Factors controlling hydrochemical and trophic state variables in 86 shallow lakes in Europe

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Abstract

In order to disentangle the causes of variations in water chemistry among European shallow lakes, we performed standardised sampling programs in 86 lakes along a latitudinal gradient from southern Spain to northern Sweden. Lakes with an area of 0.1 to 27 000 ha and mean depth of 0.4–5.6 m located in low to high altitudes were investigated within the EC project ECOFRAME 1–4 times during June–October 2000–2001. Several variables like conductivity, alkalinity, abundance of submerged plants, concentrations of suspended solids, total nitrogen and phosphorus were latitude-dependent decreasing from south to north. Secchi depth, concentrations of total nitrogen, total phosphorus, suspended solids, and chlorophyll *a* correlated strongly with the presumed quality classes of the lakes. We came to the conclusion that the variability of shallow lakes in Europe is still mostly dependent on natural differences. Variables connected to lake morphometry, seasonality, basin geology and climate explained altogether nearly half of the total variability of lakes. The trophic state factor, describing mostly the human influence on lakes, was the strongest single factor responsible for nearly a quarter of the total variability of the studied European lakes.

Introduction

Investigations based on a large number of lakes usually cover small geographic ranges. This kind of regional study is known from many parts of the World like Denmark (Jensen et al., 1990), Norway (Faafeng & Hessen, 1993), Estonia (Ott et al., 1999), and Florida (Duarte et al., 1992), United Kongdom (Maberly et al., 2003), and Germany (Mathes et al., 2003). Wider geographical overviews (Schindler, 1978; Kalff, 1991; Cobelas & Rojo, 1994) are generally based on data collected from the literature, inevitably leading to inclusion of variability caused by methodological differences. In order to improve our understanding of the considerable large scale variations in lake water chemistry, we performed standardised sampling programs throughout Europe.

In the present paper, we summarise the results of statistical analyses of general limnological data performed according to a unified methodology on a set of 86 shallow lakes ranging in latitude from southern Spain to northern Sweden. The aim of our study was to find out which part of the total variability in water chemistry among European shallow lakes could be explained by natural, i.e. climatic and morphoedaphic differences, and which part could be attributed to anthropogenic influences.

Description of the lakes studied

Eighty-six shallow lakes in Europe were chosen to cover most of the European latitudinal and longitudinal ranges and the major part of the variability in terms of lake size, basin geology, and nutrient status. Eighteen lakes were from Spain and six to ten lakes from each of the other countries including Denmark, Estonia, Finland, Germany, Great Britain, Ireland, The Netherlands, Poland, and Sweden. Lakes with an area from 0.1 to 27 000 ha (median 27 ha) and mean depth from 0.4 to 5.6 m (median 1.6 m) distributed within a latitude range from 39° to 68.5° N (Table 1) and in low to high altitudes. Polymixis was the main criterion to distinguish between shallow and deeper lakes (Padisák & Reynolds, 2003). The lakes differed in their thermal regimes from non-freezing to lakes with a more than 4 months ice-cover. The conductivity of lake water ranged from 5 to 18 900 μS cm^{-1}, but according to the median value (306 μS cm^{-1}) most of the water bodies were freshwater lakes. The basins were either calcareous, silicious, peaty or a combination of these types.

Materials and methods

In the year 2000, 66 shallow lakes of different ecological quality were sampled 2–3 times during June–October by each of the 11 partners (6 by each partner) connected to the European Union project ECO-FRAME. A general limnological characterisation of the lakes was made in terms of altitude and latitude of the location, morphometric features (area, mean and maximum depth), basin geology, and ice conditions. In order to characterise vegetation abundance, the percentage of the lake volume 'infested' by submerged macrophytes (PVI) (Canfield et al., 1984) was calculated. A similar set of physical and chemical variables including water transparency as Secchi depth, conductivity, pH, total alkalinity, light absorbance at 400 nm, and the concentrations of total phosphorus, total nitrogen, and chlorophyll a was measured by each partner. In the year 2001, 20 new lakes were chosen to displace some of the earlier ones. The new set of lakes was sampled only once according to a simplified sampling program from which measurements of total alkalinity, light absorption, and suspended solids concentration were omitted.

Water samples were taken as integrated tube or sampler samples from the central part of the lake. Water transparency (SD) was measured with Secchi disc. Conductivity (COND) and pH (PH) were measured in unfiltered water using electronic pH and conductivity meters. We used methyl orange to determine the end point in total alkalinity titration with 0.05 N HCl. Chlorophyll a (CHL) was extracted from filters with 96% ethanol and concentration calculated according to Arvola (1981). Suspended solids (SS) were determined on preweighed Whatman GF/C filters after drying at 105 °C for 2 h. As a measure of humic substances concentration, spectrophotometric light absorption at 400 nm (A400) was measured in filtered (Whatman GF/C) water against distilled water using 5-cm cuvettes. Total phosphorus (TP) was measured by the molybdenum blue reaction according to Murphy & Riley (1962) after potassium persulfate digestion. For total nitrogen (TN) mostly the Kjeldahl method was used, however partners were free to use their own methods.

Codings were used for some variables to make them numeric. To describe basin geology (GEOL), code 1 was used for predominantly mineral soils, both calcareous and siliceous, and code 2 for organic (peaty) basins. In cases where both types of soils were almost equally represented, the code 1.5 was used.

Table 1. Descriptive statistics of the main variables characterising the set of 86 shallow European lakes

Variable, unit	Abbreviation	Valid N	Mean	Median	Min.	Max.	Std.Dev.
Month, number	MONTH	203	7	7	6	10	1
Secchi depth, m	SD	203	1.5	1.1	0.2	6.9	1.3
Conductivity, μS cm^{-1}	COND	203	978	306	5	18 900	2767
North latitude, degrees	LAT	203	52.3	52.4	39.0	68.5	7.2
Mean depth, m	ZAV	203	1.8	1.6	0.4	5.6	0.9
Maximum depth, m	ZMAX	189	3.9	2.7	1.0	16.0	2.6
Area, ha	AREA	203	669	27	0.1	27 000	3329
Percentage volume infested (PVI) by submerged plants, %		186	19	7	0	100	26
Suspended solids, mg l^{-1}	SS	155	14.1	7.3	0.2	127.2	20.1
Light absorption at 400 nm, 5 cm^{-1}	A400	149	0.11	0.09	0.01	0.85	0.11
pH	PH	203	6.38[a]	8.11	4.28	9.93	0.96
Alkalinity, meq l^{-1}	ALK	137	2.12	1.68	0.03	6.61	1.60
Total phosphorus, mg m^{-3}	TP	203	98	53	2	753	120
Total nitrogen, mg m^{-3}	TN	203	1916	1206	227	12 938	2029
Chlorophyll *a*, mg m^{-3}	CHL	198	40.6	16.4	0.3	426.9	64.0

[a] Negative logarithm of the average $[H^+]$ concentration.

All investigators were asked to give an expert opinion of the ecological quality of the lakes. This status (STATUS) of lakes was evaluated in a scale of five categories recommended by the EU Water Framework Directive (EC Directive, 2000) with code 1 corresponding to bad, 2 to poor, 3 to moderate, 4 to good, and 5 to high status. To describe the length of the ice-cover (ICE), code 0 was used for non-freezing lakes, code 1 for lakes frozen for less than 2 months, and code 2 for lakes where the ice-cover lasts more than 2 months. The altitude (ALT) was marked by 1 for lowland lakes, by 2 for middle-altitude lakes, and by 3 for high-altitude lakes.

Statistical analysis of data was performed using STATISTICA for Windows 5.0 (StatSoft, Inc., 1995). For cluster analysis, nine variables measured in all 86 lakes (SD, COND, LAT, ZAV, ICE, PH, TP, TN, CHL) were standardised by subtracting the mean of each variable and dividing the residuals by the standard deviation. Using the *k*-means clustering procedure, the lakes were grouped into five clusters. We used Principal components as the extraction method for factor analysis and 'Varimax normalised' as the rotation type. Eigenvalue >1 was used as the criterion for the appropriate number of factors. Missing values were deleted pairwise.

Table 2. Numbers of lakes in clusters separated on the basis of nine variables (SD, COND, LAT, Zav, ICE, PH, TP, TN, CHL) using the *k*-means clustering procedure

Country	Cluster					
	1	2	3	4	5	Total
Sweden			1	1	5	7
Finland				1	5	6
Estonia				6	3	9
Denmark				5	1	6
Germany			6	2	1	9
United Kingdom	1	3	6			10
Ireland			8		1	9
Poland		1		5		6
The Netherlands		1	5			6
Spain (Leon region)		2	9		1	12
Spain (Valencia region)	3	1	2			6
Total:	4	8	37	20	17	86

Results

Cluster analysis

Three variables (TP, TN, ICE) of the nine used for grouping the lakes had a significantly smaller within-cluster variability compared with the between-cluster variability when the lakes were divided into five
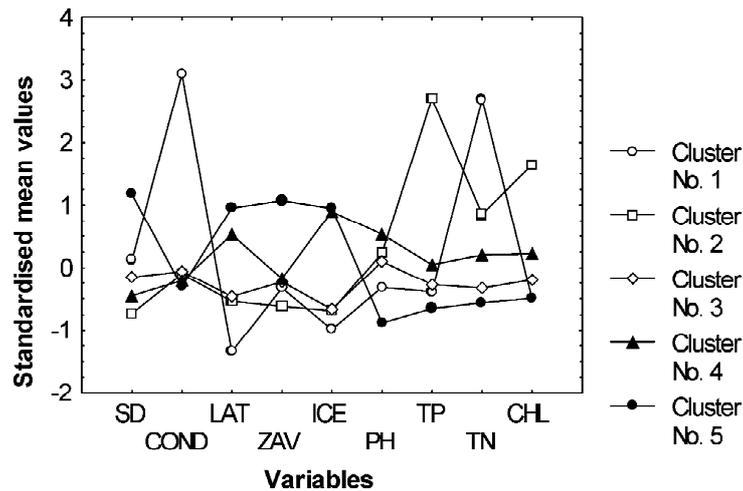
Figure 1. Standardised mean values of variables in clusters of lakes.

clusters. According to the standardised mean values of the variables (Fig. 1) the first cluster could be described as consisting of southern lakes with increased salinity and nitrogen concentration but with relatively low phosphorus and chlorophyll concentrations. This cluster contained four lakes (Table 2): three from Valencia region and one from the U.K. because of its extreme nitrogen concentration (Little Budworth Mere, 11.5 mg N l^{-1}). Cluster 2 joined generally turbid lakes with high TP and high CHL with missing or short ice-cover. Cluster 3 was the largest containing 37 lakes. It was the medium group in almost every respect. Cluster 4 consisted mainly of shallow northern lakes, with low water transparency in spite of low chlorophyll concentrations. The lakes in cluster 5 were generally deeper and characterised by low trophic state and high transparency.

Relationships between the variables

All well-known water quality parameters like Secchi depth, concentrations of suspended solids, total nitrogen, total phosphorus and chlorophyll were exponentially related with the presumed quality classes of the lakes (Fig. 2). Differences between the median values of the variables in neighbouring quality classes were mostly statistically significant except between 'poor' and 'bad', because only three lakes were considered 'bad'. High quality lakes were significantly deeper than the lakes qualified as 'moderate', 'poor' or 'bad'. Several variables correlated significantly ($p < 0.01$) with geographic latitude. There was a northward increase in ICE ($r = 0.59$), ln AREA ($r = 0.49$),

and ln ZAV ($r = 0.31$), and a decrease in ln COND ($r = -0.58$), ln TN ($r = -0.49$), ln ALK ($r = -0.44$), ln PVI ($r = -0.38$), PH ($r = -0.31$), ln SS ($r = -0.26$), ln SD ($r = 0.22$), and ln TP ($r = -0.22$). Neither CHL nor A400 correlated with latitude.

There were groups of interrelated variables (Fig. 3) that could be defined as variables connected with lake basin geology (PH, ALK, COND), with trophic status (LAT, ALK, TP, TN, CHL) and with water optics (ZAV, SD, SS, A400, CHL). Slightly saline lakes under marine influence caused a loss of linearity in the alkalinity-conductivity relationship.

Factor analysis

Seven factors explaining more than 70% of the total variance were extracted from 19 variables included in the analysis (Table 3).

Discussion

The high number of latitude-sensitive variables and the strength of correlations demonstrates the sensitivity of mostly physically driven shallow lakes to geological and climatic forcing. Similarly to Kalff (1991) who studied the effect of latitude on nutrients, biomass and production in lakes worldwide, we found a southward increase in TP and no trend in CHL.

Four variables commonly used to characterise the trophic status of lakes (SD, SS, TP, CHL) had the highest loadings (abs. value >0.5) to F1 in the factor
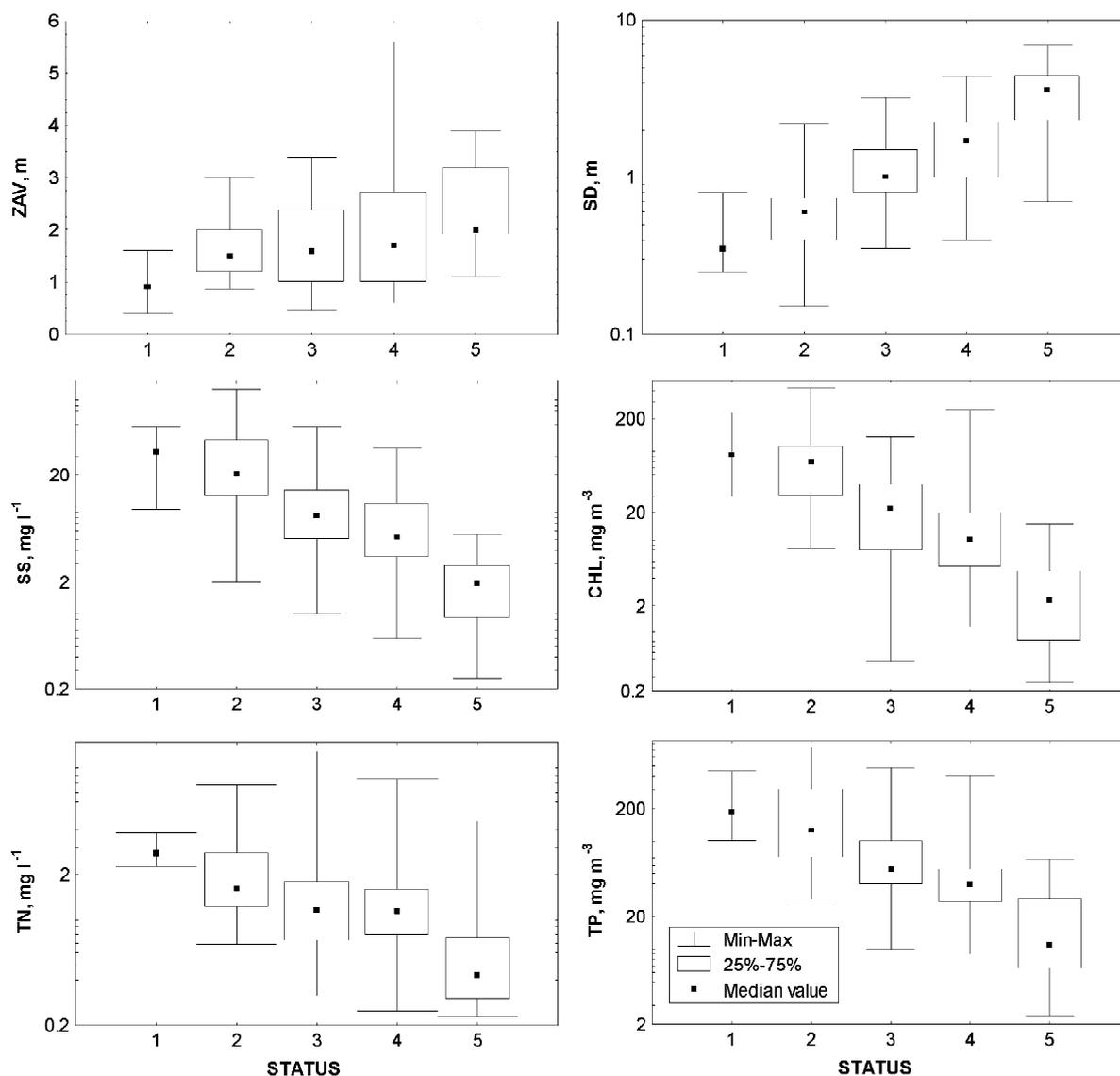
Figure 2. Variability of lake mean depth and of variables commonly used as water quality indicators within presumed water quality classes for lakes investigated. Water quality in lakes was estimated as expert opinion from 'bad'=1 to 'high'=5.

analysis. In spite of the wide range of climatic regions and lake types involved, this 'trophic state factor' explained the largest part of the variability in the database. A certain fraction of the differences in trophic status can be attributed directly to natural differences in soil fertility regarding, e.g. the morphoedaphic index by Vighi & Chiaudani (1985). Even more, the exceptionally high phosphorus concentrations in some meres of North West England included in the analysis may be of natural origin dependent on the local geochemistry (Moss et al., 1997). However, in most cases

anthropogenic eutrophication is responsible for high nutrient concentrations in lakes and has become the leading force in structuring lake ecosystems in Europe. As naturally more fertile soils are preferably used for agriculture, anthropogenic eutrophication emphasises the natural differences. LAT and variables correlated with latitude (PVI, COND and TN) had largest factor weights in F2. F3 was the depth factor. Deeper lakes were generally less humic and had a higher transparency. F4 was mostly influenced by altitude, ice conditions and basin geology and so it characterised,
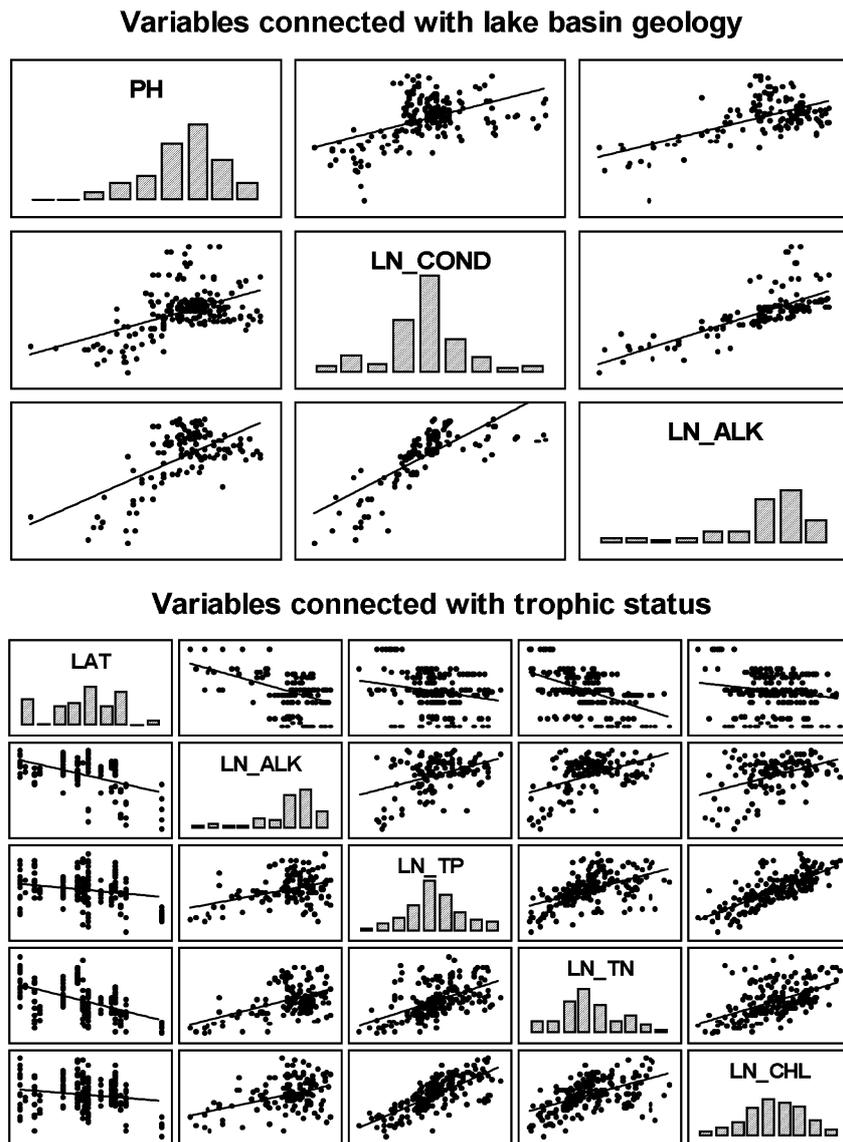
Variables connected with lake basin geology

Variables connected with trophic status

Figure 3. Regression matrices of intercorrelated variables. Distribution histograms of the variables are shown in the diagonal fields. Natural logarithm was used to normalise the distribution of most of the variables.

in some respect, also the maritime-continental transition. Factors 5–7 were strongly influenced by one variable each: F5 by sampling month, F6 by lake area, and F7 by sampling year.

Based on the analyses we came to the conclusion that the variability of shallow lakes in Europe is still mostly dependent on natural differences. Variables connected to lake morphometry, seasonality, basin geology and climate explained altogether nearly half of the total variability of lakes. The trophic state factor describing mostly the human influence on lakes

has become the strongest single factor responsible for nearly a quarter of the total variability of European lakes.
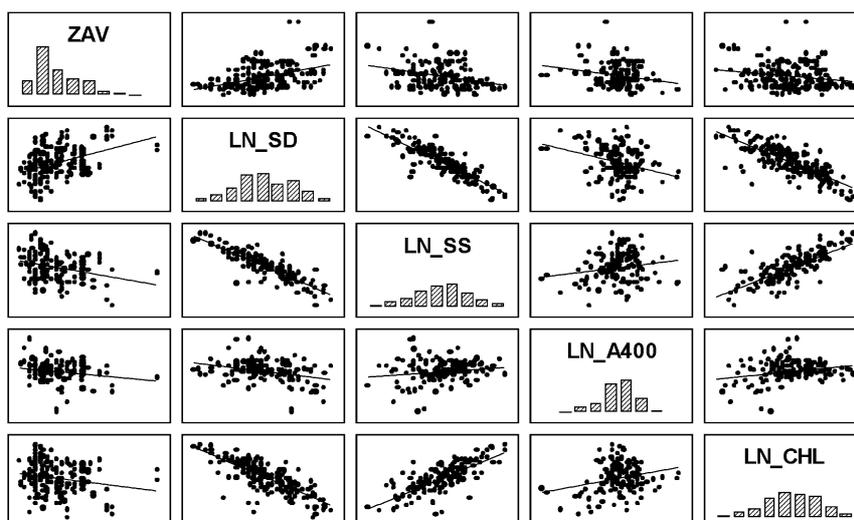
Variables connected with water optics

Figure 3. (Continued.)

Table 3. Factor weights of 19 variables used in the analysis. Weights with an absolute value >0.7 are marked in bold

Variable	Factor						
	F 1	F 2	F 3	F 4	F 5	F 6	F 7
MONTH	0.01	−0.02	0.08	0.03	**0.84**	0.00	−0.26
YEAR	−0.02	0.06	0.01	0.01	−0.23	0.05	**0.82**
SD	0.51	−0.01	0.58	0.13	0.00	−0.23	−0.03
COND	0.02	0.65	−0.02	0.11	−0.09	−0.08	0.07
LAT	0.16	**−0.81**	0.17	0.26	−0.05	−0.08	0.04
ALT	−0.16	0.30	−0.11	**0.81**	−0.03	0.16	0.02
ZAV	0.17	−0.21	**0.79**	−0.01	0.14	0.04	0.07
ZMAX	0.18	−0.23	**0.83**	−0.06	0.10	−0.03	0.10
AREA	0.06	−0.19	0.01	0.16	0.02	**0.79**	0.10
GEOL	−0.02	−0.19	−0.14	0.53	−0.37	−0.40	−0.27
PVI	0.36	0.67	−0.33	0.01	0.04	0.03	−0.13
ICE	0.13	−0.43	0.22	0.69	0.27	0.07	0.07
SS	**−0.89**	0.11	−0.12	0.07	0.12	0.03	0.02
A400	0.11	−0.25	−0.62	0.06	0.35	−0.20	0.30
PH	−0.33	0.31	−0.14	0.03	−0.18	0.53	−0.37
ALK	−0.11	0.43	0.08	−0.34	0.06	0.44	−0.06
TP	**−0.72**	−0.05	−0.18	−0.13	−0.14	−0.06	−0.05
TN	−0.49	0.61	−0.02	0.35	0.02	−0.05	0.20
CHL	**−0.88**	0.01	−0.05	0.11	−0.03	0.07	−0.02
Eigenvalue	4.25	2.34	1.86	1.65	1.31	1.15	1.01
Explained variance	22	12	10	9	7	6	5
Cumulative explained variance	22	35	44	53	60	66	71

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