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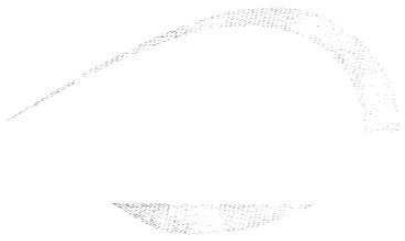

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Water balance of flow-through lakes located in the catchment of the Mała Wełna River

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Abstract: The paper presents a study on water balance of two biggest lakes, through which the Mała Wełna River flows, i.e. Lakes Kłeckie and Gorzuchowskie. Components of this balance were assessed on the base of investigations and field observations carried out in characteristic hydrological years of period 2001-06 in the catchment of the Mała Wełna River downstream to the cress-section at Kiszkowo. The area of the catchment to this section is 342 km². Investigations showed that the water volume, participating in the circulation in the lakes, depended on the hydrometeorological situation and on their position in the drainage system. The biggest role in the water balance of the lakes was played by the surface phase of the horizontal water exchange, enhanced by high values of catchment/lake area ratio. The Kłeckie and Gorzuchowskie Lakes during the period of the study served the drainage function, although an analysis of underground recharge of the lakes in successive years classified them to the group of lakes with a changeable function in the underground water circulation. Depending on the character of a hydrological year the underground inflow to the lake or underground discharge predominated. Probably it was mainly caused by the effect of hydro-engineering structures located below the lakes, which had a modifying effect on the hydrological regime of the river, lakes and ground water in adjacent areas.

Key words: Mała Wełna catchment, flow-through lake, water balance, hydrological function

Introduction

Lakes constitute an essential element of the early post-glacial landscape, they are the base for the drainage of surface and underground waters both in the more shallow aquifer horizons of potamic watercourses, as well as deeper horizons. Depending on their position in the hydrographic system, specific relationships occur binding a lake with the river network, which determine the hydrological regime (Bajkiewicz-Grabowska 2002). Lakes have a natural capacity to compensate for discharge, which depends first of all on the location of a reservoir in the catchment and hydrometeorological conditions. This capacity is enhanced by lake damming. Especially the effect of anthropogenic factors on water levels in lakes, although neglected in limnological studies, may accelerate eutrophication and lead to the transformation of communities of aquatic organisms (Górniak and Piekarski 2002). The role of a lake in river-lacustrine systems may be best assessed on the basis of analysis of water balance developed for a multiannual period.

The aim of the study was to prepare water balance for two biggest lakes, through which the Mała Wełna River flows, i.e. Lakes Kłeckie and Gorzuchowskie, and to evaluate components of the balance in characteristic years.

Methods

Investigations and field observations were carried out in hydrological years of 2001 -2006 in the catchment of the Mała Wełna River at section Kiszkowo. The area of the catchment to the section is 342 km². Analyses included daily measurements of precipitation using a Hellmann's rain gauge at Kiszkowo and water levels at the section line closing the catchment. Water levels in the Kłeckie and Gorzuchowskie Lakes were measured on a monthly basis, similarly as hydrometric measurements at the cross-section 9 located along the river as well as at the section closing the Dębina watercourse (Fig. 1). Hydrometric measurements included depth sounding and complete point recordings of flow rate using a hydrometric current

meter by Valeport BFM002. In the course of the study regular observations of ground water levels were conducted on a monthly basis at three wells (3 m deep) located in areas adjacent to the lakes.

Collected homogenous meteorological and hydrometric data made it possible to perform independent calculations of water balance elements. Calculations of water circulation were performed for monthly and annual time intervals, according to the basic water balance equation, which included two forms of water exchange, i.e. vertical exchange (lake-atmosphere) and horizontal exchange in the surface and underground phases (lake-catchment).

$$(P\text{-}E) + (D_1\text{-}H_1) + \Delta Z = \Delta R$$
$$\Delta Z = D_2 - H_2$$

where: P – precipitation falling on lake surface, E – evaporation from water table surface, D_1 – inflow from the river and from the immediate catchment, H_1 – discharge into the river, ΔZ –underground supply to the lake, ΔR – change in lake retention, D_2 – underground inflow, H_2 – underground runoff.

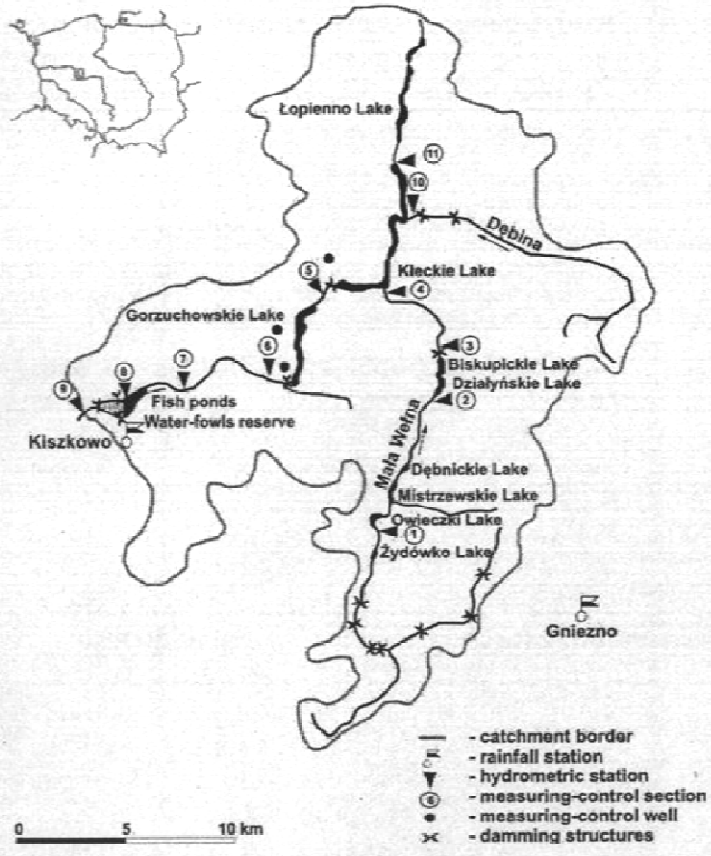

Fig. 1. Catchment of the Mała Wełna River to the section at Kiszkowo

When developing water balances of the lakes monthly precipitation totals were corrected introducing a correction according to Kowalczyk and Ujda (1987). Evaporation from the water table surface was calculated using empirical formulas according to Davidoff and Ivanoff, using daily measurements of water-saturation deficits, relative humidity, wind velocity and air temperature, recorded at the Arboretum Zielonka station of the Forest Experimental Station, located approx. 11 km south-west of Kiszkowo.

Surface inflow of water to Kłeckie Lake (in the Wełnianka River, from the immediate catchment) and to Gorzuchowskie Lake (from the immediate catchment) were calculated using hydrological analysis. The Kiszkowo gauge section was used as an analog section. Changes in retention were defined as a difference in water levels in the lakes at the beginning and end of the balance period, which resultants of the underground supply of the lakes were calculated from the balance difference and compared with changes in ground water levels in adjacent areas.

Balance components were calculated in volumetric units (m^3) and in mm of water layer. The area and capacity of the lakes in individual months were determined from area and capacity curves, developed on the basis of batimetric data from the Institute of Inland Fisheries in Olsztyn.

Study site description

The catchment of the Mała Wełna River is located in the Wielkopolska-Kujawy Lowland, the total area of the catchment is 689.95 km^2, while the length of the river is 85.85 km. According to the code system for hydrographic units the catchment was assigned code 1866 (Czarnecka 2005). Since 1998 the Sub-department of Hydrology and Water Resources, the Agricultural University of Poznań has been running comprehensive investigations and field observations in the catchment with the area of 342 km^2. Up to the Kiszkowo section line the river flows through eight lakes with a total area of 392.8 ha, jointly in the catchment there are 19 lakes and a complex of fish ponds with an area of 780.5 ha, which gives the lake index of 2.3%. The surface area of the analyzed lakes ranges from 3 to approx. 210 ha, while mean depths range from 1.2 to 6.9 m. Only four lakes have maximum depths of more than 10 m. The total capacity of lakes is 20.5 million m^3, equivalent to the retention index of

60 mm. Ribbon lakes Kłeckie and Gorzuchowskie are the biggest water reservoirs located in the catchment, occupying the area of 209.7 and 94.3 ha, respectively, with mean depths of 4.7 and 2.5 m. Immediate catchments of these lakes are 22.18 km² (Kłeckie) and 18.12 km² (Gorzuchowskie), with total catchment areas of 235.28 km² and 253.66 km², respectively. The ratio of the total area of the lake catchment to the area of the lake for Lake Kłeckie is 112 and for Lake Gorzuchowskie – 269, respectively. Cross slopes for areas immediately adjacent to Lake Kłeckie range from 13 to 55‰ – with a mean of 31‰, while in case of Lake Gorzuchowskie they are from 14 to 90‰ – with a mean of 37%. Immediate catchments of the lakes are typically agricultural, as according to the criteria proposed by an expert team of Nachlik (2004) they are characterized by a very high share of arable land (78.2 and 88.7%) and a very low share of grassland (1.8 and 2.4%, respectively). Also the share of forested areas is low (8.8%) in the immediate catchment of Lake Kłeckie and very low (1.8%) in the catchment of Lake Gorzuchowskie. Below the analyzed lakes the Mała Wełna was built up with weirs, making it possible to dam water in the lakes and modifying the hydrological regime of the river, lakes and ground waters in adjacent areas.

Results

Weather conditions in the catchment in the period of the study were analyzed on the basis of deviations of annual precipitation totals, recorded at a rain-gauging station in Kiszkowo, and mean air temperatures, recorded at the Arboretum station of the Experimental Forest Station in Zielonka, in view of multiannual data recorded in the period of 1988/1989 - 1997/1998 at the station of the Institute of Meteorology and Water Management in Gniezno, located at a distance of 25 km from Kiszkowo. In the multiannual period of 1989 - 2006 mean annual precipitation index was 513 mm, including 202 mm in the winter half-year and 311 mm in the summer half-year. Mean annual air temperature was 8.6°C, including 14.9°C in the summer half-year and 2.2°C in the winter half-year. Weather conditions in terms of air temperature were characterized following a method developed by Lorenc (1998), while in terms of precipitation according to Kaczorowska (1964). The first two years of the study with precipitation totals of 581 and 596 mm, respectively, were humid (probability of exceedence p=32% and p=26%). In 2001, a normal year, temperature was close to the average value (p=63%), while in 2002, a slightly warm year, mean annual temperature was higher than the multiannual mean by 0.7°C (p=16%) (Fig. 2). In the next three years of the study precipitation levels were lower than the average, in 2003 (very dry and slightly cool) annual precipitation total was 345 mm (p=95%) at a mean air temperature of 7.7°C (p=84%). In the next two years, 2004 (dry and normal) and 2005 (dry and slightly warm), precipitation was lower than the multiannual mean by 65 and 57 mm, respectively (p=74% and p=68%), and temperatures were higher than the average by 0.2 and 0.8°C. The last year of the study with precipitation total of 565 mm (p=37%) and a temperature of 9.2°C was average and slightly warm.

Flow rates of the Mała Wełna River at the section line upstream of the Kłeckie Lake varied and ranged from NNQ = 0 $m^3 \cdot s^{-1}$ to WWQ = 1.485 $m^3 \cdot s^{-1}$. Mean flow rate in the years 2001-06 was SSQ_{XI-X} = 0.136 $m^3 \cdot s^{-1}$, while mean annual flow rates ranged from 0.039 $m^3 \cdot s^{-1}$ in 2004 (dry and normal) to 0.287 $m^3 \cdot s^{-1}$ in 2002 (humid and slightly warm). In the successive section lines located between the lakes and below Lake Gorzuchowskie mean annual flow rates of the Mała Wełna River were approx. 2.2 and 2.4 times higher than at the section line above Lake Kłeckie. The coefficient of flow rate variability of mean annual extreme flow rates in the period of study below Lake Gorzuchowskie, expressed as a ratio of WWQ/SWQ was 2.1, while the

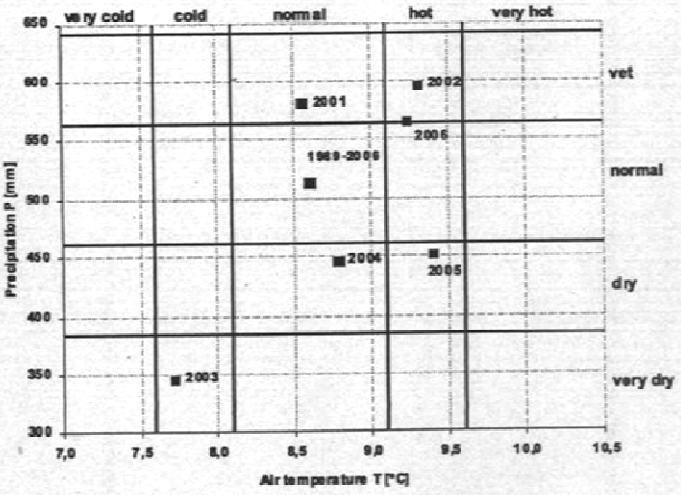

Fig. 2. Thermal and precipitation characteristics of hydrological years 2001 - 2006 in view of multiannual data for the period 1989-2006

coefficient of flow rate ranges (SWQ-SNQ)/SSQ was 3.6; these values were generally lower than in the river without lakes, which are characterized by different flow rate variation dynamics. In case of the volume and distribution of runoff from the catchment a significant effect was found for the 5 weirs and 9 gates located along the Mała Wełna River and on its tributaries and the lakes, through which the river flows and fish ponds located above the section line closing the catchment.

Fluctuations in water levels in the lakes were characterized by seasonal cyclicity. The highest water level was observed during the spring thaw at the turn of February and April, while the lowest in the autumn season at the turn of September and November. The highest water level in Lake Kłeckie was recorded in March 2001 (humid and normal in terms of air temperature), while in Lake Gorzuchowskie in March 2002 (humid and slightly warm). The lowest water levels were recorded in 2004, dry in terms of precipitation and normal in terms of air temperature. Mean annual amplitudes of water levels in the lakes were 58 cm in Lake Kłeckie and 53 cm in Lake Gorzuchowskie. Coefficients of water level variation were 0.78 and 0.40, respectively. In the years of the study a significant downward trend was observed for water levels in the lakes.

The volume of water, which participated in the circulation in the lakes depended on the hydrometeorological situation (greater water volumes participating in humid years) and on their location in the drainage system (greater water volumes participated in the lakes with a greater total catchment area). On average annually in Lake Kłeckie there were 10.7 million m^3 water in circulation, while in Lake Gorzuchowskie it was 11.1 million m^3. The highest balance totals in the lakes were recorded in 2002, a humid and slightly warm year, while the lowest – in 2004, dry in terms of precipitation and normal in terms of air temperature. Differences in water volumes participating in circulation in those years in Lake Kłeckie amounted to 17.04 million m^3 and in Lake Gorzuchowskie - to 17.61 million m^3. High variation of balance totals for the flow-through lakes in the opinion of Borowiak and Barańczuk (2006) may be explained by low underground supply and high surface inflow.

Analysis of components of water balance showed that the vertical water exchange was more important in Lake Kłeckie than in Lake Gorzuchowskie. In the period of the study evaporation from lake surface dominated over supply from precipitation in the vertical phase of water circulation. On average in the years 2001 - 2006 the lakes were supplied by precipitation of 548 mm, which amounted to 10.1 and 4.3% of the input to the balance in Lake Kłeckie and Gorzuchowskie, respectively. Depending on humidity in a given year the supply volume ranged from 385 to 671 mm. On average approx. 593 mm water evaporated from the lakes annually, which constitutes 11.0 and 4.6% of the output of the balance; this value - depending on climatic conditions, i.e. temperature, water vapour pressure and wind velocity - ranged from 496 to 653 mm.

The dominant role in water balance of the lakes was found for the surface phase of the horizontal water exchange. On the input side the river inflow constituted on average 84.8% and 91.1% in Lakes Kłeckie and Gorzuchowskie. In the river inflow to Lake Kłeckie waters of the Mała Wełna constituted 46%, waters of the Dębina watercourse 26%, waters of the Wełnianka 16% and the surface runoff from the immediate catchment 12%, while Lake Gorzuchowskie was supplied mainly by waters of the Mała Wełna and only approx. 7% came from the immediate catchment. On the output side the biggest role was played by the river runoff, which constituted 87.7% and 93.0%, respectively (Fig. 3).

Depending on the hydrometeorological situation in individual years the share of surface inflow in the input side of the balance ranged from 61.9 to 91.6% in Lake Kłeckie and from 74.4 to 93.6% in Lake Gorzuchowskie, while surface runoff constituted 69.6 to 89.0% and 83.1 to 94.8%, respectively, of the output side of the balance. A markedly less significant role in water circulation in the lakes was found for underground supply, which on average accounted for 5.1% and 4.6% for the input side in Lakes Kłeckie and Gorzuchowskie, while underground runoff accounted for 1.1% and 2.1%, respectively. It was observed that Lakes Kłeckie and Gorzuchowskie in the period of the study served the drainage function, which depends mainly on the morphometry of the lake basin and the arrangement of local geological structures. Analysis of the underground supply of the lakes in successive years classified them to the group of lakes with varied functions in the underground water circulation. Depending on the character of a given hydrological year, either the underground supply to the lake or the underground runoff predominated. Volumes of the underground supply and their directions did not depend on the volume of water, which was exchanged in a

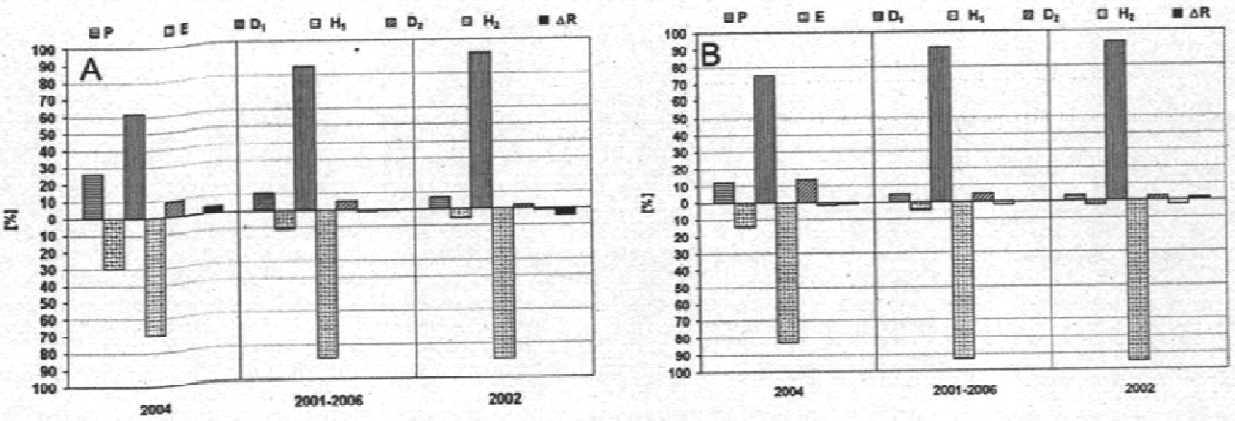

Fig. 3. Water balance of Lakes Kłeckie (A) and Gorzuchowskie (B) in the mean year for the period of 2001 - 2006 and in years with lowest and highest balance totals

given year, which finding does not confirm earlier reports by Bajkiewicz-Grabowska (2004). Probably the primary effect was exercised by weirs located below the analyzed lake, which facilitated water damming in those reservoirs and had a modifying effect on the hydrological regimes of the river, lakes and ground waters in adjacent areas.

The output side of the mean balance in the lakes was supplemented by changes in retention, which constituted only 0.3% water participating in the cycle. In the years, in which lake retention resources decreased, this element in the input side of the balance in Lake Kłeckie constituted from 3.6 to 14.0% and in case of Lake Gorzuchowskie from 0.7 to 1.3%. In the years in which water levels in the lakes were recorded to increase, changes in retention on the output side of the balance constituted from 0.6 to 6.5% and from 0 to 3.4% in Lakes Kłeckie and Gorzuchowskie, respectively.

Quotients of the total inflow and runoff in the lakes ranged from 0.90 to 1.09 (mean 1.01) and they were similar to those in flow-through lakes of north-eastern Poland. This confirms a hypothesis that flow-through lakes, especially those which are successive reservoirs along the course of the river, discharge an identical amount of water as they are supplied. The structure of balance in the analyzed lakes depended on the ratio of the area of the lake to that of the catchment, which in case of Lake Kłeckie was 0.010 and in case of Lake Gorzuchowskie it was 0.004. In such reservoirs the vertical water exchange is of secondary importance in water circulation, while horizontal water circulation plays the main role, especially its surface phase, which confirms reports by Danilovich and Lopuch (2006) and Kilkus and Stonevicius (2004). Calculated coefficients of runoff increase in the analyzed lakes were lower than 0.5, which shows that these reservoirs serve the role of transit objects in the river-lacustrine system of the Mała Wełna according to the classification of lake functions in water circulation, proposed by Borowiak and Barańczak (2006).

Analysis of correlations between annual changes in ground water levels and changes in retention recorded in the lakes showed that the strongest relationship (R^2=0.75) is found between Lake Gorzuchowskie and the well located at a distance of 270 m from the lake. In case of wells located approx. 1 150 m from Lake Gorzuchowskie and approx. 1200 m from Lake Kłeckie no significant effect of the lake (at p_α=0.05) was found on ground water levels in adjacent areas, coefficients of determination amounted to R^2=0.54 and R^2=0.32, respectively (Fig. 4).

Conducted analyses showed a lack of a significant relationship between annual changes in ground water levels recorded in wells located in areas adjacent to the lakes and resultants of underground supply.

Conclusions

1. The biggest role in the lake water balance was found for the surface phase of the horizontal water exchange, which was significantly affected by high lake coefficients.
2. Ribbon lakes Kłeckie and Gorzuchowskie in the period of the study served mainly the drainage function. Analysis of components of water balance in successive years showed that, depending on the character of a given year, either underground supply to the lake or underground runoff predominated,

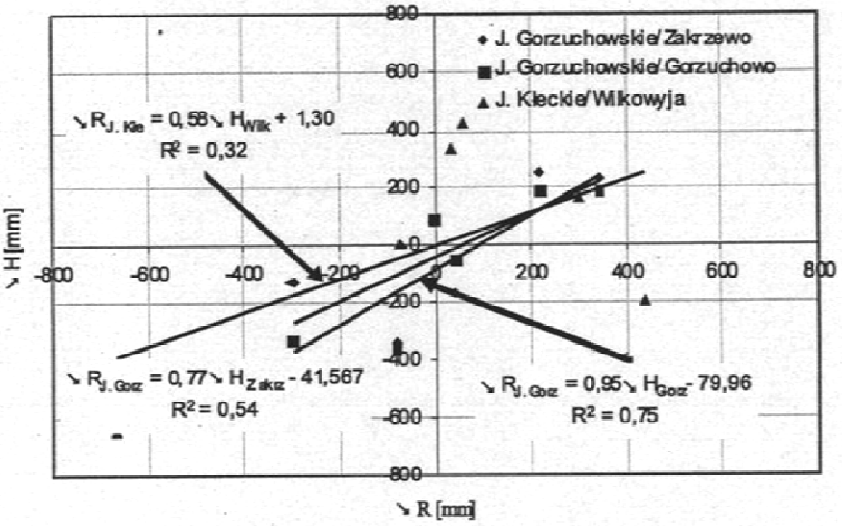

Fig. 4. Dependence between annual changes in ground water levels and changes in retention of Lakes Kłeckie and Gorzuchowskie

which classifies them to the category of lakes with varied functions in the underground water circulation. Probably the main effect was exercised by hydro-engineering structures located below the lakes, which modify the hydrological regime of the river, lakes and ground waters in adjacent areas.

3. In the period of the study no significant relationship was observed between annual changes in ground water levels in shallow wells located in areas adjacent to the lakes, and resultants of underground supply.

Acknowledgments

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References

Bajkiewicz-Grabowska E., 2002, Obieg materii w systemach rzeczno-jeziornych (Circulation of matter in the river-lake system), UW Warszawa, p. 255.

Bajkiewicz-Grabowska E., 2004, The role of lakes in natural groundwater drainage. Vol. 11 Miscellanea Geographica: 175-184.

Borowiak D., Barańczuk J., 2006, Diversity of surface outflow from lakes which perform different hydrological functions. Limnological Review 6: 13-20.

Czarnecka H. (red.), 2005, Atlas podziału hydrograficznego Polski cz. 1 i 2 (Map of Hydrographic Division of Poland), IMGW Warszawa, p. 682.

Danilovich I., Lopuch P., 2006, Water balance and water regime of the lakes in Belarus. Limnological Review 6: 61-64.

Górniak A., Piekarski K., 2002, Seasonal and multiannual changes of water levels in lakes of northeastern Poland. Polish Journal of Environmental Studies Vol. 11, No. 4: 349-354.

Kilkus K., Stonevicius E., 2004, Water balance structure of glacial tunnel lakes. Geografija Vol. 40, No. 1: 15-18 (in Lithuanian).

Kaczorowska Z., 1964, Opady w Polsce w przekroju wieloletnim„ (Precipitation in Poland in long-period averages), Pr. Geogr. IG PAN 33: 12–127.

Kowalczyk S., Ujda K., 1987, Pomiary porównawcze opadów atmosferycznych (Comparative measurements of precipitation), Mat. Badawcze, Seria Meteorologia, 14, IMGW, Warszawa.

Lorenc H., 1998, Ocena stopnia realizacji programu „obserwacje meteorologiczne i badania klimatyczne w systemie zintegrowanego monitoringu środowiska przyrodniczego" oraz synteza uzyskanych wyników badań za okres 1994-1997 In: Kostrzewski (ed.) Zintegrowany monitoring środowiska przyrodniczego. Funkcjonowanie i tendencje rozwoju geoekosystemów Polski, 9th Symposium of ZMŚP. Biblioteka Monitoringu Środowiska Warszawa: 113-118.

Nachlik E. (red.), 2004, Identyfikacja i ocena oddziaływań antropogenicznych na zasoby wodne dla wskazania części wód zagrożonych nieosiągnięciem celów środowiskowych (Identification and impacts assessment of anthropogenic pressures on water resources to indicate water bodies at risk of non-achievement of the environmental objectives), Seria Inż. Środ., Monografia 318, p. 192.