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ANALYSIS OF SELECTED RESERVOIRS FUNCTIONING IN THE WIELKOPOLSKA REGION

Mariusz Sojka, Joanna Jaskuła, Joanna Wicher-Dysarz, Tomasz Dysarz

Poznań Univeristy of Life Sciences

Abstract. The paper presents the problems related to the functioning of reservoirs in the Wielkopolska province and suggests their possible solutions. The reservoirs chosen as examples include typical dam constructions with a single water body (Jeziorsko, Rydzyna), two water body objects with separated preliminary part (Stare Miasto, Kowalskie, Radzyny) and lateral constructions (Pakosław, Jutrosin). The reservoirs were built in period from 1970 to 2014. They differ in construction, functions and water management rules.

Analysis of the main problems related to the reservoir functioning is aimed at finding ways of improving the construction of new reservoirs that would satisfy increasingly stringent environmental and legal restrictions and the methods of water management in the reservoirs. On the basis of a questionnaire filled in by the reservoir operators, the main problem is water quality. Especially the huge inflow of biogenic compounds causes blooms of algae and overgrowth with riparian vegetation. Some difficulties are also related to management of the reservoirs of multi-purpose operation. It is difficult to take into account the requirements of environmental flow maintenance, flood protection, water supply for agriculture and water use for tourism and recreation and hydropower generation, etc.

Keywords: reservoirs, sediment deposition, water quality, Wielkopolska region

INTRODUCTION

In Poland the seasonal variations of water resources as well as the non-uniformity of their spatial distribution are significant. The most abundant water is available in winter and in the beginning of spring, when the water demands are relatively small. In summer, when the agricultural and forests demands are the highest, the available water resources are small and do not meet the needs. On the other hand, the distribution of resources is non-uniform. Seasonally, water deficits occur in over 75% of the country area. The

Corresponding authors – Adres do korspondencji: dr inż. Joanna Wicher-Dysarz, Department of Hydraulic and Sanitary Engineering, Poznań University of Life Sciences, ul. Piątkowska 94A, 60-649 Poznań, e-mail: jwicher@up.poznan.pl.

deficits are the deepest and the most frequent in three regions located in the central part of Poland. These are Wielkopolskie, Kujawsko-Pomorskie and Mazowieckie Voivodships. The greatest flood hazard is observed in regions located in the southern part of Poland, such as Małopolskie, Podkarpackie, Śląskie, Opolskie and Dolnośląskie Voivodships. The increase in national economy effectiveness requires stable water supply, which is related to more uniform distribution of water resources over the year. It may be achieved by construction of water reservoirs. The reservoirs are multi-purpose elements of the water system. Amongst others, the main two aims of their functioning are water supply and flood protection.

Over the last 50 years the approach to planning and design of reservoirs has changed on the basis of experiences with the already existing objects. In the initial period the dam reservoirs were constructed as single water bodies. They are relatively simple, but prone to many negative phenomena, e.g. sediment deposition and degradation of water quality [Dysarz and Wicher-Dysarz 2007, Dysarz and Wicher-Dysarz 2011, Wicher-Dysarz and Przedwojski 2005, Wiatkowski 2015]. The solutions to these problems could be new constructions of storage reservoirs, e.g. dam reservoirs consisting of two water bodies including the main and the so-called preliminary parts. Such solutions enable reduction in the sediment deposits spread and better control of water quality in the main part [Kasperek and Wiatkowski 2008, Dysarz and Wicher-Dysarz 2013, Wicher-Dysarz and Kanclerz 2012, Jaskuła et al. 2015]. Another solution proposed for prevention of negative effects of several processes in the reservoirs is construction of lateral reservoirs, which has been applied more frequently in the last decades [Przybyła and Kozdrój 2013, Przybyła et al. 2014]. The lateral reservoirs have slight impact on hydrological regime of rivers and they are less prone to sedimentation due to their location with respect to the channel. In Wielkopolska region the water stored in the reservoirs is used primarily for irrigations. The other purposes of the reservoirs functioning are flood protection, hydropower generation, fishing and recreation. In Wielkopolska region there are 36 reservoirs (dammed lakes and man-made reservoirs) operated by Wielkopolskie Management of Drainage, Irrigation and Infrastructure (WZMiUW).

The total capacity of these reservoirs is $57.8 \cdot 10^6$ m^3. The next two reservoirs, Jeziorsko and the Poraj, are located on the Warta river and they are operated by Regional Board for Water Management (RZGW).

The reservoir is a dynamic system, which is subject to changed due to interactions with the environment. The problems of reservoirs functioning may be divided into technical, non-technical and administrative (Table 1).

Table 1. Classification of problems related to reservoir functioning and operation

Technical	Non-technical	Administrative
Dam failure;	Water resources;	Reservoir operation;
Failure of water release elements;	Water quality;	
Damage to the reservoir embankments;	Sediment accumulation;	
Failure of other structures, e.g. fish-pass, hydroplant, etc.;	Vegetation growth;	
	Bloom of cyanobacteria;	

The aim of this paper is analysis of problems related to reservoir functioning and operation in the Wielkopolska region. The analysis is made for selected reservoirs of different constructions, i.e. single body reservoirs (Jeziorsko, Rydzyny), double water body reservoirs with preliminary part (Kowalskie Lake, Stare Miasto, Radzyny) and lateral reservoirs (Pakosław, Jutrosin). The problems diagnosed are analyzed taking into account several elements: (1) morphometric parameters of construction, (2) physiographic conditions in the drainage basins, (3) hydrologic conditions, (4) water quality in the inflows, (5) conditions of wastewater management in the drainage basin.

MATERIAL AND METHODS

Analysis of the reservoir functioning was made in three steps. At first the reservoir operators, WZMiUW and RZGW in Poznań, were asked to fill in the questionnaire on reservoir operation and functioning. The survey was made in 2016. In the second step, on the basis of a thorough literature peruse, the main problems related to the reservoir functioning were identified. In the last step the results of our investigation of Jeziorsko, Stare Miasto, Kowalskie, Radzyny and Rydzyny reservoirs were analyzed. We examined the reservoir impact on the flow regime, the sedimentation in the reservoirs and pollution of water and bottom deposits.

The hydrological conditions were characterized on the basis of daily flows observed in 1951–1990. The mean flows were calculated for each river in the cross-section. The analyzed values were determined for location of the main dam of the standard reservoirs built along the river, or for location of inlet structures in the lateral objects. For this purpose the data for period 1950–1990 as well as the information from *Atlas of Gauge Stations for National Monitoring of the Environment – Catchment of the Oder River* were used. The rivers on which the analyzed reservoirs are located, are monitored systematically by the Institute of Meteorology and Water Management (IMGW-PIB). The data for Rów Dąbiecki are based on mean unit outflows from "Hydrological Atlas of Poland". The calculated mean flows with the information about the reservoir capacity for Normal Water Level (NPP) enabled determination of average time of water exchange in the reservoir.

The parameters describing water quality in the rivers inflowing to the analyzed reservoirs were evaluated on the basis of annual reports published by the Regional Inspection for the Environment Protection (WIOŚ). The classification of water quality indexes for flowing waters in provinces of Wielkopolska and Łódzkie for periods 2013–2015 was used. The analysis included 13 indexes of water quality describing physical and chemical parameters (water temperature, dissolved oxygen, biochemical oxygen demand, total organic carbon, electric conductivity, total hardness, pH, ammonium nitrogen, Kjeldahl nitrogen, nitrate nitrogen, total nitrogen, phosphates, and total phosphorus). Conditions of water and wastewater management in the direct watersheds of the investigated reservoirs were analyzed on the basis of the data available from Local Database (BDL) of Central Statistical Office (GUS) in Warsaw.

RESULTS

Taking into account the hydrographic features the reservoirs are located in the Oder river basin (Fig. 1). As regards the administrative division, the reservoirs are located in the Wielkopolskie Voivodship. The exception is the Jeziorsko reservoir, which is located on the border of the Wielkopolskie and Łódzkie Voivodships.

Fig. 1. Reservoirs location

The Jeziosko and Poraj reservoirs are managed by the Regional Board for Water Management in Poznań. The Wielkopolskie Management of Drainage, Irrigation and Infrastructure takes care of the Kowalskie, Stare Miasto, Radzyny, Rydzyna, Pakosław and Jutrosin reservoirs.

The oldest of them is the Kowalskie reservoir on the Główna river, which started to operate in 1984. The newest one is the Rydzyna reservoir in the stream called Rów Dąbiecki. This object has been working since 2013. The greatest is the Jeziorsko reservoir. Its inundation area for Normal Water Level (NPP) is 3694 ha. The smallest one is the Pakosław reservoir with inundation area of 26.6 ha. The basic parameters of the reservoirs are shown in Table 2.

The Kowalskie reservoir is located on the Główna river. This river is a right-side tributary of the Warta river. The outlet of the Główna river is located at km 240 of the Warta river. The main dam of the Kowalskie reservoir is located at km 15+423 of the Główna river. The total watershed area of this reservoir is 189.38 km^2. The Kowalskie is a two water-body object with separated preliminary part. The additional dam, splitting the reservoir into two parts, is located at km 19+888 of the Główna river. The inundation area of the preliminary part is 40.4 ha. The area of the main part equals 162.8 ha [Wicher-Dysarz and Kanclerz 2012].

Table 2. Basic parameters of the reservoirs and their functions

Name	River	Start of operation	Inundation area MaxPP/NPP [ha]	Capacity MaxPP/ NPP [mln m^3]	Mean depth [m]	Construction	Functions
Kowalskie Lake	Główna	1984	203/195.1	6.580/5.970	3.1	dam reservoir of two water bodies with preliminary part	flood wave reduction, supply of water for agriculture, maintenance of low flows, tourism, recreation, fish farming
Jeziorsko	Warta	1986	4230/3694	202.800/143.00	4.5	dam reservoir of single water body	flood protection, management of water resources, electricity production, fish farming, recreation, tourism, maintenance of conditions for water birds
Radzyny	Sama	2000	118.87/109.44	3.451/2.880	1.6	dam reservoir of two water bodies with preliminary part	flood wave reduction, water retention for agriculture, in the winter period water supply for of sugar refinery in Szamotuły, tourism, recreation, fish farming
Stare Miasto	Powa	2006	/90.68	2.637/2.159	2.4	dam reservoir of two water bodies with preliminary part	flood protection, water retention for agriculture, maintenance of minimum acceptable flow, electricity production, tourism, recreation, fish farming
Pakosław	Orla	2006	29.80/26.60	1.010/0.330	1.3	lateral	reduction of flood wave, water retention for agriculture, increase of groundwater table in the reservoir impact zone, fire protection of nearby forest areas, tourism, recreation, sport fishing
Jutrosin	Orla	2011	91.40/90.50	2.100/1.900	2.1	lateral	reduction of flood wave, water retention for agriculture, increase of groundwater table in the reservoir impact zone, fire protection of nearby forest areas, tourism, recreation, sport fishing
Rydzyna	Rów Dąbiecki	2013	41.7/40.6	0.963/0.757	1.9	dam reservoir of single water body	flood protection of Rydzyna town, flood wave routing, maintenance of low flows, water retention for agriculture, tourism, recreation, sport fishing

The Jeziorsko reservoir is located in the central part of the Warta river course, from km 484+300 (main dam) to km 503+800 (inlet). The inundation area is 9021.8 km^2.

The next reservoir, the Radzyny, was built on the Sama river. The Sama is a left-side tributary of the Warta river. The outlet of the Sama is located at km 181+900 of the Warta river. The construction of this reservoir is similar to the Kowlaskie one. The Radzyny is a two water-body reservoir with separate preliminary part. The main dam is located at km 20+760 of the Sama river. The additional dam is at km 23+540. The inundation area of the preliminary part is 29.13 ha. The area of the main part is 80.31 ha. The watershed area of this reservoir equals 239.90 km^2 [Jańczak et al. 2005].

The next reservoir analyzed is the Stare Miasto one. This reservoir is located in the Powa river, which is a left-side tributary of the Warta river. The outlet of the Powa is located at km 396+100 of the Warta. The main dam of the reservoir is in km 13+800 of the Powa river. The Stare Miasto reservoir is two water bodies object with additional dam located in km 12+000. The inundation area of the main part is 63.68 ha and the preliminary part area equals 27.00 ha. The watershed area of this reservoir is 302.35 km^2.

The Pakosław and Jutrosin reservoirs are located in the watershed of the Orla river. The Orla stream is the third order channel and outflows to the Barycz river at km 34+600. Pakosław and Jutrosin are lateral reservoirs. The inlet structures are located at km 32+715 and km 45+710 of the Orla river [Przybyła et al. 2014]. The watershed area of the Pakosław reservoir is 788.98 km^2. The Jutrosin reservoir has the watershed of the area 516.23 km^2.

The last of the analyzed reservoirs is a single water-body reservoir called Rydzyna. This reservoir is located on the stream called Rów Dąbiecki. The Rów Dąbiecki is stream of the fourth order and a right-side tributary of the Rów Dąbiecki channel. The outlet of the Rów Dąbiecki is located in km 8+100 of the Polski Row. The main dam is built at km 1+935. The total watershed area of the Rydzyna reservoir is 26.4 km^2.

Over 32 years, since the oldest reservoir started to operate, the problems related to functioning of the analyzed objects have been observed. On the basis of the questionnaire data, analysis of available scientific publications and our own research, it has been established that the most frequent problem of reservoirs functioning is the water quality (Tab. 3). The problems with water quality are related to the amount of biogenic compounds transported to reservoir with water flow and sediments deposited in the water body. The results of high load of biogenic compounds are seasonal bloom of algae and reservoir overgrowth with riparian vegetation. The intensive overgrowth has been observed in the relatively new reservoirs like Stare Miasto, Radzyny, Pakosław and Jutrosin.

The amount of the biogenic compounds in the reservoir depends on the land use in the watershed. In the watersheds of Rydzyna, Kowalskie, Radzyny, Pakosław and Jutrosin reservoirs the arable lands dominate (Table 4). In addition there is threat of biogenic compounds inflow from point sources. The ratio of people using sewage systems in the reservoir watersheds varies from 21.8% (Stare Miasto) to 67.5% (Radzyny). In such conditions, the loads of the biogenic compounds in the analyzed reservoirs are great. The unit loads of the total nitrogen inflowing into the reservoirs equal from 82.7 to 209.0 g $\cdot$ m^{-2}. The loads of total phosphorus vary from 3.6 to 14.7 g

· m^{-2}. These values significantly exceed permissible and dangerous levels determined for the analyzed reservoirs on the basis of the Vollenweider model (1976). The ratio of nitrogen to phosphorous N:P in these reservoirs varies from 13.7 to 38.4. In practice, the N:P ratio lower than 10 means the deficits of nitrogen, while N:P greater than 20 implies the deficit of phosphorous. In the majority of the reservoirs the phosphorous is the factor limiting the bio-production.

Table 3. Problems related to reservoir functioning and operation

Kind of problem	Reservoir						
	Jeziorsko	Rydzyna	Kowalskie Lake	Stare Miasto	Radzyny	Pakosław	Jutrosin
Dam failure							
Dam seepage							
Dam break							
Dam subsidence					+		
Dam movement				+	+		
Failure of water release elements							
Wrong functioning of the fish pass - design errors				+			
Wrong functioning of hydroplant - design errors				+			
Fluvial processes - bank erosion							
Lack of inflows suitable to maintenance of NPP		+		+	+		
Poor water quality		+	+		+	+	+
Sediment accumulation	+			+			
Bloom of algae	+	+	+	+	+	+	+
Overgrowth with riparian vegetation	+		+	+	+	+	+
Problems of management related to different functions of the reservoir	+			+		+	+

Table 4. Reservoir characterization and nitrogen and phosphorus unit loads

Parameters	Reservoir						
	Jeziorsko	Rydzyna	Kowalskie Lake	Stare Miasto	Radzyny	Pakosław	Jutrosin
Average time of water retention in the reservoir [d]	33	109	90	20	50	122**	122**
Intensity of water exchange [-]	11.0	3.3	4.1	18.6	7.4	3*	3*
Index of arable lands [%]	46.1	56.9	62.1	45.2	71.2	73.2	81.2
People using sewage system [%]	36.3	52.1	57.1	21.8	67.5	46.8	47.9
Average load of the nitrogen inflowing to the reservoir [g $N \cdot m^{-2}$]	134.8	138.6	112.0	179.0	209.0	82.7	139.9
Average load of the phosphorous inflowing to the reservoir [$g \cdot P \cdot m^{-2}$]	6.4	3.6	8.2	14.7	9.9	4.1	6.9
Permissible / dangerous load of nitrogen [$gP \cdot m^{-2} \cdot r^{-1}$] ***	0.92/1.85	0.55/1.10	0.74/1.47	0.63/1.27	0.50/0.99	0.44/0.88	0.59/1.17
Permissible / dangerous load of phosphorous [$gP \cdot m^{-2} \cdot r^{-1}$] ***	0.06/0.12	0.04/0.07	0.05/0.10	0.04/0.08	0.03/0.07	0.03/0.06	0.04/0.08
Average ratio N:P [-]	21.1	38.4	13.7	12.2	21.2	20.4	20.4

Analysis of morphometric parameters of the reservoirs shows that the analyzed objects are relatively shallow. Because the thermal stratification of lakes and reservoirs is not observed if the mean depths are in the range 1.3–4.5 m, the seasonal vertical circulation of water does not take place in them, which makes the investigated objects prone to degradation. Particularly prone to degradation are Rydzyna, Kowalskie, Pakosław and Jutrosin reservoirs in which the intensity of the water exchange is lower than 5 times a year. Such a low intensity of water exchange per year classifies them into the limnetic reservoirs. The retention time of water in the Rydzyna, Kowalskie, Pakosław and Jutrosin reservoirs varied from 90 to 122 days, which makes them vulnerable to eutrophication. As the development of plankton is known to depend not only on the content of nutrients in the water, but also significantly on the water retention time. Additionally, the low flow velocity is accompanied by the faster heating up of surface layer of water, which together with its sufficient biogenic content and abundant sunshine, creates favorable conditions for the development of plankton.

The problems with working out optimal decision rules are observed in almost each analyzed reservoir. They stem from the fact that the reservoirs are bound to carry out a number of functions whose realization is often related to conflicting demands. An example may be the obligation for retention of water for agricultural needs and maintenance of assumed water level for recreation and fish farming.

The problems of the sediment deposition in the reservoir are much less frequent. They were noted only in two reservoirs. The process of sediment accumulation in the reservoir is linked to the reservoir performance. The reservoirs may work with a constant water level as well as with varying headwater. The second type of the reservoir functioning is typical of multi-purpose objects. The process of sediment accumulation in constant water level conditions differs significantly from the same process occurring in the conditions of seasonal changes in water level. Also the type of reservoir is of importance. In the dam reservoir such as the Jeziorsko one, the sediments are deposited mainly in the inlet part. It is a result of rapid decrease in the flow velocity and the related decrease in transport capacity of the stream. The deposits cause an increase in the water levels in the inlet part as well as in the backwater part of the inflowing river [Przedwojski and Wicher-Dysarz 2005, Wicher-Dysarz and Dysarz 2011]. The bottom slope also decreases drastically in this reach. It may also cause scattering of sediments and movement of deposits downstream into the deeper parts of the reservoir.

Because of the ornithological reserve that has been functioning since 1998 in the Jeziorsko reservoir, it is not possible to make any works aimed at changes in the reservoir banks and bottom such as regulation, removal of trees, dredging, etc.. Hence, the measurements done there are homogeneous and suitable for proper recognition of the processes occurring. The reservoir operates in the annual cycle and the water level variation reaches 5.5 m. In the 30 years of the reservoir performance, the average increase in the bottom elevations in the inlet part of the reservoir should be of about 2.25 cm. However, the distribution of the sediments in the inlet part in non-uniform. The accumulation takes the form of local islands and bottom upheavals near agglomerations of vegetation [Wicher-Dysarz and Dysarz 2011].

Especially intensive process of sediment accumulation was observed in the Stare Miasto reservoir during the first years of the reservoir functioning. Since that time seve-

ral negative processes related to sediment transport have been observed. This reservoir undergoes changes in the annual cycle. The range of water level variation in the main part is 1.5–2.0 m. In the preliminary part, a constant water level is kept all the year. The highest intensity of the sediment accumulation is observed in the preliminary part of the reservoir. The availability of historical data from 2006 and field measurements from 2013 enable the assessment of sediment deposits. The amount of accumulated material is about 0.026 million m^3 after 7 years of the reservoir operation. It gives the average amount of the preliminary part sedimentation as 3.6×10^{-3} million m^3 per year. On the other hand, the sediment deposition is not observed in the main part of the reservoir.

In the last years, the problems with maintenance of suitable water levels during summer low flows have been observed in the Radzyny, Stare Miasto and Rydzyna reservoirs. The especially low flows or their total lack is typical of the Rów Dąbiecki, which is the main water source for the Rydzyna reservoir.

The technical problems related to the exploitation of the dam and release structures are reported less frequently. If they are observed, the main reasons are small failures and typical ageing of the structures used. The problems of the dam subsidence and small movement are only observed in the Radzyny reservoir. In the Stare Miasto reservoir the internal dam was moved during the flood in 2014. In this reservoir the problems with improper functioning of the fish pass and hydroplant are observed. The reasons for such difficulties are related to the design assumptions.

CONCLUSION

1. The reservoirs functioning in agricultural environment in the Wielkopolska province is prone to huge biogenic loads. The results are seasonal blooms of algae.
2. The dynamic process of riparian vegetation overgrowth is a result of small depths, lack of stratification and huge exposition to solar radiation, inflow of biogenic compounds and significant changes in water level.
3. In planning of new reservoirs, their location and morphometric parameters should be chosen so as to minimize the influence of external factors causing degradation of water quality.
4. The functions of the reservoirs should be planned in such a way that the possibly conflicting interests of different users are minimized.

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ANALIZA FUNKCJONOWANIA WYBRANYCH ZBIORNIKÓW WODNYCH NA OBSZARZE WIELKOPOLSKI

Streszczenie. W pracy przedstawiono problematykę funkcjonowania zbiorników retencyjnych w województwie wielkopolskim na przykładzie zbiorników jednostopniowych (Jeziorsko, Rydzyna), dwustopniowych z wydzieloną częścią wstępną (Stare Miasto, Jezioro Kowalskie, Radzyny), oraz zbiorników lateralnych (Pakosław i Jutrosin). Zbiorniki te zostały wybudowane w latach 1970–2014, charakteryzują się one różną konstrukcją, funkcjami oraz sposobem prowadzenia gospodarki wodnej. W pracy omówiono główne problemy funkcjonowania zbiorników retencyjnych w kontekście budowy nowych zbiorników. Uwzględniono ograniczenia środowiskowe i prawne oraz zmiany w podejściu do sposobu prowadzenia gospodarki wodnej. Na podstawie kwestionariusza wypełnionego przez operatorów zbiorników, głównym problemem funkcjonowania w zbiornikach wodnych jest niedostateczna jakość wody. Akumulacja związków biogennych w zbiorniku prowadzi do okresowych zakwitów sinic oraz intensywnego przyrostu roślinności litoralnej. Celem pracy było określenie problemów zwianych z zarządzaniem zbiornikami wielofunkcyjnymi, które muszą pogodzić zarówno wymagania środowiskowe, ochronę przeciwpowodziową, zaopatrzenie w wodę dla rolnictwa i wykorzystanie wody do celów turystycznych i rekreacyjnych oraz wytwarzania energii wodnej itp.

Słowa kluczowe: zbiorniki retencyjne, osadzenie się rumowiska, jakość wody, Wielkopolska

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