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Linear Free Energy Relationships for Metal-Ligand Complexation: Bidentate Binding to Negatively-Charged Oxygen Donor Atoms

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Abstract

Stability constants for metal complexation to bidentate ligands containing negatively-charged oxygen donor atoms can be estimated from the following linear free energy relationship (LFER): $\log K_{ML} = \chi_{OO}(\alpha_O \log K_{HL,1} + \alpha_O \log K_{HL,2})$ where K_{ML} is the metal-ligand stability constant for a 1:1 complex, $K_{HL,1}$ and $K_{HL,2}$ are the proton-ligand stability constants (the ligand pK_a values), and α_O is the Irving-Rossotti slope. The parameter χ_{OO} is metal specific and has slightly different values for 5 and 6 membered chelate rings. LFERs are presented for 21 different metal ions and are accurate to within approximately 0.30 log units in predictions of $\log K_{ML}$ values. Ligands selected for use in LFER development include dicarboxylic acids, carboxyphenols, and *ortho*-diphenols. For *ortho*-hydroxybenzaldehydes, α -hydroxycarboxylic acids, and α -ketocarboxylic acids, a modification of the LFER where $\log K_{HL,2}$ is set equal to zero is required. The chemical interpretation of χ_{OO} is that it accounts for the extra stability afforded to metal complexes by the chelate effect. Cu-NOM binding constants calculated from the bidentate LFERs are similar in magnitude to those used in WHAM 6. This LFER can be used to make $\log K_{ML}$ predictions for small organic molecules. Since natural organic matter (NOM) contains many of the same functional groups (i.e. carboxylic acids, phenols, alcohols), the LFER $\log K_{ML}$ predictions shed light on the range of appropriate values for use in modeling metal partitioning in natural systems.

Keywords

metal complexation; carboxylic acids; phenols; linear free energy relationships; natural organic matter

1. Introduction

Linear Free Energy Relationships (LFERs) were originally developed to provide methods for estimation of physical and chemical properties of organic molecules. The pioneering

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Electronic Annex Available. A description of the proton and metal binding reactions and parameterization of $\log K$ values in WHAM VI, a listing of all of the ligands used to construct the bidentate LFER, and a table of all metal-ligand $\log K_{ML}$ values from the NIST Critical database used in LFER development.

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work of Brönsted and Pedersen (1924) showed that rate constants for base catalysis of nitramide were linearly correlated to the basicity of the catalyst. Since rate constants and equilibrium constants are relatable to changes in Gibbs free energy, the correlations were termed “free energy relationships” (Hammett, 1938). Important LFERs that followed include the Hammett relationships which quantified the effect of substituents and leaving groups on ester hydrolysis (Hammett, 1935; Hammett, 1937). Perhaps more importantly, Hammett's work showed the usefulness of describing chemical reactivity (equilibrium constants or rate constants) in terms of parameters that describe molecular structure and susceptibility to undergo reaction. LFERs have since been successfully applied to deduce reaction mechanisms, develop synthesis routes, and estimate the biological activity of various organic chemicals (Williams, 2003).

LFERs for metal ions have garnered less attention, but they can provide similar information as their organic counterparts. Irving and Rossotti (1956) introduced the following relationship for metal complexation to monodentate ligands containing negatively-charged oxygen functional groups:

$$\log K_{ML} = \alpha \log K_{HL} + \beta \quad (1)$$

where $\log K_{HL}$ and $\log K_{ML}$ are the proton and metal complexation equilibrium constants, respectively. K_{HL} and K_{ML} correspond to the following reactions:

Note that the value of $\log K_{HL}$ is equivalent to the pK_a value of the ligand.

The α and β in Eq. 1 are metal-specific constants which we have termed the Irving-Rossotti slope and intercept respectively. We have shown that Eq. 1 holds for complexation of 24 metal ions with monodentate ligands containing negatively charged oxygen donor atoms (Carbonaro and Di Toro, 2007). In all cases, β is very close to a value of zero, and thus a single parameter relates the pK_a ($\log K_{HL}$) of a functional group to its ability to bind with metal ions (Martell and Hancock, 1996). Eq 1. allows for easy estimation of $\log K_{ML}$ for monodentate complex formation since the pK_a of organic ligands containing negatively charged oxygen donor atoms are easily measured or can be estimated with computational methods based on LFERs and perturbed molecular orbital theory (Hilal et al., 1996). Since Eq. 1 may hold for other donor atoms, a subscript has been used to identify the electron donor. Thus α_O represents the Irving-Rossotti slope for monodentate ligands containing negatively-charged oxygen donor atoms.

LFERs for estimation of the stability constants for bidentate and higher denticity ligands have been proposed previously (Nieboer and McBryde, 1969; Smith et al., 1985a; Smith et al., 1985b; Martell and Hancock, 1996). Martell and Hancock (1996) showed that the $\log K_{ML}$ for various bidentate ligands was correlated with the logarithm of the stability constant

of the first hydrolysis complex, MOH^{z-1} . The data for many metals fall on a straight line, thus yielding the following LFER:

$$\log K_{\text{ML,bidentate}} = a \log K_{\text{MOH}} + b \quad (4)$$

where a and b are the slope and intercept resulting from linear regression. Extrapolation of the regression line revealed a tendency to intercept a $\log K_{\text{ML}}$ value close to $\log 55.5$, the molarity of water. Thus, the intercept was forced through $\log 55.5$, effectively setting $b = 1.74$. The value for a increases as the strength of the bidentate ligand increases.

Hancock and Marsicano (1976; 1978) also derived an additive approach linking stability constants for reactions of metals with amines, aminocarboxylates, and carboxylates to their respective stability constants with ammonia and acetate. In general for aminocarboxylate complexes, $\log K_{\text{ML}}$ was described by the following:

$$\log K_{\text{ML}} = 1.152 n \log K_{\text{M}(\text{NH}_3)} + m \log K_{\text{M}(\text{Ac})} + \left(\sum_{i=1}^{n-1} i \right) \lambda_{\text{N}} + \left(\sum_{i=1}^m i \right) \lambda_{\text{O}} + (m+n-1) \log 55.5 \quad (5)$$

In Equation 5, the overall $\log K_{\text{ML}}$ is dependent upon the sums of the $\log K_{\text{ML}}$ values for monodentate complexation with ammonia and acetate respectively. The constants n and m represent the number of amine and carboxylate functional groups in the aminocarboxylate complex. The λ_{N} and λ_{O} represent correction terms to account for a combination of factors including increases in the ΔH for metal complexation upon going from primary to secondary or tertiary amines, increased strain energies and electron repulsion (Hancock and Marsicano, 1978). Also, an additional $\log 55.5$ was added for each chelate ring to account for the chelate effect. The Hancock equations are well parameterized for Cu^{2+} , Co^{2+} , Ni^{2+} , Fe^{2+} and Fe^{3+} (Hancock and Marsicano, 1976) and are capable of making accurate predictions for multidentate aminocarboxylate ligands such as NTA and EDTA (Dimmock et al., 1995).

Another additive approach was developed by Harris (1983) for metal complexation with multidentate ligands containing oxygen, nitrogen and sulfur donor atoms. A metal-specific chelate parameter was included which had different values for five and six-membered rings. The Harris LFER was parameterized for Ni^{2+} , Cd^{2+} , Zn^{2+} , and Fe^{2+} . RMSE between observed and calculated values of $\log K_{\text{ML}}$ were approximately 0.8 units.

More recently, Cabaniss (2008) parameterized quantitative structure-property relationships (QSPRs) for the prediction of conditional stability constants (pH 7.0 and $\mu = 0.1 \text{ M}$) for 1:1 metal-ligand complexes. The Cabaniss QSPR is unique in that it requires no steric or atom connectivity information. Parameterizations were performed for Al^{3+} , Ca^{2+} , Cd^{2+} , Cu^{2+} , Ni^{2+} , Pb^{2+} , and Zn^{2+} , and reported standard deviations of prediction for the conditional $\log K_{\text{ML}}$ values vary from 0.67 to 1.05 units.

Oxygen-containing functional groups play an important role in the biogeochemical cycling of metals in aquatic and terrestrial environments. Carboxylic acids and phenolic groups are primarily responsible for binding of protons and metals to low molecular weight organic acids (LMWOAs) (Marschner, 1995). In the rhizosphere, LMWOAs such as acetate, lactate, malate, citrate and oxalate originate from root exudation, plant residue decomposition and microbial metabolism and have been detected in soil solutions at concentrations ranging from 0.1 to 100 μM (Jones, 1998).

Humic substances containing carboxylic acid and phenolic functional groups are responsible for proton and metal binding to aquatic and soil natural organic matter (NOM) (Stevenson, 1985; Leenheer et al., 1995b; Leenheer et al., 1995a). Hypothetical structures of NOM which contain an abundance of these groups have been proposed from various spectroscopic characterization methods including ^{13}C NMR, ^1H NMR, and FTIR-IR (Leenheer et al., 1998). The estimated pK_a values of these functional groups of the hypothetical NOM models do an adequate job at representing experimental proton titration data (Atalay et al., 2009). There is also spectroscopic evidence these groups are the most important for metal binding (Larive et al., 1996; Hertkorn et al., 2004; Schilling and Cooper, 2004). Combinations of carboxylic and phenolic groups to form bidentate and tridentate complexes have been proposed to explain the strong metal complexation observed at low total metal concentrations (Tipping, 2002).

The Windermere Humic Aqueous Model (WHAM) family of equilibrium speciation models for describing metal binding to NOM utilize numerous monodentate, bidentate, and tridentate binding sites for metal ions (Tipping, 1994; Tipping, 1998). To “build” a bidentate ligand into the model, linear combinations of monodentate ligands are used (i.e. two monodentate sites are used to make one bidentate site) (Tipping, 2002). The stability constants for the bidentate sites are assumed to be the additive sum of the logarithm of the stability constants ($K_{\text{ML},1}$ and $K_{\text{ML},2}$) of the individual monodentate sites:

$$\log K_{\text{ML,bidentate}} = \log K_{\text{ML},1} + \log K_{\text{ML},2} \quad (6)$$

This approach has worked very well as versions V and VI of WHAM have been well calibrated to laboratory experiments, and have gained widespread use in equilibrium speciation modeling of metal binding to the humic and fulvic acid fractions of NOM.

This paper describes a new bidentate LFER for estimating the $\log K_{\text{ML}}$ value for 1:1 metal complexes with ligands containing negatively charged oxygen donor atoms. The LFER is derived from Irving-Rossotti slopes that were developed for monodentate ligands, and utilizes an additive approach to estimate $\log K_{\text{ML}}$. This work differs from previously developed LFERs in that the final LFER relationship is generally applicable to a large number of metal ions (21 total), and has superior predictive capabilities for $\log K_{\text{ML}}$ values (approximately 0.30 units). A total of 230 metal-ligand complexation constants were used in the bidentate LFER parameterization. A secondary objective of this work is to compare LFER estimated values of $\log K_{\text{ML}}$ values to those used in metal-NOM speciation models. This comparison serve as an independent check on the values that are used in these models, and provide insight on how to improve existing model formulations.

2. Methods

2.1 Thermodynamic Constant Selection Criteria and Ionic Strength Corrections

All thermodynamic constants were taken from the NIST Critically Selected Stability Constants of Metal Complexes Database (Martell et al., 2004), where metal-ligand and proton-ligand complexation reactions are described according to Equations (2) and (3). All K_{HL} and K_{ML} values were corrected to an ionic strength of $\mu = 0.0$ mol/L using the Davies Equation (Davies, 1962) with $b = 0.2$. The Davies equation does an adequate job of correcting equilibrium constants to zero ionic strength for $\mu < 0.5$ mol/L (Morel and Hering, 1993). In many cases, however, constants from the NIST database were only available at $\mu = 1.0$ mol/L. For lack of a better method, the Davies equation was also used to correct these values. Constants listed at ionic strengths greater than 1.0 mol/L were not included in the

analysis. The majority of the constants used in developing LFERs were listed at 25°C. However constants at temperatures ranging from 20°C to 30°C were used without correction. Constants outside of this range were not employed. A table of all the thermodynamic data used to develop LFERs is included in the Electronic Annex.

Direct extension of the LFERs to temperatures other than 25°C is hindered by the lack of thermodynamic data. However, ΔH values for monodentate and bidentate complexes in the database are relatively small in magnitude, exhibiting absolute values ranging from 0 to 30 kJ/mol. Thus, corrections on $\log K_{ML}$ are also relatively small. For example, the van't Hoff equation predicts a change of $\log K_{ML}$ equal to approximately 1.0 units for a temperature increase from 25 to 100°C and ΔH value of 30 kJ/mol.

2.2 Ligand Selection

Bidentate ligands are Lewis bases that donate two pairs of electrons to a metal atom. Functional groups with oxygen atoms capable of electron pair donation include carboxylic acids, phenols, alcohols, carbonyls, ethers and esters. In aqueous solution, carboxylic acid and phenolic oxygen atoms have the most geochemical and environmental relevance concerning metal complexation, and therefore were the focus of LFER development.

The ligands employed in LFER development were carefully selected from the database such that they met the following criteria: i) they possess 2 functional groups containing negatively-charged oxygen donor atoms with $\log K_{HL}$ values between 1 and 14, ii) they are capable of forming only bidentate complexes with metal ions, (iii) steric hindrances to metal binding are not expected to influence the extent of metal–ligand complexation, and (iv) negatively-charged oxygen donor atoms are the only functional group that imparts charge. These criteria were imposed to minimize contributions from other physical and chemical factors which may decrease or increase the extent of metal binding.

The bidentate ligands that meet criteria i) through iv) fall into different groupings based upon the type of functional groups present and the structural arrangement of groups (Table 1). For example, dicarboxylic acids, diphenols, and carboxyphenols each possess a total of two carboxylic acid or phenol functional groups and were considered for LFER development. The numbers of atoms in the chelate ring are expected to influence $\log K_{ML}$, and therefore they were given separate classifications (Table 1). LFER development was limited to bidentate ligands that form 5 or 6 membered chelate rings.

Ligands such as α -hydroxycarboxylic acids (e.g., lactic acid, glycolic acid), α -keto carboxylic acids (e.g., glyoxylic acid), and *ortho*-hydroxybenzaldehydes were not included in our original monodentate LFER development (Carbonaro and Di Toro, 2007). Despite the fact that the NIST database reports one $\log K_{HL}$ value, they are capable of forming bidentate complexes through the use of alcohol or carbonyl oxygen atoms (Portanova et al., 2003). In actuality, the alcohol and carbonyl groups do possess more than 1 $\log K_{HL}$ (pK_a) value. For example, protonation of the alcohol group of a hydroxycarboxylic acid to form an alkyloxonium cation exhibits a pK_a value of around -1.7 (Carey, 2007). These ligands were included for analysis as part of the bidentate LFER and were classified as “1- pK_a ” bidentate ligands to distinguish them from the “2- pK_a ” bidentate ligands discussed earlier.

An additional requirement for LFER development was there must be a sufficient number of data points for each metal ion. Thus, metal ions were not evaluated if they had less than 4 bidentate $\log K_{ML}$ values in the database. Use of all of the criteria discussed above yielded a total of 332 $\log K_{ML}$ values for 21 metal ions. This dataset was employed in the LFER development. All $\log K_{HL}$ and $\log K_{ML}$ values can be found in the Electronic Annex.

2.3 Irving-Rossotti Slopes

The Irving-Rossotti slope and intercept (α and β respectively) are parameters that have been used to describe the relationship between proton and metal stability constants for monodentate ligands (Eq. 1). Previous work has shown that the relationship for ligands containing negatively charged oxygen donor atoms has an intercept of approximately zero (Carbonaro and Di Toro, 2007). Since β is approximately equal to zero, the value of α can be used to make estimates of the metal-ligand stability constant. Since slopes can also be obtained for other ligand donor atoms (e.g., nitrogen, sulfur), a subscript notation has been used to denote the identity of the ligand donor atom.

The value of α_O is metal specific but independent of the ligand identity. The magnitude of its value therefore indicates the relative binding preference of metal ions towards complexation with monodentate ligands containing negatively-charged oxygen donor atoms.

2.4 Regression Analysis

One-parameter (slope is fitted, intercept is set equal to zero) and two-parameter (slope and intercept are fitted) linear regression analyses were performed using analytical solutions resulting from traditional minimization of least-squares approaches (Acton, 1966). In all cases, the number of data points used in the regression, n , is reported. Resulting slopes and intercepts are reported to three significant figures since most of the thermodynamic data employed in regression analysis are reported to the same level of precision. Error estimates on slopes and intercepts from linear regression analysis represent 95% confidence intervals (Peters et al., 1974). Visual Basic for Applications (VBA) code was written so that all results from regression and statistical analyses could be performed using Microsoft EXCEL.

3. Results and Discussion

3.1 Bidentate LFER Development

Irving-Rossotti slopes provide a method for calculating the $\log K_{ML}$ value for a monodentate ligand containing negatively-charged oxygen donor atoms provided that the $\log K_{HL}$ value (the pK_a) is known (Irving and Rossotti, 1956; Martell and Hancock, 1996; Carbonaro and Di Toro, 2007). The WHAM method for calculating $\log K_{ML}$ values for bidentate ligands (Eq. 5) assumes that the contributions of each metal binding site to the Gibbs free energy (or $\log K_{ML}$) are additive (Tipping, 2002). As a test of this hypothesis, the Irving-Rossotti monodentate LFER was used to calculate the individual contributions of each binding site of 2- pK_a bidentate ligands. The calculation shown below is essentially a combination of Equations 1 and 6:

$$(\log K_{ML})_{SUM} = \alpha_O \log K_{HL,1} + \alpha_O \log K_{HL,2} \quad (7)$$

The quantity $(\log K_{ML})_{SUM}$ represents the result of this additive hypothesis. It is straightforward to test the accuracy of Eq. 7 by comparing $(\log K_{ML})_{SUM}$ values with actual values for 1:1 metal-ligand complexes from the NIST database, $(\log K_{ML})_{NIST}$.

Predicted Cu^{2+} $(\log K_{ML})_{SUM}$ versus $(\log K_{ML})_{NIST}$ values for a series of bidentate ligands containing negatively-charged oxygen donor atoms are presented in Figure 1. Open circles and open triangles represent 2- pK_a bidentate ligands that form 5-membered rings and 6-membered rings respectively (Table 1). The dashed line represents a 1:1 line which indicates perfect agreement between $(\log K_{ML})_{SUM}$ and $(\log K_{ML})_{NIST}$. The $(\log K_{ML})_{SUM}$ values calculated using Eq. 7 systematically underestimate $(\log K_{ML})_{NIST}$ values. However, the

difference between $(\log K_{\text{ML}})_{\text{SUM}}$ and the 1:1 line increases linearly with increasing values of $(\log K_{\text{ML}})_{\text{NIST}}$. Also, this difference approaches zero as $(\log K_{\text{ML}})_{\text{NIST}}$ approaches zero.

1- pK_{a} bidentate ligands are shown in Figure 1 as filled circles (5 membered rings) and filled triangles (6 membered rings). Since these ligands only possess one pK_{a} in the database, we used the Irving-Rossotti monodentate LFER (Eq. 1, $\beta = 0$) to calculate $(\log K_{\text{ML}})_{\text{SUM}}$. As was the case for the 2- pK_{a} bidentate ligands, $(\log K_{\text{ML}})_{\text{SUM}}$ values systematically underestimate the $(\log K_{\text{ML}})_{\text{NIST}}$ value. Furthermore, the 1- pK_{a} and 2- pK_{a} , $(\log K_{\text{ML}})_{\text{SUM}}$ values fall on the same line. The solid line represents results from linear regression analysis with the intercept forced through zero (slope = 0.678, $r^2 = 0.986$). Oxalic acid (Figure 1, open diamond) was the only outlier and was not used to compute the slope (as discussed below).

The linear relationship between $(\log K_{\text{ML}})_{\text{NIST}}$ and $(\log K_{\text{ML}})_{\text{SUM}}$ along with the fact that the intercept is zero allows for a single parameter, the reciprocal slope of the line shown in Figure 1, to account for the underprediction of Equations 1 and 7. Therefore, these equations were modified to include a correction term. For 2- pK_{a} bidentate ligands:

$$(\log K_{\text{ML}})_{\text{LFER}} = \chi_{\text{OO}} (\alpha_{\text{O}} \log K_{\text{HL},1} + \alpha_{\text{O}} \log K_{\text{HL},2}) \quad (8)$$

where χ_{OO} is the reciprocal slope from Figure 1, and $(\log K_{\text{ML}})_{\text{LFER}}$ is the predicted $\log K_{\text{ML}}$ from the bidentate LFER. For 1- pK_{a} bidentate ligands:

$$(\log K_{\text{ML}})_{\text{LFER}} = \chi_{\text{OO}} (\alpha_{\text{O}} \log K_{\text{HL},1}) \quad (9)$$

Eq. 9 is essentially the same as Eq. 8 with $\log K_{\text{HL},2}$ set equal to zero.

The applicability of these LFERs to all metals was tested by plotting $(\log K_{\text{ML}})_{\text{SUM}}$ versus $(\log K_{\text{ML}})_{\text{NIST}}$ for all metals for which sufficient data were available in the NIST Critical database. The result for 20 metal ions is shown in Figure 2. With a few exceptions, the relationship shown in Figure 1 for Cu^{2+} holds very well for all of the metals tested, and 1 parameter regression lines yielded good relationships between $(\log K_{\text{ML}})_{\text{SUM}}$ and $(\log K_{\text{ML}})_{\text{NIST}}$. The reciprocal slope of the regression line, χ_{OO} , is shown on Figure 2 for each metal. Oxalic acid data points (open diamonds) were consistently below the regression line and were not used to calculate χ_{OO} .

For some metals, specifically, Be^{2+} , Ca^{2+} and Pb^{2+} , 5-membered rings (circles) and 6-membered rings (triangles) appeared to fall on separate regression lines. Thus, 1 parameter linear regressions were performed separately for ligands that form 5-membered and 6-membered rings. The resulting reciprocal slopes for 5-membered rings, χ^5_{OO} , and for 6-membered rings, χ^6_{OO} , for all metal ions tested are listed in Table 2. In some cases, there was insufficient data to determine both χ^5_{OO} and χ^6_{OO} for a metal ion (e.g. Ag^+ and Th^{4+}).

To examine how ring size affects the value of the slope correction, a subset of the χ_{OO} , χ^5_{OO} and χ^6_{OO} values are shown for the alkaline earth and first row transition metals in Figure 3. Values of χ_{OO} , χ^5_{OO} and χ^6_{OO} are extremely consistent across all the first row divalent transition metals with an approximate value of 1.5. For the alkaline earth metals, χ_{OO} values have much more variability, and χ^5_{OO} and χ^6_{OO} values tend to be significantly different than one another. Similar differences can be seen in the post-transition metals (Table 2). Unfortunately, lack of available $\log K_{\text{ML}}$ data in the database prevents further analysis

across rows or down columns of the periodic table. There does not appear to be a strong correlation between the χ values of metal ions and their ionic radii, charge to radii ratio, or any other physical/chemical parameter.

The additive approach is apparently very successful in predicting $\log K_{ML}$ for metal-ligand complexes with ligands containing oxygen donor atoms. This may be because replacement of aquo ligands by these donor atoms does not alter the electronic structures (i.e. d orbital splitting) of metal ions (Schalfer and Gliemann, 1969). The additive approach may not be viable when the coordination environment produces a change in geometry (e.g. octahedral to tetrahedral) because the energy levels of d orbitals are affected. The approach for estimating $\log K_{ML}$ for metal complexes is analogous to the estimation method for bond enthalpies of organic chemicals which utilizes an additive approach relying upon typical values for bond within these molecules (e.g. C-C, C-H, etc.).

3.2 Outliers

Based upon its position below the regression lines in Figure 2, oxalic acid is uniquely stronger than its bidentate ligand counterparts. Despite rather acidic carboxylic acid functional groups ($pK_{a1} = 1.255$, $pK_{a2} = 4.266$), it is adept at complexing metal ions. Oxalic acid is distinctive in that it is the only dicarboxylic acid that is capable of forming 5 membered rings. Its position as an outlier was not of concern in LFER development since it sits in its own bidentate ligand category.

Two additional ligand classes fall into the 1- pK_a 6-membered ring category: β -hydroxycarboxylic acids and β -ketocarboxylic acids. Within these two categories, only three ligands were identified in the NIST database (3-hydroxypropanoic acid, 3-hydroxybutanoic acid, and acetoacetic acid). Of these ligands, there were only 17 $\log K_{ML}$ values available for the 21 metal ions considered. For these 1- pK_a ligands, the monodentate LFER provided closer agreement with NIST values than the bidentate LFER. For example, 3-hydroxybutanoic acid has $(\log K_{ML})_{NIST}$ values equal to 0.82 (Ca^{2+}), 1.04 (Zn^{2+}), and 2.98 (UO_2^{2+}). Predictions using the monodentate LFER (Eq. 1) yield values very close to NIST values: 0.88 (Ca^{2+}), 1.39 (Zn^{2+}), and 2.83 (UO_2^{2+}). As a result, these ligand classes were not used to parameterize the bidentate LFER. The closeness with which the NIST values agree with monodentate LFER values suggests that these ligands form monodentate complexes with metal ions.

For salicylic acid, stability constants for Ba^{2+} , La^{3+} , Eu^{3+} , and Th^{4+} from the NIST database were much smaller than bidentate LFER predicted values and were considered outliers. Ba^{2+} , La^{3+} , and Eu^{3+} exhibit $(\log K_{ML})_{NIST}$ values that were very close to those calculated using the monodentate LFER which suggests that the values in the NIST database correspond to measurement of monodentate complexes. Overall, a total of 42 out of 332 values were considered outliers (16 for oxalic acid, 17 for β -hydroxycarboxylic acids and β -ketocarboxylic acids, 4 for salicylic acid) which resulted in use of 290 $\log K_{ML}$ values for the bidentate LFER development.

3.3 The Chelate Effect

The chelate effect (Schwarzenbach, 1952) is a term used to describe the general observation that multidentate ligands form thermodynamically more stable complexes than analogous complexes containing monodentate ligands. In the bidentate LFER, the chelate effect is effectively accounted for by the value of χ^5_{OO} or χ^6_{OO} . Written in terms of the standard Gibbs energy change of reaction, χ_{OO} is a multiplier which increases the contribution of the two binding sites:

$$\Delta G_{ML}^0 = \chi_{OO} \alpha_O (\Delta G_{HL,1}^0 + \Delta G_{HL,2}^0) \quad (10)$$

The interpretation of χ_{OO} is that it is a scaling parameter on the Gibbs energy for metal complex formation that accounts for the chelate effect. The χ_{OO} parameter presented here is an alternative approach to traditional methods of quantifying the chelate effect which provides a simple empirically-derived parameter capable of comparing the magnitude of the effect across metal ions.

The magnitude and chemical origin of the chelate effect has been the subject of much controversy (Martell and Hancock, 1996). The original explanation by Schwarzenbach (1952) was that once the first donor atom had coordinated the metal ion, any subsequent donor atoms moved in a restricted volume about the metal ion. Attempts at quantifying the magnitude of the chelate effect have usually involved comparison of the magnitude of the stability constant of a 1:1 complex (where X is a bidentate ligand):

with the stability constant of a comparable 1:2 complex (where Y is a monodentate ligand) (Martell and Hancock, 1996):

Schwarzenbach (1952) originally suggested that the magnitude of the effect could be simply determined by taking the difference between the stability constants:

$$\text{“chelate effect”} = \log K_1 - \log \beta_2 \quad (13)$$

The proposed definition shown above is now considered to be improper because its magnitude is dependent upon the units of activity chosen to define the reference state of the complexes (Adamson, 1954; Frausto da Silva, 1983).

Adamson (1954) noted that the entropy change for a reaction of the form:

is approximately equal to the translational entropy of the additional solute generated in the reaction. The increase in entropy of translation generated by 1 mole of solute at the standard state of 1.0 M can be written as $\Delta S^0 = R \ln 55.5$, where 55.5 represents the molarity of water (Martell et al., 1994). This theoretical result increases $\log K_{ML}$ by 1.74 (the base 10 logarithm of 55.5) for each chelate ring that forms. Many of the proposals for quantifying the chelate effect that followed have built upon the work of Schwarzenbach and Adamson (Simmons, 1979; Frausto da Silva, 1983; Martell et al., 1994).

3.4 Comparison to Existing Bidentate LFERs

Martell, Hancock and coworkers (1976; 1978; 1996) made use of the Adamson idea to formulate LFERs for the stability constants of bidentate and polydentate ligands. In Figure 4a, a Figure from Martell and Hancock (1996) is reproduced using data from the NIST Critical database. The $(\log K_{ML})_{NIST}$ value for three bidentate ligands containing negatively-charged oxygen donor atoms (catechol, 5-nitrosalicylic acid, and malonic acid) are plotted versus the $(\log K_{ML})_{NIST}$ value for formation of the first metal hydrolysis species. Solid lines are the result of a 1 parameter linear regression where the y-intercept is forced through 1.74.

The Martell and Hancock (1996) LFER shown in Figure 4a takes the form:

$$\log K_{ML, polydentate} = a \log K_{ML, monodentate} + b \quad (15)$$

where a and b are the slope and intercept resulting from the regression. Extrapolation of the data revealed a tendency for bidentate ligands to intercept a $\log K_{ML}$ value close to $\log 55.5$, the theoretical result hypothesized by Adamson (1954). Thus, the intercept was forced through a value of $\log 55.5$, which effectively set the b parameter in Eq. 14 equal to 1.74 for bidentate ligands. For polydentate ligands, the intercept tended towards multiples of $\log 55.5$, depending upon the denticity of the ligand. Thus, the value of b was parameterized as:

$$b = (n - 1) \log 55.5 \quad (16)$$

where n represents the ligand denticity. The value for a increases as the strength of the bidentate ligand increases.

The general forms of Martell and Hancock's polydentate LFER (Eq. 15) and the Irving-Rossotti bidentate LFER (Eq. 7) presented here are different. We opted not to include $\log 55.5$ as a correction for bidentate ligand $\log K_{ML}$ values for two reasons. First, if the same data shown in Figure 4a are regressed using a 2 parameter linear regression (Figure 4b), the intercept increases as the "strength" of the bidentate ligand increases. This phenomenon is consistent with the observation that the χ_{OO} correction increases with increasing values of $\log K_{ML}$ (Figure 2).

Secondly, the lack of an intercept in Eq. 7 permits the formulation of useful mathematical relationships between monodentate and bidentate stability constants. This is illustrated in Figure 4c and 4d. In Figure 4c $(\log K_{ML})_{NIST}$ values for the same three bidentate ligands shown in Figure 4a and 4b are plotted versus the Irving-Rossotti slope, α_O . In Figure 4d, $(\log K_{ML})_{NIST}$ values are normalized to the sum of the ligand pK_a values and plotted versus α_O . The dashed and solid lines represent results from 1 and 2 parameter linear regressions, respectively. The dashed line has a slope of 1.33.

The excellent relationship between $(\log K_{ML})_{NIST}$ and α_O (Figure 4c) is somewhat expected as a result of the relation between α_O and $\log K_{ML}$ ($L = OH^-$) (Carbonaro and Di Toro, 2007). The relationship between $(\log K_{ML} / (pK_{a1} + pK_{a2}))_{NIST}$ and α_O (Figure 4d) was not anticipated but is very instructive. The bidentate ligand $\log K_{ML}$ value normalized to the sum of the pK_a values increases as a function of α_O with an intercept nearly equal to zero. Note that the data points shown in Figure 4d are the same data shown in Figure 4a and represent 20 different metals and 3 different bidentate ligands. All data points conform to the same regression line with a moderate amount of variability. Expansion to all 230 data points

used in the LFER development (Figure 5) yielded similar results with a slope equal to 1.44 (intercept forced through zero) and an r^2 of 0.779.

The relationship shown in Figure 4d and in Figure 5 can be derived directly from the bidentate LFER (Eq. 7). Dividing both sides of Eq. 7 by $(pK_{a1} + pK_{a2})$ results in an equation of the form:

$$\log K_{ML} / (pK_{a1} + pK_{a2}) = \chi_{OO} \alpha_O \quad (17)$$

Plotting the left hand side of Eq. 17 versus α_O yields a linear relationship of slope χ_{OO} . The variability seen in the $\log K_{ML}$ values of Figure 4d results from different metals possessing slightly different values of χ_{OO} (Table 2). These results suggest that a rough approximation of the $\log K_{ML}$ value for bidentate ligands can be obtained through the use of a “universal χ_{OO} ” value of 1.44.

3.5 Error Analysis

The predictive capabilities of the bidentate LFER were assessed by calculating the RMSE for each metal ion using χ^5_{OO} or χ^6_{OO} for 5 and 6-membered rings respectively. These values are listed in Table 2. All of the RMSE values are less than 0.50, and the majority of values were less than 0.35. The first row transition metals for which the dataset was largest yielded RMSE values between 0.21 and 0.37.

To visualize the overall error associated with the LFER predictions, $(\log K_{ML})_{NIST} - (\log K_{ML})_{SUM}$ and $(\log K_{ML})_{NIST} - (\log K_{ML})_{LFER}$ are shown in Figure 6 a) and b) for all metals and ligand combinations used in the LFER development. The improvement upon adding the χ^5_{OO} and χ^6_{OO} correction is evident. Only 16 out of 290 (5.5%) $\log K_{ML}$ values showed differences between $(\log K_{ML})_{NIST}$ and $(\log K_{ML})_{LFER}$ of greater than 1.0.

The four circles grouped together in Figure 6b at a $(\log K_{ML})_{NIST}$ value of around 5.0 and an error of approximately +2 are for Th^{4+} . This large error is the result of a single data point which has undue weight in the Th^{4+} 1 parameter regression (Figure 2, Th^{4+} panel, blue circle). If this point is removed from the regression, the value of χ^5_{OO} increases from 1.02 to 1.56 and the errors become considerably less than 1.0 unit. The value of 1.56 for χ^5_{OO} (Th^{4+}) falls more in line with the other metal ions and the “universal χ ” value of 1.44.

In Figure 7, LFER $\log K_{ML}$ values are plotted versus the NIST value for 5 first row divalent transition metal ions and calcium. The symbol notation is the same as in Figure 1. Perfect agreement between LFER and NIST values is indicated by the 1:1 line. The dashed lines represent error of ± 1.0 unit. For the six metals shown, all errors are within ± 1.0 unit. The box plot inset displays the 10th, 25th, 50th, 75th and 90th percentile prediction errors. Median (50th percentile) values are very close to zero indicating minimal prediction bias.

3.6 Estimation of Binding Constants for Metal-NOM Complexation

Since LFERs now exist for estimating $\log K_{ML}$ values for monodentate and bidentate 1:1 complexes, it is instructive to compare estimated $\log K_{ML}$ values to what is used in current metal-NOM speciation models. NOM is assumed to contain the same functional groups (i.e. carboxylic acids and phenols) as was used to develop the Irving-Rossotti LFERs. The comparison shown here is for WHAM VI, which has gained wide usage and acceptance in speciation modeling of aquatic systems. A brief description of the proton and metal binding description in WHAM VI is presented in the Electronic Annex.

To test the realism of the equilibrium constants in WHAM VI, $\log K_{ML}$ values for monodentate and bidentate ligands were calculated using the pK_a values of the Type A (carboxylic acid) and Type B (phenolic) proton binding sites. The resulting LFER $\log K_{ML}$ constants are analogous to the WHAM VI $\log K_i$ and $\log K_{i,j}$ constants (see the Electronic Annex). The comparisons are presented for Cu^{2+} in Figure 8a for monodentate binding to WHAM VI humic acid and fulvic acid. In general, monodentate LFER constants are smaller than their WHAM VI counterparts. This is particularly true for the type B sites with pK_a values greater than 7.0 where differences are greater than 1.0 unit. The Type A sites are much closer in magnitude and show differences of less than 1.0 unit.

A similar analysis for bidentate constants is presented in Figure 8b, except the horizontal axis represents the average pK_a value of the bidentate ligand. The LFER constants pass through the “weak” WHAM VI constants for average pK_a values less than 7.0. For average pK_a values greater than 7.0, the LFER constants pass through the “medium” WHAM VI constants. This is true for both WHAM VI humic acid and fulvic acid constants.

The analysis presented in Figure 8 sheds light on the magnitude and distribution of the binding constants used in WHAM VI. The WHAM VI Type B monodentate constants have considerably larger $\log K_{ML}$ values than those estimated from the LFER. The “weak” and “moderate” WHAM VI bidentate sites fall somewhat in line with LFER calculated values, however the “strong” sites have values anywhere from 3 to 5 units larger than LFER calculated values. The “strong” bidentate sites in WHAM VI have constants too large to represent bidentate ligands containing negatively charged oxygen donor atoms. It is possible that these low abundance strong sites in WHAM VI represent nitrogen or sulfur donor atoms which are expected to exhibit larger stability constants with metal ions.

It is also important to note that for both monodentate and bidentate constants, the LFER $\log K_{ML}$ values show a linear relationship with the pK_a or average pK_a value in accordance with Eq. 1 and Eq. 7 respectively. The WHAM VI constants do not show this relationship as a result of their unique parameterization (see Electronic Annex). As metal-NOM speciation models continue to evolve, these observations may be potentially useful.

4. Conclusions

Equilibrium speciation modeling software such as MINTEQA2, MINEQL+, WHAM and PHREEQC have extensive databases of metal-ligand stability constants, however, they are not comprehensive. Filling data gaps via experimental measurement is not practicable due to the large effort involved (Dimmock et al., 1995). The bidentate LFER (Eq. 7) provides an alternate means of estimating the $\log K_{ML}$ value for 1:1 metal complexes with bidentate ligands containing negatively charged oxygen donor atoms, and can be used quite easily to supplement databases where data gaps are present. Predictions are accurate to approximately 0.3 log units based upon RMSE values. The bidentate LFER has only two metal-specific parameters (α_O and χ_{OO}) and use of the LFER requires knowledge of only the pK_a value(s) of the bidentate ligand, and the number of atoms in the chelate ring. Unlike previous LFERs, parameters for a large number of metal ions (Table 2) are available.

Applications of this LFER extend past simple $\log K_{ML}$ prediction for small organic molecules. Since NOM contains many of the same functional groups (i.e. carboxylic acids, phenols, alcohols), the LFER $\log K_{ML}$ predictions shed light on the range of appropriate values for use in modeling metal partitioning in natural systems. Extension of these LFERs to other functional groups such as neutral nitrogen donor atoms and negatively charged sulfur donor atoms is possible and will be described in future publications.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

- Acton, F. Analysis of Straight Line Data. Dover Publications, Inc.; New York, NY: 1966.
- Adamson AW. A proposed approach to the chelate effect. *J Am Chem Soc.* 1954; 76:1578–1579.
- Atalay YB, Carbonaro RF, Di Toro DM. Distribution of Proton Dissociation Constants for Model Humic and Fulvic Acid Molecules. *Environ Sci Technol.* 2009; 43:3626–3631. [PubMed: 19544864]
- Brönsted JN, Pedersen K. Die katalytische zersetzung des Nitramids und ihre physikalisch-chemische bedeutung. *Z Phys Chem.* 1924; 108:185–235.
- Cabaniss SE. Quantitative structure-property relationships for predicting metal binding by organic ligands. *Environ Sci Technol.* 2008; 42:5210–5216. [PubMed: 18754371]
- Carbonaro RF, Di Toro DM. Linear free energy relationships for metal–ligand complexation: Monodentate binding to negatively-charged oxygen donor atoms. *Geochim Cosmochim Acta.* 2007; 71:3958–3968.
- Carey, FA. Organic Chemistry. McGraw Hill; 2007.
- Davies, CW. Ion Association. Butterworths; Washington D.C.: 1962.
- Dimmock PW, Warwick P, Robbins RA. Approaches to predicting stability constants. *Analyst.* 1995; 120:2159–2170.
- Frausto da Silva JJR. The chelate effect redefined. *J Chem Ed.* 1983; 60:390–null.
- Hammett LP. Some relations between reaction rates and equilibrium constants. *Chem Rev.* 1935; 17:125–136.
- Hammett LP. The effect of structure upon the reactions of organic compounds benzene derivatives. *J Am Chem Soc.* 1937; 59:96–103.
- Hammett LP. Linear free energy relationships in rate and equilibrium phenomena. *Trans Faraday Soc.* 1938; 34:0156–0164.
- Hancock RD, Marsicano F. Chelate effect - Simple quantitative approach. *Journal of the Chemical Society - Dalton Transactions.* 1976:1096–1098.
- Hancock RD, Marsicano F. Parametric correlation of formation constants in aqueous solution. 1. Ligands with small donor atoms. *Inorg Chem.* 1978; 17:560–564.
- Harris WR. Structure-reactivity relation for the complexation of Ni, Cd, Zn, and Fe. *J Coord Chem.* 1983; 13:17–28.
- Hertkorn N, Perdue EM, Ketrup A. A potentiometric and Cd-113 NMR study of cadmium complexation by natural organic matter at two different magnetic field strengths. *Anal Chem.* 2004; 76:6327–6341. [PubMed: 15516125]
- Hilal SH, El-Shabrawy Y, Carreira LA, Karickhoff SW, Toubar SS, Rizk M. Estimation of the ionization pK_a of pharmaceutical substances using the computer program SPARC. *Talanta.* 1996; 43:607–619. [PubMed: 18966526]
- Irving H, Rossotti H. Some relationships among the stabilities of metal complexes. *Acta Chem Scand.* 1956; 10:72–93.
- Jones DL. Organic acids in the rhizosphere – a critical review. *Plant and Soil.* 1998; 205:25–44.
- Larive CK, Rogers A, Morton M, Carper WR. Cd-113 NMR binding studies of Cd - Fulvic acid complexes: Evidence of fast exchange. *Environ Sci Technol.* 1996; 30:2828–2831.
- Leenheer JA, Brown GK, MacCarthy P, Cabaniss SE. Models of metal binding structures in fulvic acid from the Suwannee River, Georgia. *Environ Sci Technol.* 1998; 32:2410–2416.

- Leenheer JA, Wershaw RL, Reddy MM. Strong-Acid, Carboxyl-Group Structures in Fulvic Acid from the Suwannee River, Georgia. 1. Minor Structures. *Environ Sci Technol*. 1995a; 29:393–398.
- Leenheer JA, Wershaw RL, Reddy MM. Strong-Acid, Carboxyl-Group Structures in Fulvic Acid from the Suwannee River, Georgia. 2. Major Structures. *Environ Sci Technol*. 1995b; 29:399–405.
- Marschner, H. Mineral Nutrition of Higher Plants. Second. Academic Press; 1995.
- Martell, AE.; Hancock, RD. Metal Complexes in Aqueous Solution. Plenum Press; New York: 1996.
- Martell AE, Hancock RD, Motekaitis RJ. Factors affecting stabilities of chelate, macrocyclic and macrobicyclic complexes in solution. *Coord Chem Rev*. 1994; 133:39–65.
- Martell AE, Smith RM, Motekaitis RJ. NIST Critically Selected Stability Constants of Metal Complexes. NIST. 2004
- Morel, FMM.; Hering, JG. Principles and Applications of Aquatic Chemistry. J. Wiley & Sons, Inc.; New York: 1993.
- Nieboer E, McBryde WAE. Free-energy relationships in coordination chemistry. I. Linear relationships among equilibrium constants. *Can J Chem*. 1969; 48:2549–2573.
- Peters, DG.; Hieftje, GM.; Hayes, JM. Chemical Separations and Measurements: Theory and Practice of Analytical Chemistry. Saunders College Publishing; Philadelphia, PA: 1974.
- Portanova R, Lajunen LH, Tolazzi M, Piispanen J. Critical evaluation of stability constants for alpha-hydroxycarboxylic acid complexes with protons and metal ions and the accompanying enthalpy changes Part II. Aliphatic 2-hydroxycarboxylic acids. *Pure Appl Chem*. 2003; 75:495–540.
- Schaller, HL.; Gliemann, G. Basic Principles of Ligand Field Theory. Wiley-Interscience; New York: 1969.
- Schilling M, Cooper WT. Identification of copper binding sites in soil organic matter through chemical modifications and (CP)-C-13-MAS NMR spectroscopy. *Environ Sci Technol*. 2004; 38:5059–5063. [PubMed: 15506199]
- Schwarzenbach G. Der Chelateffekt. *Helv Chim Acta*. 1952; 35:2344–2359.
- Simmons EL. More on the chelate effect. *J Chem Ed*. 1979; 56:578–579.
- Smith RM, Martell AE, Motekaitis RJ. Prediction of stability constants. I. Protonation constants of carboxylates and formation constants of their complexes with class a metal ions. *Inorg Chim Acta*. 1985a; 99:207–216.
- Smith RM, Motekaitis RJ, Martell AE. Prediction of stability constants. II. Metal chelates of natural alkyl amino acids and their synthetic analogs. *Inorg Chim Acta*. 1985b; 103:73–82.
- Stevenson, FJ. Geochemistry of soil humic substances. In: Aiken, GR.; McKnight, DM.; Wershaw, RL.; MacCarthy, P., editors. Humic substances in soil, sediment and water. Wiley; New York: 1985.
- Tipping E. WHAM - A chemical equilibrium model and computer code for waters, sediments, and soils incorporating a discrete site/electrostatic model of ion-binding by humic substances. *Comp Geosci*. 1994; 20:973–1023.
- Tipping E. Humic ion-binding model VI: An improved description of the interactions of protons and metal ions with humic substances. *Aquat Geochem*. 1998; 4:3–48.
- Tipping, E. Cation Binding by Humic Substances. Cambridge University Press; Cambridge, UK: 2002.
- Williams, AA. Free Energy Relationships in Organic and Bioorganic Chemistry. Royal Society of Chemistry; 2003.

Figure 1.

Predicted Cu^{2+} $(\log K_{\text{ML}})_{\text{SUM}}$ values versus observed $(\log K_{\text{ML}})_{\text{NIST}}$ values for a series of bidentate ligands ($n = 36$) containing negatively-charged and neutral oxygen donor atoms. Circles and triangles represent ligands that form 5-membered rings and 6-membered rings respectively. Open symbols represent ligands that possess functional groups that exhibit two pK_{a} values in the database (e.g. 7. isopropylmalonic acid). Filled symbols represent ligands that possess functional groups that exhibit one pK_{a} in the database (e.g. 1. glyoxylic acid). The solid line represents results from linear regression analysis with the intercept forced through zero (slope = 0.678, $r^2 = 0.986$).

Figure 2. Predicted $(\log K_{ML})_{SUM}$ values versus $(\log K_{ML})_{NIST}$ values for a series of bidentate ligands containing negatively-charged oxygen donor atoms for 20 metal ions. See the Figure 1 caption for symbol notation. The reciprocal slope, χ_{OO} , and number of data points used in linear regression analysis, n , are indicated on each plot.

Figure 3. Bidentate LFER parameters, χ_{OO} , χ^5_{OO} , and χ^6_{OO} for alkaline earth metals, and first row transition metals. Error bars represent 95% confidence intervals obtained from 1 parameter linear regressions as discussed in the text.

Figure 4.

In a), the $(\log K_{ML})_{NIST}$ value for three bidentate ligands containing negatively-charged oxygen donor atoms (catechol, 5-nitrosalicylic acid, and malonic acid) are plotted versus the $(\log K_{ML})_{NIST}$ value for formation of the first metal hydrolysis species. Solid lines are the result of a 1 parameter linear regression where the line is forced through $(0, \log 55.5)$. In b), the same data is plotted as in a), except that the solid lines represent the results of 2 parameter linear regressions. In c), $(\log K_{ML})_{NIST}$ values for the same three bidentate ligands are plotted versus the Irving-Rossotti slope, α_O . In d), the NIST $\log K_{ML}$ values normalized to the sum of the ligand pK_a values are plotted against α_O . The dashed and solid lines represent results from 1 and 2 parameter linear regressions, respectively.

Figure 5.

The NIST $\log K_{ML}$ values normalized to the sum of the ligand pK_a values are plotted against α_O for 290 metal-ligand stability constants. The solid line represents results from a 1 parameter linear regression which yielded a reciprocal slope (universal χ) of 1.44.

Figure 6.

In a) the difference between the NIST and SUM log K_{ML} values are plotted versus the NIST value. In b), the difference between the NIST and LFER log K_{ML} values are plotted versus the NIST value. In both a) and b), all of the data used to develop the bidentate LFER is shown for all 21 metals. The symbol notation is the same as used in Figure 1.

Figure 7.

LFER log K_{ML} values are plotted versus the NIST value for 5 first row divalent transition metal ions and calcium. The solid lines represent 1:1 lines. Dashed lines are offset by 1 unit from the 1:1 line. Insets to each plot are box and whisker representations of the 10th, 25th, 50th, 75th and 90th percentile prediction error. Data points in the inset represent errors falling less than 10th and greater than the 90th percentiles, respectively.

Figure 8.

Irving-Rossotti LFER calculated Cu^{2+} $\log K_{\text{ML}}$ for WHAM VI a) monodentate and b) bidentate ligands. In a), the x-axis represents the pK_a values used for monodentate sites in WHAM VI. In b), the x-axis represents the average pK_a values used for bidentate sites in WHAM VI. Triangles and squares represent $\log K_{\text{ML}}$ values used in WHAM VI. Circles represent $\log K_{\text{ML}}$ values calculated using the Irving-Rossotti LFERs.

Table 1

Summary of ligands used to construct the bidentate LFER⁽¹⁾.

Category	Ring Size	Number of pK _a values	n	Example(s)
Dicarboxylic acids	5	2	1	oxalic acid ⁽²⁾
Dicarboxylic acids	6	2	12	malonic acid, benzylmalonic acid
<i>ortho</i> -Diphenols	5	2	5	catechol, 4-chlorocatechol
<i>ortho</i> -Carboxyphenols	6	2	9	salicylic acid, <i>m</i> -cresotic acid
<i>ortho</i> -Hydroxybenzaldehydes	6	1	5	salicylaldehyde, 5-nitrosalicylaldehyde
α -Hydroxycarboxylic acids	5	1	8	glycolic acid, mandelic acid
α -Ketocarboxylic acids	5	1	3	glyoxylic acid, pyruvic acid

⁽¹⁾ A full listing of ligands and pK_a values can be found in the Electronic Annex (Table 1).

⁽²⁾ The log K_ML for oxalic acid was consistently under-predicted, therefore it was not used to calibrate the LFER.

Table 2

Summary of monodentate and bidentate LFER parameters for negatively-charged oxygen donor atoms.

Metal ion	$\alpha_0(I)$	χ_{OO}	χ^5_{OO}	χ^6_{OO}	RMSE
<i>Alkaline earths</i>					
Be ²⁺	0.433	1.65 ± 0.17 (n = 11)	1.39 ± 0.11 (n = 4)	1.87 ± 0.05 (n = 7)	0.18
Mg ²⁺	0.196	1.96 ± 0.21 (n = 14)	1.94 ± 0.31 (n = 5)	1.97 ± 0.30 (n = 9)	0.34
Ca ²⁺	0.194	1.50 ± 0.18 (n = 16)	1.92 ± 0.12 (n = 6)	1.31 ± 0.12 (n = 10)	0.15
Si ²⁺	0.171	1.35 ± 0.20 (n = 8)	1.25 ± 0.32 (n = 5)	1.52 ± 0.04 (n = 3)	0.07
Ba ²⁺	0.158	1.40 ± 0.18 (n = 9)	1.24 ± 0.16 (n = 5)	1.60 ± 0.09 (n = 4)	0.05
<i>First row transition</i>					
Mn ²⁺	0.255	1.55 ± 0.09 (n = 12)	1.55 ± 0.11 (n = 7)	1.54 ± 0.21 (n = 5)	0.21
Fe ²⁺	(0.287)	(1.43) (n = 4)	(1.38) (n = 2)	(1.51) (n = 2)	---
Co ²⁺	0.306	1.42 ± 0.06 (n = 18)	1.43 ± 0.07 (n = 7)	1.41 ± 0.11 (n = 11)	0.26
Ni ²⁺	0.301	1.51 ± 0.06 (n = 23)	1.52 ± 0.08 (n = 9)	1.51 ± 0.10 (n = 14)	0.33
Cu ²⁺	0.466	1.47 ± 0.03 (n = 35)	1.45 ± 0.07 (n = 12)	1.48 ± 0.03 (n = 23)	0.37
Zn ²⁺	0.304	1.52 ± 0.06 (n = 27)	1.61 ± 0.09 (n = 10)	1.45 ± 0.07 (n = 17)	0.32
Fe ³⁺	0.861	1.19 ± 0.05 (n = 15)	1.12 ± 0.06 (n = 4)	1.24 ± 0.04 (n = 11)	0.35
<i>Second row transition</i>					
Cd ²⁺	0.306	1.30 ± 0.05 (n = 18)	1.36 ± 0.06 (n = 7)	1.24 ± 0.08 (n = 11)	0.17
Ag ⁺	(0.177)	(1.38) (n = 4)	---	(1.41) (n = 3)	
<i>Post-transition</i>					
Al ³⁺	0.607	1.39 ± 0.09 (n = 9)	1.31 ± 0.12 (n = 4)	1.46 ± 0.12 (n = 5)	0.29
Pb ²⁺	0.442	1.17 ± 0.34 (n = 6)	1.57 ± 0.32 (n = 4)	(1.02) (n = 2)	0.09
<i>Lanthanides</i>					
La ³⁺	0.414	1.30 ± 0.12 (n = 17)	1.29 ± 0.23 (n = 9)	1.32 ± 0.07 (n = 8)	0.47
Ce ³⁺	0.451	1.39 ± 0.20 (n = 11)	1.82 ± 0.15 (n = 7)	1.24 ± 0.18 (n = 4)	0.15
Eu ³⁺	0.530	1.18 ± 0.12 (n = 13)	1.17 ± 0.19 (n = 9)	1.19 ± 0.05 (n = 4)	0.47
<i>Actinides</i>					

Metal ion	$\alpha_0^{(I)}$	χ_{00}	χ_{500}^5	χ_{600}^6	RMSE
Th ⁴⁺	0.902	1.04 ± 0.25 (n = 6)	1.02 ± 0.25 (n = 5)	---	0.58
UO ₂ ²⁺	0.621	1.23 ± 0.05 (n = 15)	1.14 ± 0.09 (n = 6)	1.28 ± 0.02 (n = 9)	0.26

^(I) Values for α_0 are from Carbonaro and Di Toro (2007).