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ORIGINAL PAPER

THE USE OF WATER QUALITY INDICES (WQI AND SAR) FOR MULTIPURPOSE ASSESSMENT OF WATER IN DAM RESERVOIRS

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Abstract

The paper intends to show the potential of diverse benefits of two water quality indices used to assess 4 dammed lakes in lowland area in NE Poland: the Water Quality Index (WQI), developed by the Scottish Development Department, used in the assessment of water potential for human consumption, fisheries, industries and recreation, as well as the Sodium Adsorption Ratio (SAR), recommended by the Salinity Laboratory of the US Department of Agriculture, used in the water assessment for the irrigation purpose. Our study was based on the results of a water quality monitoring programme, in which the following water parameters have been analyzed: pH, dissolved oxygen, electrical conductivity, biological oxygen demand, chemical oxygen demand, NH_4^+, NO_3^-, Cl^-, SO_4^{2-}, Na^+, Ca^{2+}, Mg^{2+} and HCO_3^-. The water quality parameters differed among the studied reservoirs, and represented a medium (Wykrot) and poor class (Grodzisk Duży, Karwacz and Łoje) on a 5-degree WQI scale. The SAR was less diversified and water in the studied reservoirs showed class I. The results revealed that the water in all the reservoirs is suitable for irrigation with no hazard to the soil structure as well as for breeding of fish that tolerate lower water aeration. This water can be also used for recreational purposes, although direct contact with water is not recommended. The water quality indices (WQI and SAR) showed a great potential in the assessment of water for multi-purpose usage. The WQI and SAR are excellent tools for summarizing overall water quality conditions over space and time. When used together, they are also a method of providing relevant information for specific water use that can be more readable for planners and managers.

Keywords: water assessment, SAR, WQI, man-made lakes.

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INTRODUCTION

A key element of proper water management is the assessment of both quantity and quality of water resources (HOUSE 1989, OBOLEWSKI 2009, OBOLEWSKI, GLIŃSKA-LEWCZUK 2013, KOC et al. 2010, WONS et al. 2014, SZEJBA et al. 2016). The multisectoral use of water resources, i.e. for water supply and sanitation, agriculture, industry, urban development, hydropower generation, inland fisheries, transportation, recreation, low and flat land management and other activities, requires rational water quality measures. Analysis of a single water quality parameter in relation to its standard value, due to a large number of data processed, is laborious and difficult to be interpreted by non-specialists. The importance of managing water resources in an efficient and sustainable manner requires the development and application of new water classification systems in order to gather, assimilate, analyse and display multisectoral information on water resources and to optimize decision making. Among them, water quality indices have been developed as simple and easy tools addressed to engineers, managers and decision-makers in the field of water quality and its potential use (HOUSE, ELLIS 1987, CUDE 2001). Thus, classification of water according to specific types of use has become increasingly important.

Applying a general water quality index to the multipurpose use of water may lead to conclusions which do not seem entirely valid, primarily because the importance and influence of water quality properties vary for different uses (STONER 1978). For example, water temperature is relatively unimportant in water used for irrigation but is of vital importance for aquatic life. Most of the analytical data presently available do not contain a complete suite of properties required for an application to one or more of the indices. The assessment of water for public purposes with the Water Quality Index WQI is based on water quality parameters selected according to: (1) hazard to human health, (2) significant economic benefits, (3) significant aesthetic effects, and (4) the ability to render suitable water to the majority of consumers (STONER 1978**)**. The index the Sodium Adsorption Ratio (SAR) has been developed to assess whether water is suitable for irrigation (WILCOX 1955). The SAR is a measure of the degree to which irrigation water tends to enter into cation-exchange reactions in soil. High values of the SAR imply that sodium may be replacing absorbed calcium and magnesium in the soil, which is damaging to the soil structure.

The aim of the study was to evaluate water in four lowland dam reservoirs for multisectoral use based on quality indices (WQI and SAR).

MATERIALS AND METHODS

Study objects

The water quality monitoring has been performed on four dam lakes: Grodzisk Duży, Karwacz, Łoje, and Wykrot, located on the Północno-Mazowiecka Lowland in north-eastern Poland (Figure 1), within the coordinates: 52°57′36″N and 53°19′42″N as well as 20°48′32″E and 21°43′57″E.

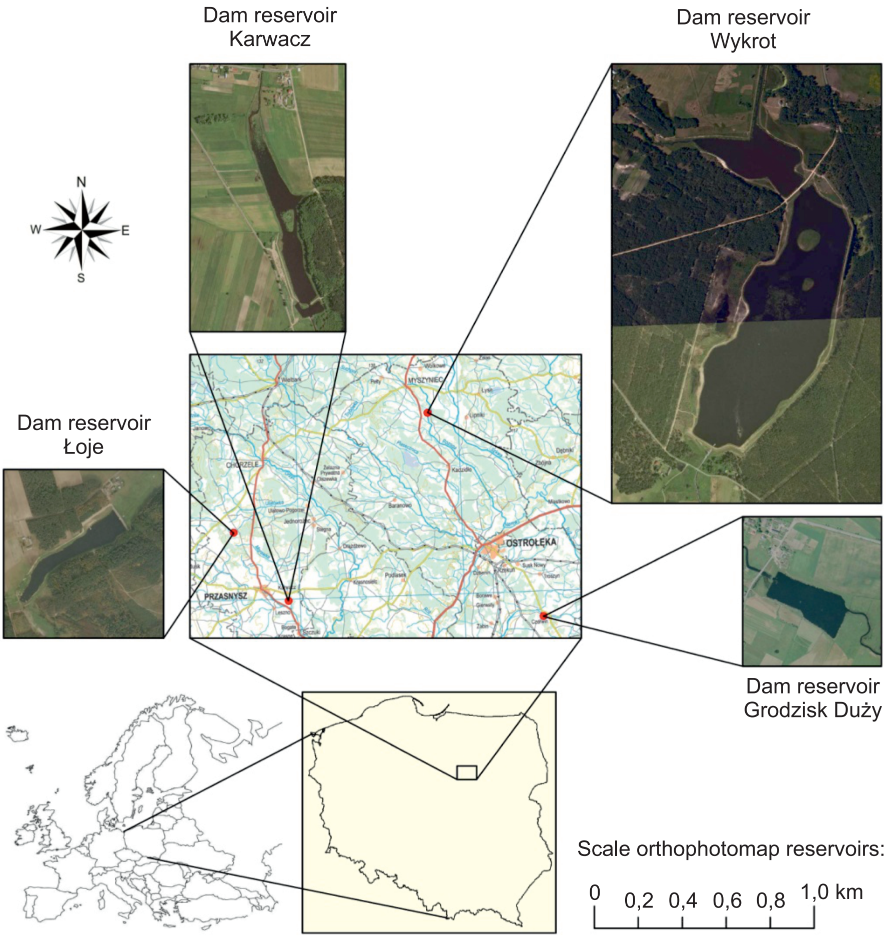


Fig. 1. Location of the dam reservoirs

The origin of the reservoirs is related to the construction of dams on rivers. Wykrot Lake is divided by a weir into a preliminary and main part. Its main tributary is the Rozoga River. A smaller watercourse called the Pełtówka and a reclamation ditch also recharge the preliminary reservoir.

Agricultural and forestry land uses prevail in the catchment of Wykrot Reservoir. The rivers supplying Wykrot and Grodzisk Duży receive outflows from wastewater treatment plants (in a distance 8 and 2 km above the reservoirs, respectively). No point sources of pollution have been identified in the catchments of Karwacz and Łoje. Basic morphometrical parameters of the reservoirs are presented in Table 1.

Table 1

Morphometrical parameters of the reservoirs covered by the present study

Parameter	Reservoir				
	Grodzisk Duży	Karwacz	Łoje	Wykrot	
				preliminary basin	main basin
Location on the river:	Orz	Morawka	Łojówka	Rozoga	
Catchment area (km^2)	300	155	6	275	
Water table area (ha)	5.1	10.2	4.6	8.3	43.7
Capacity (10^3 m^3)	68	122	55	83	687
Average depth (m)	1.3	1.2	1.2	1.0	1.5

Water sampling and analytical procedures

Water for chemical analyses was sampled monthly, in each year of the study (2007–2013), from the subsurface layer in the middle part of each of the four dam lakes. *In situ* measurements of pH, dissolved oxygen (DO), electrolytic conductivity (EC) were performed using a YSI 6600R2™ calibrated multiprobe (Yellow Springs, OHIO, USA). The concentrations of NH_4^+, NO_3^-, Cl^-, SO_4^{2-}, Na^+, Ca^{2+}, Mg^{2+}, HCO_3^- as well as biological oxygen demand (BOD_5), chemical oxygen demand (COD) were determined in a laboratory with the use of standard analytical methods (APHA 1992).

Water Quality Index (WQI)

The Water Quality Index (WQI) was calculated based on physico-chemical water parameters recommended by the Scottish Development Department (House 1989).

The water quality index (WQI) used in the research had been chosen out of many WQI calculating methods based on water quality parameter (Smith 1990, Cude 2001, Gupta et al. 2009). We applied a modification of the original Scottish Water Quality Index (House 1989, Bordalo et al. 2001, Ionuş 2010, Breabăn et al. 2012). The 9-parameter index consists of an aggregation of three groups of parameters: physical (temperature, conductivity, total suspended solids), chemical (dissolved oxygen pH, ammonia, nitrate) and organic (biological oxygen demand, chemical oxygen demand). All data were log-10-transformed to standardize the data to a mean of zero and a standard deviation of one to eliminate scale biases.

The chosen method for the aggregation of sub-indices (weighted arithmetic average) is particularly suitable for the indexation of general water quality, as stated by HOUSE (1989). The final, modified, arithmetic, weighted index is the result of squaring the sum of the products of water quality ratings (q_i) and weighing each individual parameter (w_i) according to the following equation (BORDALO et al. 2001):

$$WQI = \frac{1}{100}\left[\sum_{i=1}^{n} q^i \cdot w_i\right]^2,$$

where:

n – number of sub-indices aggregated,

qi – quality rating, expressed as the 0 - 100 sub-index rating for each variable

w_i – weight of each individual parameter (Table 2).

We followed four main steps involved in the development of a water quality index (ABBASI 2012): i) parameter selection; ii) transformations of the parameters of different units and dimensions to a common scale; iii) assignment of suitable weights to the respective parameters; iv) evaluation of the final index score through the aggregation of the respective sub-index. Modification of the WQI method relies on the adjustment of water physico-chemical parameters to the prevailing anthropogenic influences on water resources in NE Poland (Table 2).

Table 2

List of physico-chemical properties of water used for the WQI calculations and weights assigned to each individual water parameter (w_i)

Parameter	EU water quality standards	Median ranking	Intermediate weighting	Final weighting
Dissolved oxygen (DO)	100**; 6***	11	0.244	0.25
Biological oxygen demand (BOD_5)	5**; 3***	9	0.200	0.20
Chemical oxygen demand (COD)	40**	7	0.155	0.16
Electrical conductivity (EC)	2500 uS cm^{-1} *; 1000 uS cm^{-1} **	5	0.111	0.11
Ammonium (NH_4^+)	0.5 mg dm^{-3} *	4	0.088	0.09
Nitrate (NO_3^-)	50 mg dm^{-3} *' **	4	0.088	0.09
pH	>6.5; <9.5	2	0.044	0.04
Chlorides (Cl^-)	250 mg dm^{-3} *, **	2	0.044	0.04
Sulphates (SO_4^{2-})	250 mg dm^{-3} *	1	0.022	0.02
Total		45	1.000	1.00

Denotations: * The Drinking Water Directive (Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption); ** Surface water regulations (1989); *** Freshwater Fish Directive [78/659/EEC]

The WQI values obtained were referred to five water quality classes: 10 - 25% – very polluted, 26 - 50% – polluted, 51 - 70% – reasonable, 71 - 90% – good, 91-100% – very good (House, Ellis 1987).

An advantage of the WQI is that it allows determination of a potential economic use of water, which in itself is an important instrument to be employed in water management. To achieve this aim, a scale was developed showing how given water resources can be used (Table 3).

Table 3

Classification of water usage domains according to WQI values (House, Ellis 1987)

WQI score	Potable water supply	Fish and wildlife	Industry	Recreation
100	No treatment		selected uses	
	required		without treatment	
90		suitable for all		
		species of fish and	minor purification if	suitable for all
80	Minor purification	wildlife	high quality water is	recreation
			required	activities
70				
		doubtful for game	no treatment for	
60		fish.	most uses	
		supports populations		doubtful for direct
50	Conventional	of coarse fish		contact sports
	treatment		advanced treatment	
40			required for most	indirect and
		reasonable coarse	uses	non-contact
30	Advanced treatment	fisheries		activities only
			only industries	
20			needing poor quality	non-contact uses
	Doubtful use	tolerant species only	water	only
10				
	Unacceptable	unacceptable	unacceptable	unacceptable

Sodium adsorption ratio (SAR)

The SAR is commonly used as an index for evaluating the sodium hazard associated with an irrigation water supply, indicating potential hazard to the soil structure (Rashidi, Seilsepour 2008). The SAR is a measure of a degree to which Na^+ in water used for irrigation has a tendency to replace calcium and magnesium in the soil sorption complex. The sodium adsorption ratio (SAR) has been calculated according to Stoner (1978):

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}},$$

where:

Ca^{2+}, Mg^{2+}, Na^+ – the concentrations of ions in milliequivalents per liter (meq dm^{-3}).

As a rule, water that has a SAR > 3 is safe for crop irrigating and other landscape plants. Water that has a SAR < 9 can cause severe permeability problems when applied to fine-textured soils (for example, silty clay loam) and should be avoided. High values of the SAR are the evidence of intensive ion exchange, harmful for the soil structure and leading to soil degradation. Sandy soils (typical of the studied area) are usually less susceptible to problems related to the structure and soil permeability. Thus, the SAR calculated for light sandy soils can be slightly higher.

When water used for irrigation contains relatively high amounts of bicarbonate ions, bicarbonate can affect the calcium and magnesium concentrations in soil to which the water is applied. For this reason, some researchers (e.g. Lesch, Suarez 2009) report an "adjusted SAR" that takes into account the water's bicarbonate and total salinity as well as calcium, sodium and magnesium contents. In the case of the reported dam reservoirs, which are not characterized by an elevated level of bicarbonates and salinity, the primary SAR formula given by House (1989) has been used.

Statistical procedures

Significant differences in the WQI and SAR among the studied reservoirs emerged from an application of the one-way analysis of variance (ANOVA) followed by the Duncan's multiple range test at $p \leq 0.05$. Principal Component Analysis (PCA) has been used to simplify the problem of data reduction. PCA, a powerful multivariate statistical technique, is applied to reduce the dimensionality of a data set while retaining as much as possible the variability present in the data set and allowing for an assessment of associations between variables. In the present study, hierarchal cluster analysis (HCA) has been employed in a data set to detect similarity between the studied lakes in terms of overall water quality parameters. The data set was treated by the Ward's method of linkage with the Euclidean distance as a measure of similarity. All statistical calculations were performed in Statistica v.10.0 PL and CAP5 (Pisces Conservation Ltd., Hampshire, UK).

RESULTS AND DISCUSSION

The analyzed reservoirs possess features of eutrophic lakes, with the water pH close to neutral and moderate mineralization expressed by the EC within 286 μS cm^{-1} do 546 μS cm^{-1} (Table 4). Like most of water bodies in post-glacial landscapes, the ionic composition of water is dominated by HCO_3^- and Ca^{2+} with a considerable share of SO_4^{2-} ions. Although they are flow-through water reservoirs, with a high average water-dissolved oxygen content (9.04 - 10.39 mg dm^{-3}), the lakes are characterized by the high variation of oxygen resources, from periodic oxygen deficits to water oversaturation with oxygen. Grodzisk Duży is distinguished by demonstrably higher concentrations of nutrients and analyzed ions. For example, its water has much higher concentrations of nitrates (8.65 mg dm^{-3}) than the other three reservoirs (from 0.84 mg dm^{-3} in the water of Wykrot to 3.28 mg dm^{-3} in the water of Karwacz). Similarly, Grodzisk Duży had distinctly higher concentrations of Na^{+} (9.3 mg dm^{-3}), Ca^{2+} (84.8 mg dm^{-3}) and Mg^{2+} (13.7 mg dm^{-3}) than determined in the waters of the other three lakes (Na^{+}: from 5.1 mg dm^{-3} in the water of Łoje to 7.6 mg dm^{-3} in the water of Karwacz; Ca^{2+}: from 50.4 in the water of Łoje to 74.4 mg dm^{-3} in the water of the preliminary basin of the reservoir Wykrot; Mg^{2+}: from 7.3 mg dm^{-3} in the water of both preliminary and main basins of Wykrot to 10.2 mg dm^{-3} in the water of Karwacz).

Table 4

Water quality parameters of the studied dam lakes

Dam reservoir		pH*	DO	EC	NO_3^-	NH_4^+	Cl^-	SO_4^{2-}	HCO_3^-	Na^+	Ca^{2+}	Mg^{2+}
Grodzisk Duży n = 68	x	6.81	10.24	546	8.65	0.17	18.60	165.3	189.3	9.3	84.8	13.7
	±SD	-	0.44	16.12	0.79	0.02	0.52	13.49	1.88	0.13	2.27	0.45
Karwacz n = 62	x	6.56	9.72	433	3.28	0.08	14.00	138.8	170.2	7.6	72.3	10.2
	±SD	-	0.38	11.82	0.52	0.01	0.44	10.93	2.13	0.20	1.72	0.46
Łoje n = 48	x	6.56	10.39	286	1.86	0.07	8.40	146.0	107.7	5.1	50.4	8.7
	±SD	-	0.46	8.53	0.44	0.01	0.19	14.51	2.33	0.13	1.71	0.36
Wykrot preliminary basin n = 99	x	5.98	9.04	419	0.84	0.28	12.70	107.3	163.8	6.7	74.4	7.3
	±SD	-	0.30	8.84	0.05	0.05	0.30	6.62	2.17	0.10	0.91	0.21
Wykrot main basin n = 99	x	5.90	9.51	412	0.88	0.23	12.70	116.8	160.0	6.6	71.8	7.3
	±SD	-	0.33	7.84	0.06	0.02	0.33	6.42	2.72	0.09	0.95	0.21

Denotations: x – arithmetic mean; ±SE – standard error of mean. * pH – median. Units except for pH and EC (μS cm^{-1}) are given in mg dm^{-3}

The difference in the overall water quality between the four dam lakes has been demonstrated in a PCA biplot (Figure 2). The PCA results showed that the PC1 and PC2 accounted for 86.81% of the total variation in the environmental data.

PC1 explained 48.51% of the variance and PC2 explained 38.31% of the variance. Among the parameters of the highest positive eigenvectors participated by VA1 there are ones related to parameters of anthropogenic pollution like BOD_5, COD. Negative relations to VA1 were shown by sulphates and nitrates. Mineral parameters of water (chlorides, conductivity) are negatively related to PC2, while a positive relation was shown by DO and pH. Both the PCA and hierarchical cluster analysis show distinct dissimilarity among the studied objects. The HCA generated a dendrogram as shown in

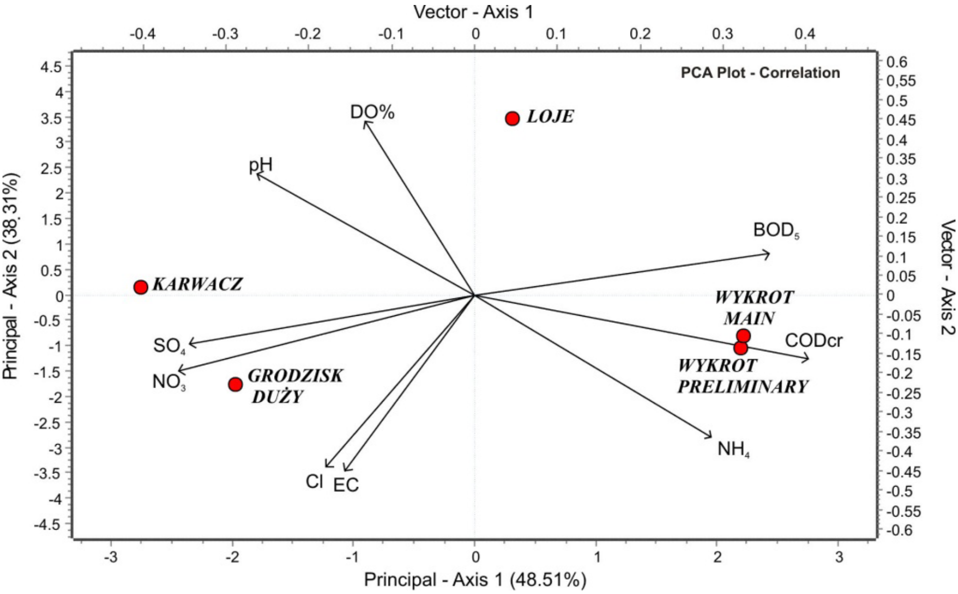


Fig. 2. Ordination diagram of the PCA of water quality parameters for the 4 dam lakes: Wykrot main, Wykrot preliminary, Grodzisk Duży, Łoje and Karwacz. Environmental variables are represented by arrows that approximately point towards the factor direction of maximum variation. The length of an arrow is proportional to the importance of that variable in assemblage ordination

Figure 3, grouping the lakes according to the water quality database. The 4 lakes (sampling sites) were divided into two clear clusters. Cluster 1 corresponds to relatively less polluted Łoje, Wykrot preliminary, and Wykrot main lakes, while cluster 2 corresponds to more polluted water (Grodzisk Duży and Karwacz lakes).

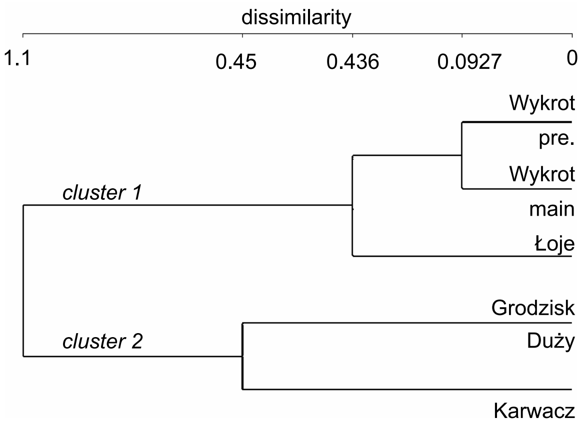


Fig. 3. Tree diagram of cluster analysis of the sites based on physico-chemical data, obtained by using the Ward's method as a linkage rule and the Euclidean distances as a metric for distance calculation

The computed WQI value enabled us to reduce the multiparametric information on the quality of water described with 10 physico-chemical parameters to one figure. The mean values of the water quality indices for the individual water reservoirs from the period of 2007-2013, referred to the adopted scale, are presented in Table 5 and Figure 4. They suggested that the waters in the analyzed water bodies belonged to the following categories: polluted: water in Grodzisk Duży 61.8% of the total number of samples, Łoje 66.7%, and Karwacz 80.7%. The water in Wykrot was of better quality. In the main basin, 37.7% of the total number of samples were classified as reasonable and 39.1% as polluted. In the preliminary basin, 32.7% of all samples belonged to the class denoted as reasonable and 46.2% as polluted. On average, during the period covered by the study, the highest WQI values, and therefore the highest water quality, were determined in the main basin of Wykrot lake (51.13%), while the lowest ones were detected in Karwacz (31.88%).

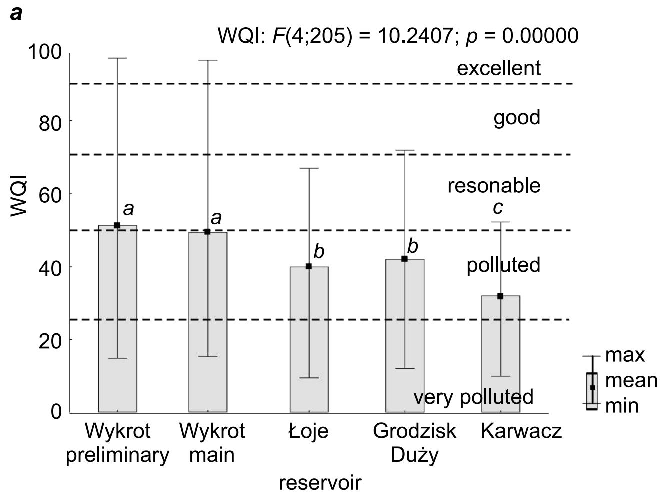
Table 5

Water quality Index (WQI) calculated for the water in the dam reservoirs as well as its classification considering % share of samples in a particular class

Dam reservoir	Mean WQI ±SD	Very polluted	Polluted	Reasonable	Good	Excellent
		10-25%	26-50%	51-70%	71-90%	91-100%
Grodzisk Duży	$41.60^{b} \pm 14.2$ (*cv* = 34%)	11.8	61.8	23.5	2.9	0
Karwacz	$31.88^{c} \pm 9.83$ (*cv* = 31%)	16.1	80.7	3.2	0.0	0.0
Łoje	$39.81^{b} \pm 13.8$ (*cv* = 33%)	12.5	66.7	20.8	0.0	0.0
Wykrot preliminary	$49.21^{a} \pm 17.8$ (*cv* = 35%)	8.7	39.1	37.7	11.6	2.9
Wykrot main	$51.13^{a} \pm 17.4$ (*cv* = 34%)	9.6	46.2	32.7	7.7	3.8

The same superscripts denote groups of means not significantly different in the Duncan's multiple range test (one-way ANOVA, $p \leq 0.05$); *cv* – variability coefficient (%)

The results obtained from the examined reservoirs indicated a lower quality of water than in many dam lakes in Europe and beyond. For example, relatively high WQI values were found for dam lakes in Romania, in the Iasi county: Dam Lake Halceni 75.2%, Pond Vladeni 73.0%, Pond Larga Jijia, and rivers: Miletin 71.5%, Jijia 53.2% (Breabăn et al. 2012), with the maximum value of 74 - 90% for the Mortu River in SW Romania (Ionuş 2010). Much lower WQI values were obtained for waters in rivers in South -East Asia (Palupi et al. 1995). For instance, results of a monitoring study on the Bangpakong River in Eastern Thailand (Bordalo et al. 2001) showed



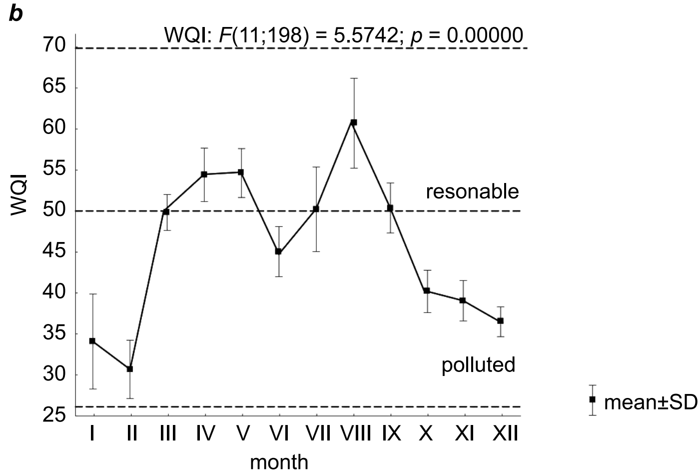


Fig. 4 *a* – Comparison of Water Quality Index (WQI) calculated for the studied dam lakes; *b* – Monthly changes in average WQI for the studied dam lakes. The same superscripts denote lakes not significantly different in the Duncan's multiple range test (one-way ANOVA, $p \leq 0.05$)

that the mean WQI was 37.4%, which leaves no doubt that measures should be taken urgently to protect the quality of water in this river.

The highest variability of the WQI values was demonstrated by the water in Wykrot, while the lowest one was achieved for the water in Karwacz. The waters in Wykrot presented a wide range of values, which classified them to both the lowest and the highest water quality class. Higher WQI values appeared in months with higher temperatures of water, when the processes of sedimentation, photosynthesis and biosorption promote the withdrawal of nutrients from water, in contrast to autumn and winter months, when the intensity of biogeochemical processes declines (Figure 4*b*). A similar distribution of the variability in water quality in the course of a year was recorded in the dam lakes Miranda, Pocinho and Crestuma on the Duoro River in Spain (Bordalo et al. 2006).

The water in the analyzed dam reservoirs was characterized by the SAR index value of < 0.37 (Table 6). Thus, there is no risk of any intensive replacement of calcium and magnesium contained in the soil sorptive complex by the sodium found in water used for irrigation that would be harmful to the soil structure. Hence, the water from the examined artificial lakes is suitable for irrigation in agriculture.

Table 6

SAR mean values (±SD) calculated for the water in the dam reservoirs

SAR	Reservoir				
	Grodzisk Duży	Karwacz	Łoje	Wykrot	
				Preliminary basin	Main basin
Mean	0.25^{c}	0.22^{c}	0.17^{a}	0.20^{b}	0.20^{b}
±SD	0.03	0.05	0.02	0.03	0.03
Min- Max	0.19-0.37	0.01-0.28	0.14-0.24	0.15-0.34	0.15-0.32

The same superscripts denote groups of means not significantly different in the Duncan's multiple range test (one-way ANOVA, $p \leq 0.05$)

For the sake of rational management of water resources, it is essential to determine their quality and to relate this information to a potential economic use of water. To this aim, the computed WQI values were compared to the rank scale developed by House and Ellis (1987). Table 7 contains a list of

Table 7

The assessment of potential usefulness of water in dam reservoirs based on WQI and SAR indices

Dam reservoir	WQI				SAR
	potable water supply	fish and wildlife	industry	recreation	irrigation
Grodzisk Duży	-	+	+	+	+++
Karwacz	-	+	+	+	+++
Łoje	-	+	+	+	+++
Wykrot – preliminary basin	-	++	++	++	+++
Wykrot – main basin	-	++	++	++	+++

Denotations: +++ very high; ++ high; + moderate; - useless

the principal directions in the management of water from dam reservoirs. A four-degree classification: very high, high, moderate and useless, was proposed in order to facilitate the interpretation of possible use of water according to the values of the WQI and SAR derived for the dam lakes submitted to our study and the rank scale comprised in Table 3.

Our analysis revealed that the waters from the four dam reservoirs should not be used for human consumption. However, they are suitable for irrigation. The water from Wykrot can be used to a high degree for fish rearing and for supplying industrial plants which do not require high quality water; it can also be used for recreational activities which do not entail direct contact with water. The remaining reservoirs (Grodzisk Duży, Karwacz and Łoje) contain water whose quality allows the above types of use only to a moderate degree.

CONCLUSIONS

The use of WQI and SAR for the assessment of water from four dam reservoirs located in NE Poland, reported in this paper, indicated that this water is generally suitable for potential specific use. Both indices were designed to provide directly comparable values of parameters such that various waters can be judged for use in specific categories. By providing information on "good" and "bad" water quality for specific use categories, the WQI enable managers and other nontechnical personnel to carry out effective management of water resources. Water in dam reservoirs should be of a particular concern as it shows a variety of specific types of use.

The water quality indices proved to be very useful in the determination of main directions in the management of water resources from the dam reservoirs. These include using water to supply agricultural irrigation systems and – to a high degree in the case of Wykrot lake but only to a moderate degree in the case of the other reservoirs – to supply fish farms as well as industrial plants that do not require high quality water or for recreation activities that do not entail direct contact with water.

The analysis also demonstrated that the water quality indices (WQI and SAR) are a tool, easy to use by all types of users, which facilitates rapid and easy interpretation of a large number of data. However, work should be continued to improve the practical application of the WQI in water resources management.

CONFLICT OF INTERESTS

None of the authors of this paper has a financial or personal relationship with other people or organizations that could inappropriately influence or bias the content of this paper.

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