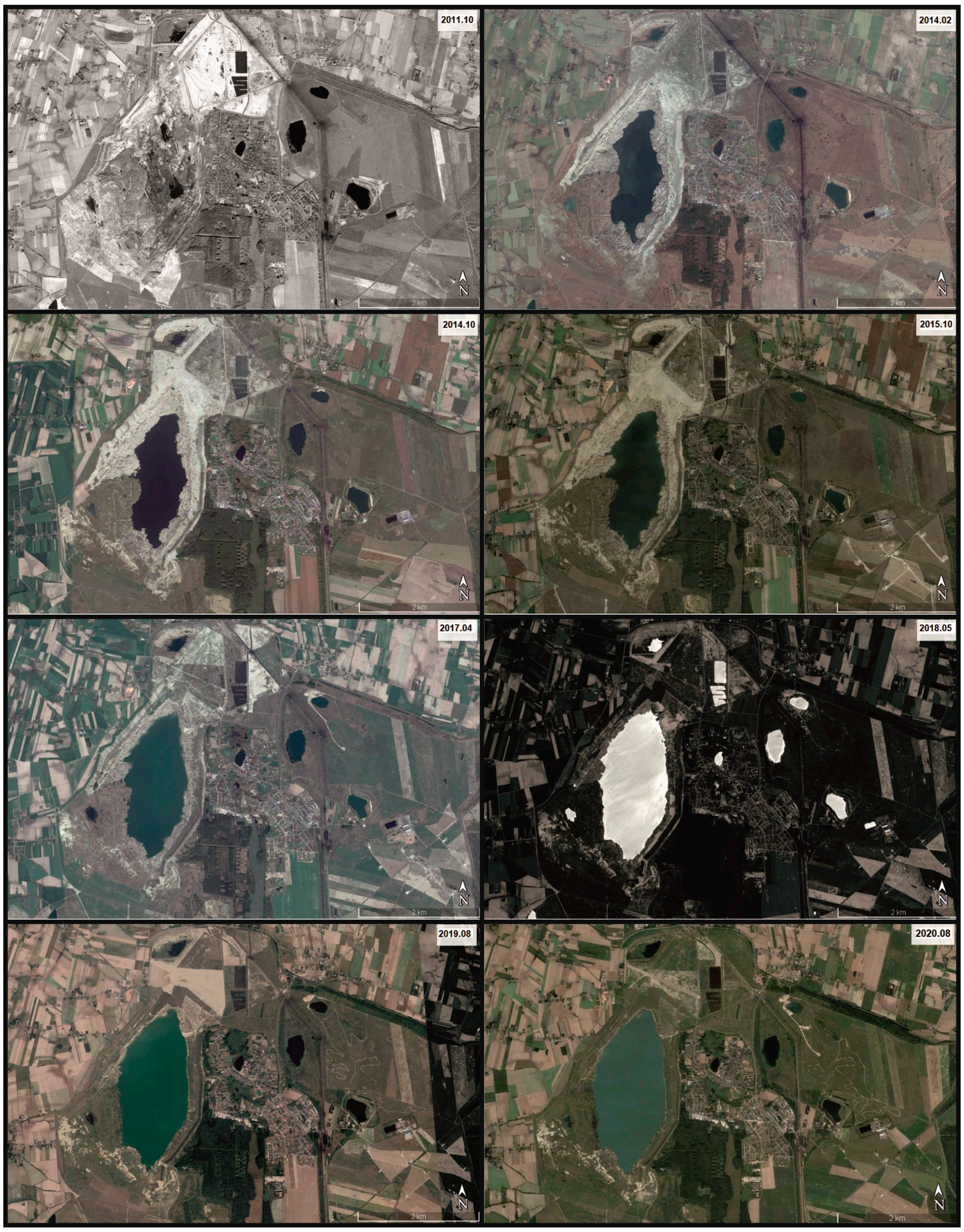

Figure 7. Illustration of changes in the surface area of the Kleczew reservoir emerging in the excavation after the Kazimierz Północ open pit mine in the years 2013–2020 (based on data obtained from GoogleEarthPro).

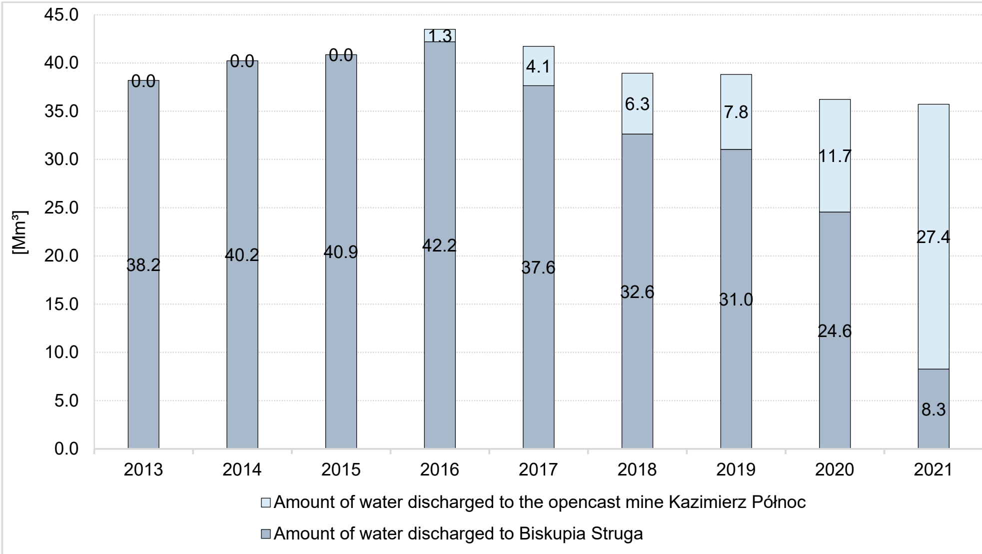

Figure 8. Amount of mine water discharged to the post-mining water reservoir Kazimierz Północ in comparison to water discharged from the opencast mine Jóźwin IIB (own elaboration based on data of PAK KWB Konin).

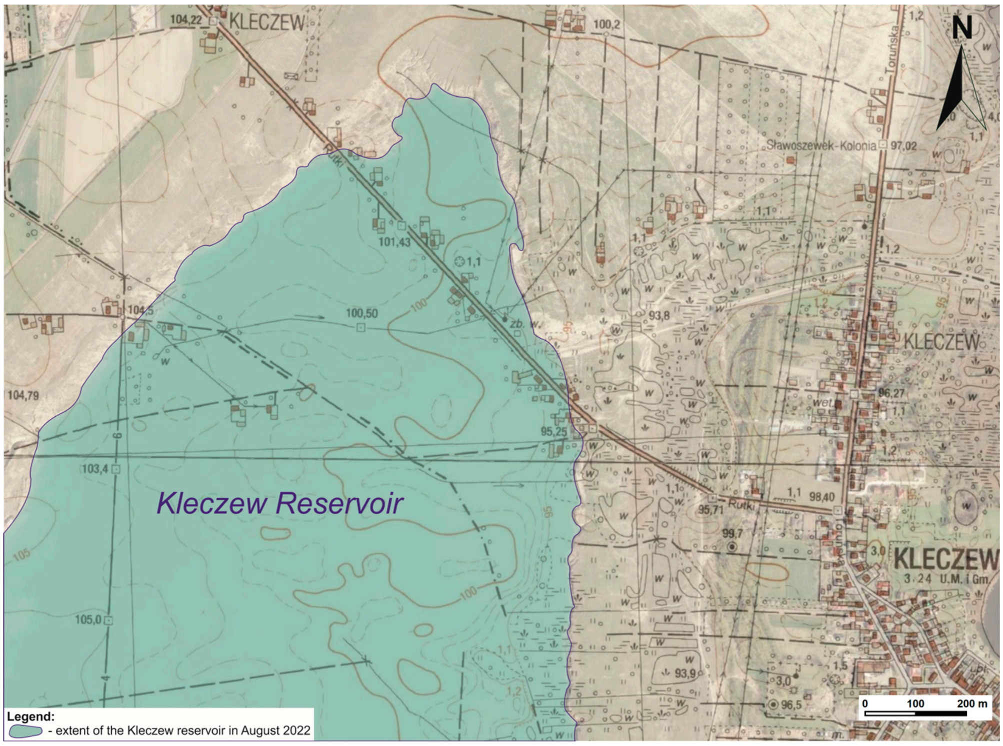

Figure 9. Range of the new post-mining water reservoir Kazimierz Północ in August 2020 on the background of a topographic map from the 1980s showing the historic ordinate of the surface water level (source: https://mapy.geoportal.gov.pl/imap/Imgp_2.html?gpmap=gp0, accessed on 20 July 2022).

It should also be remembered that the new post-mining water reservoir Kazimierz Północ within the surrounding area will initiate new habitat conditions for many plant and animal species. The observation of new post-mining water reservoirs suggests that it will show good or very good quality and high transparency of water, therefore providing the conditions for the development of rare, demanding fish species such as vendace (*Coregonus albula*) or whitefish (*Coregonus lavaretus*) [56]. The high capacity and diverse morphology of the reservoir bottom guarantees its habitation by diverse ichthyofauna. The water body with appropriately conducted fish stocking will become very attractive for anglers, and will offer a chance for the restoration of rare fish species inhabiting lakes.

The depth of the lake and water transparency will attract divers. The reservoir's surface area of several hundred hectares and favourable wind conditions will offer perfect conditions for the development of sailing, and particularly the increasingly popular kitesurfing. Local self-governments expect great possibilities of tourist development, and see a great recreational potential for residents. The new reservoir, together with the surrounding green belt, will also improve the microclimate of the study area and reduce dustiness in the nearby municipalities. It might eventually also be partly equipped with floating solar panels that, due to the vicinity of the existing energy engineering complex, would be easily connected to the transmission network, meeting the conditions of reception and further distribution.

5. Conclusions

Considering the increasing water deficits and the improvement of the natural environment in post-mining areas in east Wielkopolska, broad-scale measures were undertaken aimed at the fastest possible filling of post-mining reservoirs and at normalising hydrological relations in the area. Their first stage was a change in the system discharging waters from the drainage of the opencast mine Jóźwin IIB, aimed at an increase in the supply of the nearby reservoir forming in the opencast mine Kazimierz Północ, which closed in 2013. In earlier years, the majority of mine water was directed through ditches to Biskupia Struga, and further to Lake Gosławskie, i.e., outside of the catchment of the study area. During that time, a maximum of 0.4 m^3/s of mine water was discharged to the post-mining water reservoir Kazimierz Północ, which is simultaneously filled with groundwater from drained aquifers and precipitation. In consideration of the fact that the drainage of the opencast mine Jóźwin IIB will be discontinued in a few years, at the end of 2019 a decision was made on a change in the direction of water discharge for the purpose of the faster filling of the new reservoir. In the middle of 2020, the pipeline discharging waters to the new reservoir was remodelled, allowing for the redirection of water volume of up to 0.8 m^3 s s^{-1} towards it. As a result, the water level in the reservoir in the second half of the year began rising by an average of approximately 0.7 m/month (in comparison to 0.2 m $month^{-1}$ over the previous two years). In December 2020, another pipeline was added, permitting the redirection of up to 1.5 m^3 s^{-1} of mine water towards the Kleczew reservoir. This accelerated the process of filling the reservoir, and at the end of 2021, i.e., after one and a half years of functioning of the supply system, the reservoir reached approximately two thirds of its planned volume in comparison to the one third determined after six years of filling. Considering the target parameters of the reservoir, the forecasted time of functioning of the opencast mine Jóźwin IIB, and the limit on groundwater supply resulting from a decrease in the pressure gradient, it is estimated that its filling will occur in the first quarter of 2023, and not over a decade as originally assumed. It will cause the faster restoration of groundwater levels in the vicinity of the new reservoir, and consequently contribute to the improvement of water relations in nearby catchments within the range of the depression cone of the flooded opencast mine in a perspective covering the following several years.

The main conclusions are as follows:

1. Remodelling of the system of drainage of the opencast mine Jóźwin IIB and redirecting the majority of mine water to the post-mining water reservoir Kazimierz Północ in 2020 contributed to a considerable acceleration of flooding of the reservoir.
2. The maintenance of the rate of increase in the water level in the post-mining water reservoir Kazimierz Północ suggests that it will be completely filled in the third quarter of 2023, and not, as originally assumed, around 2030.
3. The emerging reservoir increasingly shows seasonal variability in the groundwater supply, depending on the precipitation amount and evaporation, as well as an increase in the share of groundwater drainage towards the nearby opencast lignite mine Jóźwin IIB.

4. Faster filling of the post-mining water reservoir Kazimierz Północ will contribute to the improvement of hydrological relations in the area, particularly in areas located to the west.
5. The new Kleczew reservoir, with a volume of 150 Mm^3, will improve the state of water resources in Wielkopolska, provide conditions for the development of valuable and rare plants and animals, and permit tourist development in the post-mining areas.

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