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A new antrhropogenic lake Kuźnica Warężyńska – thermal and oxygen conditions after 14 years of exploitation in terms of protection and restoration

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Abstract: The results of the first limnological studies of the Kuźnica Warężyńska anthropogenic reservoir, by flooding the sand mine excavation, in 2005, are presented. Measurements of water temperature and the concentration of oxygen dissolved in water were made every month, from April to December, every 1 meter deep from the surface to the bottom (22 m). Kuźnica Warężyńska anthropogenic lake was classified according to Olszewski and Patalas as dimictic, eumictic, stratified, stable, and extremely limnic. In terms of the share of the littoral zone in the total area, the reservoir is classified as grade II according to Dołgoff, where the pelagic zone is similar to the littoral zone. After 14 years of the reservoir's existence, during the summer stagnation period, the oxygen in the hypolimnion is completely depleted, from the 10th meter deep to the bottom, 22 m. The analysis of the vertical distribution of the regression coefficient for the relationship between water temperature and the concentration of dissolved oxygen in water indicates the influence of the oxygen-free groundwater supplying the reservoir as a factor that may, in addition to the decomposition of organic matter, initiate anaerobic processes in the bottom water layer of the reservoir. When circulation ceases, the bottom eruption of oxygen-depleted groundwater is, during the summer and winter stagnation, a factor that shapes the anaerobic environment in the bottom layers of water early, initiating the internal enrichment process. Hydrological conditions, morphometry and thermal-oxygen relations of the Kuźnica Warężyńska reservoir are favorable for undertaking technical measures – changing the method of draining water from the surface to the bottom – to protect the quality of water resources.

Introduction

Created in areas without natural lakes, anthropogenic limnic ecosystems constitute a great natural and economic value [Gierszewski 2018, Kostecki 2014, Rzętała 2008, Lossow 2000]. Limnic aquatic ecosystems created as a result of flooding the workings of exploited sand mine workings with water, which are not in fact dam reservoirs, Rzętała [Rzętała 2007] proposes to call them "anthropogenic lakes".

The importance and value of these reservoirs increase with the size of their surface area, volume and water retention capacity [Buhrer et all 2001]. The broadly understood "value of the reservoir" consists of its retention capacity, which minimizes the damage caused by flood conditions [Lossow 2000]. Water has value as a medium for municipal and industrial economy [Rzętała 2008]. The value of the reservoir is expressed through infrastructure and investments related to tourism and recreation. The presence of the reservoir increases the value of the areas surrounding the reservoir from the point of view of their development [Kostecki 2014] The condition for value indicators is good and durable, high quality water resources and good ecological condition of the ecosystem. [Kajak 1998].

The basic factors determining the ecological state of the reservoir include thermal and oxygen relations [Biedka 2014, Dunalska et all 2012, Dobiesz et all 2009]. Water temperature is the main physical factor influencing the course of metabolic processes inside reservoirs in aquatic ecosystems [Mc Callum et all 2012, Marszelewski et all 2006, Kostecki 1994]. Insolation and air temperature increase water temperature and divide water masses into thermally differentiated layers. Thermal stratification affects the concentration and distribution of oxygen in water [Olszewski 1959, Patalas 1960]. The second, most important element determining the way the lake functions is oxygen dissolved in water. There are strong relationships between the themperature thermals of water masses and the concentration of oxygen dissolved in water [Dobiesz & Lester 2009; Kvambekk & Melvold 2010].

The oxygen content in water, from the point of view of the functioning of the limnic ecosystem, is the most important indicator of water quality [Dunalska 2003, Garbacz et all 2018]. The oxygen concentration in lake water depends on climatic conditions [Zhang 2015, Adrian et all 2009], morphometric conditions, on factors related to water trophies and pollution, and on the intensity of biological processes [Kintisch 2015, Mesyasz et al. 2015, Pełechata et al. 2015, Swinton et al. 2015]. In lakes, oxygen is consumed in the processes of organic matter oxidation, therefore in situations where they are characterized by a high degree of trophy, its deficiencies may occur [Biedka 2013, Terasma et all 2006]. As the water temperature rises, the solubility of oxygen in water decreases. In limnic and stratifying ecosystems, in the summer, oxygen deficiencies in the hypolimnion are observed, as well as strong oxygenation of water in the epilimnion in midday hours and the lack of oxygen in the epilimnion in early morning hours, which is the cause of the phenomenon of choking that threatens higher animal organisms [Kajak 1998, Kostecki 2014a]. Due to the role of oxygen dissolved in water in the life of aquatic organisms, lowering its content below 20–30% of saturation causes disturbances in the biocenosis [Kajak 1998, Patalas 1960].

The observed climatic changes, especially the successive increase in air temperature, affect the changes in the temperature of lake waters, having consequences in their functioning [Adrian et all 2009, Skowron 2008] The more and more frequent lack of ice cover and the shortening of the period of its occurrence, result in the lack of stagnation in winter and an extension of the autumn and spring circulation [Kostecki 2013]. In turn, high air temperatures in summer accelerate and intensify thermal-oxygen stratification [Jańczak et all 2006, Skowron 2008, Kostecki 1994] The content of dissolved oxygen in epilimnion is subject to large daily fluctuations. Depending on the trophic level of the reservoir, in particular on the phosphorus abundance, the photosynthesis process results in water saturation with oxygen, which may significantly exceed 100% of the theoretical saturation. In midday hours, the values of saturation from 140% to 200% were recorded. On the other hand, in aphotic conditions (at night), intense phytoplankton respiration may cause rapid drops in oxygen concentration in the epilimnion [Dobiesz et all 2009, Marszelewski et all 2006].

Anthropogenic limnic ecosystems are particularly vulnerable to degradation due to contamination with organic substances introduced into the water of streams feeding them [Kostecki 2014, Rzętała 2007]. Oxygen deficits in the bottom layers of water, in stratifying reservoirs, trigger the process of phosphorus release from bottom sediments, increasing the eutrophication of the lake [Biedka 2014, Lossow 2000]. Due to the role of temperature and oxygen concentration in lake water determining the efficiency of the ecosystem, there is a need for systematic observations, especially of newly emerging anthropogenic ecosystems, in order to better understand the processes taking place [Biedka 2013, Dunalska et all 2012].

The Silesian Voivodeship is the most industrialized region of Poland. This area is strongly transformed as a result of industrial anthropopression [Kostecki 2014, Rzętała 2008]. There is not a single natural limnic ecosystem in this area. There are only water reservoirs of anthropogenic origin (dam reservoirs, flooded sand pits, hollows in the areas of mining damage). Large reservoirs, dams and those created in the post-sand workings, are located on the outskirts of the industrial region, while the reservoirs created in areas settled as a result of mining damage, in its central part [Kostecki 2014]. Due to small number of limnic ecosystems, each newly created water reservoir is a valuable natural and economic element [Kostecki 2001, Rzętała 2007].

One of the most burdensome forms of anthropopressure is the environmental impact of mining, underground and surface mining industries. Exploitation of mineral deposits causes effects in the form of transformations of the earth's surface. Typical forms of transformation are excavations of sand, gravel and clay mines, and sinkholes in the areas of the so-called "mining damage" resulting from the surface exploitation of minerals. [Rzętała 2008]. As a result of the depletion of sand deposits in the surface system, depressions are created, often of a large area and depth [Kostecki 2014, 2014a]. As soon as the deposit is exhausted, the resulting basin is filled with water, or a nearby watercourse, and with groundwater [Rzętała 2008, Kostecki 2014]. Due to environmental conditions, in highly industrialized areas, surface waters, and especially limnic ecosystems, are exposed to factors causing their rapid degradation [Dunalska et all 2012, Kostecki 2001]. This is especially true of cases when the water of a watercourse being a receiver of saline mine water, industrial, municipal or rainfall wastewater [Pistelok 2016, Rzętała 2007] is used to fill the excavation.

The creation of anthropogenic limnic ecosystems (also called "water remediation"), is one of the methods of solving problems related to surface transformations as a result of human economic activity, which is deeply justified in the conditions of increasing water deficit [Kostecki 2014]. For this reason, anthropogenic limnic ecosystems should be under systemic, administrative and technical protection.

This work was carried out as a supplementary part of the statutory activity of the Department of Water Protection and Water Management, Institute of Environmental Engineering of the Polish Academy of Sciences in Zabrze, Poland. The aim of this study was to describe the formation of thermal and oxygen relations of the Kuźnica Warężyńska water reservoir as elements showing the current state, and the resistance of the anthropogenic limnic ecosystem to the impact of human pressure, 14 years after its creation. The results obtained are the first in the history of this reservoir. They constitute the background for other studies and a frame of reference in terms of temporal changes.

Study area

The object of the research is the reservoir of the same name Kuźnica Warężyńska (Pogoria IV), created in 2005 as part of the water reclamation of the sand mine excavation "Kuźnica Warężyńska". Exploitation of the backfill sand mine has been carried out since 1972. The process of filling the reservoir began in 2002, when the groundwater flooding the excavation was no longer pumped into the Przemsza River and the first increase in water was recorded in the northern part of the excavation. The tank was put into operation in August 2005. It was included in the system of Przeczyce and Pogoria III reservoirs, creating a set of retention reservoirs enabling the regulation of the water level both during floods and periods of water shortage. The reservoir ensures an inviolable flow in the Czarna Przemsza River and flood protection of the river valley covering the cities of Będzin, Sosnowiec, Mysłowice and Jaworzno. It is the youngest anthropogenic lake in Poland. The limnological research carried out as part of the statutory topic of the IPIS PAS in Zabrze provided the first and, so far, the only results describing the water quality of this ecosystem in the history of this reservoir. Kuźnica Warężyńska reservoir is located in the commune of Dąbrowa Górnicza and Wojkowice Kościelne (commune of Siewierz) in the Silesian Voivodeship. It is located in Kotlina Dąbrowska (Dąbrowska Valley) in Silesian Upland.

Morphometric conditions are an important element of the lake ecosystem functioning [Olszewski 1959, Kajak 1998]. The presented profiles (Figs. 2, 3, 4, and 5) of the tank depth show the longitudinal asymmetry of the depth. There is a gutter shape of the reservoir bowl, deep in the northern part, and wide and shallow southern part. These two parts have a similar area, respectively, the northern part – 263 ha and southern part – 297 ha. However, they differ in volume. The northern part has a volume of 44.4 million m^3, and the southern part – 7.4 million m^3.

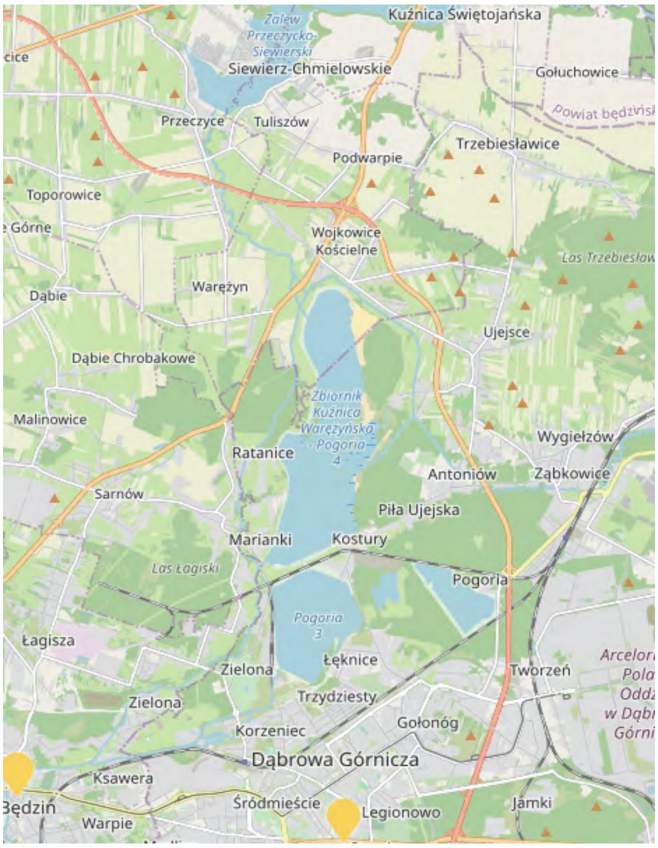


Fig. 1. Location of Kuźnica Warężyńska Lake

Table 1. Morphometric characteristics of the Kuźnica Warężyńska Lake

Indicator	Value	Sources
The catchment area of the Czarna Przemsza River to the water gauge in Kuźnica Podleśna	680 km^2	Own calculations
Lake ares	560 ha	RZGW Gliwice
Lake capacity	51,6mln m^3	RZGW Gliwice
Maksimum depth	23,6 m	Own calculations
Average depth	9,21 m	Own calculations
The lenght of the coastline	13 km	RZGW Gliwice
Coast line development factor	1,55	Own calculations
The lenght of the lake	5425 m	Own calculations
The width of tle lake	1750 m	Own calculations
Average width	1150 m	Own calculations
Elongation ratio	4,7	Own calculations
Island indicator	0,015	Own calculations
Total area of the islands	8,35 ha	Own calculations
Schindler’a coefficient	13,2	Own calculations
Ohle.s coefficient	121,4	Own calculations
Area of the northern basin	263 ha	Own calculations
Area of the southern basin	297 ha	Own calculations
Northern part area share	47%	Own calculations
Southner part area share	43%	Own calculations
Capacity of the northern part	44,4 millions m^3	Own calculations
Capacity of the southner part	7,4 millions m^3	Own calculations
Northern part volume fraction	86%	Own calculations
Southner part volume fraction	14%	Own calculations

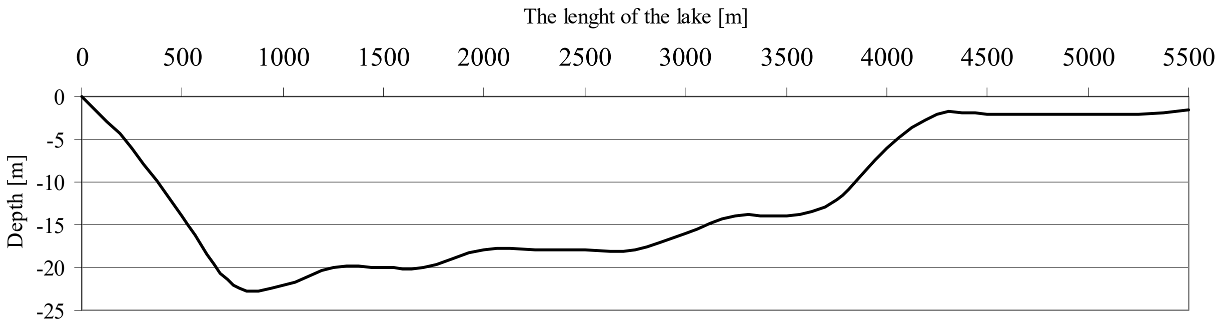


Fig. 2. Longitudinal depth profile of Kuźnica Warężyńska lake – author's own measurements

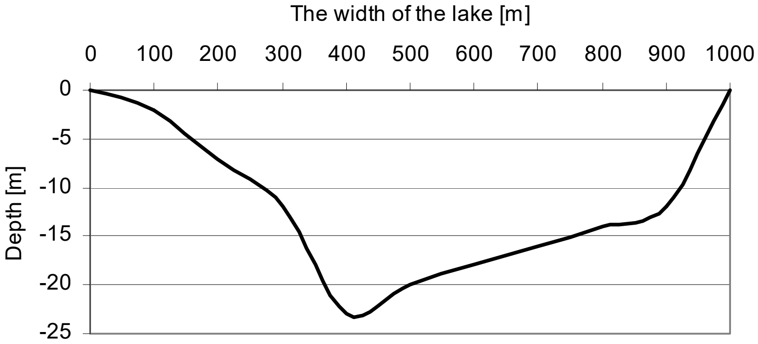


Fig. 3. Transverse depth profile of the Kuźnica Warężyńska lake, in the first kilometer of the large axis

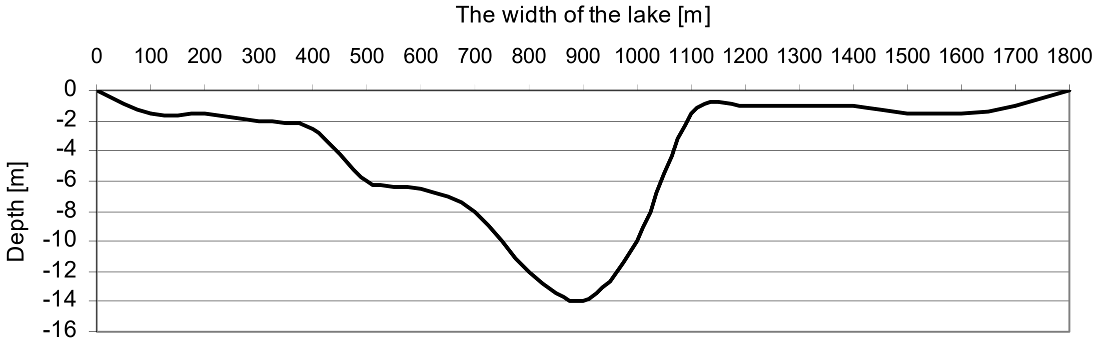


Fig. 4. Transverse depth profile of the Kuźnica Warężyńska lake, in the fifth kilometer of the large axis

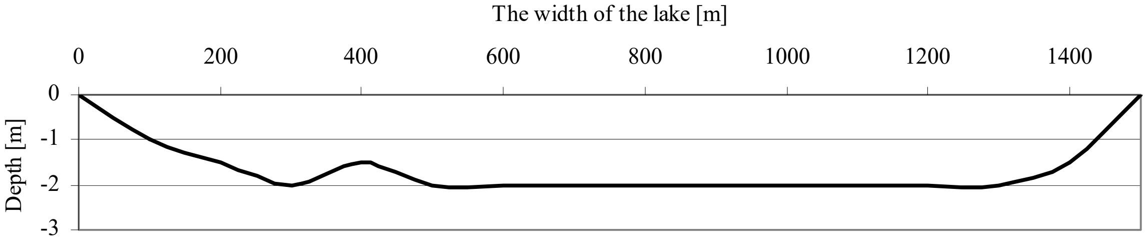


Fig. 5. Transverse depth profile of the Kuźnica Warężyńska reservoir, in the seventh kilometer of the large axis

Material and methods

Temperature and oxygen concentration and saturation were measured nine times, at monthly intervals, from April to December in 2019, at a depth of 22.5 m. in the northern part of the reservoir, in a vertical profile, from the surface to the bottom, every 1m deep (Fig. 6). The water temperature, the concentration of oxygen dissolved in water and the water oxygen saturation were measured with the CX-401 multifunction meter ("Elmetron" company in Zabrze). Measurements were made in situ, with a membrane electrode on a long (25 m) cable, with a temperature sensor and atmospheric pressure compensation.

Morphometric indicators were determined by planimetric map of the reservoir in the scale of 1: 25000. The given values may change over the years and with the stabilization of the lake shores. For the analysis of oxygen ratios in the vertical profile, a rectilinear relationship between the water temperature and the solubility of oxygen in water was used. In the absence of factors disturbing this relationship, this principle would be maintained. In lakes, this dependence overlaps with the processes inside reservoirs, in particular the process of primary production (photosynthesis), and aerobic and anaerobic metabolic processes, to a different extent for different depths. The author assumed that the influence of these processes can be demonstrated by differences between the theoretical value of the regression coefficient for oxygen solubility in water, and the values calculated for individual levels of the water column depth. The values of the R^2 and r-Pearson correlation coefficient calculated for the vertical profile are shown in Fig. 10.

Results and Discussion

Temperature

The highest values of epilimnion temperatures are marked in red. Thermocline temperatures are marked in yellow. The occurrence of homothermia of water masses is marked in blue. In spring, at the end of the second decade of April, homothermia of the water masses of the reservoir was recorded. The water temperature of the surface layer was 8.1°C and the water temperature above the bottom was 7.3°C. The division of the reservoir water masses into thermally differentiated layers occurred from May to the end of October. For the first time a thermocline with a thickness of 1 meter and a gradient of 1.4°C/m, between 4 and 5 meters deep, was recorded in the third decade of May. Above there was an epilimnion with a thickness of 4 meters and a temperature of 15.6°C÷15.3°C. During the summer stagnation, the epilimnion thickness gradually increased from 4 meters in May, to 5 meters in June and July, and then to 6 meters at the end of August. Due to the increase in air temperature from April (10°C) to June (33°C), in the third decade of June, the temperature of an epilimnion with a thickness of 5 meters reached 25.7°C. Until the end of August, the temperature of the surface layer of water was 24.8°C in July and 24.6°C in the last days of August. The temperature of the lower edge of the epilimnion was 24.4°C in June, 23.2°C in July and 22.9°C in August. The drop in air temperature since the end of August caused the upper water layers to cool down, which increased the epilimnion's range to 10 meters with its simultaneous cooling to 17°C at the surface and 16.7°C at the 10th meter depth. A further drop in water temperature caused the epilimnion to thicken to a depth of 12 meters in the last days of October. At that time, the temperature of the epilimnion was 13.2°C at the surface and 13.4°C at the 12th meter of depth. Within 30 days, the temperature of the epilimnion decreased from over 24°C in August to 16.9°C in September. From May to the end of October, the upper edge of the thermocline decreased systematically from 4 meters in May to 12 meters in October. In May the thickness of the metalimnion between the 4th and 5th meters of depth was 1 meter. In June, the thermal jump layer increased in thickness and occurred between 5 and 10 meters deep. The temperature of the upper level of the thermocline was at that time 23.7°C and the lower level 12.2°C, so the total gradient of the thermocline was 11.7°C, and the maximum gradient of 5.4°C/m was recorded between the 5th and 6th meter depth. At the end of July, the metalimnion stretched between the 5th and 12th meters, and in August between the 6th and 15th meters of depth. From May to the end of October, the lower edge of the thermocline lowered from 5 meters in May to 12 meters in October. From May to October, the total thermocline gradients were 1.4°C, 11.7°C, 11.9°C, 9.3°C, 6.2°C, and 3.4°C, respectively. In the period from April to the end of October, the water temperature of the hypolimnion was from 7.7°C to 8.2°C above the bottom and from 8.4°C to 9.4°C in the water layer below the thermocline, at a depth of 9 m. The temperature of the hypolimnion from 7.3°C to 8.2°C, from April to the end of October, can be considered average [19] The presented (Fig. 7) course of temperature changes shows a strong thermal stratification of water masses.

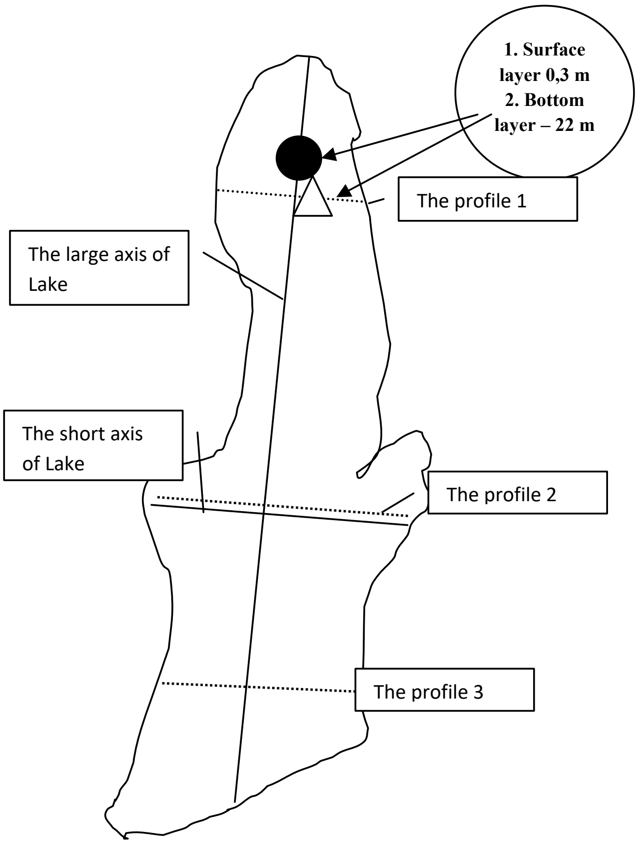


Fig. 6. The stand for measuring temperature and oxygen concentration in the water of the Kuźnica Warężyńska reservoir

Oxygen concentration in water

In the case of dissolved oxygen in water, the oxycline layer is marked in yellow. The presence of oxygen deficiency in the hypolimnion is marked with the gray scale (Table 3). The first symptoms of oxygen depletion in the bottom layer of water were found in the third decade of May. In late June, the appearance of oxycline was recorded between 11 and 14 meters deep. The total oxycline gradient was 3.2 mgO$_2$. At that time, the onset of oxygen deficiency in the hypolimnion was observed. The complete absence of oxygen in the three-meter-high layer of water above the bottom was found at the end of July. At that time, oxycline comprised a 6-meter stretch of water between the 6th and 12th meters of depth. Its overall gradient was 9.1 mgO$_2$. An additional oxycline with a gradient of 1.5 mgO$_2$ appeared between the 19th and 20th

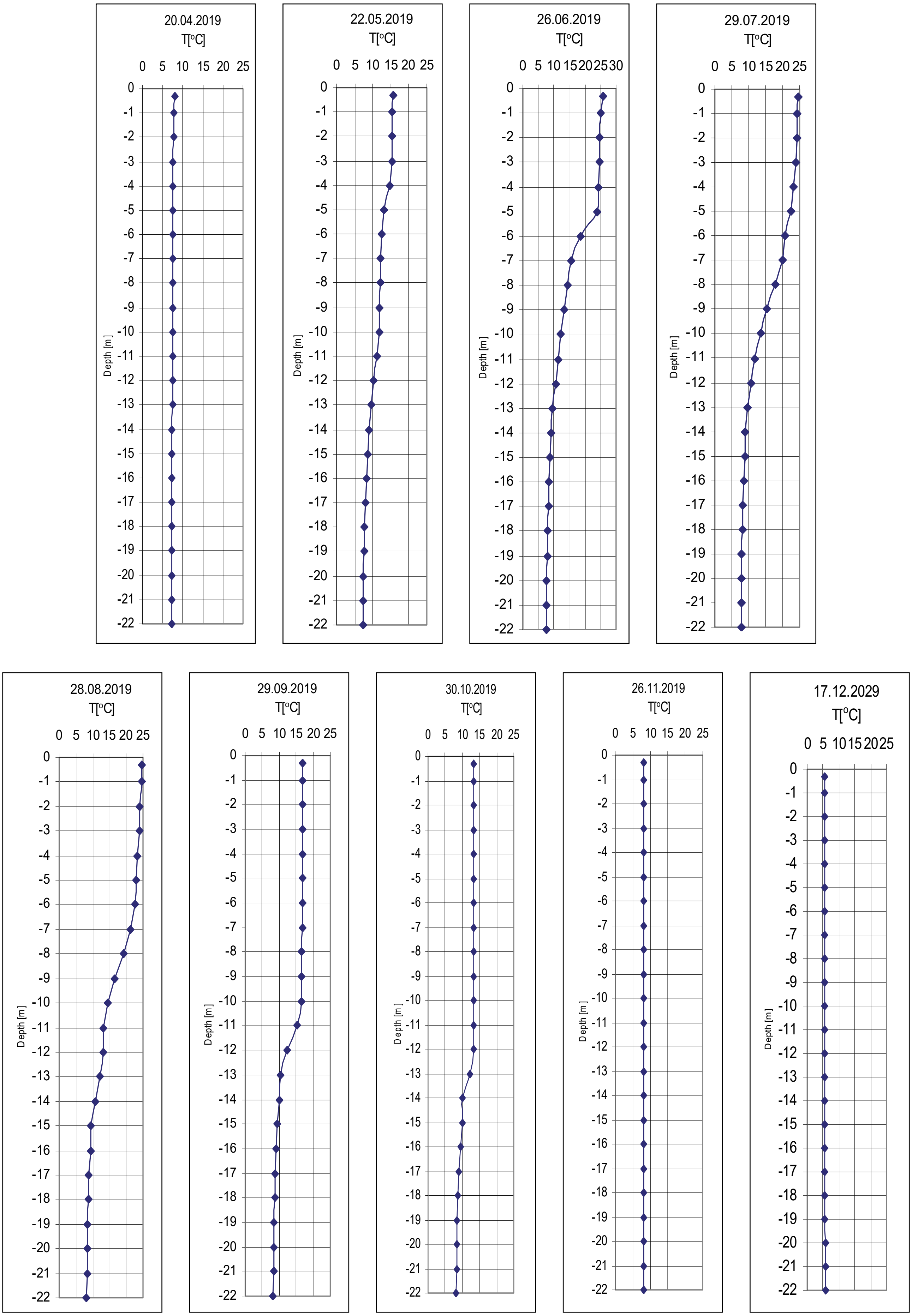


Fig. 7. Temperature profiles in the Kuźnica Warężyńska lake

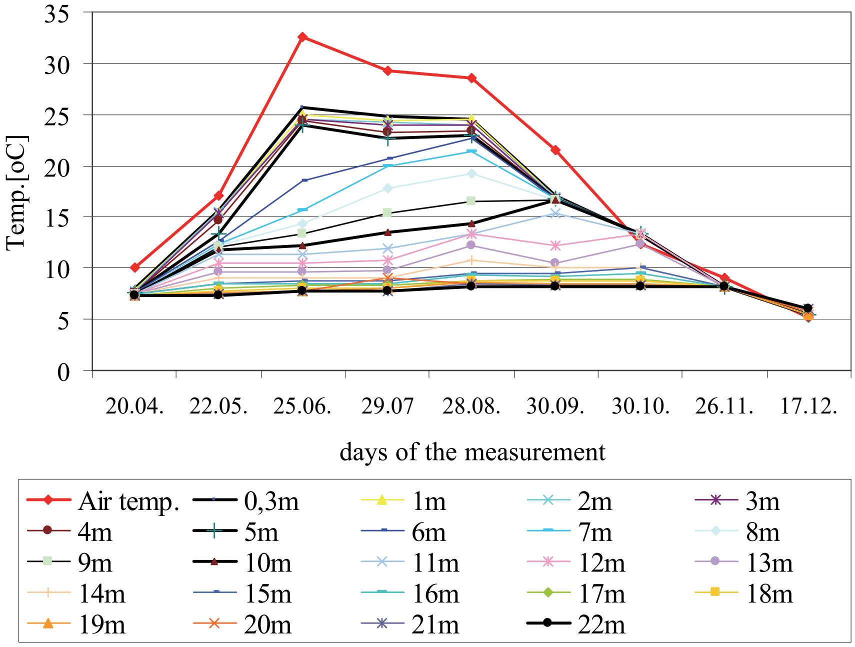


Fig. 8. Water temperature of the KUźnica Warężyńska reservoir

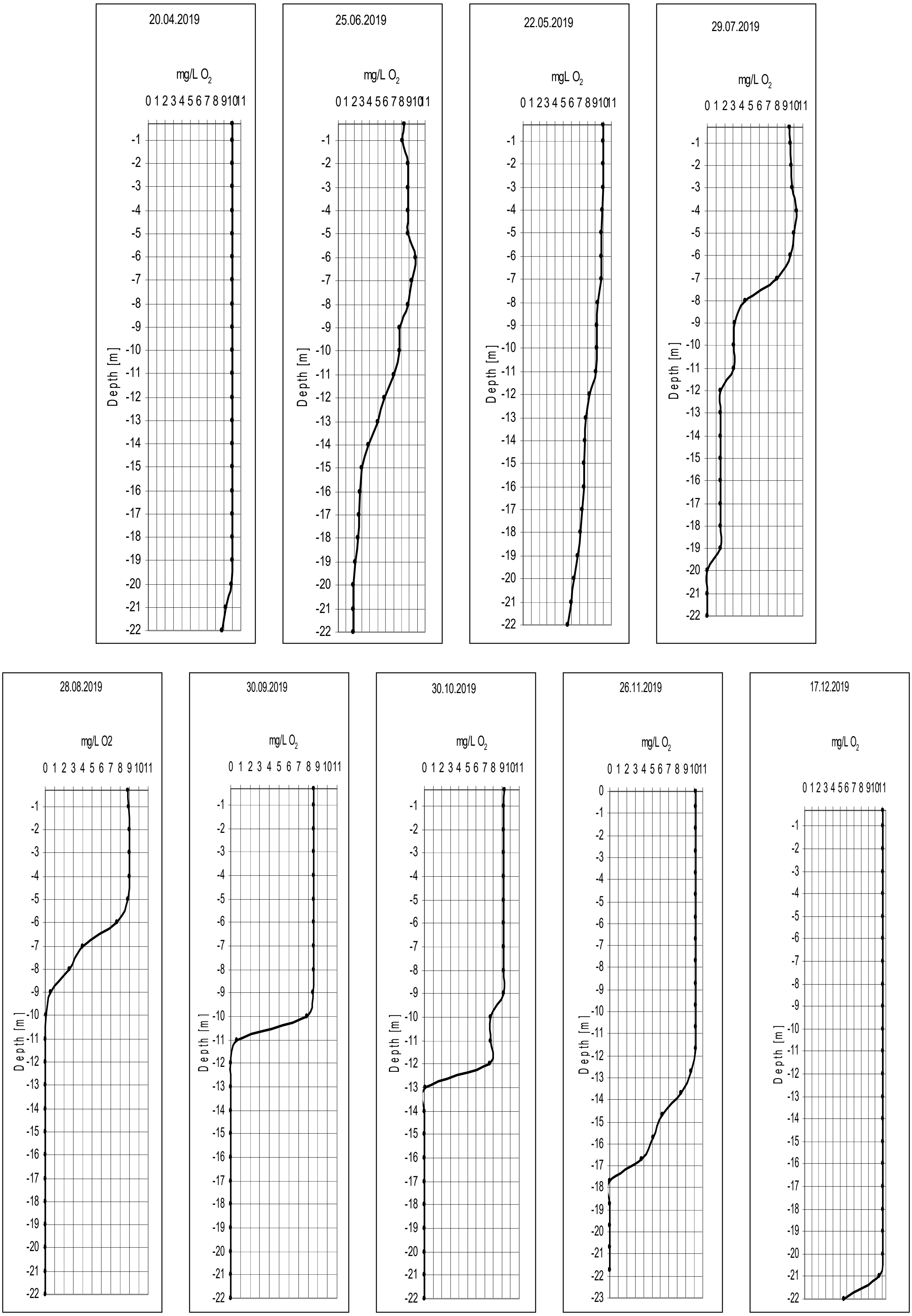
meters of depth. Measurements made in the last days of August showed no oxygen below the 10th meter depth. At that time, the oxycline layer – between the 5th and 9th meters of depth had a gradient of 8.2 mgO_2. The thickness of the deoxygenated layer increased by 0.4 m/day. The rate of decrease in oxygen concentration was 0.012 $mgO_2/dm^3 \cdot d^{-1}$. From the end of August, the oxygen conditions in the reservoir improved. The level of the lower edge of oxycline dropped from 9 meters deep in August to 17 meters deep in late November. The period of complete lack of oxygen in the hypolimnion of the reservoir was 139 days in the reporting year.

The increase in the thickness of the oxygenated water layer was 0.12 m/day. The increase rate in oxygen concentration in the hypolimnion was determined at 0.08 $mgO_2/dm^3 \cdot d$. The results of the measurements of oxygen concentration showed the oxygen deficits in the hypolimnion (Fig. 9), which were unfavorable from the point of view of the ecological condition of the reservoir. Strong oxygen stratification with complete lack of oxygen in the bottom layers of water creates conditions for the initiation of anaerobic processes, including the reduction of sulphates to hydrogen sulphide and for the release of phosphorus from bottom sediments [Biedka 2014, Dunalska 2003, Kostecki 2014]. Terasma et all (2006) emphasizes the role of the sedimentation process of suspensions containing organic matter, as well as the flocculent deposition of mineral particles in the deepest parts of the lake, which aggravates oxygen deficits.

Oxygen saturation of water

The degree of oxygen saturation of the water in the tested reservoir is shown in Table 3. Water oxygenation is interpreted as a reaction to overfertilization [Kintisch 2009, Kajak 1998]. The results of the measurements revealed that there were no intense blooms of phytoplankton organisms in the epilimnion of the reservoir. Only once, in July, an oxygen saturation of 120% was recorded in water, indicating more intensive phytoplankton development. Both earlier, in June, and later, in August, the water oxygen saturation did not exceed 110%.

Saturation of epilimnion with oxygen above 120% is marked in red. The periods of oxygen deficiency in the hypolimnion are marked with the gray scale. Homo-oxygen states are marked in blue. The conducted research showed thermal and oxygen stratification of the reservoir water masses. The summer stagnation period was approximately 173 days. During the summer stagnation, water masses were divided into epilimnion with a thickness from 4 m to 9 m and high temperatures – from 23°C to 26°C, a thermal jump layer with a thickness from 1 m to 9 m and a cool hypolimnion with a thickness from 7 m to 12 m. Full homothermia during the spring circulation was recorded in the second decade of April, at a water temperature of 8.3°C÷7.1°C. Autumn homothermia was recorded in the third decade of November, at the temperature of 8.2°C in the entire water column. The temperature of the surface layer of water strongly depends on the air temperature ($R^2 = 0.9778$). The curves of temperature changes and the concentration of oxygen dissolved in water in the vertical profile of the water column had a wedge-shaped course. The degree of water saturation with oxygen and the seasonal variability of this indicator show a low intensity of primary production in the upper, trophogenic layer of the lake. At the same time, the deficiencies and the total lack of oxygen below the thermo and oxycline show the fact that even nowadays not very intensive primary production process produces and supplies to the hypolimnion in the form of falling suspensions (detritus) sufficient organic matter to completely deplete oxygen in the hypolimnion [Terasma et all 2006, Pełechata et all 2015]. This situation resembles the thermal-oxygen relations in the Pławniowice reservoir [Kostecki 2001]. Calculated using the Patalas formula [Patalas 1960], the effective mixing range during the summer stagnation period corresponds to the position of the lower edge of the metallimnion and is 10.2 m.



20.04.2019

25.06.2019

22.05.2019

29.07.2019

28.08.2019

30.09.2019

30.10.2019

26.11.2019

17.12.2019

Fig. 9. Oxygen profiles in the Kuźnica Warężyńska lake – 2019

This indicates the possibility of re-suspension of suspended solids from bottom sediments during summer stagnation [Biedka 2014, Swinton et all 2015, Dołgoff 1948]. A positive oxygen balance is the basic condition for the harmonious functioning of the limnic ecosystem [Gierszewski 2015, Lossow 2000]. Equally important is the even distribution of oxygen in water, which is practically never the case. The solubility of oxygen in water is inversely related to the water temperature. With increasing temperature, the solubility of oxygen in water decreases [Marszelewski et all 2006, Patalas 1960]. In the conditions of limnic ecosystems, in the absence of factors disturbing this relationship, this principle would be respected. Under the conditions of the limnic ecosystem, this dependence is overlapped with the processes inside reservoirs, in particular the process of primary production (photosynthesis), and aerobic and anaerobic metabolic processes. The author assumed that the influence of these processes can be demonstrated by the differences between the theoretical value of the regression coefficient and the values calculated for individual water column depth levels. The vertical profiles of the water column with Pearson's R^2 and "r" correlation coefficients are shown below. Fig. 10 presents the values of the R^2 and "r" coefficients, calculated for the Kuźnica Warężyńska reservoir, and their vertical distribution in the water column from the surface to the bottom.

The deviation from the theoretical value of the correlation coefficient between the water temperature and the concentration of dissolved oxygen in the water may result from either the oxygenation of the water due to intense photosynthesis, or the lack of oxygen. Characteristic changes in the coefficient value are visible in the vertical profile of the water column. The general range of changes in the value of the "R^2" coefficient was from 0.3800 to 0.831. The vertical distribution of the coefficient values indicates the occurrence of 3 layers with different intensity of processes inside the reservoirs. In the first layer, the epilimnion of the tested reservoir, the value of the "R^2" coefficient decreased from 0.6362 at the surface (0.3 m) to 0.3888 at the 4th meter of depth. This indicates an increase in primary production intensity from the surface to the 4th meter deep. The next layer – the metallimnion – covers the thickness from the 4th to the 10th meter deep. This layer saw an increase in the value of the "R^2" coefficient from 0.3800 at the 4th meter of depth to 0.7086 at the 8th meter and a decrease again to 0.4132 at the 10th meter. Such a course of changes may indicate the influence of water transparency limiting the intensity of photosynthesis to 8 meters and the microbiological processes in the compensation layer [Jańczak et all 2006]. In the hypolimnion, the value of the "R^2" coefficient at a depth of 13 to 21 meters of the water column was uniform. The changes ranged from 0.7963 to 0.7856. This proves that in this cold layer of water, metabolic processes are

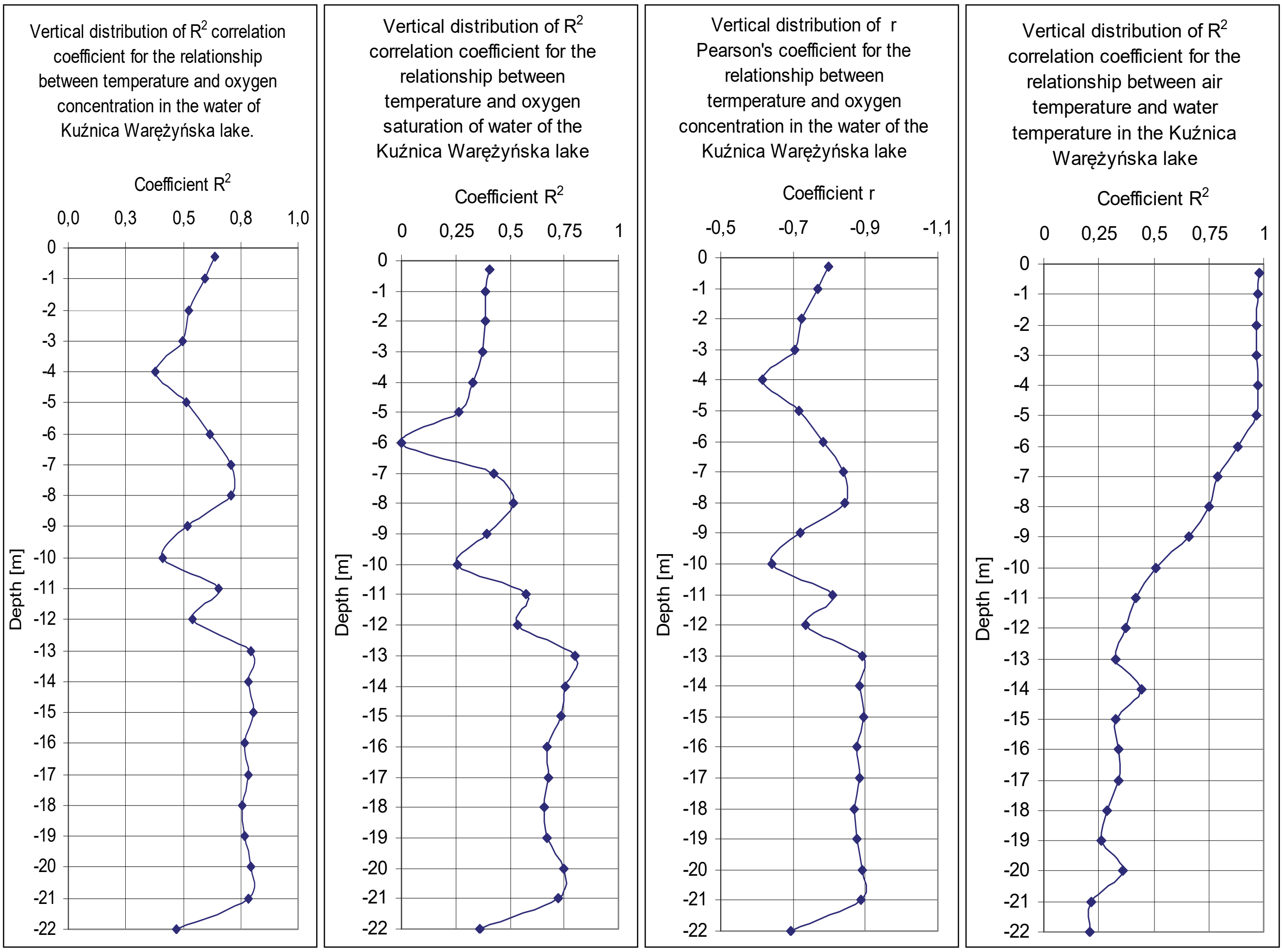


Fig. 10. Values of the regression coefficient in the vertical profile of the water column of Kuźnica Warężyńska Lake

the least intense. The division of the water column into layers, based on changes in the “R²” coefficient, is also confirmed by changes in the “r” coefficient of Pearson (Fig. 4 C).

According to the author, special attention should be paid to the low value of the coefficient “R²”: and “r” (Pearson) in the layer of water above the bottom, between 21 and 22 meters of depth. Despite the low temperature, similar to the temperatures at the higher depth levels, the value of the coefficient “R²” for the oxygen concentration was 0.4722, while 1 meter higher it was 0.7856. For the value of the “R²” coefficient for water saturation with oxygen 0.3628 at the bottom (22 m) at 0.7197 at a depth of 21 m. The value of the “r” – Pearson coefficient at the bottom was -0.6922 and -0.8863, respectively (Fig. 6). The total oxygen depletion in the hypolimnion of the tested reservoir over a very short period of time (37 days) is noteworthy (Tables 2 and 3). It is generally believed that this is the result of oxygen depletion in the process of mineralization of organic matter [Biedka 2013, Terasma et all 2006, Dunalska et all 2012]. According to the author, the cause of such a state may also be supplying the reservoir with oxygen-free underground waters infiltrating into the reservoir in its deepest parts, which is characteristic of water reservoirs created in the post-sand workings [Kostecki 2014]. This is confirmed by the decreased values of the regression coefficient for the water layer above the bottom, caused by the early appearance of the thermocline after the first appearance of the thermocline and the lack of oxygen in the hypolimnion from the bottom.

The negative impact of oxygen-depleted groundwater is limited during the spring and autumn circulation. As soon as the thermocline appears, mixing of water masses under the influence of wind is limited to the epilimnion [Jańczak et all 2006]. From now on, the groundwater deprived of oxygen may initiate reducing conditions in the reservoir, even before the falling organic matter in the form of detritus reaches the bottom of the reservoir from the trophogenic layer [Kajak 1998]. Thus, in anthropogenic lakes, limnic ecosystems, created in exhausted workings of sand mines, the infiltration of groundwater (excavation exploitation often ends when the bottom aquifers break through) will be the factor initiating the process of releasing pollutants from bottom sediments, including the process of internal enrichment. The degradation of the ecosystem will be stronger if municipal pollutants are introduced into the reservoir along with water of the supply stream [Lossow 2000].

Morphometric conditions are an important element of the lake’s functioning [Anischenko et all 2015, Moses et all 2011, Stefanidis et all 2012]. The northern and southern parts of the studied reservoir differ in terms of morphometry. The northern, gutter part is – deep (22 m ÷ 18 m), with steep bottom slopes. The southern part is much shallower (6 m ÷ 1.5 m) and wider (1.5 km).

In terms of fishing, the northern part can be described as a whitefish lake, and the southern part as a rope-pike lake [Chybowski et all 2016]. The north-south orientation of the reservoir and its elongated shape are unfavorable from the point of view of mixing water masses under the influence of wind. The morphological conditions of the areas surrounding the Kuźnica Warężyńska reservoir cause a specific field isolation,

Table 2. Water temperature [°C] of the Kuźnica Warężyńska reservoir – 2019.
(The bold line shows the occurrence of the thermocline)

Depth [m]	20.04.2019	22.05.2019	25.06.2019	29.07.2019	28.08.2019	30.09.2019	30.10.2019	26.11.2019	17.12.2019
0,3 m	8,1	15,6	25,7	24,8	24,6	17	13,2	8,2	5,4
1	7,9	15,5	24,9	24,4	24,5	16,9	13,3	8,2	5,4
2	7,7	15,5	24,6	24,2	24	16,9	13,4	8,2	5,4
3	7,6	15,3	24,5	24	24	16,8	13,4	8,2	5,4
4	7,6	**14,7**	24,4	23,2	23,4	16,8	13,4	8,2	5,4
5	7,6	**13,3**	**23,9**	**22,6**	22,9	16,8	13,4	8,2	5,4
6	7,6	12,6	**18,5**	**20,6**	**22,6**	16,8	13,4	8,2	5,4
7	7,5	12,3	**15,6**	**19,9**	**21,4**	16,8	13,4	8,2	5,4
8	7,5	12,2	**14,4**	**17,8**	**19,2**	16,7	13,4	8,2	5,4
9	7,5	12	**13,3**	**15,4**	**16,5**	16,7	13,4	8,2	5,4
10	7,5	11,8	**12,2**	**13,5**	**14,4**	**16,7**	13,4	8,2	5,4
11	7,5	11,3	11,3	**11,9**	**13,3**	**15,3**	13,4	8,2	5,4
12	7,5	10,4	10,5	**10,7**	**13,3**	**12,2**	**13,4**	8,2	5,4
13	7,5	9,6	9,6	9,8	**12,2**	**10,5**	**12,3**	8,2	5,4
14	7,4	9	9,1	9,1	**10,8**	10	**10**	8,2	5,4
15	7,4	8,5	8,7	8,8	**9,5**	9,5	10	8,2	5,4
16	7,4	8,4	8,5	8,5	9,3	9,2	9,4	8,2	5,4
17	7,3	8	8,3	8,3	8,8	8,9	8,9	8,2	5,4
18	7,3	7,8	8	8,1	8,7	8,7	8,7	8,2	5,4
19	7,3	7,6	7,8	8	8,6	8,5	8,5	8,2	5,4
20	7,3	7,5	7,7	9	8,5	8,3	8,3	8,2	5,8
21	7,3	7,4	7,7	7,8	8,4	8,3	8,3	8,2	6
22	7,3	7,3	7,7	7,8	8,2	8,2	8,2	8,2	6

Table 3. The concentration of dissolved oxygen [mgO$_2$/dm^3] in the water of the Kuźnica Warężyńska reservoir – 2019. (The bold line shows the occurrence of the oxycline)

Depth [m]	20.04.2019	22.05.2019	25.06.2019	29.07.2019	28.08.2019	30.09.2019	30.10.2019	26.11.2019	17.12.2019
0,3	10	10	8,4	9,5	8,8	8,6	9,3	10,2	11,1
1	10	10	8,1	9,6	8,9	8,6	9,2	10,2	11,1
2	10	10	8,8	9,7	9	8,6	9,2	10,2	11,1
3	10	10	8,8	9,8	9	8,6	9,2	10,2	11,1
4	10	9,9	8,8	10,3	9	8,6	9,2	10,2	11,1
5	10	9,8	8,8	10	**8,8**	8,6	9,2	10,2	11,1
6	10	9,7	9,8	**9,6**	**7,7**	8,6	9,2	10,2	11,1
7	10	9,7	9,3	**8**	**4**	8,6	9,2	10,2	11,1
8	10	9,3	8,8	**4,4**	**2,6**	8,6	9,2	10,2	11,1
9	10	9,2	7,8	**3,2**	**0,6**	8,5	**9,2**	10,2	11,1
10	10	9,2	7,8	**3,1**	0,1	7,9	**7,7**	10,2	11,1
11	10	9,1	**7**	**3,1**	0	0,6	**7,7**	10,2	11,1
12	10	8,3	**5,8**	**1,5**	0	0	**7,6**	10,2	11,1
13	10	7,8	**5**	1,5	0	0	**0,1**	**9,6**	11,1
14	10	7,7	**3,8**	1,5	0	0	0	**8,4**	11,1
15	10	7,6	3	1,5	0	0	0	**6,2**	11,1
16	10	7,6	2,8	1,5	0	0	0	**5,1**	11,1
17	10	7,4	2,6	1,5	0	0	0	**3,8**	11,1
18	10	7,2	2,5	1,5	0	0	0	**0**	11,1
19	10	6,8	2,1	1,5	0	0	0	0	11,1
20	9,9	6,4	1,9	0	0	0	0	0	11,1
21	9,9	6	1,9	0	0	0	0	0	**10,6**
22	9,9	5,5	1,9	0	0	0	0	0	5,5

Table 4. Oxygen saturation [%] of water in the Kuźnica Warężyńska Lake – 2019

Depth [m]	20.04.2019	22.05.2019	25.06.2019	29.07.2019	28.08.2019	30.09.2019	30.10.2019	26.11.2019	17.12.2019
0,3	100	104	109	118	110	92	90	100	100
1	100	104	108	120	110	92	90	100	100
2	100	104	108	120	111	92	90	100	100
3	100	104	108	121	110	92	90	100	100
4	100	104	108	126	109	92	90	100	100
5	100	104	108	121	105	92	90	100	100
6	100	104	108	111	91	92	90	100	100
7	100	104	102	91	47	92	90	100	100
8	100	104	102	49	29	92	89	100	100
9	100	104	78	49	6	92	89	100	100
10	100	104	78	49	1	92	75	100	100
11	100	104	78	49	0	7	75	100	100
12	100	77	78	49	0	0	75	100	100
13	100	77	48	49	0	0	0.1	92	100
14	100	77	48	49	0	0	0	80	100
15	100	77	48	49	0	0	0	74	100
16	100	77	48	9	0	0	0	62	100
17	100	77	48	6	0	0	0	40	100
18	100	77	48	3	0	0	0	0	100
19	100	77	48	2	0	0	0	0	100
20	100	77	48	0	0	0	0	0	100
21	100	77	11	0	0	0	0	0	100
22	100	77	11	0	0	0	0	0	44

limiting the loads of pollutants introduced into the reservoir [Rzętała 2008]. Describing the current state of thermal-oxygen relations provides a frame of reference for tracking changes that will occur over time.

Conclusions

The Kuźnica Warężyńska anthropogenic lake was classified according to Olszewski and Patalas as dimictic, eumictic, stratified, stable.

- In terms of susceptibility to macrolite fouling, the reservoir was classified as grade II according to Dolgoff, i.e. having similar pelagic and littoral zones.
- The analysis of the differences between the theoretical value of the regression coefficient between the water temperature and the concentration of dissolved oxygen in water, and the actual value calculated for individual depth levels, allows to show the diversification of the intensity of metabolic processes in the vertical profile of the water column.
- After only 14 years of its existence, strong oxygen deficits, causing reducing conditions in the hypolimnion, pose a threat to the reservoir, favoring the release of phosphorus from bottom sediments.
- Early and rapidly progressing oxygen deficit in the bottom layer of water suggests the influence of a process other than the decomposition of organic matter inside the reservoir.
- Feeding the hypolimnion of the lake by groundwater – characteristic of water reservoirs created in the workings of sand mines – is a threat to anthropogenic limnic ecosystems. In the period of summer and winter stagnation, bottom eruption of oxygen-depleted groundwater is a factor shaping the anaerobic environment in the bottom layers of water, initiating the process of internal enrichment.
- Permanent supply of the lake by groundwater, ensuring the exchange of water in the lake, regardless of the transfer of water from the Czarna Przemsza River is a favorable factor from the point of view of ecosystem reclamation by means of the removal of hypolimnion water.
- The hydrological conditions, morphometry and thermal--oxygen relations of the Kuźnica Warężyńska reservoir are favorable for undertaking technical measures – changing the method of draining water from the surface to the bottom – to protect the quality of water resources.
- The morphometric conditions allow for the separation, in terms of fishing, of two different parts of the lake: the northern part as a whitefish lake, and the southern part as a rope-pike lake. Such a situation increases the natural value of this ecosystem.

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Nowe jezioro antropogteniczne Kuźnica Warężyńska – stosunki termiczne i tlenowe po 14 latach eksploatacji – w aspekcie ochrony i rekultywacji

Streszczenie: Przedstawiono wyniki pierwszych, od chwili powstania, poprzez zalanie wyrobiska kopalni piasku w 2005 r., badań stosunków termiczno-tlenowych nowego antropogenicznego zbiornika Kuźnica Warężyńska. Pomiary temperatury wody i stężenia rozpuszczonego w wodzie tlenu wykonywano od kwietnia do grudnia, co miesiąc, w odstępach co jeden metr głębokości od powierzchni do dna (22 m). Jezioro antropogeniczne Kuźnica Warężyńska sklasyfikowano, wg. Olszewskiego i Patalasa, jako dimiktyczne, eumiktyczne, stratyfikowane stabilne, skrajnie limniczne, z cechami B-mezotrofii. Pod względem wielkości udziału strefy litoralowej w całkowitej powierzchni, zbiornik sklasyfikowano jako I-go stopnia wg. Dołgoffa. Po czternastu latach istnienia zbiornika, w okresie stagnacji letniej dochodzi do całkowitego wyczerpania tlenu w hypolimnionie, od dziesiątego metra głębokości do dna (22 m). Analiza pionowego rozkładu współczynnika regresji dla zależności pomiędzy temperaturą wody a stężeniem rozpuszczonego w wodzie tlenu wskazuje na wpływ zasilających zbiornik, pozbawionych tlenu, wód podziemnych, jako na czynnik mogący, oprócz procesu rozkładu materii organicznej, inicjować procesy beztlenowe w przydennej warstwie wody zbiornika. Z chwilą ustania cyrkulacji, denna erupcja pozbawionych tlenu wód podziemnych stanowi, w okresie stagnacji letniej i zimowej czynnik kształtujący wcześnie środowisko beztlenowe w przydennych warstwach wody, inicjujący proces wzbogacania wewnętrznego. Warunki hydrologiczne, morfometria oraz stosunki termiczno-tlenowe zbiornika Kuźnica Warężyńska są korzystne dla podjęcia technicznych zabiegów, polegających na zmianie sposobu odprowadzania wody z powierzchniowego na denny, służących ochronie jakości zasobów wodnych.