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Primary Research Paper

The importance of lake morphometry and catchment characteristics in limnology – ranking based on statistical analyses

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Abstract

This work introduces an interpretational key to quantify and understand how much of variations among lakes in fundamental ecosystem characteristics that may be related to lake morphometry, catchment area features, measurement uncertainties and other factors (mostly climate). The size and form of lakes regulate many general transport processes, such as sedimentation, internal loading and outflow, which in turn regulate many abiotic state variables, such as concentrations of phosphorus, colour, water chemical variables and water clarity, which regulate primary production, which regulate secondary production. This paper discusses relationships between key abiotic state variables, lake morphometry and catchment area characteristics using empirical/statistical analyses based on data from 95 lakes. It has been shown that of the studied variables Secchi depth depends most on morphometry (34%); 31% of the variations among the lakes in Secchi depth may be related to catchment area characteristics, 1% to uncertainties in empirical data and 34% to "other" (climatological) factors. The corresponding figures for alkalinity, which depends least on lake morphometry are, 0% related to morphometry, 34% to catchment conditions, 1% to empirical uncertainty and 58% to other causes. For all other studied variables, i.e., conductivity, hardness (CaMg), calcium, iron, colour, pH and phosphorus the corresponding figures vary between these values. The interpretational key helps to explain the mechanistic reasons for these statistical/empirical results.

Introduction and aim

Comparative studies in limnology often aim to find general factors regulating and explaining why lakes differ in fundamental properties, such as trophic and humic level (see Håkanson & Peters, 1995). Many factors (x-variables) could potentially influence the variability among and within lakes of a given y-variable. The statistical analysis based on empirical data can be used to rank the importance of how the x-variables influence y. In these contexts, one must clearly differentiate between statistical and causal analyses. Statistical treatments can never mechanistically "explain" why certain x-variables end up with a high correlation towards y, but results from correlations and regressions can provide important information for further mechanistic interpretations and modelling. Regression analyses can be performed for many reasons, e.g., to compare modelled values with empirical data, to test hypotheses about relationships and to develop statistical/empirical models. Many textbooks examine regression analyses (e.g., Draper & Smith, 1966; Mosteller & Tukey, 1977; Pfaffenberger & Patterson, 1987; Taylor, 1990; Newman, 1993).

Many factors influence how well one can predict a target y-variable, e.g., sampling (number of samples), analysis (precision in determining y), model structure (how and which model variables x_i are included), the reliability of the model variables and the statistical methods used to define predictive success. In this paper, the r^2-value is used as a standard criterion of predictive success since this is a widely used concept in ecosystem modelling. The benefits and disadvantages with the r^2-value are probably better known than most alternative statistical measures (e.g., adjusted r^2 or predictive power, see Håkanson, 1997; functional distance, see Monte et al., 1996 and/or confidence intervals as determined from model validations, Håkanson, 1996).

The basic aim of this comparative work is to use empirical data from 95 lakes and statistical analyses to study how morphometric parameters and catchment area features influence variables expressing important lake characteristics.

Information on the 95 lakes

The data used in this work emanate from an extensive field investigation involving 95 Swedish lakes studied during 1986–1989 as part of an experimental program to reduce mercury and radiocesium in fish (Håkanson & Peters, 1995). Morphometric data, such as volume, area and mean depth were calculated from bathymetric maps. Most lakes in this study are smaller than 1 km^2; the largest lake is 5.26 km^2, the smallest 0.02 km^2. Mean depth ranges from 0.9 to 10.1 m, with a mean of 4.2 m. The following lake variables were determined from monthly samples generally from two sites and several sampling depths per lake: pH, Secchi depth, temperature, alkalinity, total-P, conductivity, Fe-concentration, Ca-concentration, hardness (= Ca + Mg-concentration) and colour. For some variables there are not data from all 95 lakes. Theoretical water retention time and tributary water discharge are also included. Data on the catchment area, e.g., the fraction of the catchment area covered by lakes (Lake%), mires (Mire%), by various types of soils, rocks, and land uses, etc. were also determined.

Basic data on the lakes (drainage area characteristics, morphometry and water chemistry) are given in Table 1, which provides annual mean values for the period March 1986–February 1987. The data in Table 1 describes the conditions before any remedial measures (liming, fertilization,

Table 1. Basic data from the 95 Swedish lakes

	Mean	Minimum	Maximum	SD	n
(A) Drainage area parameters					
ADA (km^2)	15.8	0.36	81	16.6	
RDA	41.0	8	194	31.9	95
Lake%	2.3	0	13.1	2.8	95
Forest%	80.0	60.9	100	9.1	95
Mire%	14.2	0	35.3	8.5	95
Open land (OL)%	3.4	0	20.8	5.1	95
Rock%	9.1	0	77.0	13.8	95
Till%	67.7	3.2	96.0	19.7	95
(B) Lake morphometric parameters					
L_{max} (km)	1.82	0.22	7.80	1.43	95
D_{max} (m)	12.4	1.7	52.0	8.9	95
Area (km^2)	0.77	0.02	5.26	0.94	95
Area/ADA	0.073	0.002	0.391	0.068	95
Vol (km^3)	0.0041	0.00005	0.0495	0.007	95
B_m (km)	0.35	0.06	1.05	0.20	95
D_{mv} (m)	4.18	0.90	10.10	2.40	95
D_{rel}	1.71	0.18	7.39	1.29	95
L_d	2.43	1.40	8.20	0.96	95
V_d	1.18	0.50	2.20	0.36	95
DR	0.24	0.04	1.13	0.18	95
ET (% of area)	26	7	90	16	95
Q_{mv} (m^3/sec)	0.164	0.010	0.850	0.17	95
T (years)	0.873	0.020	4.790	0.92	95
(C) Water chemical variables					
pH_{12}	5.9	4.8	6.7	0.4	95
alk_{12} (meq/l)	0.048	0.000	0.370	0.06	95
$cond_{12}$ (mS/m)	3.96	1.58	10.88	2.19	95
TP_{12} (μg/l)	11.5	3.8	33.4	5.5	67
Fe_{12} (μg/l)	543	78	1950	358	41
Ca_{12} (meq/l)	0.17	0.08	0.80	0.12	50
$CaMg_{12}$ (meq/l)	0.24	0.09	0.64	0.11	92
Sec_{12} (m)	2.5	1.1	6.3	1.0	88
Col_{12} (mg Pt/l)	98	15	340	53	95

SD = standard deviation; n number of lakes. ADA, Drainage area; RDA, Relief drainage area; Lake%, Lake% of ADA (etc); ET, Bottom areas of erosion & transp.; B_m, Mean breadth; D_{mv}, Mean depth; L_d, Shore development; V_d, Volume development; DR, Dynamic ratio; D_{rel}, Relative depth; Q_{mv}, Mean annual water discharge; T, Water retention time; pH_{12}, Mean annual pH (12 for 12 months); Sec_{12}, Mean annual Secchi depth; Col_{12}, Mean annual colour.

etc.) were introduced. The mean annual value for lake pH (pH_{12}; 12 for 12 months) before remediation varied from 4.8 to 6.7; the mean value for all studied lakes was 5.9. The mean annual lake colour (Col_{12}) also varies widely (from 15 to 340 mg Pt/l). Most of the lakes have low alkalinity and a colour value around 100, which is typical for glacial, boreal lakes. The mean annual concentrations of total-P (TP) varied between 3.8 and 33.4 μg/l. All these lakes belong to the glacial type (see Hutchinson, 1957). There are about 83,000 lakes in Sweden, about 81,000 belong to this lake type, and the same proportions ought to apply also for Finland, Russia, Canada and northern USA. Most lakes on Earth belong to this lake type.

Methods

Variations within lakes and the highest r^2

There are uncertainties for all empirical mean values in this study and in most studies. One standard way of quantifying such uncertainties is by means of the coefficient of variation, CV (CV = SD/MV; SD = standard deviation, MV = mean value). The CV-value for within ecosystem variability (CV_w) is always related to very complex climatological, biological, chemical and physical conditions. The within-lake variations mainly depends on seasonal changes in temperature, light, winds, precipitation and bioproduction. This is exemplified using monthly data on lake colour for four years from one lake in Fig. 1(A). The data for colour shown in Fig. 1(A) for one lake are included in the data given in Fig. 1(B), where they are compared to similar data from many lakes. Figure 1(B) shows that a characteristic CV_w for lake colour varies around 0.2 (or 20%) and that there is a seasonal pattern. CV_w is generally lower than 0.2 during the growing season and higher than 0.2 during fall and winter. Table 2 gives a compilation of characteristic CV_w-values for many variables. These CV_w-values regulate the highest r^2-value that one in practice can expect when modelled values are compared to empirical data (Eq. (1))

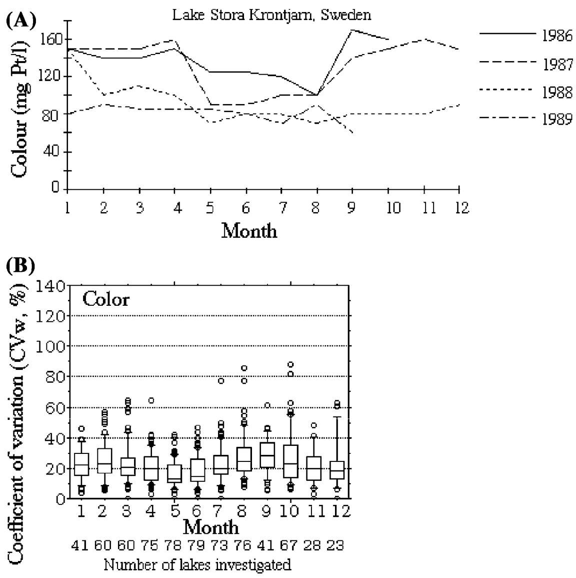

Figure 1. (A) Temporal variations in colour in Lake Stora Krontjarn, Sweden, based on monthly data from 1986, 1987, 1988 and 1989. (B) Coefficients of within-lake variations (CV_w in %) based on monthly data from four years for colour from many lakes. The box-and-whisker plots give the medians, quartiles, 10th and 90th percentiles and outliers. The figure also gives the number of lakes studied.

From a statistical point of view, an equation has been derived which gives the highest reference r^2-value as a function of (1) the number of samples (n_i) for each y_i-value in the regression, (2) the number of data points in the regression (N), (3) the standard deviations related to all individual data points, (4) the standard deviation of all points in the regression and (5) the range of the y-variable (Håkanson, 1999).

$$r_r^2 = 1 - 0.66 \cdot CV_w^2 \qquad (1)$$

The equation is valid for actual (non-transformed) y-values. From Table 2, one can see that, e.g., r_r^2 for Secchi depth is 0.99, for TP 0.92, for colour 0.97 and for pH 1.0. Note that pH is by definition a logarithmic value.

The given CV_w-values and the corresponding $r_r{}^2$-values will be used in the following to set limits for the presented r^2-values in the regressions, where the aim is to rank the role of morphometric and catchment parameters in predicting important lake variables.

Table 2. Compilation of characteristic CV_w-values for different types of lake variables (from Håkanson, 1999) and the corresponding highest r^2-values (r_r^2)

	CV_w	r_r^2		CV	r_r^2
Lake variables			Sedimentological variables		
Lake area (A)	0.01	1.00	Percent ET-areas (ET)	0.05	1.00
Mean depth (D_{mv})	0.01	1.00	Suspended particulater matter (SPM)	0.2	0.97
Maximum depth (D_{max})	0.01	1.00	Mean water content for *E*-areas	0.3	0.94
Volume (V)	0.01	1.00	Mean water content for *T*-areas	0.2	0.97
Theoretical water retention time (T)	0.1	0.99	Mean water content for *A*-areas	0.05	1.00
			Mean bulk density for *E*-areas	0.1	0.99
Water chemical variables			Mean bulk density for *T*-areas	0.1	0.99
pH	0.05	1.00	Mean bulk density for *A*-areas	0.02	1.00
Conductivity (cond)	0.1	0.99	Mean organic content for *E*-areas	0.5	0.84
Ca-concentration (Ca)	0.12	0.99	Mean organic content for *T*-areas	0.5	0.84
Hardness (CaMg)	0.12	0.99	Mean organic content for *A*-areas	0.1	0.99
K-concentration (K)	0.2	0.97	Mean TP-conc. for *E*-areas	0.5	0.84
Colour (Col)	0.2	0.97	Mean TP-conc. for *T*-areas	0.75	0.63
Fe-concentration (Fe)	0.25	0.96	Mean TP-conc. for *A*-areas	0.35	0.92
Total-P concentration (TP)	0.35	0.92	Fall velocities	0.5	0.84
Alkalinity (alk)	0.35	0.92	Age of A-sediments	0.5	0.84
			Age of ET-sediments	0.5	0.84
Lake management variables			Diffusion rates	0.5	0.84
Secchi depth (Sec)	0.15	0.99			
Chlorophyll-a concentration (Chl)	0.25	0.96	Climatological variables		
Hg.conc. in lake fish	0.25	0.96	Annual runoff rates	0.1	0.99
^{137}Cs onc. In lake fish	0.22	0.97	Annual precipitation	0.1	0.99
			Temperatures	0.2	0.97

Variations among and within lakes

The problem addressed in this section is illustrated in Table 3. The variability of any variable within an ecosystem, CV_w, in Table 3 is calculated from time-series of data: CV_w is 0.72 for lake 1 in Table 3. The CV expressing variations among lakes, CV_a, is defined from the coefficient of variation of mean monthly values from different lakes for a given period: it is 1.01 in the top row in the CV_a-column in Table 3. Figure 2 gives a compilation of such CV_w and CV_a-values for seven standard lake variables (surface water temperature, pH, alkalinity, TP, colour, Secchi depth and conductivity) based on monthly data from four years from 24 Swedish lakes. As expected from this geographically restricted area of the world, there are no significant differences between CV_w and CV_a for temperature. The median CV for temperature is even higher within lakes than among them. In contrast, the median CV for pH, colour, TP, Secchi depth and conductivity are much higher among the lakes than within the lakes. In this example, the greatest difference in CV_a and CV_w exists for conductivity; the smallest (except temperature) for pH and alkalinity. If the difference in CV_a and CV_w is large, or the ratio high (Fig. 3A and Table 4), very good regression models for water variables can be derived based on parameters describing the catchment area (see Håkanson & Peters, 1995). Figure 3(B) gives the CV_a/CV_w-ratio on the *y*-axis and the maximum obtained r^2 in regressions based only on catchment area parameters (see Table 1) on the *x*-axis. Figure 3(C) gives a regression between the CV_a/CV_w-ratio and the maximum r^2-values from regressions

Table 3. Definition of variability (= coefficient of variation) within, CV_w, and among, CV_a, lakes, for a hypothetical lake variable

Period	Lake 1	Lake 2	Lake 3	Lake 4	Lake 5	MV_a	SD_a	CV_a
1	4.2	8.5	1.5	15.9	0.7	6.16	6.24	1.01
2	4.0	4.2	0.8	18.8	9.6	7.48	7.07	0.95
3	6.8	3.1	1.5	16.5	11.8	7.94	6.21	0.78
4	15.4	1.5	10.0	15.7	14.8	11.48	6.04	0.53
5	20.1	1.4	11.6	11.0	18.0	12.42	7.32	0.79
MV_w	10.1	3.7	5.1	15.6	11.0			
SD_w	7.3	2.9	5.3	2.8	6.6			
CV_w	0.72	0.78	1.04	0.18	0.60			

based only on lake morphometric parameters (Table 1). One can note that the r^2-values are low and that morphometric parameters are not linked to the CV_a/CV_w-ratio in the same way as catchment area parameters. The reason for this will be discussed in the next section. The regressions used in Fig. 3 will be presented in a following part.

One can conclude that for some lake variables (e.g., conductivity, iron, colour, hardness and calcium), the conditions in the catchment area determine to a very high degree the characteristic long-term lake value and for those variables lake morphometry plays a relatively small role.

Conservative and reactive substances and basic mass-balances

On the other hand, lake morphometry plays a key role for variables that settle out or in other ways participate in biological or chemical lake processes. This is indicated in Fig. 4, which gives the maximum r^2 in regressions based only on lake morphometric parameters on the y-axis and the sedimentation rates for the given variables in Lake Ekoln, Sweden, on the x-axis. The results in Fig. 4 are important and will be explained in this section.

The sedimentation rates in Fig. 4 emanate from empirical measurements from a 10-year period of both input and output to this lake. Table 5 gives a compilation of sedimentation rates and fall velocities for many variables included in that study (data from Håkanson & Jansson, 1983). To understand the results in Fig. 4, one must also discuss basic features of mass-balance models (see Vollenweider, 1968; OECD, 1982). The lake may be envisioned as a reactor tank with complete mixing during the calculation time (dt). The basic mass-balance model for the flow of matter, or a substance (X), to and from a lake may be described by the following differential equation:

$$V \cdot dC/dt = Q \cdot C_m - Q \cdot C - V \cdot C \cdot (v/D_{mv}) \cdot PF \qquad (2)$$

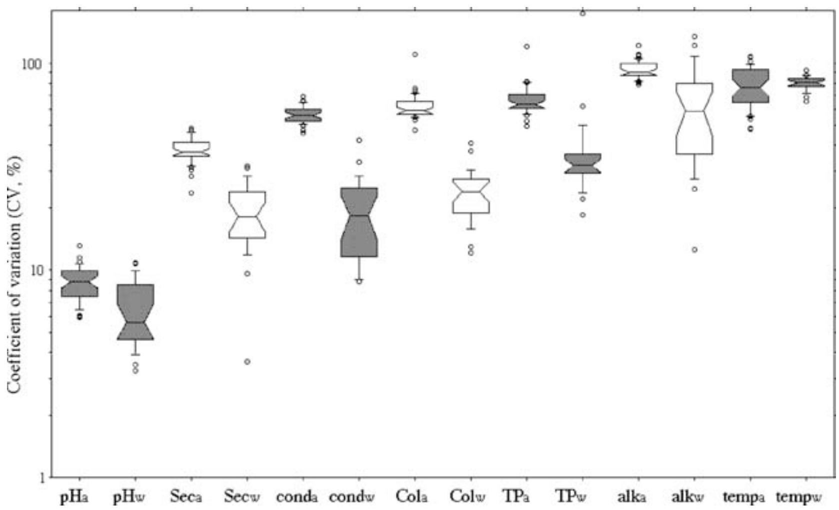

Figure 2. Box-and-whisker plots (showing 10, 25, 50, 75 and 90th percentiles and outliers) of coefficients of variation (CV) for variability within (w) and among (a) lakes for lake water temperature (°C), pH, TP (μg/l), colour (Col, mg Pt/l), Secchi depth (m) and conductivity (m S/m). Based on monthly data from 24 lakes.

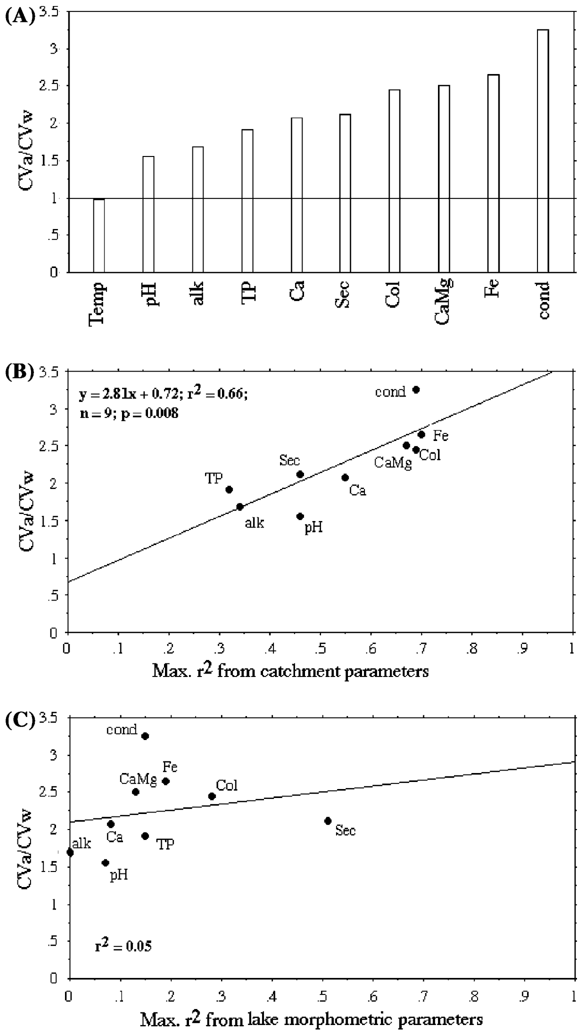

Figure 3. (A) The ratio of among lake variability to within lake variability for ten standard variables based on monthly data from 24 lakes. (B) The relationship between the "Among/Within" ratio and the maximum r^2-values obtained for empirical regression models based on catchment area parameters (listed in Table 1) for these water chemical variables (alk_{12} means mean annual alkalinity, i.e., the value is based on data from 12 months, etc.). (C) The same the "Among/Within" ratio versus the maximum r^2-values obtained for empirical regression models based on lake morphometric parameters.

where

V is the lake volume (generally m^3); dC/dt is the change in lake concentration (dC) of the given substance per unit of time (dt); e.g., in g/m^3 per year; C is the mean concentration of the substance in the lake (g/m^3); C_m = the mean concentration of the substance in the tributary (g/m^3); Q_{mv} the mean annual tributary water discharge to the lake (here m^3/year); V the lake volume (m^3); v is the fall velocity of the particulate phase (m/year); D_{mv} = the mean depth of the lake (m); PF is the particulate fraction (dimensionless). The only

Table 4. Results for various lake variables giving the r^2-values obtained when these variables have been regressed against lake morphometric parameters, catchment area parameters, lake morphometrtic plus catchment area parameters (listed in Table 1); and the ratio between the CV-values for these variables among and within lakes

Variable	r^2 vs lake morphometry	r^2 vs catchment	r^2 vs lake + catchment	CV_{among}/CV_{within}
Temperature	–	–	–	0.98
pH_{12}	0.07	0.46	0.46	1.55
alk_{12}	0	0.34	0.34	1.69
TP_{12}	0.15	0.32	0.37	1.91
Ca_{36}	0.08	0.55	0.62	2.07
Sec_{36}	0.51	0.46	0.65	2.12
Col_{36}	0.28	0.69	0.68	2.45
$CaMg_{12}$	0.13	0.67	0.71	2.51
Fe_{36}	0.19	0.70	0.71	2.65
$cond_{12}$	0.15	0.69	0.72	3.26

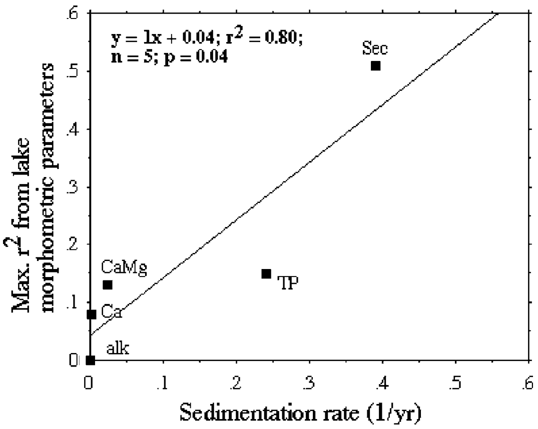

Figure 4. The relationship between the maximum r^2-values obtained for empirical regression models based on lake morphometric parameters versus the sedimentation rate (1/year) for five lake variables (Secchi depth, total phosphorus concentrations, hardness = CaMg, calcium concentrations and alkalinity) using data for Lake Ekoln, Sweden. For this lake there has been a full mass-balance so that both the inflow and the outflow have been measured for the period 1967–1977. The theoretical lake water retention time for Lake Ekoln is 2.07 years. The lake area is 18.6 km^2 and the mean depth 19 m (data from Håkanson & Jansson, 1983).

Table 5. Sedimentation rates (1/year) and fall velocities (m/year) for standard lake variables based on measured data on inflow and outflow for Lake Ekoln, Sweden (area = 18.6 km^2; mean depth = 19 m), for the period 1967–1977 (from Håkanson & Jansson, 1983)

	Variable	Sedimentation rate	Fall velocity
Conservative	Alkalinity	0	0
	Chloride	0	0
	Calcium	0	0
	Sodium	0.005	0.1
	Magnesium	0.048	0.9
	Sulfate	0.048	0.9
	Potassium	0.048	0.9
	Colour	0.082	1.6
	Organic nitrogen	0.15	2.9
	Phosphate-P	0.16	3.0
	Total-N	0.22	4.2
	Nitrate-N	0.22	4.2
	Total-P	0.24	4.6
	Nitrite-N	0.25	4.8
	Silicon	0.26	4.9
	Particulate-P	0.32	6.1
	Suspended part. matter	0.39	7.4
	Secchi depth	0.40	7.6
Reactive	Ammonia-N	0.41	7.8

fraction that can settle out by gravity; PF = 1-DF, where DF the dissolved fraction (generally approximated to be the bioavailable fraction, i.e., the fraction available for direct uptake by biota in the lake water); $PF = C_P/C_T$, where C_P is the particulate concentration (g/m^3) and C_T the total concentration (g/m^3).

The simplest way of solving this equation is to assume steady-state conditions. This means that one conserves mass and puts $Q_{in} = Q_{out} = Q$. This gives

$$C = Q_{mv} \cdot C_{in}/(Q_{mv} + V \cdot PF \cdot v/D_{mv}) \qquad (3)$$

The theoretical lake water retention time (T in years) is defined as the ratio between the lake volume and the mean annual water discharge, i.e., $T = V/Q_{mv}$. The sedimentation rate (R_{sed}) is $R_{sed} = PF \cdot (v/D_{mv})$. The sedimentation rate (= rate constant) of the substance C has the dimension 1/time, here 1/year. R_{sed} expresses how large fraction of the mass of the substance that settles during the given time. Equation (3) is graphically illustrated in Fig. 5, which highlights the importance of the particulate fraction in predicting TP-concentrations (Fig. 5(A)), and the mean depth and T in predicting TP (Fig. 5(B)).

Substances which only appear in dissolved phase, such as alkalinity, chloride and calcium (Table 5) are generally referred to as conservative or non-reactive, i.e., substances which do not change (settle, evaporate or are being transformed in the lake). Most allochthonous particles and

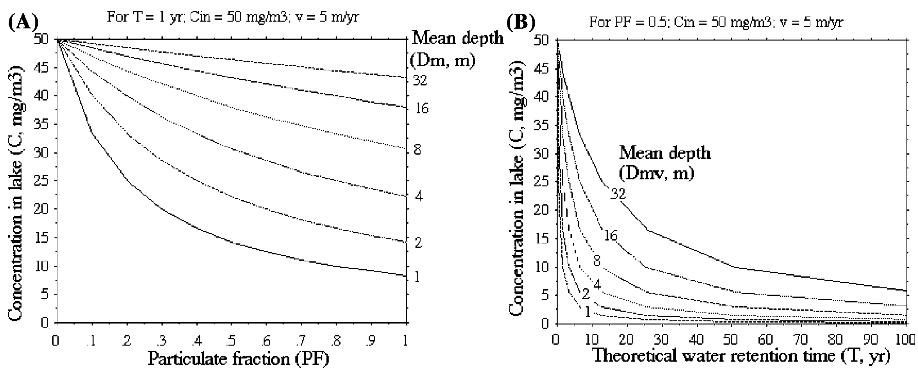

Figure 5. Illustration of the basic mass-balance model. (A) Gives the mean concentration in lake water as a function of the particulate fraction and the mean depth for a lake with a theoretical lake water retention time, T, of 1 year, a mean annual tributary concentration, C_{in}, of 50 mg/m^3 and a fall velocity of the particulate matter of 5 m/year. (B) Gives the mean concentration in lake water as a function of the theoretical lake water retention time and the mean depth for a lake with a particulate fraction, PF, of 0.5, a mean annual tributary concentration, C_{in}, of 50 mg/m^3 and a fall velocity of the particulate matter of 5 m/year.

Table 6. Correlation matrix giving correlations coefficients, *r*, among lake morphometric parameters based on data from 95 glacial, boreal lakes

	Alt	V_d	log (A)	log (ADA)	log (ADA/A)	log (D_{mv})	log (D_{max})	log (DR)	log (D_{rel})	log (ET)	log (L_d)	log (RDA)	log (Q_{mv})	log (T)
Alt	1													
V_d	−0.26	1												
log(A)	0.00	−0.33	1											
log(ADA)	−0.14	−0.14	0.65	1										
log(ADA/A)	−0.17	0.22	−0.40	0.44	1									
log(D_{mv})	0.14	−0.47	0.30	0.16	−0.16	1								
log(D_{max})	0.21	−0.73	0.37	0.19	−0.21	0.94	1							
log(DR)	−0.11	0.13	0.58	0.39	−0.22	−0.59	−0.49	1						
log(D_{rel})	0.21	−0.48	−0.39	−0.30	0.09	0.71	0.71	−0.92	1					
log(ET)	−0.25	0.47	−0.21	0.06	0.33	−0.47	−0.54	0.21	−0.37	1				
log(L_d)	−0.03	−0.35	0.28	0.18	−0.12	0.06	0.19	0.20	−0.03	−0.18	1			
log(RDA)	0.20	−0.03	−0.43	−0.29	0.16	0.18	0.15	−0.52	0.47	−0.18	−0.39	1		
log(Q_{mv})	−0.10	−0.18	0.67	0.98	0.40	0.22	0.25	0.36	−0.25	−0.01	0.19	−0.27	1	
log(T)	0.14	−0.40	0.51	−0.21	−0.86	0.59	0.61	−0.06	0.21	−0.43	0.12	−0.08	−0.17	1
log(V)	0.05	−0.46	0.92	0.59	−0.38	0.65	0.68	0.22	−0.02	−0.36	0.25	−0.27	0.63	0.65

pollutants, which are transported to the lake from the catchment, have a PF higher than zero and are distributed in a typical patterns with lobes of decreasing concentrations with distance from the source of pollution, or from the river mouth (Håkanson & Jansson, 1983).

The cohesive materials that follow Stokes' law generally have a great affinity for pollutants. This group includes many types of detritus, humic substances and plankton (Salomons & Förstner, 1984). Related to lake functional aspects, there are basically three major categories of matter in lake water: (1) PF, which is the only fraction settling by gravitation, (2) the dissolved fraction, which is very important for direct biouptake, e.g., by phytoplankton and often referred to as the bioavailable fraction, and (3) the colloidal fraction, which is neither subject to direct uptake nor to sedimentation because the particles are too small. The particulate fraction and the colloidal fraction may be subject to mineralization by bacterioplankton. If the sedimentation rate is close to zero, the particle or aggregate is conservative in the sense that it may not be deposited in the lake. In many lakes (Table 5), Cl, Ca and alkalinity are typically conservative substances, and colour, organic matter, TP, Si, particulate-P and suspended matter are more reactive.

From this, one can conclude that lakes of different size and form will not have the same sedimentation rates for different substances since the sedimentation rate is basically defined by the ratio between the fall velocity (v in m/year) divided by the mean depth (D_{mv} in m, defined by the ratio between the volume and the area). It is interesting to note the significant, logical and positive relationship in Fig. 4 between the sedimentation rate, which expresses how the variable is retained in the system – the higher the rate the more of the substance is retained in the lake – and the r^2 from the regression models based on lake morphometric parameters. Conservative substances, like alkalinity, are not really influenced by lake morphometry. Reactive substances with sedimentation rates higher than zero, on the other hand, may be strongly influenced by morphometry.

Internal correlations among lake morphometric parameters

Table 6 gives a correlation matrix showing internal co-variations among 15 morphometric

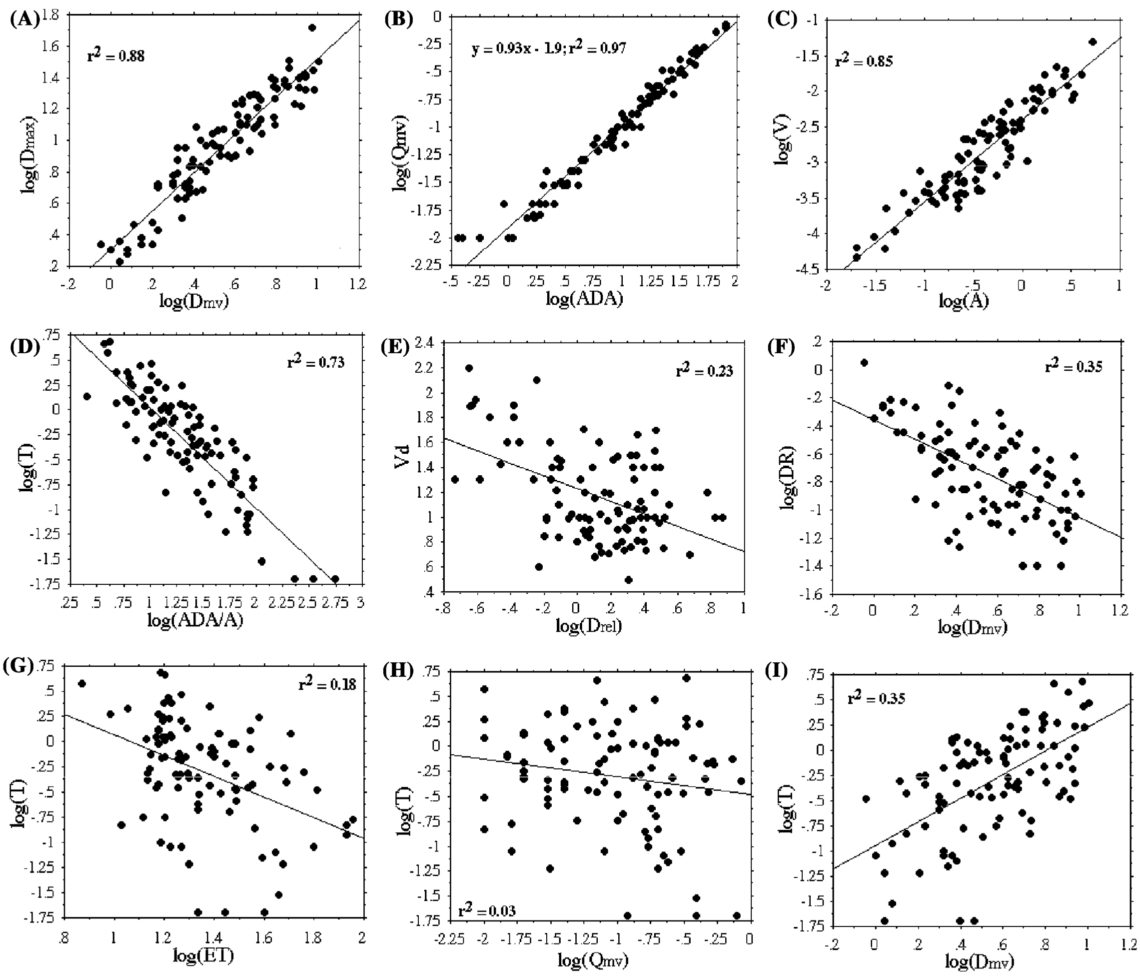

Figure 6. Nine scatter plots illustrating the statistical relationships (coefficients of determination, r^2) between important morphometrical parameters in contexts of lake ecosystem functioning based on data from 95 boreal, glacial lakes. (A) Mean depth (D_{mv} in m) vs maximum depth (D_{max} in m), (B) Area of drainage area (ADA in km^2) vs mean annual water discharge (Q_{mv} in m^3/s), (C) lake area (A in km^2) vs lake volume (V in km^3), (D) the catchment to lake ratio (ADA/A) vs theoretical lake water retention time (T in years), (E) relative depth (D_{rel}) vs volume development (V_d), (F) mean depth (D_{mv}) versus dynamic ratio (DR), (G) bottom areas of erosion and transport (ET in % of lake area) vs theoretical lake water retention time (T in years), (H) mean annual water discharge (Q_{mv} in m^3/s) vs theoretical lake water retention time (T); and mean depth (D_{mv}) vs theoretical lake water retention time (T).

parameters and Fig. 6 shows nine regressions between important morphometric parameters. The idea is to demonstrate internal correlations among these parameters. Parameters showing high internal correlations, i.e., those belonging to the same statistical cluster, may replace on another in regression models. From Fig. 6, one can note that using this data-base, there is a strong ($r^2 = 0.88$), logical correlation between the mean depth (D_{mv}) and the maximum depth (D_{max}; 6A). There is also a strong ($r^2 = 0.97$) and important relationship between the catchment area (ADA in km^2) and the mean annual water discharge (Q_{mv} here given in m^3/s; 6B). This regression may also be expressed as $Q_{mv} = 0.0091 \cdot ADA^{0.93}$. Since Q_{mv} is physically defined by $Q_{mv} = SR \cdot ADA$ (where SR is the specific runoff of water from land in m^3/km^2·s), one can conclude that SR on average is about 0.009 for these catchments. There is also a logical and strong ($r^2 = 0.85$) correlation between lake area (A) and volume (V; 6C). Since the mean water discharge (Q_{mv}) may be predicted very well from ADA, and since there is a strong relationship between volume and area, one can expect that the theoretical water retention time (T), which is defined as $T = V/Q_{mv}$, should be highly correlated to the catchment area to lake area ratio (ADA/A). This is also the case, as shown in Fig. 6(D) ($r^2 = 0.73$). One might expect that there should also be a strong relationship between the volume development (the form factor, V_d) and the relative depth (D_{rel}) since both these parameters express aspects of lake form, but this is not the case (6E; $r^2 = 0.23$). The reason is that they express different elements of lake form ($V_d = 3 \cdot D_{mv}/D_{max}$ and $D_{rel} = D_{max} \cdot \sqrt{\pi}/(20.0 \cdot \sqrt{A})$. From the definition of the dynamic ratio ($DR = \sqrt{A}/D_{mv}$; A in km^2, D_{mv} in m), one might also expect that DR should be highly related to the mean depth (D_{mv}), but this is not the case (6F; $r^2 = 0.35$). Also these two parameters express different form elements. The theoretical lake water retention time (T) and the ET-areas (ET; erosion and transportation areas for fine sediments) are both fundamental components of dynamic mass-balance models since T regulates the retention time of water, and everything dissolved and suspended in the water, and ET regulates resuspension and internal loading. Figure 6(G) shows that there is only a weak correlation between these two variables ($r^2 = 0.18$) for these lakes. Figure 6(H) illustrates that there is no significant correlation ($r^2 = 0.03$) between the theoretical lake water retention time (T) and water discharge (Q_{mv}) in spite of the fact that T is defined as V/Q_{mv}. Two lakes can have the same inflow of water but very different volumes. There is a stronger relationship between T ($= V/Q_{mv}$) and D_{mv} ($= V/A$) than between T and Q_{mv} (6I; $r^2 = 0.35$).

Generally, in building empirical/statistical models, it is a requirement that the included x-variables should emanate from different clusters. However, in complex lake ecosystems "everything depends on everything else" and it is not possible find "independent" variables, as this term is often used in many statistical contexts. It is evident that, e.g., lake TP, pH and colour are determined by independent methods and that they belong to different functional classes and play different roles in aquatic systems, but they are anyhow statistically related. There are many reasons for this: all of them may be transported a lake by the same tributaries, many internal processes, like wind-induced resuspension and mixing, affect them in similar ways, and they are all transported out of the lake together with all other dissolved and suspended substances.

From these correlations, one can conclude that different morphometric parameters are defined to express different elements of lake size and form, and that lakes can take many shapes. All lakes are individuals and will also react individually to changes in loading of nutrients or toxins.

Regressions

The main aim of this section is to try to clarify the role of lake morphometry and catchment characteristics in predicting and understanding important lake variables. Table 7 gives a typical set-up for the following parts. First, the table shows how lake morphometric parameters, then how catchment area parameters, then how lake morphometric plus catchment areas parameters and, finally, how lake morphometric plus catchment area parameters plus water chemical variables can statistically explain variations among lakes in mean annual hardness ($CaMg_{12}$). These calculations use the data from the 95 lakes (Table 1) and statistical methods discussed in detail by Håkanson & Peters (1995) concerning transformations, time and area compatibility of data, variants (i.e., mean values from different periods) and procedures of stepwise multiple regressions. Those methods will not be discussed here.

Hardness (i.e., Ca + Mg) has a low sedimentation rate (Table 5) and is not retained in lakes very much and cannot be predicted well from lake morphometric data. Table 7(A) shows that 13% ($r^2 = 0.13$) of the variability among these lakes in hardness may be statistically explained by variations in relative depth (D_{rel}), the most powerful morphometric predictor. On the other hand, the variation in $CaMg_{12}$ among the lakes may be explained very well by differences in catchment area characteristics. The ladder in Table 7B shows that log ($CaMg_{12}$) may be predicted quite well from four catchment parameters. The r^2-value after 4 steps is 0.67. The regressions are based on Open land% (OL%), i.e., the percentage of the catchment area with open (often cultivated) land; OL% has a positive effect ($r^2 = 0.46$) on log ($CaMg_{12}$); altitude (r^2 increases from 0.46 to 0.60),

Table 7. Ladder (using stepwise multiple regression analysis according to Håkanson & Peters, 1995) for the mean annual hardness of lake water ($y = \log(\mathrm{CaMg}_{12})$; CaMg_{12} in in meq/l)

Step	Parameter	r^2	Model
(A) CaMg_{12} vs morphometric parameters			
1	$x_1 = \log(D_{rel})$	0.13	$y = -0.642-0.190\cdot x_1$
(B) CaMg_{12} vs catchment parameters			
1	OL%	0.46	$y = -0.748+0.024\cdot x_1$
2	Alt	0.60	$y = -0.556+0.019\cdot x_1-0.001\cdot x_2$
3	log(OA)	0.63	$y = -0.427+0.018\cdot x_1-0.001\cdot x_2-0.115\cdot x_3$
4	log(RDA)	0.67	$y = -0.201+0.016\cdot x_1-0.0009\cdot x_2-0.142\cdot x_3-0.131\cdot x_4$
(C) CaMg_{12} vs morphometric and catchment parameters			
1	OL%	0.46	$y = -0.748+0.024\cdot x_1$
2	Alt	0.60	$y = -0.556+0.019\cdot x_1-0.001\cdot x_2$
3	$\log(D_{mv})$	0.63	$y = -0.485+0.018\cdot x_1-0.001\cdot x_2-0.133\cdot x_3$
4	log(OA)	0.66	$y = -0.352+0.017\cdot x_1-0.0009\cdot x_2-0.136\cdot x_3-0.118\cdot x_4$
5	log(RDA)	0.70	$y = -0.157+0.015\cdot x_1-0.0009\cdot x_2-0.121\cdot x_3-0.142\cdot x_4-0.117\cdot x_5$
6	D_{rel}	0.71	$y = -0.127+0.015\cdot x_1-0.0009\cdot x_2-0.172\cdot x_3-0.146\cdot x_4-0.139\cdot x_5+0.21\cdot x_6$
(D) CaMg_{12} vs morphometric, catchment and water variables			
1	$\log(\mathrm{cond}_{12})$	0.76	$y = -1.09+0.779\cdot x_1$
2	$\log(\mathrm{alk}_{12}+0.01)$	0.90	$y = -0.796+0.745\cdot x_1+0.202\cdot x_2$
3	log(RDA)	0.91	$y = -0.652+0.697\cdot x_1+0.222\cdot x_2-0.061\cdot x_3$

The table lists the r^2-values and the regressions at each step. $F > 4$. Data for 95 lakes.

percentage of outflow areas (OA%, i.e., the upstream lakes and wetlands; r^2 increases to 0.63), and relief (log(RDA); r^2 increases to 0.67). The relief is defined from the largest height difference in the catchment ($\mathrm{RDA} = \mathrm{d}H/\sqrt{\mathrm{ADA}}$; RDA = relief of drainage area; dH = the max. height difference in the drainage area; ADA = area of drainage area in m^2). Note that altitude, outflow areas and relief all have negative effects on CaMg_{12}.

Table 7(C) accounts for both morphometric and catchment parameters. Then r^2 reaches 0.71 after six steps. It is important to stress that all parameters are more or less related (Table 6). This means that $r^2 = 0.13$ from Table 4.8A and $r^2 = 0.67$ from Table 7(B) adds up to 0.71 (Table 7(C)), not to 0.80.

In the following, similar r^2-value as from Table 7 will be given for many lake variables and the results will also be used in a final analysis on the role of lake morphometry and catchment characteristics in predicting lake variables. Those regression are compiled in Appendix A.

Table 7(D) also includes chemical variables. The r^2-value reaches 0.91 after three steps, when conductivity (step 1; $r^2 = 0.76$), alkalinity ($r^2 = 0.90$) and relief (RDA) are accounted for in the model. The two first regressions given in Table 7(D) simply describe how hardness co-vary with conductivity and alkalinity, since they belong to the same cluster of water variables (see Håkanson & Peters, 1995)

Results

Predicting key abiotic variables

In this section, the focus will first be set on the three limnological state variables, phosphorus, colour and pH expressing important elements of lake structure and function (see Håkanson & Boulion, 2002).

Phosphorus. Total phosphorus (TP) has long been recognized as the nutrient most likely to limit lake primary productivity in many lakes (Schindler, 1977, 1978; Chapra, 1980; Peters, 1986; Wetzel, 2001). In this section, the regressions in Table 8 shows, how mean annual TP-

Table 8. Compilation of data related to the highest reference r^2 (r_r^2) and the inherent uncertainties in the given variables [$= 100\cdot(1-r_r^2)$], the maximum r^2-vales obtained in the regressions based on lake morphometric parameters, catchment area parameters and pooled morphometric and catchment parameters and the corresponding percentages of the variations in the given lake variables [calculated as %morf = $100\cdot(r^2\text{morf}\cdot r^2\text{pooled}/(r^2\text{morf} + r^2\text{catch})$]

	r_r^2	r^2 from morf	r^2 from catch	r^2 pooled	morf (%)	catch (%)	inherent uncertainty (%)	Other sources (%)
Conductivity	0.99	0.15	0.69	0.72	13	59	1	27
Hardness (CaMg)	0.99	0.13	0.67	0.71	12	59	1	28
Calcium	0.99	0.08	0.55	0.62	8	54	1	37
Colour	0.97	0.28	0.69	0.68	20	48	3	29
pH	1	0.07	0.46	0.46	6	40	0	54
Alkalinity	0.92	0	0.34	0.34	0	34	8	58
Total-P	0.92	0.15	0.32	0.37	12	25	8	55
Secchi depth	0.99	0.51	0.46	0.65	34	31	1	34
Iron	0.96	0.1	0.69	0.71	9	62	4	25

"Other sources" means variations that may be related to climatological factors causing seasonal variations within lakes.

concentration (TP_{12}) may be predicted from (A) lake morphometric parameters, (B) catchment parameters and (C) both. Particulate phosphorus has a relatively low fall velocity (Table 5), the particulate fraction is about 0.56 (Håkanson & Boulion, 2002). So, TP is not generally retained well in lakes and it cannot be predicted very well from morphometric data. One should also note that the highest reference r_r^2 is only 0.92 because the characteristic CV_w is as high as 0.35 for TP (Table 2). Table A.1 shows that 32% ($r^2 = 0.32$) of the variability among these lakes in TP_{12} may be statistically explained by variations in the following three catchment area parameters: (1) the percentage of rocks, Rock% ($r^2 = 0.12$), the percentage of open (cultivated) land, OL%, and lake area to catchment area ratio (A/ADA). The r^2-value after three steps is 0.32 ($n = 65$ lakes). This is a about 35% of the explainable variability ($= 0.32/0.92$) It should be noted that no single factor gives a very high r^2 for mean annual TP. Rock% appears with a logical minus sign – the more bare rocks in the catchment, the lower the transport of phosphorus from land to water. Open land% appears with a plus sign – the more cultivated land, the higher the transport of phosphorus from land to water. The larger the catchment area relative to the lake area, the higher the transport from land to water.

If both morphometric and catchment area parameters are accounted for, r^2 is 0.37 after four steps, and the theoretical lake water retention time (T) enters at the last step. This increases r^2 from 0.32 to 0.37.

Coloured substances. There are many publications on coloured substances in aquatic systems (Schindler, 1971; Christman & Gjessing, 1983; Gorham et al., 1983, 1986; Aiken et al., 1985; Engstrom, 1987; Hayes et al., 1989). Rasmussen et al. (1989) demonstrated that colour in 337 lakes from Canada and northern USA. was (1) positively related to the drainage ratio (the ratio between the size of the drainage area and lake area, ADA/A); (2) negatively related to the slope of the drainage area, presumably because drainage areas that are steep or have a high relief generally have thinner organic horizons, fewer bogs and mires and more ground water discharge; mountain lakes are often exceptionally clear; and (3) negatively related to lake mean depth and lake area suggesting that the turnover of coloured substances may also be related to resuspension. The best general regression model explained 60% of the statistical variance in lake colour among these North American lakes.

Table A.2 gives a ladder for lake colour using this database. When only morphometric parameters are included in regressions against colour (mean values based on data from 3 years, Col_{36} in mg Pt/l), 28% of the variability can be accounted for statistically. Theoretical lake water retention time enters at step 1. The longer the retention time, the lower the concentration of coloured materials in the water. This is logical since more of the coloured substances should find time to settle when T is large. The deeper the lake (step 2), the lower the colour values. In deep lakes, resuspension is smaller and the time for these humic particles to settle is longer.

When only catchment area characteristics are included, the percentage of the drainage area covered in rocks enters at step 1. Where Rock% is high, drainage areas are more infertile so less coloured and organic materials are likely to be transported from land to water, thus lowering the values of lake colour. This seems logical, but it is interesting to note that this factor was more important than Mire%, Lake% and Forest%. In agreement with results presented by Rasmussen et al. (1989), the drainage ratio enters at step 2 and increases r^2 from 0.24 to 0.45. Lake% enters at the third step ($r^2 = 0.58$). The higher the Lake%, the more coloured substances are trapped upstream and the lower the colour values in a given lake. The more mires, the higher the colour values in the lake ($r^2 = 0.63$). This is logical and expected. Also the percentage of till in the catchment increases lake colour values ($r^2 = 0.66$). In the final step in the model based on catchment parameters, ones find altitude. The higher the altitude, the lower the colour ($r^2 = 0.69$).

All other parameters describing lake morphometry and drainage area characteristics are weakly correlated with lake colour. Colour values may be statistically explained very well by differences in catchment area characteristics among the lakes. When both morphometric and catchment area parameters are accounted for, r^2 reaches 0.68 after six steps.

pH. The literature on lake pH and anthropogenic acidification of land and water, its ecological damage and economical consequences is extensive (Ambio, 1976; Likens et al., 1979; Overrein et al., 1980; Merilehto et al., 1988). It seems that a pH of about 5.5 may represent a boundary condition for lake ecosystem functioning (Ivanova et al., 1993; Ivanova 1997; Krylov et al., 1997; Håkanson & Boulion, 2002).

The ladder for mean annual lake pH (pH_{12}) is given in Table A.3. pH_{12} may not be predicted well from lake morphometric parameters. There is a very weak relationship between lake area and pH ($r^2 = 0.07$). The causal reasons for this are not clear but a larger area would imply a larger bioproduction and that would increase pH. The main reason for the low r^2 has been discussed and relates to the ratio between CV_a and CV_w, which is close to 1 for pH (Fig. 3). Lake pH is known to be difficult to predict (Håkanson & Peters, 1995) since it depends on acid rain, transport of substances from land influencing the H^+-activity and substances buffering the H^+-activity, seasonal variations in lake bioproduction, etc.

Using catchment area parameters, the r^2-value after seven steps is 0.46 and that model is first based on Open land% (OL%). This positive correlation is logical since more open (cultivated) land implies more fine sediments, more ions, higher buffering capacity, more agricultural fertilizers, and higher nutrient loading, a higher production and a higher lake pH. As expected, the correlation to mires is negative because mires produce humic substances, which lower pH. The statistically significant effect of relief (RDA) is difficult to explain mechanistically, but the statistical correlation is nevertheless positively significant for these lakes. The larger the catchment (ADA) in absolute terms, the higher the lake pH. The larger the catchment area relative to the lake area, the higher pH. There is a negative relationship between pH and altitude – lakes at higher altitudes often have lower pH. This may be an effect of temperature and lower production at higher altitudes. There is a logical negative relationship between rocks in the catchment and low pH.

Using both lake morphometry and catchment area parameters, the r^2-value after six steps is 0.46 and that model is based on the parameters just mentioned.

It is interesting to note that the characteristic within-lake variability (CV_w) for pH is small (0.05; see Table 2). This indicates that it would be possible to predict lake pH well, but these models do not do that. One should then note that pH by definition is a logarithm. Basically, the H^+-activity is likely to vary much like alkalinity with a CV_w of 0.35 and a corresponding r_r^2 of 0.92.

Water chemistry (alkalinity, calcium, iron and conductivity). These standard water variables play many different roles in lakes (Wetzel, 2001). Alkalinity, calcium, hardness (CaMg), conductivity and pH form a cluster of variables showing high internal correlations. Fe is more related to colour (Håkanson & Peters, 1995). Can these variables be related to lake morphometry?

Table A.4 shows the results for alkalinity, which cannot be predicted by morphometric variables. The reason is that mass-balances (Table 5) show that alkalinity is conservative. The ladder for alkalinity vs. catchment parameters shows that r^2 after 4 steps is just 0.34. So, $\log(\mathrm{alk}_{12}+0.01)$, which is the transformation yielding the most normal frequency distribution, is not predicted well from catchment characteristics. The model is based on the same parameters as the model for pH_{12}, and the same explanations may be used for the significant positive effects of Open land% (OL%), relief (RDA) and catchment area (ADA), and the negative relationship with altitude (Alt).

Table A.5 gives the results for calcium (Ca_{36}). These results are similar to those for hardness (CaMg; Table 7). One can note that $\log(\mathrm{Ca}_{36})$ may be predicted quite well from catchment parameters (r^2 after 3 steps is 0.55) but not from morphometric parameters ($r^2 = 0.08$) because calcium is quite conservative (Table 5). If morphometric and catchment parameters are pooled, r^2 is 0.62. Altitude is the most important x-variable – the higher the altitude, the lower the Ca-concentrations. There are positive correlations to Open land %, dynamic ratio (DR) and relative depth (D_{rel}), but these are weaker than the correlation to the shoreline development (L_{d}).

Iron has been determined as "acid-soluble" Fe and analyzed mainly to study the amounts of suspended humus and iron oxides and hydroxides. Highly significant relationships between Fe and colour have been demonstrated in previous works (see Wetzel, 2001). The "ladders" for the 3-year mean values of Fe-concentrations (Fe_{36}), as predicted from map characteristics, are given in Table A.6. Because of the high correlation between Fe and colour, these results are similar to the results shown for colour. Mire% ($r^2 = 0.32$) and Till% appear with positive correlations towards Fe_{36}. All other parameters (mean depth, outflow areas (= OA), altitude, mean water discharge (Q_{mv}), maximum depth, Rock% and the A/ADA-ratio] appear with negative signs. r^2 after six steps is 0.71. The highest reference r_{r}^2 (Table 2) for Fe is 0.96. Thus, all other factors that could potentially (statistically) affect Fe give an unexplained residual of about 25% (0.96–0.71). It is likely that Fe, like colour, is rather conservative (Table 5) which explains the low correlation towards lake morphometric parameters.

The results for conductivity ($\log(\mathrm{cond}_{12})$) are shown in Table A.7. Like hardness and Ca, cond_{12} may be predicted very well from catchment parameters. The r^2-value after five steps is 0.69. Conductively is a conservative variable, just like calcium and magnesium, so lake morphometry does not predict conductivity well ($r^2 = 0.15$ from the relative depth). The pooled parameters give an r^2 of 0.72, which is high.

It is interesting to note that the interpretational key related to the factors influencing the variability within and among lakes and the mass-balance considerations provide very useful information in understanding the given results for all these water chemical variables.

Secchi depth. Many factors are known to influence the Secchi depth (Vollenweider, 1958, 1960; Carlson, 1977, 1980; Preisendorfer, 1986): (1) autochthonous production (the amount of plankton, detritus, etc. in the water – more plankton means a lower Secchi depth); (2) allochthonous materials, such as the amount of coloured matter (humic, fulvic and minerogenic substances from tributaries); (3) the amount of resuspended material (materials resuspended from the lake bed via wind/wave activity, slope processes, etc.). These factors are not independent: high sedimentation leads to high amounts of resuspendable materials; high resuspension leads to high internal loading of nutrients and increased production; a high amount of coloured substances means a smaller photic zone and a lower production; a high input of coloured substances and a high production would mean a high sedimentation, etc. Wallin et al. (1992) showed that Secchi depth should be much greater than the observed values if only plankton cells were responsible for the light extinction. This means that particles other than plankton cells are perhaps the most important factors for determining Secchi depths. It was also concluded that the empirical relationship between Secchi depth and chlorophyll-a largely depends on the chlorophyll-a concentration co-varying with the total amount of suspended particles. This has been discussed also in other studies (Kiefer & Austin, 1974; Tilzer, 1988). The maximum depth of the photic zone is generally set to about two times the Secchi depth and the effective (or mean) depth of the photic zone is often set equal to the Secchi depth (Håkanson & Peters, 1995). Several studies have quantified and ranked variables of significance to predict how mean values of Secchi depth vary among lakes (Håkanson & Lindström, 1997; Nürnberg & Shaw, 1998). The most important "water" variables were: lake colour (expressing allogenic input of different types of humic materials), TP-concentration and temperature (measures of production of autogenic materials). The most important "geological" parameters were: the mean depth (linked to resuspension) and the ratio between the drainage area and lake area (expressing the linkage between catchment and lake).

Lake morphometry (D_{mv}) influences Secchi depth very much ($r^2 = 0.46$). This is shown in Table A.8. This describes the fact that internal lake processes (resuspension, diffusion, etc.) affect Secchi depth very much: the larger the mean depth, the larger the Secchi depth. The next most important morphometric factor is the theoretical water retention time (T). By accounting for T, r^2 increases to 0.51. This is a logical result, Secchi depth is highly related to suspended particulate matter (SPM; see Håkanson & Boulion, 2002), which by definition settles out in lakes. There are many compensatory and seemingly conflicting arguments to explain the role of morphometry in predicting Secchi depth. Secchi depth depends on colour, which has a low sedimentation rate; Secchi depth depends on TP, because TP increases primary production; Secchi depth depends on SPM, which settles out in lakes and reduce Secchi depth; Secchi depth depends on resuspension, which increases Secchi depth and depends on sedimentation. The ranking based on statistical analyses of empirical data is objective and the results cannot be falsified by more data, which can only clarify the domain of the empirical model. If only catchment parameters are used, one can note that r^2 after three steps is as high as 0.46, which is lower than the result after two steps using morphometric parameters. Rock% enters at step 1. If Rock% is high the transport of coloured substances, suspended inorganic materials and nutrients would be small. The ratio A/ADA gives a positive correlation – large lakes with small catchments generally have clear waters. Water discharge (Q_{mv}) has a positive r-value, which is more difficult to explain. When morphometric and catchment parameters are pooled, r^2 after four steps is 0.65.

Numerous factors in a lake and its catchment can potentially influence Secchi depth. With data like these, it is possible to quantitatively rank such influences and derive predictive models based on just a few, but the most important factors influencing among-lake variability in mean Secchi depth. The model based on map parameters could (statistically) account for 65% of the variability. This is high in relation to the highest r_r^2 of about 0.99 (Table 2).

A "natural or reference" Secchi depth can be estimated directly from the model based on map parameters. This prediction would account for differences in catchment area and lake morphometry. If the actual mean long-term Secchi depth differs from this predicted reference value, such divergences may be discussed in a quantitative manner.

Conclusion

This work has discussed regressions and the role of lake morphometric and catchment parameters in predicting water variables. Figure 7 is an attempt to summarize this information. It gives three categories in a lake-type triangle, with lake catchment parameters at the top, and morphometric parameters and "other causes" for variations at the base. All lake variables could be distributed in this triangle and this tells much about the factors causing variations in the given variable. Conductivity, hardness (CaMg), calcium, iron, colour, pH, alkalinity, Secchi

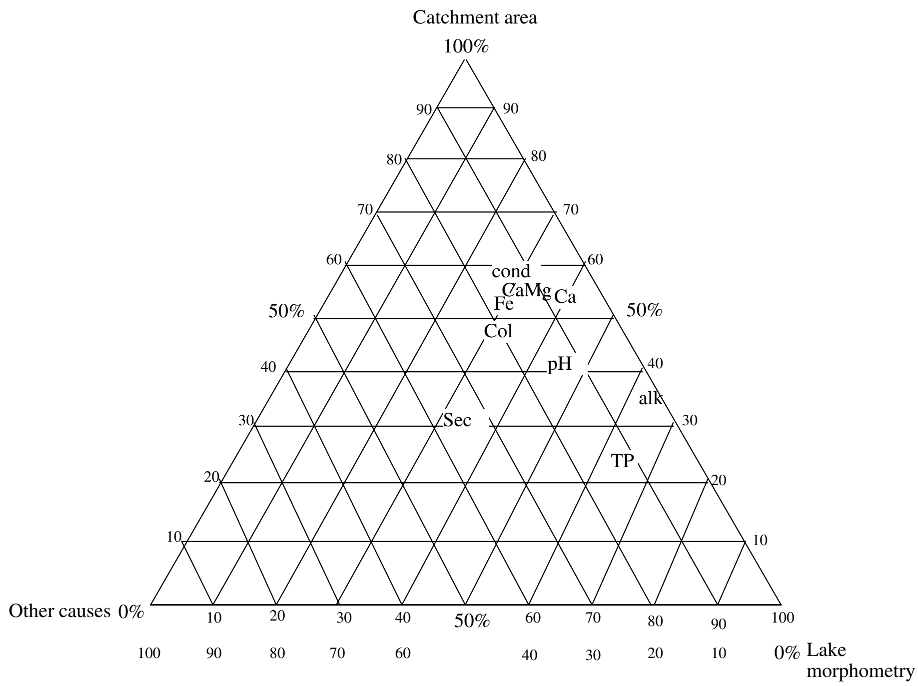

Figure 7. Diagram showing how catchment area parameters (top), lake morphometric parameters (down, right) and other factors (down left; these factors include water chemical variables, climatological variables causing seasonal changes, etc.) influence predictions of the given water variables (conductivity, hardness = CaMg, calcium, iron, alkalinity, pH, total phosphorus and Secchi depth).

depth and TP-concentrations may be identified in the diagram.

The calculations to obtain the data in Fig. 7 are shown in Table 8. To place a given variable in the triangle, one needs data on the maximum r^2 from regressions based only on lake morphometric parameters, maximum r^2 from catchment area parameters, maximum r^2 from both lake morphometric and catchment parameters and characteristic CV_w for the given variable so that the highest reference r^2 (r_r^2) can be obtained. This gives, e.g., that 13% of the variability in mean annual values of lake conductivity may be linked to variations among lakes in morphometric parameters, 59% may be related to variations in catchment characteristics, 1% to inherence uncertainties in conductivity values and the rest, 27% to other causes, mainly climatological factors.

From this diagram, one can note that among the discussed variables Secchi depth is highly related to lake morphometry. The interpretational key explains why, and it has to do with the fact that Secchi depth is closely related to suspended particulate matter (SPM), which by definition settles out in lakes.

Finally, it should be stressed that the results behind the interpretational key are meant to be valid for most lake types and lake variables since the principles behind the interpretational key are general and related to

(1) mechanistic principles of dynamic mass-balance modelling, (2) statistical analyses of catchment and lake data, (3) inherent uncertainties in empirical data and highest reference r^2 and (4) fundamental principles regulating variations in variables within and among lakes.

Table A.1. Ladder for the mean annual concentration of total phosphorus in lake water ($y = \log(TP_{12})$; TP_{12} in μg/l)

Step	Parameter	r^2	Model
(A) TP_{12} vs morphometric parameters			
1	$\log(D_{mv})$	0.15	$y = 1.173 - 0.274 \cdot x_1$
(B) TP_{12} vs catchment parameters			
1	log(1 + Rock%)	0.12	$y = 1.101 - 0.110 \cdot x_1$
2	OL%	0.25	$y = 1.076 - 0.129 \cdot x_1 + 0.015 \cdot x_2$
3	log(A/ADA)	0.32	$y = 0.939 - 0.143 \cdot x_1 + 0.014 \cdot x_2 - 0.109 \cdot x_3$
(C) TP_{12} vs morphometric and catchment parameters			
1	$\log(D_{mv})$	0.15	$y = 1.173 - 0.274 \cdot x_1$
2	OL%	0.24	$y = 1.140 - 0.274 \cdot x_1 + 0.012 \cdot x_2$
3	log(1 + Rock%)	0.32	$y = 1.171 - 0.208 \cdot x_1 + 0.014 \cdot x_2 - 0.101 \cdot x_3$
4	$T^{0.1}$	0.37	$y = 1.541 - 0.082 \cdot x_1 + 0.015 \cdot x_2 - 0.110 \cdot x_3 - 0.463 \cdot x_4$

The table lists the r^2-values and the models at each step. $F > 4$. Data from 65 lakes.

Table A.2. Ladder for mean lake colour based on data from 36 months ($y = \log(Col_{36})$; Col_{36} in mg Pt/l)

Step	Parameter	r^2	Model
(A) Col_{36} vs morphometric parameters			
1	$T^{0.1}$	0.24	$y = 2.913 - 1.024 \cdot x_1$
2	$\log(D_{mv})$	0.28	$y = 2.721 - 0.695 \cdot x_1 - 0.231 \cdot x_2$
(B) Col_{36} vs catchment parameters			
1	log(1+Rock%)	0.24	$y = 2.089 - 0.213 \cdot x_1$
2	$(A/ADA)^{0.3}$	0.45	$y = 2.504 - 0.262 \cdot x_1 - 0.902 \cdot x_2$
3	log(1 + Lake%)	0.58	$y = 2.747 - 0.250 \cdot x_1 - 1.2530 \cdot x_2 - 0.269 \cdot x_3$
4	Mire%	0.63	$y = 2.617 - 0.217 \cdot x_1 - 1.207 \cdot x_2 - 0.283 \cdot x_3 + 0.006 \cdot x_4$
5	Till%	0.66	$y = 2.360 - 0.149 \cdot x_1 - 1.248 \cdot x_2 - 0.260 \cdot x_3 + 0.009 \cdot x_4 + 0.003 \cdot x_5$
6	Alt	0.69	$y = 2.269 - 0.121 \cdot x_1 - 1.20 \cdot x_2 - 0.245 \cdot x_3 + 0.012 \cdot x_4 + 0.005 \cdot x_5 - 0.0007 \cdot x_6$
(C) Col_{36} vs morphometric and catchment parameters			
1	log(1 + Rock%)	0.24	$y = 2.089 - 0.213 \cdot x_1$
2	$T^{0.1}$	0.49	$y = 3.075 - 0.215 \cdot x_1 - 0.215 \cdot x_2$
3	log(1 + Lake%)	0.56	$y = 3.309 - 0.193 \cdot x_1 - 1.230 \cdot x_2 - 0.195 \cdot x_3$
4	log(OA)	0.65	$y = 2.990 - 0.889 \cdot x_1 - 1.194 \cdot x_2 - 0.280 \cdot x_3 + 0.255 \cdot x_4$
5	Till%	0.66	$y = 2.734 - 0.103 \cdot x_1 - 1.199 \cdot x_2 - 0.271 \cdot x_3 + 0.313 \cdot x_4 + 0.02 \cdot x_5$
6	$(A/ADA)^{0.3}$	0.68	$y = 2.565 - 0.127 \cdot x_1 - 0.710 \cdot x_2 - 0.301 \cdot x_3 + 0.286 \cdot x_4 + 0.0025 \cdot x_5 - 0.581 \cdot x_6$

The table lists the r^2-values and the models at each step. $F > 4$. Data from 91 lakes.

Table A.3. Ladder for the mean annual pH of lake water ($y = pH_{12}$)

Step	Parameter	r^2	Model
(A) pH_{12} vs morphometric parameters			
1	$\log(A)$	0.07	$y = 5.968 + 0.208 \cdot x_1$
(B) pH_{12} vs catchment parameters			
1	log(1 + OL%)	0.13	$y = 5.726 + 0.376 \cdot x_1$
2	Mire%	0.21	$y = 5.976 + 0.303 \cdot x_1 - 0.015 \cdot x_2$

Table A.3. (Continued)

Step	Parameter	r^2	Model
3	log(RDA)	0.26	$y = 5.409 + 0.385 \cdot x_1 - 0.013 \cdot x_2 + 0.330 \cdot x_3$
4	•ADA	0.32	$y = 5.081 + 0.364 \cdot x_1 - 0.015 \cdot x_2 + 0.431 \cdot x_3 + 0.062 \cdot x_4$
5	log(ADA/A)	0.39	$y = 5.180 + 0.338 \cdot x_1 - 0.016 \cdot x_2 + 0.564 \cdot x_3 + 0.101 \cdot x_4 - 0.309 \cdot x_5$
6	•Alt	0.44	$y = 5.598 + 0.269 \cdot x_1 - 0.014 \cdot x_2 + 0.626 \cdot x_3 + 0.104 \cdot x_4 - 0.367 \cdot x_5 - 0.035 \cdot x_6$
7	log(1 + Rock%)	0.46	$y = 5.754 + 0.241 \cdot x_1 - 0.016 \cdot x_2 + 0.666 \cdot x_3 + 0.110 \cdot x_4 - 0.351 \cdot x_5 - 0.044 \cdot x_6 - 0.153 \cdot x_7$
(C) pH_{12} vs morphometric & catchment parameters			
1	log(1 + OL%)	0.13	$y = 5.726 + 0.376 \cdot x_1$
2	Mire%	0.21	$y = 5.976 + 0.303 \cdot x_1 - 0.015 \cdot x_2$
3	•A	0.28	$y = 5.847 + 0.242 \cdot x_1 - 0.019 \cdot x_2 + 0.269 \cdot x_3$
4	log(RDA)	0.38	$y = 4.902 + 0.347 \cdot x_1 - 0.017 \cdot x_2 + 0.378 \cdot x_3 + 0.520 \cdot x_4$
5	•Alt	0.42	$y = 5.223 + 0.283 \cdot x_1 - 0.014 \cdot x_2 + 0.402 \cdot x_3 + 0.572 \cdot x_4 - 0.033 \cdot x_5$
6	log(1 + Rock%)	0.46	$y = 5.443 + 0.244 \cdot x_1 - 0.017 \cdot x_2 + 0.440 \cdot x_3 + 0.635 \cdot x_4 - 0.045 \cdot x_5 - 0.188 \cdot x_6$

The table lists the r^2-values and the models at each step. $F > 4$. Data from 93 lakes.

Table A.4. Ladder for the mean annual alkalinity of lake water ($y = \log(0.01 + alk_{12})$; alk_{12} in meq/l)

Step	Parameter	r^2	Model
(A) alk_{12} vs morphometric parameters; no significant relationships			
(B) alk_{12} vs catchment parameters			
1	log(1 + OL%)	0.11	$y = -1.484 + 0.268 \cdot x_1$
2	log(RDA)	0.25	$y = -2.220 + 0.367 \cdot x_1 + 0.459 \cdot x_2$
3	Alt	0.30	$y = -2.027 + 0.297 \cdot x_1 + 0.486 \cdot x_2 - 0.001 \cdot x_3$
4	•ADA	0.34	$y = -2.259 + 0.296 \cdot x_1 + 0.551 \cdot x_2 - 0.001 \cdot x_3 + 0.036 \cdot x_4$
C alk_{12}vs morphometric and catchment parameters; same as B.			

The table lists the r^2-values and the models at each step. $F > 4$. Data from 93 lakes.

Table A.5. Ladder for the calcium concentration in lake water based on data from 36 months ($y = \log(Ca_{36})$; Ca_{36} in meq/l)

Step	Parameter	r^2	Model
(A) Ca_{36} vs morphometric parameters			
1	$\log(L_d)$	0.08	$y = -0.881 + 0.373 \cdot x_1$
(B) Ca_{12} vs catchment parameters			
1	Alt	0.39	$y = -0.465 - 0.002 \cdot x_1$
2	$\sqrt{OL\%}$	0.51	$y = -0.591 - 0.001 \cdot x_1 + 0.060 \cdot x_2$
3	$RDA^{0.1}$	0.55	$y = 0.042 - 0.001 \cdot x_1 + 0.061 \cdot x_2 - 0.454 \cdot x_3$
(C) Ca_{12} vs morphometric and catchment parameters			
1	Alt	0.39	$y = -0.465 - 0.002 \cdot x_1$
2	$\sqrt{OL\%}$	0.51	$y = -0.591 - 0.001 \cdot x_1 + 0.060 \cdot x_2$
3	$DR^{0.1}$	0.55	$y = -1.233 - 0.001 \cdot x_1 + 0.047 \cdot x_2 + 0.822 \cdot x_3$
3	$\sqrt{D_{rel}}$	0.62	$y = -3.211 - 0.002 \cdot x_1 + 0.039 \cdot x_2 + 2.862 \cdot x_3 + 0.258 \cdot x_4$

The table lists the r^2-values and the models at each step. $F > 4$. Data for 49 lakes.

Table A.6. Ladder for the mean concentration of iron in lake water based on data from 36 months ($y = \log(Fe_{36})$; Fe_{36} in μg/l)

Step	Parameter	r^2	Model
(A) Fe_{36} vs morphometric parameters			
1	$\log(D_{mv})$	0.10	$y = 2.868 - 0.387 \cdot x_1$
(B) Fe_{36} vs catchment parameters			
1	$Mire\%^{0.7}$	0.32	$y = 2.290 + 0.213 \cdot x_1$
2		0.44	$y = 2.204 + 0.164 \cdot x_1 - 0.035 \cdot x_2$
3	$(A/ADA)^{0.3}$	0.51	$y = 2.436 + 0.188 \cdot x_1 - 0.043 \cdot x_2 - 0.578 \cdot x_3$
4	Till%	0.56	$y = 2.363 + 0.156 \cdot x_1 - 0.035 \cdot x_2 - 0.792 \cdot x_3 + 0.003 \cdot x_4$
5	log(Alt)	0.61	$y = 3.098 + 0.184 \cdot x_1 - 0.037 \cdot x_2 - 0.787 \cdot x_3 + 0.007 \cdot x_4 - 0.511 \cdot x_5$
6	$Q_{mv}^{0.1}$	0.69	$y = 3.893 + 0.163 \cdot x_1 - 0.028 \cdot x_2 - 1.117 \cdot x_3 + 0.009 \cdot x_4 - 0.554 \cdot x_5 - 0.846 \cdot x_6$
(C) Fe_{36} vs morphometric & catchment parameters			
1	$Mire\%^{0.7}$	0.32	$y = 2.290 + 0.213 \cdot x_1$
1	$\log(D_{max})$	0.48	$y = 2.620 + 0.067 \cdot x_1 - 0.389 \cdot x_2$
3	OA%	0.57	$y = 2.509 + 0.155 \cdot x_1 - 0.343 \cdot x_2 - 0.029 \cdot x_3$
4	$(A/ADA)^{0.3}$	0.62	$y = 2.707 + 0.176 \cdot x_1 - 0.328 \cdot x_2 - 0.037 \cdot x_3 - 0.526 \cdot x_4$
5	log(1 + Rock%)	0.67	$y = 2.975 + 0.154 \cdot x_1 - 0.331 \cdot x_2 - 0.033 \cdot x_3 - 0.717 \cdot x_4 - 0.130 \cdot x_5$
6	$\log(L_d)$	0.71	$y = 2.934 + 0.163 \cdot x_1 - 0.363 \cdot x_2 - 0.037 \cdot x_3 - 0.800 \cdot x_4 - 0.149 \cdot x_5 + 0.349 \cdot x_6$

The table lists the r^2-values and the models at each step. $F > 4$. Data from 41 lakes.

Table A.7. Ladder for the mean annual conductivity of lake water ($y = \log(cond_{12})$; $cond_{12}$ in mS/m)

Step	Parameter	r^2	Model
(A) $cond_{12}$ vs morphometric parameters			
1	$\log(D_{rel})$	0.15	$y = 0.572 - 0.225 \cdot x_1$
(B) $cond_{12}$ vs catchment parameters			
1	OL%	0.49	$y = 0.452 + 0.028 \cdot x_1$
2	log(RDA)	0.59	$y = 0.811 + 0.024 \cdot x_1 - 0.228 \cdot x_2$
3	log(Q)	0.64	$y = 0.783 + 0.013 \cdot x_1 - 0.276 \cdot x_2 - 0.099 \cdot x_3$
4	Mire%	0.68	$y = 0.901 + 0.021 \cdot x_1 - 0.296 \cdot x_2 - 0.986 \cdot x_3 - 0.005 \cdot x_4$
5	log(1 + Rock%)	0.69	$y = 0.855 + 0.021 \cdot x_1 - 0.307 \cdot x_2 - 0.097 \cdot x_3 - 0.005 \cdot x_4 + 0.51 \cdot x_5$
(C) $cond_{12}$ vs morphometric & catchment parameters			
1	OL%	0.49	$y = 0.452 + 0.028 \cdot x_1$
2	log(RDA)	0.59	$y = 0.811 + 0.024 \cdot x_1 - 0.228 \cdot x_2$
3	$\log(V)$	0.64	$y = -0.667 + 0.023 \cdot x_1 - 0.277 \cdot x_2 - 0.077 \cdot x_3$
4	log(OA)	0.69	$y = -0.916 + 0.021 \cdot x_1 - 0.303 \cdot x_2 - 0.073 \cdot x_3 - 0.164 \cdot x_4$
5	Alt	0.72	$y = -0.989 + 0.018 \cdot x_1 - 0.283 \cdot x_2 - 0.067 \cdot x_3 - 0.148 \cdot x_4 - 0.0006 \cdot x_5$

The table lists the r^2-values and the models at each step. $F > 4$. Data from 94 lakes.

Table A.8. Ladder for the mean Secchi depth of lake water based on data from 36 months ($y = \log(Sec_{36})$; Sec_{36} in m)

Step	Parameter	r^2	Model
(A) Sec_{36} vs morphometric parameters			
1	$\log(D_{mv})$	0.46	$y = 0.154 + 0.424 \cdot x_1$
2	$T^{0.1}$	0.51	$y = -0.209 + 0.314 \cdot x_1 + 0.445 \cdot x_2$

Table A.8. (Continued)

Step	Parameter	r^2	Model
(B) Sec_{36} vs catchment parameters			
1	log(1 + Rock%)	0.15	$y = 0.301 + 0.124 \cdot x_1$
2	$(A/ADA)^{0.3}$	0.39	$y = -0.020 + 0.165 \cdot x_1 + 0.695 \cdot x_2$
3	$Q_{mv}{}^{0.1}$	0.46	$y = -0.563 + 0.171 \cdot x_1 + 0.892 \cdot x_2 + 0.578 \cdot x_3$
(C) Sec_{36} vs morphometric and catchment parameters			
1	$\log(D_{mv})$	0.46	$y = 0.154 + 0.424 \cdot x_1$
2	log(OA)	0.55	$y = 0.344 + 0.439 \cdot x_1 - 0.172 \cdot x_2$
3	$(A/ADA)^{0.3}$	0.59	$y = 0.198 + 0.418 \cdot x_1 - 0.137 \cdot x_2 + 0.279 \cdot x_3$
4	log(1 + Rock%)	0.65	$y = 0.023 + 0.354 \cdot x_1 - 0.075 \cdot x_2 + 0.451 \cdot x_3 + 0.097 \cdot x_4$

The table lists the r_2-values and the models at each step. $F > 4$. Data from 86 lakes.

References

Aiken, G. R., D. M., McKnight, R. L. Werskaw, & P., MacCarthy, 1985 (eds). Humic Substances in Soil, Sediment and Water. Wiley Interscience, New York, 692 pp.

Ambio, 1976. Special issue on acid rain. Vol 5. No. 5–6.

Carlson, R. E., 1977. A trophic state index for lakes. Limnology and Oceanography 22: 361–369.

Carlson, R. E., 1980. More complications in the chlorophyll – Secchi disk relationship. Limnology and Oceanography, 25: 379–382.

Chapra, S. C., 1980. Application of the phosphorus loading concept to the Great Lakes. In: Loehr, C., Martin, C. S. & W. Rast, (eds), Phosphorus Management Strategies for Lakes. Ann Arbor Science Publishers, Ann Arbor, 135–152.

Christman, R. F. & E. T., Gjessing, 1983 (eds). Aquatic and Terrestrial Humic Materials. Ann Arbor Science, 538 pp.

Draper, N. R. & H., Smith, 1966. Applied Regression Analysis. Wiley, New York, 352 p.

Engstrom, D. R. 1987. Influence of vegetation and hydrology on the humus budgets of Labrador lakes. Canadian Journal of Fisheries and Aquatic Sciences 44: 1306–1314.

Gorham, E., W. E. Dean, & J. E., Sanger, 1983. The chemical composition of lakes in the north-central Unites States. Limnology and Oceanography 28: 287–301.

Gorham, E., J. K., Underwood, F. B. Martin, & J.B., Ogden III, 1986. Natural and anthropogenic causes of lake acidification in Nova Scotia. Nature 324: 451–453.

Håkanson, L., 1996. A general method to define confidence limits for model predictions based on validations. Ecological Modelling 91: 153–168.

Håkanson, L., 1997. Modelling of radiocesium in lakes – on predictive power and lessons for the future. In: Desmet, G. et al. (eds), Freshwater and Estuarine Radioecology, Elsevier, Amsterdam, 3–45.

Håkanson, L., 1999. Water pollution – methods and criteria to rank, model and remediate chemical threats to aquatic ecosystems. Backhuys Publishers, Leiden, 299 p.

Håkanson, L. & V., Boulion, 2002. The Lake Foodweb – Modelling Predation and Abiotic/biotic Interactions. Backhuys Publishers, Leiden, 344 p.

Håkanson, L. & M., Jansson, 1983. Principles of Lake Sedimentology. Springer, Berlin, 316 p.

Håkanson, L. & M., Lindström, 1997. Frequency distributions and transformations of lake variables, catchment area and morphometric parameters in predictive regression models for small glacial lakes. Ecological Modelling, 99: 171–201.

Håkanson, L. & R. H., Peters, 1995. Predictive Limnology. Methods for Predictive modelling. SPB Academic Publishing, Amsterdam, 464 p.

Hayes, M. H. B., P., MacCarthy, R. L. Malcom, & R. S., Swift, 1989 (eds). Humic Substances II. In Search of Structure. Wiley Interscience, New York, 764 p.

Hutchinson, G. E., 1957. A Treatise on Limnology. Vol. 2. Geography, physic and chemistry, London.

Ivanova, M. B., 1997. The impact of active reaction and total mineralization of water on the formation of zooplankton community in lakes with nearly extreme values of these factors. The Response of Lake Ecosystems to Changes in Biotic and Abiotic Conditions. St. Petersburg, 71–86 (in Russian).

Ivanova, M. B., V. V., Boulion, V. N., Nikulina, E. B., Paveljeva, B. P., Ilyashuk, E. A., Polyakova, & L. E., Anokhina, 1993. Limnological characteristics of natural acidic lakes in the north-west of Russia. Russian Journal of Aquatic Ecology 2: 81–90.

Krylov, P. I., E. I., Plyakova, & Y. R., Galimov, 1997. Zooplankton of an acidic lakes: Strategies for survival under conditions of food limitation. The Response of Lake Ecosystems to Changes in Biotic and Abiotic Conditions. St. Petersburg, 87–106 (in Russian).

Likens, G., R., Wright, J. Galloway, & T., Butler, 1979. Acid rain. Scientific American 241: 43–51.

Merilehto, K., K. Kenttämies, & J., Kämäri, 1988. Surface Water Acidification in the ECE Region. Nordic Council of Ministers, NORD 1988:89, 156 p.

Monte, L., L., Håkanson, U., Bergström, J., Brittain, R. Heling, & V., Suolanen, 1996. Uncertainty analysis and validation of environmental models: the empirically based uncertainty analysis. Journal of Environmental Radioactivity 91: 139–152.

Mosteller, F. & J. W., Tukey, 1977. Data Analysis and Regression: A Second Course in Statistics. Addison-Wesley Publ. Reading, Mass. 588 p.

Newman, M. C., 1993. Regression analysis of log-transformed data: statistical bias and its correction. Environmental Toxicology and Chemistry 12: 1129–1133.

Nürnberg, G. K. & M., Shaw, 1998. Productivity of clear and humic lakes: nutrients, phytoplankton, bacteria. Hydrobiologia 382: 97–112.

OECD, 1982. Eutrophication of waters. Monitoring, assessment and control. OECD, Paris, 154 p.

Overrein, L. N., H. M Seip, & A., Tollan, 1980. Acid Precipitation – Effect on Forest and Fish. Final report on the SNSF-project 1972–1980. Oslo-Ås, 175 p.

Peters, R. H., 1986. The role of prediction in limnology. Limnology and Oceanography 31: 1143–1159.

Pfaffenberger, R. C. & J. H., Patterson, 1987. Statistical Methods. Irwin, Illinois, 1246 p.

Preisendorfer, R. W., 1986. Secchi disk science: visual optics of natural waters. Limnology and Oceanography 31: 909–926.

Rasmussen, J. B., L. Godbout, & M., Schellenberg, 1989. The humic content of lake water and its relationship to watershed and lake morphometry. Limnology and Oceanography 34: 1336–1343.

Salomons, W. & U., Förstner, 1984. Metals in the Hydrocycle. Springer, Heidelberg, 349 p.

Schindler, D. W., 1971. A hypothesis to explain differences and similarities among lakes in the Experimental Lakes Area, northwestern Ontario. Journal of the Fisheries Research Board of Canada 28: 295–301.

Schindler, D. W., 1977. Evolution of phosphorus limitation in lakes. Science 195: 260–262.

Schindler, D. W., 1978. Factors regulating phytoplankton production and standing crop in the world's freshwaters. Limnology and Oceanography 23: 478–486.

Taylor, J. K., 1990. Statistical Techniques for Data Analysis. Lewis, Chelsea, 200 p.

Tilzer, M. M., 1988. Secchi disk – chlorophyll relationships in a lake with highly variable phytoplankton biomass. Hydrobiologia 162: 163–171.

Vollenweider, R. A., 1958. Sichttiefe und Production. Verhandlungen Internationale Vereinigung Limnologie 13: 142–143.

Vollenweider, R. A., 1960. Beitrage zür Kenntnis optischer Eigenschaften der Gewässer und Primärproduktion. Memorie Istituto Italiano Idrobiologia 12: 201–244.

Vollenweider, R. A., 1968. The Scientific Basis of Lake Eutrophication, with Particular Reference to Phosphorus and Nitrogen as Eutrophication Factors. Technical Report DAS/DSI/68.27, OECD, Paris, 159 p.

Wallin, M., L. Håkanson, & J., Persson, 1992. Load models for nutrients in coastal areas, especially from fish farms (in Swedish with English summary). Nordiska ministerrådet, Copenhagen, 1992: 502, 207 p.

Wetzel, R. G., 2001. Limnology. Academic Press, London, 1006 p.