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A new version of the Hydrochemical Dystrophy Index to evaluate dystrophy in lakes

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ABSTRACT

Dystrophic freshwaters referred to as humic, brown, or black waters are typical for boreal or some mountainous regions where fens and coniferous forests form a significant part of basins. I evaluated the usefulness of the Hydrochemical Dystrophy Index (HDI) which has been developed for dystrophic lakes in Poland, on the basis of a rich database for lakes in Sweden and data provided by other researchers for lakes from Finland and Russia. I propose a new version of HDI for synthetic and quantitative description of habitat conditions in lakes and for use in limnological monitoring of protected areas. The state of dystrophy was evaluated using data for surface water pH, electric conductivity (EC), DIC (dissolved inorganic carbon) and DOC (dissolved organic carbon) concentrations. HDI values between 50 and 65 indicate semidystrophic conditions and with advanced a real dystrophy, they reach HDI values from 65 up to 100. Long term data shows that lake dystrophy is fairly steady with seasonal fluctuations. I show that the level of lake dystrophy is not correlated to latitude, but rather to small lake areas, regional geochemical spots, and favorable local hydrological conditions. A summary description of the main parameters of various types of humic lakes is presented.

1. Introduction

Dystrophic freshwaters classified as humic, brown, or black water are typical for boreal or mountainous regions in which fens and coniferous forests form a significant part of the basins. Dystrophic lakes are common in boreal zones (Keskitalo and Eloranta, 1999) and are found in temperate and tropical zones. Humic substances (HS) are the main factor creating a specific hydrochemical and oxygen regime of dystrophic lakes (Thurman, 1985; Wetzel, 2001). HS presence in freshwater results in a brown or more dark water color, thus many of the lakes or rivers are named as black water in boreal or tropical zones (Steinberg et al., 2006). Also dark-colored humic waters increase a solar energy adsorption and reduce a mixing potential of the relatively deep and small lakes (Jones and Arvola, 1984; Hakala, 2004). Snucin and Gunn (2000) documented a shallower and warmer epilimnion and a colder hypolimnion in brown water compare to clear water lakes. Microbiological studies clearly indicated that in the organic rich water with a low pH, the microbiological loop plays a more important role than the trophic pyramid typical for harmonious water ecosystems (Karlsson et al., 2002). Uniqueness of this ecosystem shows in a lack or rare macrophyte occurrence (Rørslett, 1991) and low plankton biomass and diversity (Jones, 1992). Dystrophic lakes are unproductive from a fishery point of view (Rask et al., 1995; Finstad et al., 2014). Humic lakes are protected in the European Union and registered in the Appendix of the Habitat Directive as "Natural dystrophic lakes and ponds" (Anonymous, 2007). These lakes, such as other EU protected habitats, require environmental monitoring and periodic assessments of their ecological status.

When assessing the water trophy or the ecological status of freshwater ecosystems, a Trophic State Index (TSI) developed by Carlson (1977) is used commonly. The TSI perfectly characterizes the abundance and availability of nutrients for the development of hydrobionts and physical characteristics of water (water transparency), ensuring ecosystem functioning.

Using the Carlson TSI formula is a proven method for harmonious lakes in which every increase in nutrient concentrations (N, P) induces phytoplankton growth, thereby stimulating the development of successive trophic levels while changing the taxonomic differentiation and consumers of consecutive orders. In harmonious aquatic ecosystems, a relationship between the average concentration of nutrients and other elements necessary for the hydrobionts development, such as Ca, Mg, K, S, DIC and Si, is common. Increase in total organic carbon resources according to the productivity of harmonious ecosystems and the index of trophy can

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Table 1
Some features of the studied lakes, hydrochemical data for all collected lakes.

Parameter	Sweden	Finland	European Russia
Number of collected lakes	244	187	264
Number of dystrophic lakes	181	180	210
Latitude (°N)	56.1–68.3	60.2–68.9	52.5–69.5
Area (km^2)	0.001–52.1	0.01–113.6	0.04–21.0
Elevation	1–974	1–316	7–326
pH	4.8–9.8	4.3–7.4	4.5–8.5
EC ($\mu S\,cm^{-1}$)	7–459	8–162	7–288
DOC ($mg\,Cd\,m^{-3}$)	0.8–65	0,5–31.0	3.4–90.9
DIC ($mg\,Cd\,m^{-3}$)	0.005–45.7	0.005–6.16	0.4–36.6
Data source	SEMP from year 2012	Kortelainen (1993)	Moiseenko et al. (2013a)

be calculated on the basis of TOC (total organic carbon) concentrations (Dunalska, 2009). Increasing TOC concentration in the surface waters stimulates redox processes; thus, a significantly statistical relationship exists between reactive manganese concentrations in water and TSI (Cudowski, 2014). In the low productive dystrophic lakes, an increased allochthonous organic matter load suppressed the production of these ecosystems (Karlsson et al., 2002; Seekell et al., 2015). Thus, this index cannot be used to assess a lake's dystrophy.

Application of the Carlson TSI formula for dystrophic water is limited, because obtained TSI values in such systems seem to be typical for eutrophic waters and are actually caused by increased concentrations of total phosphorous (Górniak et al., 1999). Additionally, dystrophic waters contain high organic carbon and alkaline metal concentrations and have low pH values (Keskitalo and Eloranta, 1999). Limiting the depth of sun radiation and low concentrations of basic ions such as Ca, Mg, K or HCO_3 caused suppression of phytoplankton development which is usually not observed in harmonious water ecosystems (Nürnberg and Shaw, 1999). Commonly used water parameters (TP, Chla, water transparency) are not sufficient to clearly distinguish between dystrophic and harmonious lakes; therefore, other indicators should be used to properly describe dystrophy. However, evaluation of the dystrophy state with quantitative indicators is needed to detail lakes description in reserves, National Parks or Nature Reserves. Thus, a low electric conductivity (EC) value can be a good indicator of mineral components in waters, especially when igneous rocks or their residuals are dominating in the lake basins (as in mountainous regions, Eastern Canada, Brazil). However, bogs have surrounding a water body two important roles, first as sources of organic components for the lake water and second as a geochemical barrier for groundwater circulating in postglacial sediments and containing $CaCO_3$. Thereby, Sphagnum bogs have an oligotrophic character with very soft waters, low alkalinity and high, organic acidity (Kurhy and Turunen, 2006).

Three water parameters pH, alkalinity and nitrogen concentration were proposed to identify dystrophic lakes in a classification of freshwaters in Great Britain (Palmer and Roy, 2001). Hakanson and Boulion (2001) categorized dystrophic lakes on the basis of water color, but not all polyhumic ecosystems with high water color can be classified as dystrophic (Sobek et al., 2007). However, Finlay et al. (2010) reported that harmonious freshwater and saline lakes in the Great Plain of Canada are comparable to dystrophic lakes in terms of color and DOC concentration; Chen et al. (2012) noted a similar situation for Lake Hulun in the northern China steppe. High DOC concentrations of more than 20 $mg\,C\,dm^{-3}$ were also noted in a Poland lowland reservoir with base pH and moderate calcium ion concentrations (Górniak, 1996). A more accurate and synthetic formula for describing lake dystrophy, the Hydrochemical Dystrophy Index (HDI), was proposed by Górniak (2004), but it was only applied to a limited number of lakes located on the periphery of the boreal zone in northern Poland.

The aim of this study was to expand the application HDI concept to a broader aspect of geographical location. A new formulation for the index application was derived and tested with a data subset from Swedish lakes and boreal lakes located in other geographic locations. The proposed new formula was used to determine long-term and seasonal variation of dystrophy levels in changing hydroclimatic conditions existed in the course of global climate change.

2. Materials and methods

2.1. Studied lakes

The basic study was performed in the most representative freshwater areas of the boreal zone in Sweden which are examined in the Swedish Environmental Monitoring Program (SEMP) (http://webstar.vatten.slu.se/db.html). From all Swedish lakes monitored in 2012, data for 244 lakes with different areas and locations (latitude 56.14°–68.35°N) were selected. The selected lakes have an area between 0.02 and 52.14 km^2 and their features are typical for a north boreal zone (Table 1). Samples were taken four times in 2012 from a depth of 0.5 m, but in the shallow lakes, data represent one sample taken from the whole water column. We selected ten Swedish lakes which were long-term monitored between 1988 and 2012 and sampled four to nine times per year according to the SEMP protocol (Table 2). Dystrophy Index was also calculated for a large group of lakes in Finland (Kortelainen, 1993) and the European part of Russia (Moiseenko et al., 2013a), using original data obtained from the researchers. The presented HDI data for humic lakes of various geographic locations represent the arithmetic mean of single HDI values calculated from each lake or samples using data which was published or provided by the individual researchers.

2.2. Hydrochemical Dystrophy Index (HDI)

For each sample from lakes or rivers, I used pH, conductivity (25 °C), DOC and ANC (acid neutralizing capacity as a alkalinity) values. In the freshwaters of the boreal zone, more than 90% of TOC occur in the dissolved form as DOC (Mattsson et al., 2005), thus in this study, TOC concentrations are identical to DOC concentrations.

DIC concentrations were calculated from ANC data measured as alkalinity, because direct DIC analysis was rare in past monitoring practice, but now is more frequent and DIC analysis is suggested to use in the new formula proposal. In the case when ANC had negative or zero values, DIC concentration was equal to 0.005 $mg\,C\,dm^{-3}$, adequate for theoretical DIC concentrations in acid water, with low ionic strength and a CO_2 concentration of 385 ppm in the air (Cole and Praire, 2010).

Hydrochemical Dystrophy Index, proposed by Górniak (2004), was calculated using the following formula:

$$HDI = (D1 \times D2 \times D3)^{0.333} \quad (1)$$

$$D1 = (9.5 - pH) \times 20 \quad (2)$$

$$D2 = \frac{100}{\log(EC)} \quad (3)$$

$$D3 = \frac{(10 \times DOC)}{DIC\_ANC} \quad (4)$$

where D1 is the subindex for water acidity, D2 is the subindex for water minerals dissolved in water, D3 is the subindex for relation between organic and inorganic forms of carbon in water; pH units, EC is electric conductivity at 25 °C in $\mu S\,cm^{-1}$, DOC, DIC concentrations are expressed as $mg\,C\,dm^{-3}$. HDI value was calculated for all terms of lake sampling, data for the lakes of other countries were calculated from a single summer sampling.

3. Results

3.1. Adaptation of the hydrochemical index of dystrophy (HDI) to characteristic boreal conditions

The HDI formula by Górniak (2004) was defined for waters situated in the southern border of the dystrophic water occurrence, where climatic conditions are more lenient (higher air temperature, lower precipitations). However, the original HDI formula used for typical boreal freshwater ecosystems entails two problems. First, a calculation of subindex D3 (4) showed extremely high values compared to the other subindices D1 and D2 (Table 3). This situation was noted in the highly acid waters with some DOC/DIC ratios higher than 10,000, too high value of D3 subindex compare to D1 and D2 subindicies with value lower than 100. Thus a final HDI value was much higher than 1000. The high value of subindex D3 led to an overestimation of lake dystrophy (Table 3). Looking for the better formula for subindex D3 approximation I have found that a DIC/DOC ratio significant correlated to water pH and mean

Table 2
Swedish lakes under studies with a long term data from SEMP.

No	Lakes	Latitude (N)	Lake area (km²)	Mean depth (m)	Catchment (km²)	Elevation (m a.s.l.)	HDI			
							Mean	SD	Max	Min
I	Rotehogstjärn	58.815	0.17	3.6	3.8	121	82.7	3.2	88.7	74.6
II	Brunnsjön	56.597	0.10	3.5	3.43	98	78.1	2.7	84.2	73.4
III	Remmarsjön	63.862	1.35	5.0	126	234	71.2	1.6	73.7	66.4
IV	Allgjuttern	57.948	0.15	11.7	1.04	130	62.6	1.0	63.4	60.3
V	Fräcksjön	58.149	0.28	6.0	4.26	59	62.8	0.9	64.1	61.0
VI	Stora Skärsjön	56.672	0.29	4.0	7.06	207	55.7	1.1	57.6	53.5
VII	Stensjön	61.643	0.59	4.3	2.43	269	72.0	1.7	77.5	68.8
VIII	Övre Skärsjön	59.837	1.65	6.1	8.85	222	82.5	3.3	88.8	77.1
IX	St. Envättern	59.115	0.38	5.0	1.39	65	65.1	1.4	67.5	62.3
X	Fiolen	57.092	1.80	3.9	5.48	226	62.6	1.4	66.0	60.6

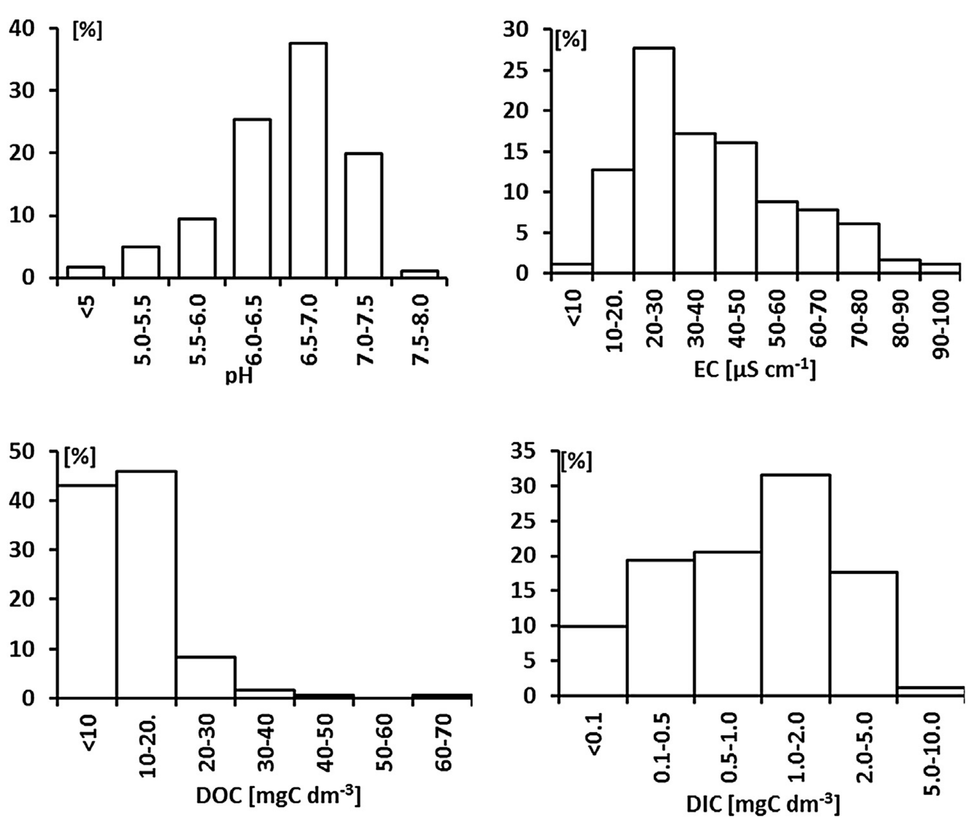

Fig. 1. Basic parameters of surface waters (depth 0.5 m) of Swedish dystrophic lakes in 2012.

Table 3
An example of HDI calculation using an older formula version and a new version of the HDI formula for selected Swedish lakes analyzed in August 2012 (depth 0.5 m).

Lakes	Analytical data				Older version of HDI formula				New version of HDI formula	
	pH	EC [$\mu S\,cm^{-1}$]	TOC [$mg\,dm^{-3}$]	DIC [$mg\,dm^{-3}$]	D1	D2	D3	HDI	D3′	HDI′
Tärnan	7.26	60.1	11.9	3.88	44.8	56.2	30.7	42.6	59.7	53.6
Grissjön	6.03	28.2	13.1	0.19	69.4	69.0	682.3	148.4	86.7	75.0
Bäen	5.97	69.3	9.8	0.17	70.6	54.3	583.3	130.8	85.3	70.1
Granvattnet	6.57	79.4	9.4	0.89	58.6	52.6	105.9	70.5	68.9	60.0

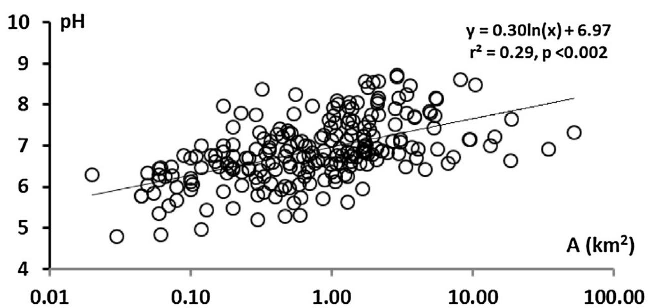

Fig. 2. Relation between lake area and pH in Swedish dystrophic lakes (data for 2012 from SEMP).

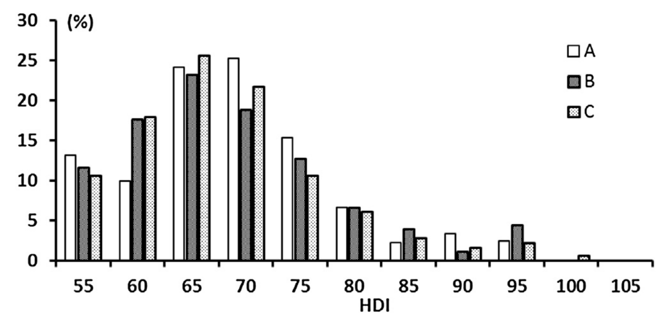

Fig. 3. Histogram of the Hydrochemical Dystrophy Index (HDI) of the studied lakes in Sweden (A), Finland (B), and European Russia (C).

form formulas (2) and (3). Thus a new version of the D3 formula is proposed in the following form:

$$D'3 = 50 - LOG\left(\frac{DIC\_ANC}{DOC}\right) \times 20, \quad (5)$$

where DIC and DOC are dissolved inorganic and organic carbon in $mg\,C\,dm^{-3}$. The new values of subindex D′3 for low DIC/DOC ratios are lower and less distinct from subindices D1 and D2. Additionally, I have found a significant statistically relation between water pH and DIC/DOC ratio (data not presented). It confirms justness of used correction at calculation of subindex. Finally, in calculating HDI index we can skip the geometric mean of subindices D1, D2, and D3 (1) and used the arithmetic mean (6) as following:

$$HDI = \frac{D1 + D2 + D'3}{3} \quad (6)$$

The results of introducing a new version of the HDI index with modification of the D′3 formula (5) and the use of formula (6) for some analyzed lakes are presented in Table 3. It shows a significant decrease of subindex D3 which is now closer to subindices D1and D2, allowing for a better estimation of the chemical condition of the lakes.

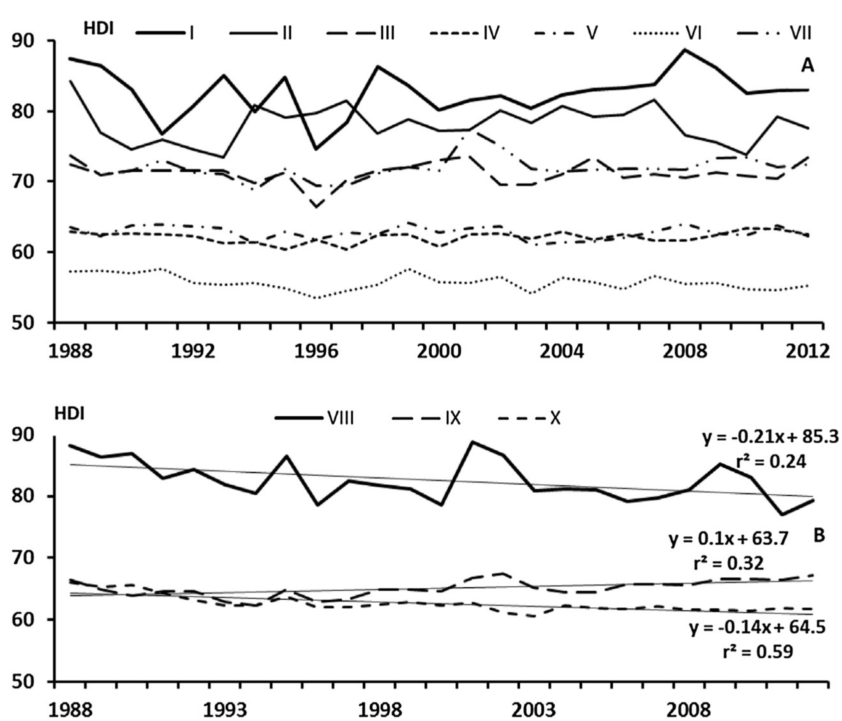

Fig. 4. Long term variation of HDI in selected lakes of Sweden. (A) Lakes without a significant trend; (B) lakes with a statistically significant trend, lakes numbers as in Table 2.

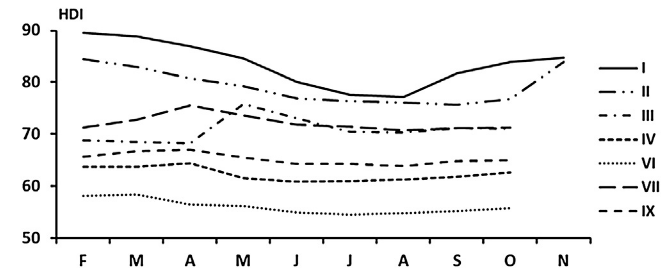

Fig. 5. Seasonal HDI changes (monthly means) in selected dystrophic lakes in Sweden; lake numbers as in Table 2.

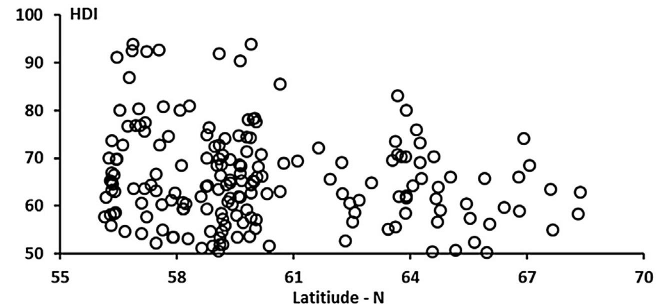

Fig. 6. Relation between Hydrochemical Dystrophy Index of Swedish lakes and latitude.

3.2. Swedish dystrophic lakes

Area and latitude of all analyzed lakes varied respectively between areas of 0.02 km^2 and 52.14 km^2, located in the latitude 56.14°–68.35°N. In the epilimnion of dysharmonious lakes, the water was slightly acid with a pH range from 4.8 to 7.8 (Fig. 1) and a median pH of 6.64.

In 38 lakes (21% of dystrophic lakes), slightly alkaline water was noted. EC values in the dystrophic lakes showed a median of 34 $\mu S\,cm^{-1}$ and did not exceed 100 $\mu S\,cm^{-1}$ (Fig. 2).

Dissolved organic carbon concentrations had the highest differentiation among the studied lake water parameters, with median values of 11.0 $mg\,C\,dm^{-3}$ (Fig. 1). I found a significant positive correlation between lake area and water pH (Fig. 2). Of the 244 studied lakes, in light of HDI calculation, dystrophic conditions were found in 181 lakes (72%), where HDI was higher than 50 (Table 1). Swedish lakes with HDI in the range of 55–65 accounted for more than 47% of dystrophic lakes (with HDI > 50) (Fig. 3). Median HDI value for all dystrophic lakes was 64.5. Lake HDI decreased gradually with an increase of lake area up to 1–2 km^2 and in the larger lakes has a similar value (Table 4).

Long-time HDI fluctuations in the selected ten lakes showed various trends, but the lakes were always dystrophic with different advancements (Fig. 4). In the two lakes Övre Skärsjön and Fiolen, the level of dystrophy, expressed by HDI, decreased in the course of 24 years (1988–2012). In the same time, in the lake Stora Envättern, the dystrophy level increased. The results of the Kruskal–Wallis test indicated that all trends are statistically significant at $p < 0.005$ (Fig. 4). A large collection of analytical data allows a better presentation of seasonal changes of dystrophy levels in terms of HDI in lakes of Sweden. The highest monthly mean HDI values for each lake occurred in the cold seasons (winter, early spring) and slowly declined toward late summer; they increased again in autumn (Fig. 5). Summer HDI data usually shows the lowest state of lake dystrophy. Seasonal HDI values, regardless of lake size or volume, increased with the advancement of lake dystrophy.

Analyzing the geographical distribution of dystrophic lakes in Sweden, I did not find a significant correlation between HDI value and latitude (Fig. 6).

3.3. Humic lakes of Finland and Russia

I analyzed a large group of lakes in Finland and Russia with similar hydrochemical conditions compared to the lakes in Sweden, thus calculated HDI values were similar to the ones of the Swedish lakes (Table 4). Of the dystrophic lakes in Finland and Russia, more than 52% had a HDI higher than 50. The differentiations of HDI between lakes of various areas was highest in the Russian lakes compared to Finish or Swedish lakes (Table 4). Also there is not statistically significant relationship between latitude and dystrophy state expressed as HDI.

4. Discussion

4.1. Carbon forms and lake type

Using a few basic water parameters, I demonstrate possibilities to distinguish a group of dystrophic (disharmonious) lakes from harmonious lakes (oligotrophic–eutrophic) using a synthetic hydrochemical index. A HDI index lower than 50 indicates a harmonious lake, in which bicarbonate concentrations are higher than necessary level for plant growth. Thus DIC/DOC ratios do not reach values below 0.1 (Górniak, 2004, 2006). In harmonious lakes, a biomass of macrophytes and species number decline with decreasing DIC concentrations. Limnological studies of dystrophic lakes in Sweden (Birk and Ecke, 2014) and Poland (Kraska et al., 1994; Banaś et al., 2012) confirm poor occurrence of macrophytes in these lakes; in some areas, macrophytes were non-existent. I speculate that DIC availability for plants is a more limiting factor than light intensity in dystrophic lakes. Only some species of the genus *Isoetes* have developed mechanisms to use free CO_2 from water or sediments under hydrocarbonate deficiency, mainly in moderate acid and humic lakes (Adamec, 2012). However, rootless aquatic plants in dystrophic lakes can directly assimilate inorganic carbon from dissolved CO_2 (Murphy, 2002) as dystrophic water are usually saturated with CO_2 (Sobek et al., 2007). Thus, restricted availability of inorganic carbon forms of carbon in dystrophic waters resulted in different specific adaptive traits in the plant communities and effected the high species diversity. The DIC/DOC ratio clear classifices water body to the harmonious or disharmonious group of lake.

In the scheme of lakes from oligotrophic to eutrophic, the basic cations concentration are not limiting factors, while phosphorous, nitrogen, or silica are main determinants of ecosystem productivity. Total phosphorous or nitrogen concentrations are not limiting in dystrophic lakes, in contrast to Ca, Mg ions. Also, natural organic matter is an important driver regulating ecosystem functionality under these specific hydrochemical conditions (Williamson and Morris, 1999). In the humic and acid dystrophic lakes with low EC values, bacterioplankton biomass is relatively high and summer photoautotrophic bacteria share in total POC is higher than 70% of the (Taipale et al., 2011). In high humic lakes with alkaline water, a high biomass of cyanobacteria is developed (Górniak, 1996).

4.2. Ecohydrology of humic lakes

The dystrophic lakes occurrence in the Northern Hemisphere is associated with a special combination of basin factors that cause low bicarbonates concentration, low pH and stabile high humic substance concentrations. For dystrophy state, the most favorable conditions are found in areas with carbonates free sediments or in areas with crystalline igneous rocks, like in Sweden or Finland. In Norway, which has similar boreal conditions but a higher share of

Table 4
Differentiation of mean HDI (±SD) in Swedish lakes – SEMP database from summer 2012, for Finnish lakes data from Kortelainen (1993), for Russian lakes original data from Moiseenko et al. (2013a), in parenthesis – number of lakes.

Lake area [km^2]	Sweden (244)	Finland (90)	Russia (259)
0.02–0.1	70.6 ± 13.1	65.0 ± 8.5	65.7 ± 10.9
0.1–0.2	66.5 ± 12.6	63.8 ± 8.4	59.6 ± 11.4
0.2–0.5	65.1 ± 11.6	62.0 ± 7.5	61.3 ± 14.4
0.5–1.0	62.8 ± 12.8	61.2 ± 10.0	60.1 ± 9.7
1–2	54.5 ± 12.4	60.7 ± 8.5	58.4 ± 12.0
2–5	49.7 ± 11.9	63.8 ± 6.2	60.4 ± 10.6
5–10	51.4 ± 12.1	54.5 ± 13.1	60.4 ± 12.8
>10	49.8 ± 9.1	58.9 ± 6.8	56.8 ± 10.9

Table 5
Hydrochemical features of dystrophic lakes in different locations of the Northern Hemisphere (for data quality see in Section 2.1).

Lakes	*N* samples	pH	EC (μS cm^{-1})	DOC (mg C dm^{-3})	DIC (mg C dm^{-3})	HDI
Eastern USA (Reche et al., 1999)						
Dystrophic lakes	20	6.2	34.3	11.4	1.08	70.8
NE Poland (Górniak, 2004)						
Wigry National Park	19	5.8	17.3	20.6	3.0	67.4
Sarema, Estonia (Selberg et al., 2011)						
Lake Pitkjarv	13	4.5	31.5	22.0	6.21	76.6
Wisconsin. USA (data for year 2012 from NTL database)						
Trout Bog	7	5.0	19.3	17.8	1.77	80.8
Cristal Bog	8	5.1	13.5	11.9	2.02	81.9
NW Ireland (Drinan et al., 2013)						
Blanket bog on sandstone	8	5.2	36.5	8.2	1.64	71.6
Blanket bog on granite	18	5.5	72.1	7.2	1.44	66.0
Western Siberia, Russia (Moiseenko et al., 2013b)						
Tundra and forest tundra	48	6.3	27.7	4.9	2.78	62.5
Northern taiga	27	5.4	15.6	10.7	1.44	77.7
Middle taiga	36	5.7	35.7	11.4	2.16	68.3
Southern taiga	11	7.1	118.0	16.1	23.2	47.5
Forest steppe	11	7.9	247.0	26.5	80.8	37.9

sedimentary deposit in lakes, waters are less humic than in Sweden or Finland (Wilander et al., 2003). Scotland geological preferences of dystrophic waters are confirmed in the high frequency of this type of lakes compare to England or Wales (Palmer and Roy, 2001) and lake dystrophy diversification in the western Ireland (Drinan et al., 2013).

Local groundwater systems in the postglacial landscapes of the Northern Hemisphere create isolated patches of small lake basins with a low flushing rate, practically unconnected to regional hydrological system. The other favorable conditions for dystrophic lakes are also associated with acid environment and high DOC concentration in water bodies formed in the topographic depressions where bog development have a place, very frequently in boreal region (Kurhy and Turunen, 2006). The basin features protecting of high HS concentrations in the dystrophic lakes are small lake area, a deep depression or middle forest location with shorter period of sun operation as well as a high relative deep of lake. Any environmental changes in the direct lake catchment can result in a gradual loss of dystrophic lake features. Different scenarios of humic lake evolution under global climate changes are presented (Schindler et al., 1997; Larsen et al., 2011; Selberg et al., 2011). I could also speculate that increased fish population in the dystrophic lakes decrease the dystrophy level (Finstad et al., 2015).

My analysis of a large group of humic lakes clearly shows that lake morphology can be an important factor regulating lake status. Dystrophic lakes are connected with small water bodies with a strong thermal water stratification. Large water bodies exhibit prolonged water mixing and increased penetration of sun radiation, thereby limiting photobleaching processes. Organic substances in dystrophic lakes have lower photobleaching rates than in alkaline waters of harmonious freshwaters (Reche et al., 1999). Also, ecohydrological factors naturally stimulate water dystrophication by varied flushing rates which are higher in valley lakes and lower in the flat moraines or fluvioglacial plains.

4.3. New formula

The newly proposed HDI proposed implemented for lakes of different geographic locations yielded promising results and shows potential to be used in various climatic zones. One example of the potential of HDI is data from Western Siberia (Moiseenko et al., 2013b). Regions in the paleo-arctic ecozone have different level of lake dystrophy, decreased according to latitude decrease. Only lakes in the northern part of the taiga zone, but not the tundra part, has high HDI values; here, water resources are much higher than in the tundra or middle taiga zones (Moiseenko et al., 2013b). The peripheral location of Polish dystrophic lakes for boreal zones is determining the low HDI values for a south east of Poland (Chmiel, 2009) as well as for northern part of country, presented in Table 5. This is an effect of unfavorable climatic and hydrological conditions for stabile water resources in the natural and artificially changed landscape under a warming climate, reaching back more than 10,000 years after glaciation.

The proposed new formula has a rather synthetic character and can be a very useful in the long term monitoring of dystrophic lakes when there is a lack of appropriate hydrobiont indicators for biomonitoring of harmonious lakes. The new formula takes into account not only the humic state of lake, but also the other hydrochemical water parameters not included in the previous formulas by Hakanson and Boulion (2001) or Dunalska (2009). The HDI formula also allows to distinguish hydrochemical types of rivers rich in humic substances, but with different characteristics dystrophic or humoeutrophic features.

Table 6
Summary of descriptions for various type of humic lakes.

Parameters	Humic lakes		
	Harmonious lakes	Dysharmonious lakes	
	Polyhumic water (humoeutrophic)	Semidystrophic	Dystrophic
HDI	<50	50–65	>65
Lakes area	Different	>0.5 km^2	<0.5 km^2
DIC/DOC	>0.1	<0.1	<0.1
Calcium	>20 mg dm^{-3}	<20 mg dm^{-3}	<10 mg–dm^{-3}
Oxygen in hypolimnion	+	+	–
Summer thermal stratification	Slight	+	+
Water residence time	Long	Short	Long
Macrophytes	+	Rare	–
Fishes	+	+/–	–
Photosynthetic bacteria	–	+/–	+

4.4. Humic lakes classification

The recent study, previous field experience of the author, and literature studies have allowed for a summary of humic water features (Table 6) for correct recognition by environmental monitoring staff or in limnological studies.

Plenty of empirical data demonstrated that humic waters exist in various harmonious lakes with alkaline pH values, DIC resources not limiting for plants, and with EC values above 150 $\mu S\,cm^{-1}$. This water type with HDI levels below 50 is common in the temperate zone, outside the boreal region, or in basins with wetlands hydrologically linked with high mineralized ground or river waters. High eutrophic and alkaline humic lakes are referred to as "humoeutrophic" (Górniak, 1996, 2006).

As Wetzel (2001) stated "dystrophy denotes a high loading of allochthonous organic matter" and lead to low autotrophy. An evident hydrochemical symptoms of dystrophy are constantly or periodical observed in semidystrophic lakes, characterized by low electric conductivity (EC < 100–150 $\mu S\,cm^{-1}$), slightly acid water (pH 6–7) and totally oxygenated water column, accelerated by water exchange processes or maintained by low plankton productivity. These usually large lakes dominate in the Scandinavian Peninsula and show HDI values in the range from 50 to 65. The term dystrophy should be reserved for small lakes with an area below 0.5 km^2, a HDI greater than 65, and a deoxygenated hypolimnion. A steeply thermal stratification of lakes probably can be related with meromictic lakes (Hakala, 2004), where the chemolithoautotrophic and photolithoautotrophic bacteria have a proper habitat for a very intensive development (Taipale et al., 2009, 2011).

The presented results confirm that most of the Scandinavian lakes are semidystrophic (HDI 50–65) or dystrophic (HDI > 65) and for this reason they should be separated from other groups of harmonious lakes in the ecological classification of European waters.

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Further reading

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