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WATER BALANCE OF SELECTED POSTMINING RESERVOIRS IN THE ŁĘKNICA REGION

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The article presents the results of the hydrological balance calculated for selected anthropogenic reservoirs and their drainage basins, which are located in the south-western part of the Lubuski District, and were created as a result of brown coal mining. The purpose of this work is the quantity evaluation of the diversification of water balance components and their influence on the quality of the environment. On basis of calculations a conclusion has been formed that negative retention (-14,14 mm) was calculated for the open drainage basins under research, and positive retention (276,90 mm) for the closed ones. In general, it has been found that the water balance of the anthropogenic reservoirs is moderately negative. However, there is a limited possibility of reclaiming them.

Keywords: hydrological balance, postmining reservoirs, anthropogenic lakeland

1. INTRODUCTION

Water is the most important substance existing in nature. It has always been a basic element of life on earth as well as of the development of human civilization. In spite of limitations, water supplies are renewable. Man's negative influence on the environment can considerably slow down the process of renewal of water supplies, which may result in e.g. a decrease in the supply of water for common use.

Therefore, in further research, it is important to analyse to what extent water management by people upsets the balance of the natural hydrological

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cycle, and how it is possible to prevent unfavourable changes in water circulation in nature.

First of all, in order to eliminate water shortages or sometimes water surpluses on earth, it is necessary to closely examine the water balance of areas of variable use. In this way it is possible to precisely assess water supply in a particular region and to determine the balance between the supply and use of water, i.e. to analyse fluctuations in water reserves and plan the right water management. This task is particularly important for regions degraded by man, an example being the post mining area in the Łęknica region described in this article [10].

2. CHARACTERISTICS OF THE AREA UNDER RESEARCH

The anthropogenic lake area in the Łęknica region is one of the largest agglomeration of surface reservoirs in Poland, created as a result of strip mining for brown coal, which lasted from the second half of the nineteenth century to the 1970s. It is situated near Łęknica in the south west of Poland.

The main factors in the formation of the geological structure and morphology of the area under research were *glacial processes (covering Pleistocene and Miocene sediments, glacial sediments, Holocene sediments and piled up Miocene sediments)* of the southern Polish and middle Polish glaciations. As a result of the squeezing of plastic sediments flakes, flaked creases and creases of variable symmetry were created at that time.

In the region under research there are mainly *Tertiary (Paleogene and Neogene) sediments* in the ground, including: fine and medium sands, clay sands or dusts with an addition of brown coals The aquifer of the area under research consists of fine or dusty sands with a summary depth of strata 3-14 m, located at the depth of several dozen metres below the surface (130,5-132,0 m above sea level) – [7].

The anthropogenic reservoirs analysed in this article are situated in the basin of the Nysa Łużycka River (fig. 1), and in the riverside area of the Nysa Łużycka River (reservoirs 60 and 62), in partial basins of its tributaries (the Chwaliszówka River – reservoir 45), or in an area without tributaries (reservoirs 46, 47, 48, 49, 50, 54, 55, 56 and other smaller ones).

Their maximum length (from 185 m to 1056 m) and width (from 77 m to 649 m) are varied. The maximum depth of the reservoirs is from 5 m to 22 m, and the surface area – from 14 000 m^2 to 206 000 m^2 [8]. The cause of the shape of the reservoirs, which is clearly elongated towards the north-east – south west is the glacitectonic structure of the region, characteristically piled up brown coal layers formed here a number of longitudinal, parallel anticline elevations, with axes oriented towards the north-east – south-west, which – after the coal deposits had been used up, resulted in the present layout of the lake district [1].

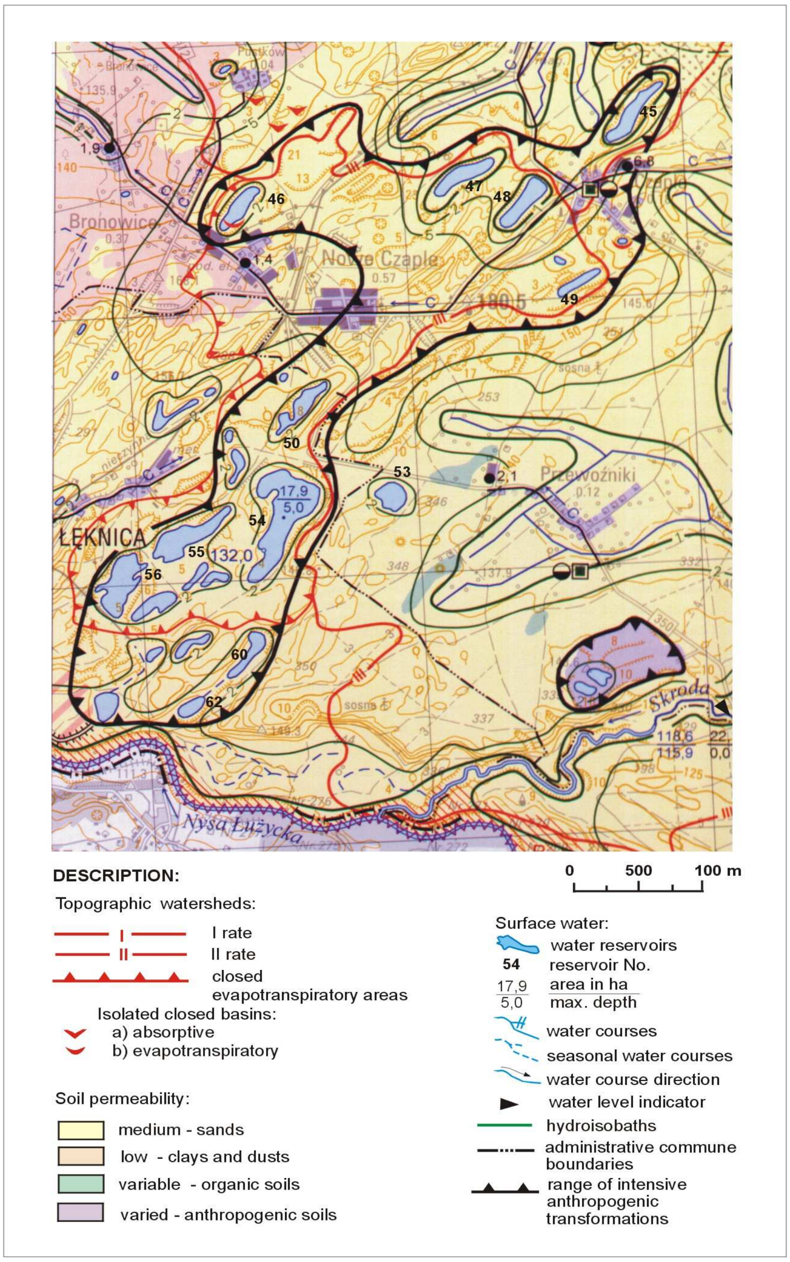

Fig. 1. Hydrography of the Łęknica region [9]

The area under research has the largest number of days with moderately warm weather and large general cloudiness (about 51 days). There are fewer than 100 ground frost days and about 30 frosty days, and also 39.4 sunny days, 198.8 cloudy days, 126.3 days with large cloudiness, 198.6 days without rain and 165.9 rainy days. The average annual amount of rain between the years 1961-2000 was 660mm, and for the year 2009 – 734 mm. The area under research is covered with snow for the shortest time in Poland (about 30-40 days). The average annual air temperature is 8.2°C, but in the year 2009 it was 9.1°C.

3. RESEARCH METHODOLOGY

The values of meteorological parameters for the hydrological year under research – 2009/10 were obtained from the rainfall post of the Institute of Meteorology and Water Management in Lęknica (supervised by the Branch of the Institute of Meteorology and Water Management in Wrocław) and from the meteorological post of the Institute of Meteorology and Water Management in Zielona Góra (supervised by the Branch of the Institute of Meteorology and Water Management in Wrocław).

Underground inflow was included during the determination of the water balance – the formula derived from the Darcy law for the calculation of a single water influx into a ditch was applied, and underground outflow, calculated by the same formula, was also included.

Retention for the basins under research was found on the basis of the balance difference determined by indications about the water surface elevation by water meters installed for this purpose between the years 2006-2009 in basins 54 and 55.

The water balance was done for one hydrological year (2009/2010), and for this reason average annual values for rainfall and evaporation were used for calculations.

The average annual rainfall for the area under research was the arithmetical average of monthly rainfall in the year 2009.

$$\mathrm{P} = \mathrm{P_I} + \mathrm{P_{II}} + \ldots + \mathrm{P_{XII}} \; [\mathrm{mm}] \tag{3.1}$$

where: P – the average annual rainfall on the surface of the area under research [mm],

$\mathrm{P_I}, \mathrm{P_{II}}, \ldots, \mathrm{P_{XII}}$ – the average monthly rainfall on the surface of the area under research [mm].

The average annual real evaporation was calculated from the L.Turc equation [4]:

$$E = \frac{P}{\sqrt{0{,}9 + \frac{P^2}{L^2}}} \; [mm] \tag{3.2}$$

where: E – the average annual real evaporation value [mm],
P – the average annual rainfall on the surface of the area under research [mm],
L – the value obtained from the formula:

$$L = 300 + 25T_p + 0,05T_p^{\ 3} \tag{3.3}$$

where: T_p – the corrected value of the temperature calculated from the formula:

$$T_p = \frac{\Sigma P_i T_i}{\Sigma P_i} \ [°C] \tag{3.4}$$

where: P_i and T_i – the values of the temperature and rainfall observed in particular months of the hydrological year.

Because of the fact that some of the basins under research are open and some of them are closed, two different equations for the water balance have been used in the article.

The Penck-Oppokow equation was used in order to determine the water balance in the drainage basins of the open reservoirs [2, 5]:

$$P = H + E + \Delta R \ \ [mm] \tag{3.5}$$

where: P – the average annual rainfall on the surface of the drainage basin of the reservoir under research [mm],
H – the amount of water flowing out of the drainage basin of the reservoir under research [mm],
E – the average annual value of evaporation from the surface of the drainage basin of the reservoir under research [mm],
ΔR – the retention difference (between the final and initial retention) in the drainage basin of the reservoir [mm].

The amount H of water flowing out of the drainage basin under research was determined by the Keller formula [11]:

$$H = 0,942 \cdot P - 405 \ [mm] \tag{3.6}$$

where: P – the average annual rainfall on the surface of the drainage basin [mm].

The retention difference ΔR in the drainage basins of the open reservoirs was determined by the transformation of the water balance equation:

$$\Delta R = P - (H + E) \ \ [mm] \tag{3.7}$$

In order to determine the water balance in the closed reservoirs the following equation was used [5]:

$$P = \Delta R + E \ [mm] \qquad (3.8)$$

where: P – the average annual rainfall on the surface of the drainage basin [mm],
ΔR – the retention difference (between the final and initial retention) [mm],
E – the average annual value of evaporation from the surface of the drainage basin [mm].

The Retention difference in the drainage basins of the closed reservoirs was determined by the transformation of the water balance equation:

$$\Delta R = P - E \ [mm] \qquad (3.9)$$

In the extended version the water balance equation for the closed reservoirs assumed the form [2]:

$$P + H_d = E + H_w + \Delta R \qquad (3.10)$$

where: P – the average annual rainfall on the surface of the reservoir under research [mm],
H_d – the underground inflow into the reservoir under research [mm],
E – the average annual value of evaporation from the surface of the reservoir under research [mm],
H_w – the underground outflow in from the reservoir under research [mm],
ΔR – the change of retention in the reservoir under research.

The quantity of the underground inflow H_d into the closed reservoirs under research was determined by the formula:

$$H_d = \frac{V}{A} \ [mm] \qquad (3.11)$$

where: A – the surface of the reservoir under research [m^2],
V – the volume of the water inflow into the reservoir, defined according to the formula:

$$V = Q \cdot t \ [m^3] \qquad (3.12)$$

where: t – the number of seconds in a year,
Q – the total flow of water in the aquifer in a particular width of its diameter, expressed by the formula [12]:

$$Q = B \cdot q \ \left[m^3/s\right] \tag{3.13}$$

where: B – $1/2$ the length of the bank of the reservoir under research [m],
q – a unit inflow into the reservoir under research, determined by the formula [12]:

$$q = k \frac{H_z{}^2 - h_z{}^2}{2R} \ \left[m^2/s\right] \tag{3.14}$$

where: k – the filtration ratio of the soil which forms the aquifer [m/s],
H_z – the height of the water surface above the base of the aquifer at the distance R from the bank of the reservoir [m] – the value adopted was determined on the basis of hydro-geological research within reservoir 54 [7],
h_z – the height of the lowered water surface in the reservoir [m] – the value adopted was determined on the basis of hydro-geological research within reservoir 54 [7],
R – the radius of the depression vortex [m] – the value adopted was determined on the basis of hydro-geological research within reservoir 54 [7].

Further data were obtained from the following dependences:

$$\frac{h_{avg(z)}}{h_{avg(54)}} = \frac{H_z}{H_{z54}}$$

$$H_z = \frac{h_{avg(z)}}{h_{avg(54)}} \cdot H_{z54} \ [m] \tag{3.15}$$

where: H_z – the height of any point of the water surface above the aquifer within the reservoir under research [m],
$h_{avg(z)}$ – the average depth of the reservoir under research [m],
$h_{avg(54)}$ – the average depth of reservoir [m],
H_{z54} – the height of a point of the water surface above the aquifer within reservoir 54 [m],

$$\frac{h_{avg(z)}}{h_{avg(54)}} = \frac{h_z}{h_{z54}}$$

$$h_z = \frac{h_{avg(z)}}{h_{avg(54)}} \cdot h_{z54} \ \ [m] \tag{3.16}$$

where: h_z – the height of the lowered water surface in the reservoir under research [m],

$h_{avg(z)}$ – the average depth of the reservoir under research [m],

$h_{avg(54)}$ – the average depth of reservoir 54 [m],

h_{z54} – the height of the lowered water surface within reservoir 54 [m],

$$\frac{h_{avg(z)}}{h_{avg(54)}} = \frac{R}{R_{54}}$$

$$R = \frac{h_{avg(z)}}{h_{avg(54)}} \cdot R_{54} \ \ [m] \tag{3.17}$$

where: R – the radius of the depression vortex of the reservoir under research [m],

$h_{avg(z)}$ – the average depth of the reservoir under research [m],

$h_{avg(54)}$ – the average depth of reservoir 54 [m],

R_{54} – the radius of the depression vortex within reservoir 54 [m].

The change of retention was determined by the observation of water meters in reservoirs 54 and 55 and calculations of changes in the volumes of these reservoirs.

In the final stage of the calculations, in order to obtain all the components of the balance equation, the underground outflow from the reservoirs H_w was calculated by the formula:

$$H_w = (P + H_d) - (E + \Delta R) \ \ [mm] \tag{3.18}$$

where: H_w – the underground outflow from the reservoir under research [mm],

P – the average annual rainfall on the surface of the reservoir under research [mm],

H_d – the underground inflow from the drainage basin into the reservoir under research [mm],
E – the average annual value of evaporation from the surface of the reservoir under research [mm],
ΔR – the change of retention observed in the reservoir under research – adopted on the basis of indications by the water meters installed in reservoirs 54 and 55 [mm].

The surfaces of the reservoirs and the lengths of the banks were determined on the basis of topographic maps which were currently available in the scale 1:10 000 [6].

4. WATER BALANCE OF SELECTED ANTHROPOGENIC RESERVOIRS AND THEIR DRAINAGE BASINS

The post mining reservoirs under research with particular drainage basins have been presented in Fig. 2.

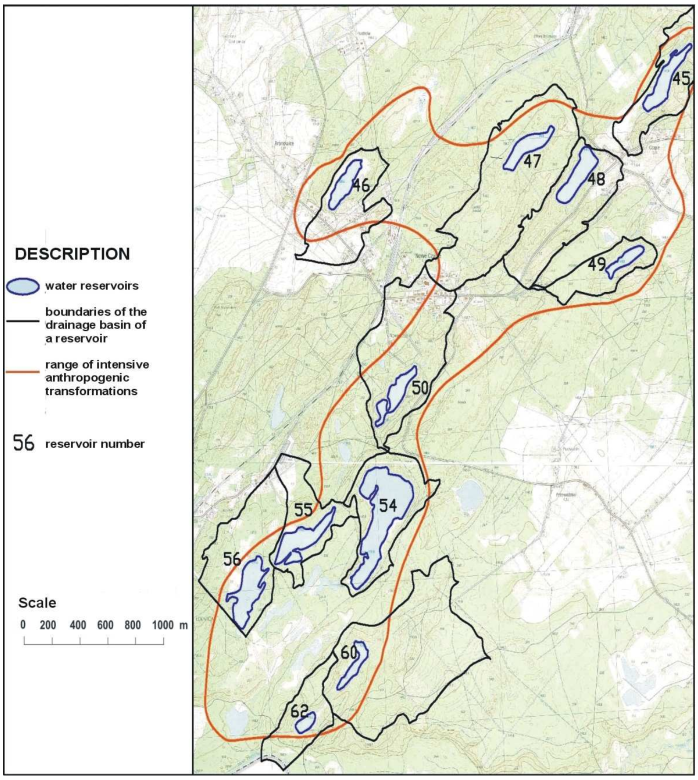

Fig. 2. Partial drainage basins of anthropogenic reservoirs in the area near Łęknica

The water balance of the drainage basins of open reservoirs (45, 60 and 62) has been presented in table 1 and fig. 3.

Table 1. Comparison of the elements of the water balance in anthropogenic open reservoirs in the area near Łęknica

Increases or inflows	Decreases or outflows
Rainfall P 738,90 mm	Real evaporation E 462,00mm
	Outflow H 291,04 mm
Retention change ΔR -14,14 mm	

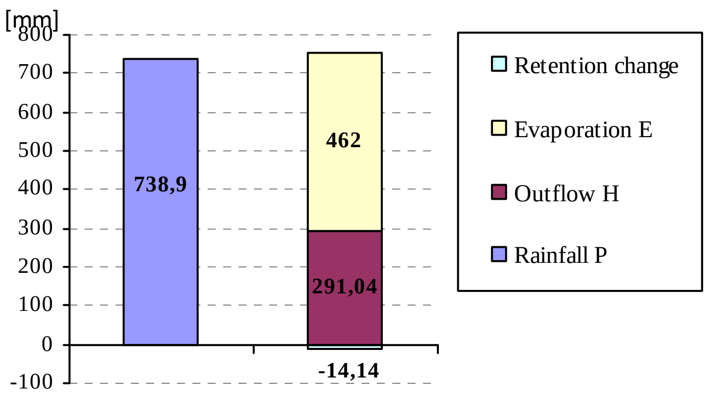

Fig. 3. Diagram of the water balance in anthropogenic open reservoirs in the area near Łęknica

The water balance of drainage closed basins (46, 47, 48, 49, 50, 54, 55 and 56) has been presented in table 2 and fig. 4.

Table 2. Comparison of elements of anthropogenic closed reservoirs in the area near Łęknica

Increases or inflows	Decreases or outflows
Rainfall P 738,90 mm	Real evaporation E 462,00 mm
Retention change ΔR 276,90 mm	

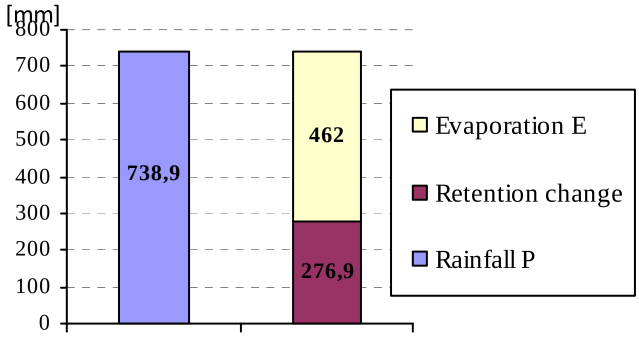

Fig. 4. Diagram of the water balance of anthropogenic water no closed reservoirs in the area near Łęknica

An example of a detailed water balance for a reservoir with the greatest average depth i.e. reservoir 48 has been presented in table 3 and fig. 5 [3]

Table 3. Comparison of elements of the water balance of reservoir 48 for the hydrological year 2009/2010

Increases or inflows	Decreases or outflows
Rainfall P 738,90 mm (34,5%)	Real evaporation E 462,00 mm (21,6%)
Inflow H_d 330,83 mm (15,4%)	Outflow H_d 557,73 mm (26,1%)
Retention change ΔR 50 mm (2,3%)	

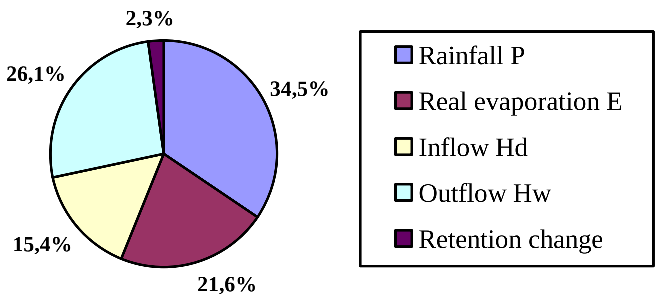

Fig. 5. Percentage distribution of the water balance of reservoir 48 for the hydrological year 2009/2010

5. CONCLUSIONS

Water balance in the anthropogenic lake district near Łęknica is determined by the type of the drainage basins of particular reservoirs (open, closed)

In the hydrological year 2009/2010 in the area of the open reservoirs the balance was negative (ΔR=-14,14 mm), and in the area of the closed reservoirs it was positive (ΔR=276,90 mm).

The value of the outflow ratio in the drainage basins under research was on average α=0,39, which indicates hydrological type II of the area (area with moderate humidity).

The water balance presented in the article indicates that there is a possibility of reclaiming the reservoirs which have been examined. However, this possibility is limited, especially in the area with closed reservoirs.

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BILANS WODNY WYBRANYCH ZBIORNIKÓW POEKSPLOATACYJNYCH W REJONIE ŁĘKNICY

S t r e s z c z e n i e

W artykule przedstawiono wyniki bilansu hydrologicznego, jaki opracowano dla wybranych zbiorników pokopalnianych oraz ich zlewni, zlokalizowanych w południowo-zachodniej części województwa lubuskiego, utworzonych w wyniku eksploatacji złóż węgla brunatnego. Celem pracy jest ilościowa ocena zróżnicowania składowych bilansu i ich roli w kształtowaniu jakości środowiska.

Na podstawie przeprowadzonych badań stwierdzono, że roczny bilans dla zlewni odpływowych wykazywał retencję ujemną (-14,14 mm), natomiast dla zlewni bezodpływowych – dodatnią (+276,90 mm). Ogółem stwierdzono umiarkowanie ujemny bilans wodny zbadanych zbiorników, wskazujący jednak na możliwość ich rekultywacji, ale - w ograniczonym zakresie.