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THE USE OF THE INTEGRATED TROPHIC STATE INDEX IN EVALUATION OF THE RESTORED SHALLOW WATER BODIES

ZASTOSOWANIE INTEGRALNEGO WSKAŹNIKA STANU TROFICZNEGO DO OCENY ODTWORZONYCH PŁYTKICH ZBIORNIKÓW

Abstract: The aim of this study was to determine the trophic status of five restored shallow lakes from a group of 30 water bodies in the Olsztyn Lakeland, which were dried in the 19th century as part of a land reclamation program. The effectiveness of the Integrated Trophic State Index (ITS) in the evaluation process was analyzed. ITS is a relatively new method for diagnosing eutrophication intensity. It analyzes the balance between production processes and organic matter decomposition through simultaneous measurements of oxygen saturation and pH of water. ITS is a versatile tool which can be applied in various types of water bodies. In this study, it was used to evaluate shallow water bodies characterized by excessive phosphorus loads and susceptibility to blue-green algal blooms in summer.

During a three-year study carried out in 2010–2012, significant correlations were observed between $\%O_2$ and pH, which is a basic prerequisite for applying the ITS method. In the analyzed water bodies, correlation coefficients were determined in the range of $r = 0.68–0.83$. ITS values varied in successive years ITS (from 7.73 to 8.67), ranging from eutrophy to hypertrophy. Most ITS scores were consistent with the values of Carlson's TSI, which indicates that used integrated trophic state index, based on the values of water pH and oxygen saturation, accurately reflect the ecological status of degraded water bodies.

Keywords: trophic state, Carlson's TSI, Integrated Trophic State Index (ITS), restored lakes, eutrophication

The trophic state is an indicator of the degree of transformation and ecological disruption of water bodies. Various methods for evaluating the trophic state have been proposed based on different criteria, such as nutrient supply, primary production levels or changes observed in trophic structure in comparison with undisturbed ecosystems [1–5]. Commonly used models evaluate the concentrations of primary biogenic compounds (nitrogen and phosphorus) and phytoplankton characteristics (concentrations of chlorophyll a and Secchi disc visibility). Those parameters are taken into account in the most popular models: the Vollenweider model [6, 7] and Carlson's Trophic State Index [8].

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In 1995, Neverova-Dziopak proposed the Integrated Trophic State Index (ITS) as a new method for evaluating primary production levels in water bodies [3]. Unlike conventional evaluation tools, this method analyzes the balance between primary production and organic matter decomposition by measuring dissolved oxygen levels and pH of water. A water body's trophic status is evaluated by diagnosing changes in an aquatic ecosystem caused by intensified primary production [3, 4]. ITS is a versatile tool which can be applied in various types of water bodies. Its main advantage is the ease of obtaining output data for trophic state assessments: only two indicators (% oxygen saturation and pH of water) which are measured during standard water quality inspections are required. ITS significantly simplifies the evaluation process. Every new method should be tested under various conditions to analyze its suitability and reliability. To date, ITS has been rarely used by researchers in evaluations of various water ecosystems [3, 9–11]. In this study, the discussed method was used to assess degraded water bodies which generally score poorly when conventional evaluation tools are applied.

The objective of this study was to evaluate the trophic status of restored shallow water bodies which constitute a rare and poorly investigated category of aquatic ecosystems. The second objective was to test the effectiveness of ITS in evaluations of eutrophic water bodies by comparing the obtained results with the values of Carlson's TSI.

Materials and methods

The study was carried out on five restored shallow lakes from a group of 30 water bodies in the Olsztyn Lakeland which had been dried in the 19th century as part of a land reclamation program and were restored or allowed to refill naturally [12]. The analyzed water bodies were restored around 1980, excluding Lake Gasiorowskie, which was refilled in the mid 1960s. All lakes are characterized by a small surface area, a low maximum depth and the predominance of farmland in their catchment areas (Table 1).

Table 1

Characteristics of the surveyed water bodies (based on own measurements)

Lake designation	Geographical location	Area [ha]		Max depth [m]	Catchment basin usage* [%]			
		Lake	Catchment basin		AL	BA	F	W
Nowe Wloki – southern section	53°54′13″ N 20°31′25″ E	15.2	173	2.6	88.0	0.3	2.9	8.8
Nowe Wloki – northern section	53°53′58″ N 20°31′42″ E	4.6	202	2.7	80.2	8.6	9.6	1.6
Setal Pond	53°54′14″ N 20°28′57″ E	3.7	103	1.5	83.9	12.2	0.0	3.9
Dobrazek	53°49′50″ N 20°47′40″ E	9.3	105	2.5	93.0	1.2	5.2	0.5
Gasiorowskie	53°43′13″ N 20°48′53″ E	6.9	34	4.0	55.8	11.8	32.4	0.0

* Land use designations: AL – agricultural land, BA – built-up area, F – forest, W – surface waters and wetlands.

Lake Nowe Wloki and Setal Pond were characterized by stable phytoplankton communities with a predominance of Cyanobacteria. Weakly developed submerged macrophytes and moderate phytoplankton blooms were observed in Lake Dobrazek. Lake Gasiorowskie was classified as a pure water system where macrophytes, mostly floating-leaf plants (*Nymphaea alba* and *Nuphar lutea*), were the most important primary producers. Progressive disappearance of vascular plants was observed in the above lake.

The study was carried out from 8th November 2010 to 10th September 2012. A total of 23 water samples were collected from each of the five analyzed lakes, at about 6 week intervals throughout the whole period of observations. The indicators for calculating ITS were measured locally with the use of the YSI 6600 multiparameter sonde. The results were calculated separately for every lake based on data from year-long measurements with the use of the following formula [3]:

$$ITS = \Sigma\ pH_i / n + a(100 - \Sigma\ [O_2\%] / n)$$

where: pH_i – water pH,
$[O_2\%]$ – oxygen saturation of water,
a – coefficient of regression between pH and $\%O_2$,
n – number of measurements.

Comparative data for determinations for Carlson's TSI were obtained simultaneously with measurements of oxygen saturation and pH of water. Only the measurements performed in the growing seasons of each analyzed year (May–September) were used to calculate Carlson's TSI. Partial TSI scores were determined based on phosphorus levels (TSI_{TP}), concentrations of chlorophyll a (TSI_{Chl}) and Secchi disc visibility (TSI_{SD}) with the use of the following formulas [7].

$$TSI_{TP} = 14.42 \cdot \ln(TP) + 4.15$$

$$TSI_{Chl} = 9.81 \cdot \ln(Chl) + 30.6$$

$$TSI_{SD} = 60 - 14.41 \cdot \ln(SD)$$

where: TP – phosphorus levels [$\mu g \cdot dm^{-3}$],
Chl – concentrations of chlorophyll *a* [$\mu g \cdot dm^{-3}$],
SD – Secchi disc visibility [m].

Phosphorus levels were determined in a laboratory with the use of ammonium molybdate and tin(II) chloride after sample mineralization. Chlorophyll concentrations were measured with the YSI 6600 sonde, and Secchi disc visibility was determined during lake measurements with the involvement of a standard black and white disc with the diameter of 20 cm. The data were processed in line with the principles applicable to ITS and Carlson's TSI. The results were verified statistically in the Statistica 10 PL application.

Results and discussion

Carlson's TSI revealed variations in the trophic status of the analyzed water bodies which ranged from moderate to high nutrient levels (Table 2). Regardless of the final result, visible disproportions in correlations between $TSI_{TP} > TSI_{Chl} \approx TSI_{SD}$ were observed in all water bodies. This correlation is characteristic of water bodies with a predominance of phytoplankton where a small euphotic zone determines the intensity of primary production. The above is triggered by the accumulation of unused phosphorus reserves in water in both mineral form and in the form of dead organic matter. The results of other studies indicate that restored shallow lakes are generally characterized by excessive phosphorus loads [13, 14]. Phosphorus ceases to limit primary production, and high levels of that element contribute to negative results of trophic state assessments performed with methods based on phosphorus concentrations. The resulting evaluations are less reliable and their results are overestimated because such methods rely on the assumption that productivity levels can be regulated by periodic phosphorus deficiencies. In water bodies with excessive nutrient loads, phosphorus plays the role of a reserve substrate in the ecosystem. In polymictic lakes, the above contributes to the preservation of high phytoplankton levels and turbid-water conditions. In such lakes, powerful mechanisms prevent the recovery of pure water conditions with a predominance of submerged vegetation which enhance the lake's general usability classification and ecological parameters [15, 16]. Such a state was also observed in the studied group of lakes, including the pure-water Lake Gasiorowskie. High values of TSI_{TP} were reported in all of the analyzed water bodies (Table 2).

Table 2

The results of trophic state assessment based on the values of Carlson's TSI in the studied lakes in 2010–2012

Lake	Year	TSI partial results			Results	
		TSI_{TP}	TSI_{Chl}	TSI_{SD}	TSI	State*
Nowe Wloki – southern section	2010	72.4	57.1	68.0	65.9	**E**
	2011	78.3	64.6	69.6	70.8	**H**
	2012	74.7	62.8	68.4	68.7	**E**
Nowe Wloki – northern section	2010	74.5	58.7	64.8	66.0	**E**
	2011	81.5	62.6	66.7	70.3	**H**
	2012	79.8	66.7	67.0	71.2	**H**
Setal Pond	2010	91.8	68.9	65.3	75.3	**H**
	2011	87.6	68.4	72.3	76.1	**H**
	2012	83.5	65.2	69.7	72.8	**H**
Dobrazek	2010	72.4	57.6	63.0	64.3	**E**
	2011	71.2	63.7	59.7	64.9	**E**
	2012	74.6	60.7	61.1	65.5	**E**
Gasiorowskie	2010	71.7	50.9	51.2	57.9	**E**
	2011	57.8	54.4	50.3	54.2	**E**
	2012	61.0	51.7	50.9	54.5	**E**

* Trophic state categories: E – eutrophic; H – hypertrophic.

The ITS method can be applied to water bodies characterized by significant correlations between oxygen saturation and pH of water. The data collected in the entire group of evaluated lakes (n = 116) confirmed the presence of such relationships, and the coefficient of correlation was determined at r = 0.743 (Fig. 1). In most water bodies, oxygen saturation was determined at 80–120 % and pH at 7.5–9.0, which is typical of lakes with moderate and high nutrient levels. Considerable statistical dispersion was observed – the lowest values were recorded in winter (oxygen saturation < 40 %, relatively low pH), whereas Setal Pond was characterized by 222.4 % oxygen saturation of pH of 10.46 in the summer of 2012. Those extreme results did not, however, diverge from the regression curve (Fig. 1).

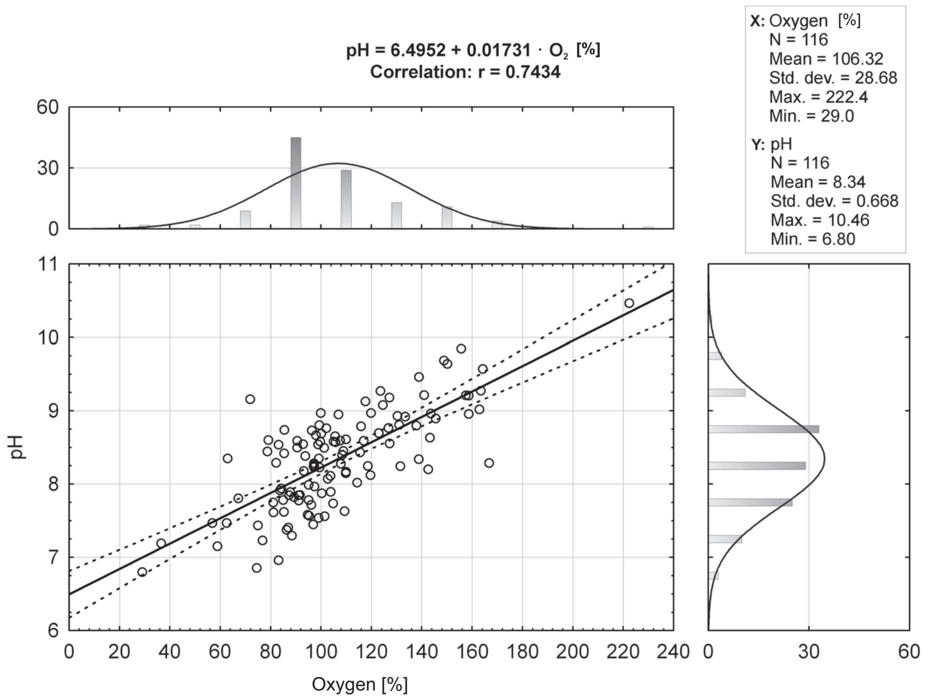

Fig. 1. Correlations between oxygen saturation and pH of water based on data collected from the analyzed water bodies, shows that changes of two groups of output parameters were interconnected

The evaluations of trophic status based on ITS values were similar to the results produced by Carlson's TSI method. In nine out of 15 analyzed water bodies, ITS scores were identical to the results of Carlson's TSI (Tables 2 and 3). The remaining results differed by one trophic class, and lower trophic states were denoted by ITS values in all cases. ITS scores were most correlated with partial TSI values based on the concentrations of chlorophyll a (TSI_{Chl}), an indicator of phytoplankton biomass. In shallow lakes, chlorophyll levels are the most robust indicator of intensive primary production because Secchi disc visibility can be limited by sediment resuspension which lowers water transparency and increases phosphorus concentrations in water [17].

ITS and TSI values diverged most significantly in 2010 which was characterized by a long winter and high precipitation levels in early summer. The above conditions contributed to lower pH of water which decreased ITS values in comparison with the remaining years of the experiment and TSI scores.

Table 3

The results of trophic state assessment based on ITS values in the studied lakes in 2010–2012

Lake	Year	Correlation coefficient	Indicators to calculate ITS value		Regression coefficient *a*	Results	
			Σ pH$_i$/*n*	Σ [O$_2$%] /*n*		ITS	State*
Nowe Wloki – southern section	2010	0.936	7.948	99.82	0.01685	7.95	**M**
	2011	0.837	8.499	112.04	0.01764	8.29	**E**
	2012	0.839	8.813	114.65	0.01724	8.56	**E**
Nowe Wloki – northern section	2010	0.764	7.915	96.03	0.02605	8.02	**E**
	2011	0.644	8.383	112.11	0.01500	8.20	**E**
	2012	0.831	8.818	117.31	0.01149	8.62	**H**
Setal Pond	2010	0.356	7.921	88.67	0.00899	8.02	**E**
	2011	0.854	8.576	113.59	0.01537	8.37	**E**
	2012	0.937	9.051	126.45	0.01370	8.69	**H**
Dobrazek	2010	0.801	7.944	108.29	0.02599	7.73	**M**
	2011	0.706	8.218	102.35	0.01754	8.18	**E**
	2012	0.690	8.707	109.98	0.01379	8.57	**E**
Gasiorowskie	2010	0.750	7.754	91.37	0.03519	8.06	**E**
	2011	0.693	8.157	96.82	0.01123	8.19	**E**
	2012	0.778	8.349	98.51	0.01834	8.38	**E**

* Trophic state categories: M – mesotrophic; E – eutrophic; H – hypertrophic.

No significant correlations were reported between ITS and TSI results (r = 0.240, Table 3). ITS scores were not correlated with any input indicators used in the TSI method (phosphorus and chlorophyll concentrations, Secchi disc visibility). ITS values reflect the intensity of primary production and organic matter decomposition which are indicative of the lake's ecological status. Methods that rely on the concentrations of biogenic compounds in water investigate lakes' ability to produce organic matter which can be limited by various factors (light availability, accumulation of toxic substances), preventing producers from

Lake Dobrazek was an exception in the analyzed group of water bodies. Significant changes in its catchment area were observed during the period of the study. The southern part of the catchment was completely transformed due to a road reconstruction project. After the project's completion in 2012, the main pipe of the road drainage system was emptied into the lake, contributing a new source of pollution. TSI values indicate that the lake did not respond to the above changes within the standard range of trophic indicators (Table 3), whereas ITS scores based on oxygen saturation and pH of water increased significantly in comparison with 2010 when the lake was classified as eutrophic/mesotrophic (Table 4). This suggests that the ITS method provided a quicker response to increased external pressure. Further work is, however, needed to validate this hypothesis.

Table 4

Pearson's matrix of correlations between TSI / ITS values and respective index components for the group of investigated water bodies in different years of the study (values in bold are statistically significant at $p < 0.05$)

Variable	ITS	TSI	Chl_a	SD	P	pH
ITS	—					
TSI	0.240	—				
Chl_a	0.334	**0.897**	—			
SD	–0.157	**–0.911**	**0.684**	—		
P	0.092	**0.843**	**0.878**	**–0.581**	—	
pH	**0.927**	0.407	0.426	–0.394	0.149	—
O_2	**0.668**	0.498	0.375	**–0.577**	0.126	**0.878**

Explanations: Chl_a – chlorophyll a; SD – Secchi disk depth; P – concentration of total phosphorus; O_2 – oxygen saturation.

An absence of correlations between phosphorus concentrations and ITS scores (Table 4) confirms that in lake ecosystems with excessive phosphorus loads, the discussed element, which controls primary production in lakes with low and moderate nutrient levels, ceases to regulate productivity [18, 19]. In lakes characterized by stable turbid-water states, the key parameter is light availability [20, 21]. In evaluations of trophic status, a narrow euphotic zone is reflected by the results of Secchi disc visibility tests. Excess phosphorus concentrations cease to determine a lake's ability to fulfill ecological and economic functions. In this case, it is no longer significant whether primary production limits are exceeded three- or 10-fold because a lake's ecological condition can be similar in both scenarios. When phosphorus loads are considerably exceeded, TSI values and the trophic status determined by the diagnostic model will point to a higher level of degradation. This has important practical implications and is of a high informative value because positive results of protective and reclamation efforts in lakes are more difficult to achieve when phosphorus loads are very high.

Conclusions

1. The evaluated five restored water bodies were characterized by high nutrient loads, in particular excessive phosphorus concentrations. During the experiment, TSI values for phosphorus were significantly higher than TSI_{Chl} and TSI_{SD}, which indicates that the euphotic zone was the key factor limiting primary production. The above correlation is characteristic of lakes with a stable turbid-water state and a predominance of Cyanobacteria.

2. In Lake Gasiorowskie, which was restored earlier than the other studied water bodies and was characterized by lower phytoplankton abundance and a high share of vascular plants, less pronounced differences were reported between phosphorus and

chlorophyll concentrations and Secchi disc visibility. The results of TSI index for this lake were the most advantageous compared to other studied sites.

3. The integrated trophic state index (ITS) revealed relatively high nutrient loads in the studied water bodies. In most lakes, ITS scores were largely consistent with TSI values. The obtained data indicate that ITS is a synthetic indicator that accounts for all functional aspects of an aquatic ecosystem. ITS values are largely independent of phosphorus loads, whereas the TSI method assigns a higher trophic class to lakes with excess phosphorus concentrations.

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ZASTOSOWANIE INTEGRALNEGO WSKAŹNIKA STANU TROFICZNEGO DO OCENY ODTWORZONYCH PŁYTKICH ZBIORNIKÓW

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Abstrakt: W pracy podjęto próbę oceny stanu troficznego pięciu płytkich zbiorników, należących do grupy około 30 obiektów Pojezierza Olsztyńskiego, współcześnie odtworzonych po osuszeniu dokonanym w XIX w. W szczególności przeanalizowano możliwość zastosowania integralnego wskaźnika troficzności (*Index of Trophical State* – ITS). Wskaźnik ten jest stosunkowo nową metodą diagnozy nasilenia procesu eutrofizacji. Bazuje na ocenie równowagi procesów produkcji i rozkładu materii organicznej, którą określa się poprzez symultaniczny pomiar nasycenia wody tlenem i odczynu. Metoda ta jest przedstawiana jako uniwersalna, mająca zastosowanie w różnych typach wód. W niniejszej pracy wykorzystano ją do oceny zbiorników płytkich, cechujących się dużym nadmiarem fosforu w obiegu i podatnych na zakwity sinic w sezonie letnim (często bardzo intensywne).

Badania w przekroju 3 lat (2010–2012) wykazały istotną statystycznie korelację pomiędzy $\%O_2$ i pH, co jest podstawowym wymogiem możliwości zastosowania wskaźnika ITS. Współczynniki korelacji dla poszczególnych obiektów wodnych wynosiły r = 0,68–0,83. Wyniki oceny stanu w kolejnych latach zmieniały się w zakresie od eutrofii do wartości wykraczających poza granicę tego stanu (ITS od 7,73 do 8,67). Uzyskane wyniki w większości przypadków były zgodne z rezultatami oceny powszechnie stosowanej metody TSI Carlsona, co wskazuje, że również w zdegradowanych zbiornikach relacja pH-O_2 odzwierciedla ich stan ekologiczny.

Słowa kluczowe: stan troficzny, TSI Carlsona, wskaźnik ITS, odtworzone jeziora, eutrofizacja