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Conductivity as a predictor of a total cations and salinity in Ethiopian lakes and rivers: revisiting earlier models

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Abstract

We used regression analyses of water samples from 18 lakes, nine rivers, and one spring in Ethiopia to (a) test the hypothesis that water bodies of relatively higher salinity ($K_{25} > 1000$ $\mu S\ cm^{-1}$) have a different conductivity to salinity relationship than waters of lower salinity ($K_{25} < 1000$ $\mu S\ cm^{-1}$), and (b) develop models to predict total cations and salinity from conductivity that can be used for Ethiopian waters and other African aquatic systems of similar chemical composition. We found no statistical difference in the bilogarithmic relationships (total cations vs. conductivity; salinity vs. conductivity) for waters of higher salinity ($K_{25} >$ 1000 $\mu S\ cm^{-1}$) and waters of lower salinity ($K_{25} < 1000$ $\mu S\ cm^{-1}$). However, comparison among our models and models from the literature suggests that developing separate equations for low and high salinity water bodies has some merit. We believe that the equations developed in this study can be used for Ethiopian waters and other African waters within the range of conductivity in this study.

Key words: Ethiopia – African inland waters – chemical composition – predictive models

Introduction

Dissolved constituents of water bodies are often determined as a major component of baseline limnological studies. The ions commonly quantified include Na^+, K^+, Ca^{++}, Mg^{++}, Cl^-, SO_4^{--}, HCO_3^-, and CO_3^- (summed as total cations and anions). These essentially constitute the total ionic salinity of most fresh waters, as other ions make only very minor contributions (WETZEL 1983; WETZEL & LIKENS 1991). Ionic concentrations are generally analyzed in a laboratory, although some other parameters are measured in the field at the point of collection. Water analyses for ionic composition should be done as soon as possible after collection; however, this may not always be possible, especially in developing countries where transportation, electric power, and trained personnel are often limiting. When resources are not available for measuring certain characters, or when historical data are required for reference, sound estimation of one variable based on another becomes necessary. Conductivity is one such parameter that is used as an estimator of total ions and total ionic salinity (also known as total dissolved solid – TDS) of a water sample. It has often been necessary to make such indirect determinations to find values for total ions and TDS for comparative purposes.

Establishing conductivity as an accurate estimator of total cations and a reliable surrogate of salinity has become important mainly because of the ease of measuring this parameter and due to the high sensitivity and precision of the method (APHA et al. 1995). However, the conventional numerical relationship values do not seem to be applicable across a broad range of lakes, and some limnologists often make conversion factors for a given

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set of lakes. For example, Talling & Talling (1965) derived a conversion factor for predicting salinity and total cations from conductivity for a set of data from African lake waters; and later, Wood & Talling (1988) derived similar relationships for a set of Ethiopian inland waters.

The objective of this study was to empirically test the relationship between conductivity and concentrations of total cations and salinity for a set of Ethiopian water bodies. We assess the possibility that the relationship between conductivity and salinity is different in saline and freshwater systems by comparing relationships of these variables in Ethiopian lakes and rivers of different salinity. Ethiopian waters are particularly suitable for examining these relationships because they exhibit a wide range of salinity. Moreover, most Ethiopian lakes are bicarbonate/carbonate-dominated lakes where specific conductance is believed to be very closely proportional to concentrations of major cations (Rodhe 1949; Wetzel 1983). This study also has the advantage that data were derived from the same methods by the same investigators.

Materials and Methods

Surface water samples were collected from 18 lakes, nine rivers, and one spring (of which 10 lakes and 8 rivers were from the Ethiopian Rift Valley) during wet and dry seasons between 1990 and 2000. Each system was sampled an average of three times (range = 1 to 11), and mean values were used in all analyses. Surface water samples from lakes and rivers were taken at sampling stations offshore using acid-washed 2-L polyethylene bottles. Water samples were transported to the laboratory in dark boxes containing lake water that maintained the temperature of the samples close to that *in situ*. Conductivity was usually measured in the field with the exception of samples from a few lakes and rivers, for which measurements were made in the laboratory within 8 to 10 hr of sample collection. A YSI model 33 S-C-T conductivity meter and a 3311 probe were used to measure conductivity, and all values were corrected to 25 °C using a temperature coefficient of 2.3% per °C (Talling & Talling 1965).

Alkalinity (bicarbonate + carbonate) was determined by titrating to pH 4.5 with standard acid within less than 8 to 10 hr of sample collection. Calcium, magnesium, potassium, and sodium were determined by the atomic absorption spectrophotometric method. Chloride was determined by the mercuric nitrate titrimetric method, and sulfate was determined by the barium sulfate turbidimetric or gravimetric method (APHA et al. 1986) depending on concentrations in the samples. Salinity, as total dissolved solids (TDS) was determined by summing the individual ions (Wood & Talling 1988).

Statistical Analyses

We used linear regression analyses to develop predictive models for salinity and total cations based on conductivity (independent variable). Data were $\log_{10}$ transformed to normalize the data and stabilize the variance. To examine whether relationships differ between low and high salinity water bodies, we classified the lakes and rivers into fresh water ($K_{25} < 1000\ \mu S\ cm^{-1}$) and saline ($K_{25} \geq 1000\ \mu S\ cm^{-1}$) by using conductivity as a basis for salinity. This is a slight modification of earlier classification used by (Zinabu & Taylor 1997), and seemed to fit well with the natural discontinuities in our data set. Analysis of covariance was used to test for a difference in the slopes and intercepts of the relationships (conductivity and salinity, and conductivity and total cations) between low and high salinity water bodies. We used polynomial regression to examine whether a non-linear function was a better fit to the joint data set (low and high salinity lakes combined) than a linear function.

We compared our models to three previous conversions from the literature:

(1) APHA et al. (1995): Conductivity ($\mu S\ cm^{-1}$) = sum of cations ($meq\ L^{-1}$)*100.

(2) Wood & Talling (1988, for Ethiopian lakes): $meq\ L^{-1}$ of total cations = 87 $\mu S\ cm^{-1}$ (conductivity) = 0.059 $g\ L^{-1}$ of TDS (salinity).

(3) Talling & Talling (1965, for African lakes): 1 $meq\ L^{-1}$ of cations = 85 $\mu S\ cm^{-1}$ (conductivity).

We calculated the difference between observed values of major cations and salinity to expected values based on conductivity for an independently derived set of samples from Ethiopian water bodies available in the literature.

Results and Discussion

Mean conductivity measurements in the Ethiopian water bodies studied here varied from 76 $\mu S\ cm^{-1}$ to 33, 700 $\mu S\ cm^{-1}$, and total cations ranged from 0.93 $meq\ L^{-1}$ to 688 $meq\ L^{-1}$ (Table 1). The lowest values were from rivers that flow into some of the Ethiopian rift-valley lakes, and the highest value was from a crater lake (Mechaferra) in the Ethiopian rift valley. For high and low salinity lakes, conductivity was a highly significant predictor of both total cations ($K_{25} < 1000\ \mu S\ cm^{-1}$: $r^2 = 0.81$; $K_{25} > 1000\ \mu S\ cm^{-1}$: $r^2 = 0.94$) and salinity ($K_{25} < 1000\ \mu S\ cm^{-1}$: $r^2 = 0.82$; $K_{25} > 1000\ \mu S\ cm^{-1}$: $r^2 = 0.93$; Tables 2 and 3). Analysis of covariance detected no significant difference in the slopes or intercepts of the two relationships (Table 2); therefore, we also combined low and high salinity data sets to derive "joint" predictive models. In these "joint" models (low and high salinity lakes combined), conductivity was a highly significant predictor of both total cations ($r^2 = 0.958$, $P < 0.001$) and

Table 1. The chemical composition of a series of Ethiopian water bodies (18 lakes, nine rivers, and one spring). Each system was sampled an average of three times (range = 1 to 11). Explanations: $^{R)}$= rivers; $^{S)}$= spring; $^{L)}$=lakes.

Water body	Conductivity (μS cm^{-1})	Salinity (g L^{-1})	Cations (meq L^{-1})	Anions (meq L^{-1})	Na^{+} (meq L^{-1})	K^+ (meq L^{-1})	Ca^{++} (meq L^{-1})	Mg^{++} (meq L^{-1})	Alkalinity (meq L^{-1})	Cl^- (meq L^{-1})	SO_4^{-} (meq L^{-1}
Bilate ^{R}	76.0	0.079	0.927	1.013	0.304	0.156	0.300	0.167	0.870	0.143	0.000
Harre ^{R}	78.0	0.076	0.897	1.004	0.226	0.051	0.370	0.250	0.890	0.114	0.000
Kulfo ^{R}	85.0	0.089	1.250	1.110	0.230	0.050	0.550	0.420	1.020	0.090	0.000
Kilole ^{L}	235.0	0.150	4.530	4.530	4.070	0.120	0.120	0.200	2.400	0.990	0.020
Kiriftu^L	319.0	0.260	3.187	3.461	1.000	0.154	1.250	0.783	2.890	0.571	0.000
Awash ^{R}	400.3	0.320	4.189	4.175	1.629	0.196	1.613	0.751	3.262	0.693	0.220
Zwai ^{L}	407.8	0.375	4.514	4.610	2.745	0.277	0.802	0.690	4.098	0.387	0.124
Bulbula ^{R}	425.0	0.965	12.401	12.408	10.599	0.475	0.788	0.540	9.373	2.827	0.209
Gibe ^{R}	468.0	0.165	2.021	2.127	0.435	0.103	0.900	0.583	1.950	0.114	0.063
Mojo ^{R}	476.0	0.344	5.476	6.227	2.413	0.261	1.759	1.043	5.321	0.639	0.290
Kilole ^{S}	551.0	0.548	5.335	7.542	1.043	0.108	2.350	1.833	7.158	0.343	0.042
Koka ^{L}	605.5	0.438	5.798	5.694	3.739	0.206	1.326	0.527	4.594	0.884	0.216
Tikurwuha ^{R}	743.2	0.460	6.810	7.066	5.405	0.506	0.586	0.312	6.077	0.733	0.204
Awassa ^{L}	839.3	0.735	8.761	8.837	6.851	0.936	0.508	0.479	7.795	0.791	0.250
Babaogaya ^{L}	882.0	0.580	10.970	10.970	3.650	2.700	3.000	1.540	9.500	1.970	0.000
Abaya ^{L}	914.6	0.833	10.695	10.788	9.344	0.397	0.621	0.333	8.655	1.736	0.397
Hayq ^{L}	923.0	0.828	11.070	11.041	4.261	0.292	0.600	5.917	9.550	1.429	0.063
Chamo ^{L}	1535.7	1.213	15.704	16.242	14.256	0.570	0.372	0.553	13.266	2.761	0.210
Bishoftu ^{L}	1632.0	0.940	40.040	40.040	33.000	1.820	1.000	4.220	17.000	4.340	0.018
Langano ^{L}	1632.7	1.461	17.267	17.449	16.284	0.535	0.251	0.197	12.249	4.792	0.409
Hora ^{L}	2166.0	0.980	26.650	26.670	17.950	1.920	0.800	5.930	16.800	5.160	0.000
Ashange ^{L}	2350.0	2.052	29.785	26.519	15.435	0.667	0.350	13.333	21.020	3.229	2.271
Horacello ^{R}	4462.0	2.323	35.520	38.933	34.300	0.778	0.269	0.174	27.000	9.244	1.048
Arenguadi ^{L}	6240.0	2.750	71.650	71.650	59.000	11.500	0.800	0.400	54.000	22.000	0.040
Tillo ^{L}	10590.0	14.171	178.720	169.290	176.100	2.490	0.100	0.030	154.500	8.710	6.080
Shalla ^{L}	23004.4	18.627	294.740	307.316	289.091	5.491	0.114	0.042	217.322	84.859	6.419
Abijata ^{L}	26008.2	19.049	328.080	320.392	326.442	7.484	0.092	0.024	231.551	83.404	5.437
Mechaferra ^{L}	33700.0	55.244	688.060	669.810	669.600	17.950	0.500	0.010	578.000	40.910	50.900

Table 2. Summary of linear regression analyses between salinity and total cation concentration (dependent variables) and conductivity (independent variable) for a series of Ethiopian water bodies that are of low conductivity (K_{25}<1000 µS cm^{-1}) and a series of systems that are of high conductivity (K_{25}>1000 µS cm^{-1}), and analyses of covariance for analyses of relationships between the two sets of water bodies. All three variables were $\log_{10}$ transformed. The mean values represent adjusted means calculated from the ANCOVA analyses (sample means adjusted for a common mean conductivity and a common regression line).

	Group	Slope	Intercept	r^2	P	Adj. mean	Antilog adj. mean	ANCOVA slope		ANCOVA intercept	
								F	P	F	P
Cation concentration (meq L^{-})	K_{25}<1000 µS cm^{-1}	0.91	−1.70	0.81	<0.001	1.09	12.30	1.11	0.302	0.45	0.510
	K_{25}>1000 µS cm^{-1}	1.06	−2.11	0.94	<0.001	1.16	14.45				
Salinity (g L^{-1})	K_{25}<1000 µS cm^{-1}	0.90	−2.82	0.82	<0.001	−0.02	0.95	2.87	0.103	0.71	0.407
	K_{25}>1000 µS cm^{-1}	1.16	−3.71	0.93	<0.001	−0.11	0.78				

Table 3. Regression models depicting relationships between conductivity (µS cm^{-1}, K_{25}) and two dependent variables [concentrations (meq L^{-1}) of total cations, and salinity (g L^{-1})] for a suite of Ethiopian water bodies. All variables were $\log_{10}$ transformed.

Water body	Dependent variable	Equation	n	r^2
Joint-linear	$\log_{10}$ (cations)	log(cat.) = 1.031 (log K_{25}) − 2.012	28	0.958
Joint-curvilinear	$\log_{10}$ (cations)	log(cat) = 0.651 (log K_{25}) + 0.059 (log $K_{25})^2$ − 1.433	28	0.960
Freshwater	$\log_{10}$ (cations)	log(cat.) = 0.908 (log K_{25}) − 1.701	17	0.809
Saline	$\log_{10}$ (cations)	log(cat.) = 1.060 (log K_{25}) − 2.105	11	0.943
Joint-linear	$\log_{10}$ (salinity)	log(sal.) = 0.992 (log K_{25}) − 3.069	28	0.947
Joint-curvilinear	$\log_{10}$ (salinity)	log(sal.) = 0.357 (log K_{25}) + 0.099 (log $K_{25})^2$ − 2.101	28	0.954
Freshwater	$\log_{10}$ (salinity)	log(sal.) = 0.909 (log K_{25}) − 2.823	17	0.817
Saline	$\log_{10}$ (salinity)	log(sal.) = 1.157 (log K_{25}) − 3.706	11	0.933

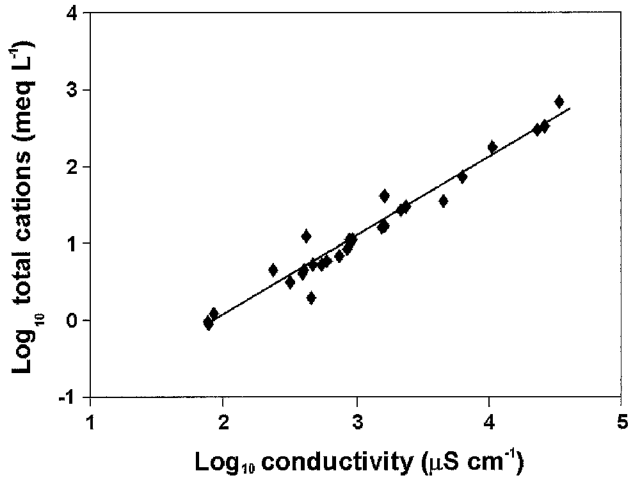

Fig. 1. Bilogarithmic relationship between total cations and conductivity for a series of Ethiopian lakes and rivers.

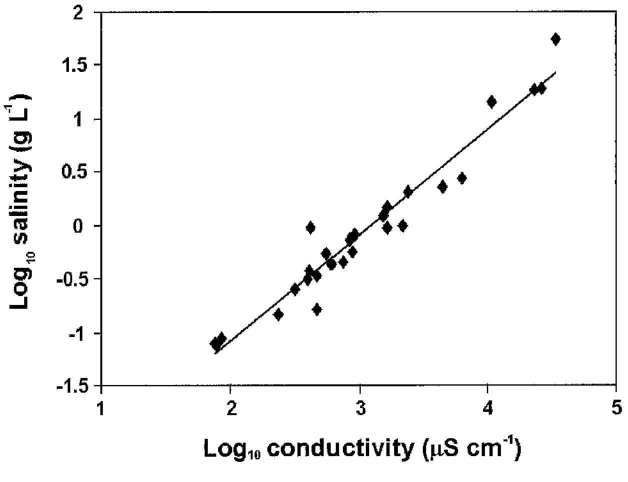

Fig. 2. Bilogarithmic relationship between salinity and conductivity for a series of Ethiopian lakes and rivers.

salinity (r^2 = 0.947, P < 0.001; Table 3, Figs. 1 and 2). A polynomial regression on the joint data set produced only a slightly better fit for both relationships (total cations: r^2 = 0.960, P < 0.001; salinity: r^2 = 0.954, P < 0.001; Table 3). This provides further support for similar bilogarithimic relationships (total cations vs. conductivity and salinity vs. conductivity) between low and high salinity lakes. Since, the model improvement provided by a non-linear function was very small (0.2% for conductivity and 0.7% for salinity), we used the joint linear

Table 4. Observed measurements of conductivity (K_{25}) and total cations from four Ethiopian rift valley lakes, and average % differences of predicted values from regression equations 1 – 3 [1= joint (linear); 2 = freshwater; 3 = saline] and other conversion functions from the literature. Values are means ± standard deviations of the means.

Lake	Reference	N	K_{25} (µS cm^{-1})	Cations (meq L^{-1})	Equation 1 % difference	Equation 2 % difference	Equation 3 % difference	APHA et al. (1995) % difference	Wood & Talling (1988) % difference	Talling & Talling (1965) % difference
Zwai	Tilahun (1988)	18	373±17	4.4±0.4	–2.1±9.8	–0.1±7.4	–3.0±7.7	–19.3±11.4	–3.8±10.0	–1.4± 9.7
Awassa	Kifle (1985)	13	849±35	8.7±1.4	13.2±5.0	2.7±16.7	11.6±15.3	–4.1±17.2	9.4±15.0	11.5±14.6
Langano	Wodajo (1982)	12	1833±112	18.8±2.9	16.8±9.1	–2.5±11.7	17.1±8.9	–2.2±11.3	11.1± 9.8	13.1±9.6
Abijata	Wodajo (1982)	12	23111±1170	342±41.1	–11.6±13.9	–87.6±23.1	–3.3±12.9	–48.2±18.4	–28.9±16.0	–26.0±15.7

Table 5. Difference (%) between predicted and observed values of total cations (meq L^{-1}) and salinity (g L^{-1}) calculated according to regression equations (independent variable is conductivity in µS cm^{-1}, K_{25}) from this study [joint (linear); freshwater; saline] and other conversion functions from the literature. The observed values of conductivity, total cations, and salinity were those of Ethiopian water bodies from Table 2 of Wood & Talling (1988). Freshwater (K_{25}<1000); saline (K_{25}>1000).

Lake		Total Cations						Salinity			
		Joint	Freshwater	Saline	APHA et al. (1995)	Wood & Talling (1988)	Talling & Talling (1965)	Joint (linear)	Freshwater	Saline	Wood & Talling (1988)
All water bodies	N	47	47	47	47	47	47	28	28	28	28
	Mean	14.6	–7.3	14.7	–4.9	8.7	10.8	–4.1	–12.8	–35.2	–23.3
	SD	17.6	32.7	18.4	22.0	19.2	18.7	24.3	31.7	50.1	28.8
	Max	52.6	57.2	49.2	46.2	53.2	54.2	50.1	57.2	59.7	39.7
	Min	–30.9	–126.5	–37.3	–73.6	–51.0	–47.5	–52.3	–104.5	–115.0	–76.4
Freshwater	N	18	18	18	18	18	18	11	11	11	11
	Mean	9.3	8.6	5.0	–5.8	8.0	10.1	–7.6	0.3	–78.9	–29.2
	SD	18.9	24.4	19.1	23.3	20.2	19.8	27.8	30.7	34.9	32.8
	Max	52.6	57.2	49.2	46.2	53.2	54.2	50.1	57.2	5.0	39.7
	Min	–30.9	–29.4	–37.3	–52.0	–32.3	–29.2	–36.4	–33.3	–115.0	–62.9
Saline	N	29	29	29	29	29	29	17	17	17	17
	Mean	17.9	–17.2	20.6	–4.3	9.2	11.3	–1.9	–21.2	–6.9	–19.5
	SD	16.1	33.7	15.4	21.6	18.8	18.4	22.3	30.3	36.1	26.3
	Max	48.2	38.0	48.1	36.9	45.1	46.3	40.2	37.9	59.7	29.0
	Min	–29.4	–126.5	–18.6	–73.6	–51.0	–47.5	–52.3	–104.5	–51.4	–76.4

models, rather than curvilinear models, in our comparisons to previous literature equations.

To compare our predictive models to previous literature equations (Talling & Talling 1965; Wood & Talling 1988; APHA et al. 1995), we first looked at the predicted (from conductivity measures) and observed values for total cations measured over seasonal cycles in four Ethiopian Rift Valley lakes from data reported in the literature. Two of these lakes (Zwai and Awassa) were of low salinity, and the other two lakes (Langano and Abijata) were of higher salinity. For the two freshwater lakes, the best predictive model was the equation for freshwater lakes derived for our set of Ethiopian water bodies. For Lake Langano (a moderately saline lake) the best predictive equation was the APHA model (–2.2%), which was slightly better than our equation derived from freshwater lakes (–2.5%). However, for Lake Abijata (the lake of highest salinity), the best predictive model was the equation derived from our set of Ethiopian water bodies of higher salinity (Table 4).

To broaden our comparison to earlier models, we compared observed values for total cations and salinity to predicted values (from conductivity measures) for a series of Ethiopian water bodies reported in WOOD & TALLING (1988). For total cations, the APHA model produced very good estimates for all lakes and rivers (combined), for fresh water bodies, and for saline water bodies (–4.9%, -5.8%, and –4.3%, respectively; Table 5). There was one anomalous exception in this analysis; our equation for saline lakes produced the best estimate for the freshwater lakes (5.0%; Table 5). However, it should also be noted that all equations produced good estimates (<10.2%) for the fresh water bodies. Differences between observed and expected results were higher for all equations for the saline waters with the exception of the APHA model. For salinity, our models produced better estimates (compared to the model of WOOD & TALLING 1988), for all lakes and rivers (joint model = –4.1%), fresh water bodies (freshwater model = 0.3%), and saline water bodies (joint model –1.9%, saline model = –6.9%; Table 5). Comparison to the APHA equation for salinity was not possible because a range of values is provided in the model.

In summary, it is clear from this study and earlier works, that conductivity is generally a very good predictor of both total cations and salinity in Ethiopian water bodies. Comparison among models suggests that developing separate equations for low and high salinity water bodies has some merit even though we found no statistical differences in the slopes and intercepts of the relationships between the two groups. The simple APHA model seems to be a good predictor of total cations, particularly in moderately saline lakes. For salinity, the models developed in this study produced very good estimates on independently derived data, when high and low salinity lakes were treated separately. We, therefore, believe that the equations developed in this study can be used for Ethiopian waters and other African waters within the range of conductivity in this study.

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