Conference Proceedings. Spring-fed Wetlands: Important Scientific and Cultural Resources of the Intermountain Region, 2002.
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Solute Composition: A Parameter Affecting the Distribution of Freshwater Gastropods

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Abstract

Paired water and gastropod samples were collected from 90 lakes, springs, and wetlands throughout the northwestern quarter of the U.S. Results suggest that a strong relation exists between the solute composition and concentration of water and the occurrence of gastropods. Solute composition refers to bicarbonate-carbonate, sulfate, and chloride anions, and sodium, calcium, potassium, and magnesium cations that make up the dominant ions within natural waters. Concentration can be considered to be the sum of ion concentration per liter and expressed as total dissolved solids (TDS) in solution.

Conclusions include: 1) solute composition appears to be at least as important as concentration for species occurrence, 2) the relative proportion of bicarbonate-carbonate and calcium can serve as an isolating mechanism for the distribution of these taxa, and 3) the underlying cause for this distribution appears to be closely linked to the geochemical solute branchpoint process. For example, *Valvata* inhabit only waters where bicarbonate-carbonate is equal to or greater than calcium. *Fossaria* occur in waters where bicarbonate-carbonate is less than calcium at higher TDS levels, whereas *Gyraulus* are found in waters dominated by either greater bicarbonate-carbonate or calcium.

Introduction

The environmental parameters affecting the distribution of aquatic mollusks are not well understood, however, it is generally accepted that the distribution of freshwater mollusks varies with physical, chemical, and biological characteristics (Thorp and Covich 1991; Pennak 1989; see Hutchinson 1993). Primary factors reported to restrict molluscan occurrence are pH, total dissolved solids (TDS), dissolved oxygen, water temperature, substrate, water depth, food supply, competition, and predation.

This paper discusses how the chemical characteristics of hydrological settings such as lakes, springs, and wetlands can determine the occurrence of gastropods. Chemical characteristics involve both the composition and concentration of the dissolved ions or solutes. Solute composition refers to the kind and relative amount of the anions (bicarbonate-carbonate, sulfate, and chloride), and the cations (sodium, calcium, potassium, and magnesium) that make up the dominant ions within natural waters. Solute concentration can be considered to be the sum of ion concentration per liter and expressed as TDS or the weight of salts in solution. The results of this study suggest that molluscan occurrence and distribution are more complicated than is realized and that Ca, HCO_3, and TDS are critical in terms of the occurrence, distribution, ecology, environmental tolerance, speciation, and evolution of freshwater gastropods.

The idea that HCO_3 and Ca might be important to molluscan distribution has been in print for over 50 years. The availability of calcium, in either the water or food supply, and differing calcium requirements have been cited as important to the occurrence of mollusks (deVorges 1903; Juday *et al*. 1935, 1939; Hunter and Hunter 1956; Hubendick 1957; Hunter 1957a,b; Russell-Hunter 1957; van der Borght 1962; van der Borght and van Puymbroeck 1964; Greenaway 1971; and Young 1975a). Boycott (1936); Macan (1950); Williams (1970); and Young (1975b) found that the occurrence of freshwater mollusks, calcium, and bicarbonate (alkalinity) are correlated, but the underlying causes of these relations remained unclear. However, Macan (1950), working with the tarns in the English Lakes District, was the first to suggest that the ratio of Ca to HCO_3 might be important to molluscan occurrence. He divided lakes into three chemical categories using calcium and bicarbonate. Hutchinson (1993) also alluded to the importance of the $HCO_3(CO_3)$/Ca ratio using Morrison's (1932) data. Unfortunately, none of the above studies discovered a clear pattern to gastropod or bivalve distribution and the solute content of their host water.

It wasn't until the disciplines of biology, geology, and hydrochemistry were integrated that a clearer understanding of how hydrochemistry can influence the distribution of taxa occurred (Forester 1983, 1987, 1991). The parameters Ca, HCO_3, and TDS are part of a chemical process termed solute evolution (Jones 1966; Hardie and Eugster 1970; Eugster and Jones 1979; Jones and Deocampo 2003), which is based on chemical properties.

Methods

Water and gastropods were collected from 90 modern lakes, springs, and wetlands on an effective moisture (precipitation minus evaporation) gradient (-100 to +30 cm per year) across the northwestern quarter of the U.S. (Figure 1) to provide the wide geographic and elevational components needed for this study. Data collected from these locations include:

- dissolved solute composition (Ca, Mg, Na, K, SO_4, Cl, $HCO_3(CO_3)$, F)
- solute concentration or TDS
- pH, conductivity, and alkalinity
- trace elements (Ba, B, Fe, Pb, Mn, Sr, Zn, Li)
- Live handpicked gastropods and sediment samples containing gastropods
- temperature (air, water surface, water and sediment interface, sediment 1 cm below sediment water interface, and shoreline mud)
- site description (depth at sampling location, size and characteristics of water body, vegetation, and fauna).

Water samples were collected and analyzed in accordance with U.S. Geological Survey (USGS) procedures. Statistical analyses were performed on Statistical Analysis Software (SAS Institute 1982, 1985; Hair *et al*. 1995).

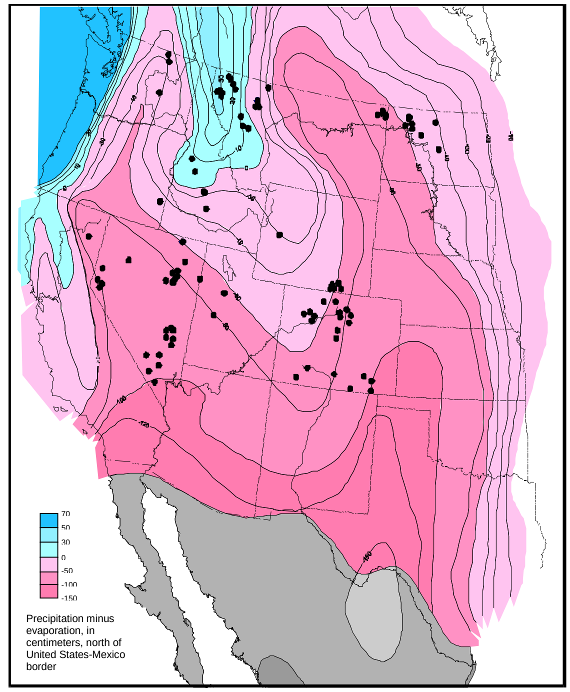

Figure 1. Mollusk sample sites relative to effective moisture, cm/year (from Winter 1990).

Results and Discussion

Lakes, springs, and wetlands in 10 western states were sampled to examine distribution patterns of gastropods. Twenty-three genera and 33 species were recovered from the 90 localities sampled. Some aquatic environments distributed over a large geographical area were found to have a similar solute composition. Conversely, some aquatic environments located in close proximity had substantial differences in solute composition. This is likely due to climate-hydrologic and rock-water differences. Thus, this dataset includes localities with molluscan assemblages from areas with similar climate and widely varying water composition.

Multivariate Analysis of Variance (MANOVA) procedure with 22 predictor variables and 205 observations determined which variables were significant in separating eight genera: *Fossaria*, *Gyraulus*, *Physella*, *Planorbella*, *Valvata*, *Stagnicola*, *Pisidium*, and

Sphaerium. Variables considered included major solutes (Ca, Mg, Na, K, SO_4, F, Cl, and HCO_3), total dissolved solids, HCO_3:Ca ratio, trace elements (Ba, B, Mn, Zn, Li, Pb, Sr, and Fe), precipitation-evaporation ratio, and temperature of the water-sediment interface.

Variables with a significance level less than 0.10 were retained. These included Li (P=0.0287), Sr (P=0.0112), Ca (P=0.0008), Mg (P=0.0061), TDS (P=0.0001), HCO_3:Ca (P=0.0654), and precipitation-evaporation ratio (P=0.0155). Next, correlation analysis determined which of these significant variables were highly correlated. Of these variables, only Ca and Sr were correlated (R^2=.89, n=200, P=0.0001). Discriminant analysis with backwards elimination was used to determine which of the remaining variables (Ca, TDS, HCO_3/Ca, and precipitation-evaporation ratio) were the most important in separating genera. Different combinations were used, although Ca and HCO_3/Ca were never used in the same analysis. Transformations (log and natural log) for scaling were made on HCO_3/Ca ratio and TDS.

Three predictor variables, calcium, bicarbonate, and TDS, produced good results. Multivariate analyses on all observations show that Ca, HCO_3, and TDS are highly significant in separating genera (Wilks lambda statistic: 0.77, F=18, 532; 2.802, P value=0.0001). The first eigenvalue accounts for 72 percent of the variation in the data set. Based on structure coefficients, canonical variable (function) 1 is primarily determined by TDS (89 percent) and Ca (71 percent) whereas canonical variable (function) 2 is based primarily on HCO_3 (83 percent).

Solutes: A Short Primer

The statistical analysis suggested that Ca, HCO_3, and TDS are all highly significant in separating genera. This raises the question of how and why these hydrochemical parameters are related to the distribution of particular molluscan genera. In other words, is there a hydrochemical process that might explain or drive this gastropod distribution?

Solute composition (the relative kind and amount of different ions) is influenced by climate variation, hydrologic setting and process, and local geology (Gorham 1961; Jones 1966; Jones and Bowser 1978; Eugster and Hardie 1978; Eugster and Jones 1979). The solute composition of water changes with mineral precipitation and other processes such as water-rock interactions, redox reactions, and clay mineral exchange (described by Jones 1966; Eugster and Hardie 1978; Thomas *et al.* 1996). Mineral precipitation occurs when waters reach calcite saturation. This can be brought about by decreased effective moisture, which often causes water to evaporate and concentrate solids. Other processes, such as solute addition from water-rock interactions including salt dissolution can also increase and concentrate solids. Redox reactions can concentrate solids through exchange between surface and sediment pore waters. Finally, clay mineral exchange can alter solute composition, such as when calcium in solution is exchanged for sodium.

As carbonate minerals (typically calcite) precipitate under equilibrium or nonequilibrium conditions, the solutes eventually become either enriched or depleted in Ca or HCO_3(CO_3). Figure 2 shows the ratio of bicarbonate to calcium in solution versus TDS for individual aquatic environments (diamonds) located throughout the United States (Forester, Smith, Palmer, Curry, unpublished data). Calcite saturation commonly occurs at about 200 to 300 mg/l TDS. At saturation, Ca and HCO_3 are removed in equal molar proportion with the precipitation of calcium carbonate. As TDS increases, the ion with the initial greater concentration will remain after the other ion is depleted. Aquatic environments with greater initial calcium than HCO_3 will deplete the water of HCO_3 (green ellipse). The reverse is true for aquatic environments with initially more HCO_3 than calcium (pink ellipse). Concomitant with this removal is the relative increase in the concentration of other ions.

The depletion of Ca or HCO_3 typically occurs between about 1,200 and 1,600 mg/l TDS in North American waters (Forester *et al.* in review). This is considered to be a triple-point junction of waters with either greater Ca or HCO_3 relative to the other ion, or equal amounts

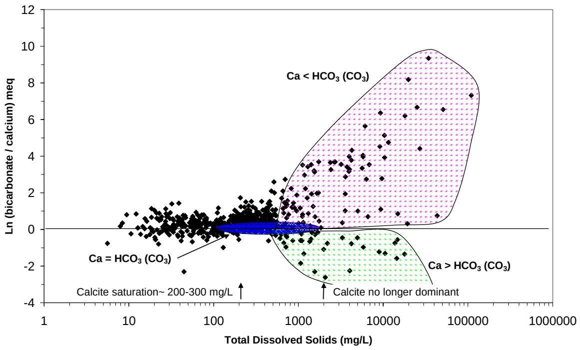

Figure 2. Ratio of calcium to bicarbonate as a function of TDS.

of each ion. Beyond this TDS range, the water is no longer a $CaCO_3$-dominated water. In other words, waters that were dominated by $CaCO_3$ below approximately 1,600 mg/l TDS are depleted of $CaCO_3$ above approximately 1,600 mg/l TDS. It is this junction of different hydrochemical waters that is a factor in the occurrence of gastropods.

The Hydrochemical Distribution of Gastropods

The statistical analysis suggested that Ca, HCO_3, and TDS are all highly significant in separating genera. The solute branchpoint theory provided a structure and the chemical basis supporting the statistical selection of these variables. This section describes the occurrence of different genera with respect to these variables and the solute branchpoint theory.

To illustrate the relation between freshwater gastropods and the HCO_3/Ca ratio of the fresh (or slightly saline) water in which gastropods live, three genera are plotted (Figures 3 through 5) as in Figure 2. Each diamond represents a sampled lake, spring, or wetland, with solid diamonds representing localities with gastropods and open diamonds representing localities without mollusks. These diamonds represent the 90 localities sampled for this study. These graphs also depict calcite saturation and the divide between $CaCO_3$-dominated waters and waters dominated by solutes other than $CaCO_3$ at TDS values between approximately 1,200 and 1,600 mg/l TDS.

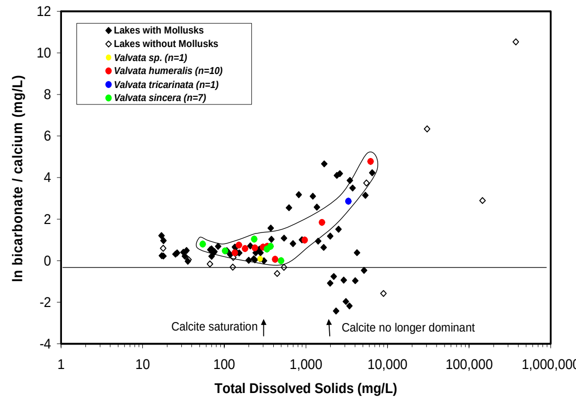

Figure 3. *Valvata* distribution.

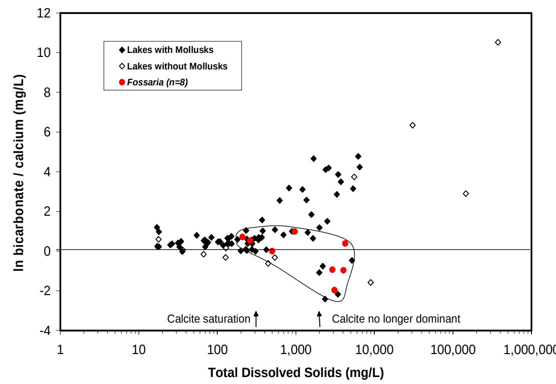

Figure 4. *Fossaria* distribution.

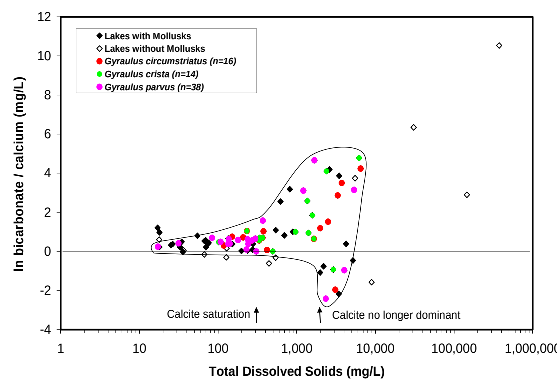

Figure 5. *Gyraulus* distribution.

Valvata spp. (Figure 3) are found exclusively in water with a greater proportion of bicarbonate relative to calcium with water ranging from approximately 60 to 6,220 mg/l TDS. Among the three species found in the dataset, two were common. One, *V. sincera*, has a more limited distribution, so this species may not be able to tolerate waters with as high a TDS and HCO_3 /Ca ratio as *V. humeralis*. However, additional samples are needed to support this hypothesis.

Fossaria spp. (Figure 4) first occur at slightly higher TDS values (210 mg/l TDS) compared to *Valvata*. Note that they first occur near the calcite saturation value of 200 to 300 mg/l TDS. At higher TDS, this genus was recovered in waters dominated by Ca relative to HCO_3, or with almost equal parts Ca and HCO_3. It is possible that *Valvata* and *Fossaria* can co-occur at TDS levels below the TDS where either Ca or HCO_3 are enriched (or depleted) but not above that TDS. However, this data set is small and, again, additional localities should be sampled to support this hypothesis.

Gyraulus spp. were found at lower salinity (17 mg/l TDS) than *Valvata*, yet they range into relatively high TDS waters (6,220 mg/l TDS) (Figure 5). However, *Gyraulus* spp. can tolerate waters dominated by either Ca or HCO_3, suggesting that these gastropods are adapted to more variable environments than either *Valvata* or *Fossaria*. Different species of *Gyraulus* may have different TDS tolerances; for instance, data from this study show that *G. parvus* occurs in lower TDS waters than *G. crista* or *G. circumstriatus*.

The 90 localities sampled suggest that aquatic gastropods show a definable response to hydrochemistry at the generic level. At the species level, there is no subset to the generic pattern of their distribution in solute space. However, with additional samples, a pattern may emerge.

The molluscan taxa inhabiting nearby water bodies can differ if the hydrochemistry of the water differs. For example, two shallow lakes sampled the same day in North Dakota are separated by an approximately 5-m-wide road. The elevation of both lakes is 690 m. The hydrochemistry of the two ponds is very different, most likely due to groundwater-rock interaction. The unnamed lake (48º 33’ 46” N latitude, 102º 24’ 28” W longitude) probably flows into Spring Lake (48º 33’ 46” N latitude, 102º 24’ 26” W longitude) on the other side of the road. The ponds are physically similar, although Spring Lake is bigger and is surrounded by *Scirpus* (bulrush), whereas the unnamed lake is surrounded by *Typha* (cattails). The TDS, HCO_3/Ca ratio, and molluscan taxa are different in each lake (Figure 6). Spring Lake TDS is 4,780 mg/l and the unnamed lake TDS is 1,150 mg/l. They both have greater HCO_3 relative to Ca, although the unnamed lake water falls in the solute field with TDS below Ca enrichment (depletion), whereas Spring Lake falls in the HCO_3 enriched-Ca depleted field. Only *Gyraulus parvus* was collected from Spring Lake; *Gyraulus parvus*, *Gyraulus crista*, *Lymnaea stagnalis*, *Stagnicola elodes*, *Stagnicola* spp., *Physella* sp. *Sphaerium* sp., and Succineidae were collected from the unnamed lake. This suggests that water bodies that are in close proximity may host different taxa because not all taxa can tolerate a high HCO_3/Ca ratio, or simply that not all taxa can tolerate higher levels of TDS.

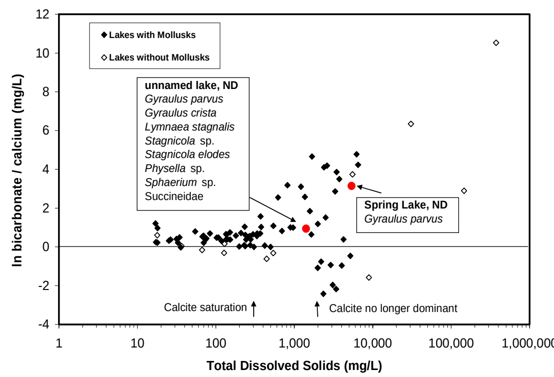

Figure 6. Adjacent lakes with different solute compositions.

Data collected for this study also suggest that water bodies with similar TDS values may host different taxa because of differing HCO_3/Ca ratios. Two lakes in Wyoming were sampled the same day. Lake Hattie (41º 14’ 07” N latitude, 105º 55’ 07” W longitude) has an elevation of 2212.2 m. Lake Gelatt (41º 14’ 14” N latitude, 105º 50’ 10” W longitude) has an elevation of 2211.3 m. Lake Hattie TDS was 2,509 mg/l; Lake Galatt TDS was 2,347 mg/l (Figure 7). However, Lake Hattie had more HCO_3 relative to Ca and Lake Gelatt vise versa. The taxa in each lake are different. Both lakes contained *Gyraulus parvus*, and *Physella* spp. *Pisidium* spp. and *Gyraulus circumstriatus* were collected in Lake Hattie and *Stagnicola* spp. and *Lymnaea stagnalis* were collected in Lake Gelatt.

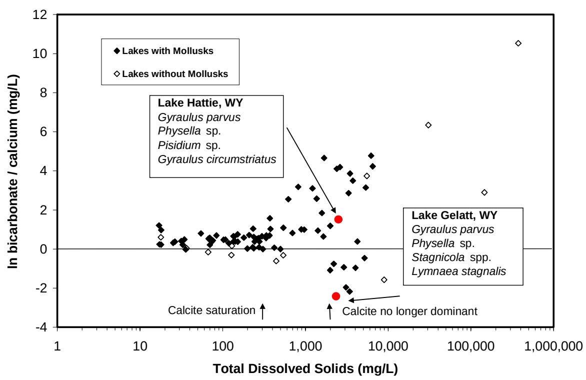

Figure 7. Neighboring lakes with similar TDS and different Ca/HCO_3 ratios.

The difference in the distribution of taxa in these two examples may be due to other environmental parameters, and not solute composition. With additional sampling, these distributions could change substantially. However, genera and species of other aquatic organisms such as ostracodes (Forester 1983, 1987, 1991; Smith 1993), diatoms (Blinn 1993), brine shrimp (Bowen *et al*. 1985), and brine flies (Herbst 2001) are also known to separate according to the HCO_3/Ca ratio.

The genera investigated show different responses to hydrochemistry; they all occupy slightly different chemical fields. Thus, HCO_3 and Ca can serve as isolating mechanisms for the distribution of lake, spring, and wetland gastropods. The genera that inhabit the greatest range of TDS and both HCO_3- and Ca-dominated waters (such as *Gyraulus*) are generalists compared to those genera that are found in a more restricted hydrochemical range (such as *Valvata*). These generalists may be adapted to greater seasonal variation in their habitats. For example, waters in areas of high evaporation might contain a more evolved solute composition with greater Ca or HCO_3. Gastropods able to tolerate a greater range of TDS and both HCO_3- and Ca-dominated water are better adapted to high variability sites than those genera restricted to lower TDS values and only HCO_3-dominated water. Conversely, the hydrochemial distribution of *Valvata* suggests that the waters it inhabits may not fluctuate as widely as those waters where only *Gyraulus* is found.

Whereas other researchers suggest that gastropods are limited by the TDS (concentration) of their host water (Pennak 1989; Hutchinson 1993), this research suggests that the upper TDS tolerated by gastropods in this dataset coincides with the change from water containing calcium and (bi)carbonate to water depleted in these ions. It may be that a primary limiting distribution factor is not high TDS, but is the change in composition from a water containing calcium carbonate to one where these solutes do not occur.

Conclusion

A strong relation exists between the solute composition of water and the occurrence of gastropods. Water and gastropods collected from 90 lakes, springs, and wetlands throughout the northwestern quarter of the U.S. suggest that 1) solute composition appears to be at least as important as concentration (TDS) for species occurrence, 2) the relative proportion of bicarbonate-carbonate and calcium can serve as an isolating mechanism for the distribution of these taxa, and 3) the underlying cause for this distribution appears to be closely linked to the hydrochemical solute triple point junction process (Jones 1966; Hardie and Eugster 1970).

Solute composition can add to our understanding of the distribution of particular genera. Management decisions where solute composition may be a consideration include the enhancement or mitigation of wetlands, change in lake or wetland volume, and change in taxa mortality rate or assemblage composition. Because solute composition is influenced by climate variation, hydrologic setting and process, and local geology, baseline data and continued monitoring of solute composition could be a valuable tool for the management of springs and wetlands. Further field investigation along these lines may result in significant implications for assessing the long-term stability and sensitivity of habitats; sustaining threatened, sensitive, or endemic taxa; colonization issues relating to species isolation between nearby water bodies; designing conservation programs;

resolving wetland/spring mitigation issues; interbasin water transfers; and groundwater pumping.

Acknowledgements

The following individuals and organizations made this research possible. Jim Firby, Rick Forester, Gary Vinyard (deceased), Peter Wigand, Jim Carr, Kelly Conrad, the Jonathan O. Davis Scholarship, and the Desert Research Institute.

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